LIMNOLOGY and OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 69, 2024, 2377–2390

doi: 10.1002/lno.12676

Nature-based shoreline protection in newly formed tidal marshes is controlled by tidal inundation and sedimentation rate

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Abstract

Many tidal marshes have been lost by past land use changes, but are nowadays increasingly restored and created to provide valuable ecosystem services such as nature-based flood and erosion protection along estuarine shorelines. To be functional for flood and shoreline erosion protection, restored and created tidal marshes should develop erosion resistant sediment beds. Here, we investigated which factors drive the spatial variations in sediment strength and erosion resistance in a developing tidal marsh restoration site. Our results show that decreasing tidal inundation frequency, decreasing sedimentation rate, and better drainage led to stronger consolidation in deeper sediment layers. This consolidation resulted in greater sediment strength, quantified here by shear strength and penetration resistance. Generally, sediment strength was greater when sediment had higher bulk density, while a higher water and fine fraction (= clay and silt) content decreased sediment strength. Overall, all measurement locations were relatively erosion resistant, likely caused by the dense root network and cohesive sediment. To restore or create resilient tidal marshes for nature-based flood and shoreline erosion protection, we should thus aim for sites with relatively low tidal inundation frequency, moderate sedimentation rates, and cohesive sediment mixtures of clay, silt, and sand, which are well drained and have potential for vegetation establishment. These conditions have a high likelihood of resulting in restored or created tidal marshes that contribute to nature-based flood and shoreline erosion protection.

Tidal marshes provide many important ecosystem services, such as carbon sequestration (McLeod et al. 2011; Duarte et al. 2013), water purification (Nelson and Zavaleta 2012), shoreline erosion prevention (Lo et al. 2017; Wang et al. 2017), and flood protection (Vuik et al. 2016; Zhu et al. 2020; Temmerman et al. 2023). Tidal marshes contribute to flood protection along estuarine shorelines by attenuating waves (Vuik et al. 2016; Zhu et al. 2020) and reducing the height of storm surges (Smolders et al. 2015; Fairchild et al. 2021). Furthermore, along estuaries where man-made dikes are present, tidal marshes in front of dikes reduce the probability and dimensions of dike breaches during storms (Zhu et al. 2020). Many tidal marshes have been embanked in the past or are currently under pressure from sea-level rise, coastal squeeze, and erosion (Doody 2013; Kirwan and Megonigal 2013). However, the value of tidal marshes as nature-based flood protection and for other ecosystem services is becoming more and more recognized (Barbier et al. 2011), which leads to a strongly increased effort to restore and create new tidal marshes around the world (Gourgue et al. 2022; ABPmer 2023).

Tidal marshes can be restored or created in previously embanked areas, through (1) managed realignment, (2) the

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

Author Contribution Statement: MS: Conceptualization; Methodology; Investigation; Formal analysis; Visualization; Writing – original draft preparation; Writing – review and editing. ST: Funding acquisition; Supervision; Conceptualization; Methodology; Data interpretation; Writing – review and editing. LO: Methodology; Data interpretation; Writing – review and editing. KS: Data interpretation; Writing – review and editing. TM: Conceptualization; Methodology; Resources; Writing – review and editing. JvdK: Funding acquisition; Supervision; Conceptualization; Methodology; Data interpretation; Writing – review and editing. PM: Resources; Writing – review and editing. TB: Funding acquisition; Supervision; Project administration; Conceptualization; Methodology; Data interpretation; Writing – review and editing.

implementation of regulated tidal exchange systems, or (3) the creation of transitional polders. In the case of (1) managed realignment, existing flood defenses are relocated landwards, allowing full tidal exchange between the estuary and newly formed marsh restoration/creation site (French 2006). With (2) the implementation of regulated tidal exchange systems, the tidal exchange occurs through structures (e.g., culverts) installed in the original embankment. Regulated tidal exchange allows for more control over the flood regime than managed realignment and can be used to introduce tidal influence in areas with relatively low elevation, such as flood control areas, designated for safety (Maris et al. 2007; Ridgway and Williams 2011; Temmerman et al. 2013; Masselink et al. 2017). In (3) transitional polders, the restoration/creation of marshes (either by managed realignment or by implementing regulated tidal exchange systems) is used as temporary measure to raise the surface elevation of farmland by sediment accretion. As soon as the surface elevation surpasses the target elevation, the marsh is returned to farmland again (Zhu et al. 2020; Weisscher et al. 2022).

Regardless of the restoration or creation method used, establishment of marshes on an unvegetated tidal area always requires a “window of opportunity” for pioneer species to establish (Balke et al. 2014). That is, seedling establishment requires skipped tidal inundations (Fivash et al. 2023), relatively calm periods to prevent dislodgement by waves and currents (Hu et al. 2015), and relatively stable sediments (Cao et al. 2018). It has been observed at a tidal marsh restoration site that sediment beds at locations with very high sedimentation rates can remain very soft and fluid (Oosterlee et al. 2020). This may be attributed to their relatively low position in the intertidal frame, as sedimentation rates are typically high when the surface elevation of the marsh within the intertidal zone is low. The latter is caused by longer and more frequent tidal inundations, which results in more supply and deposition of fine suspended sediments (Oosterlee et al. 2018; Wang and Temmerman 2013). Such soft and relatively fluid sediments may hamper vegetation establishment (Crooks et al. 2002; Mossman et al. 2012; Cao et al. 2021) and make the sediment beds vulnerable to erosion (Grabowski et al. 2011), resulting in failure to obtain resilient marshes in the long term.

An increase in sediment erosion resistance after deposition can be caused by sediment consolidation (i.e., the increase in sediment strength; Torfs et al. 1996), among other processes. Through consolidation, pore water is expelled from the sediment matrix, which makes the sediment structure denser and hence increases bulk density (Torfs et al. 1996; Brain et al. 2011; Barciela-Rial et al. 2020). There are two types of consolidation that take place in tidal marshes: self-weight consolidation and over-consolidation, also known as drying-induced consolidation. Self-weight consolidation occurs under the weight of sediment particles that are deposited on top (Zhou et al. 2016; Barciela-Rial et al. 2020), while drying-induced consolidation occurs because of sediment drying during low tides (Dong et al. 2020; Colosimo et al. 2023). In fine sediment beds, consisting of clay and silt particles (such as typically deposited in tidal marshes), consolidation increases bulk density, decreases water content, and compacts sediment structure, which all contribute to increasing cohesive strength (Grabowski et al. 2011; Chen et al. 2012; Zhou et al. 2016). Hence, erosion resistance increases when sediments consolidate. In addition to this effect of consolidation, sediment erosion resistance was also observed to increase with decreasing water content (e.g., when sediments become exposed) because of the influence of water content on the mechanical properties of clays (van Ledden et al. 2004; Nguyen et al. 2020).

The temporal development of sediment consolidation, and related sediment properties such as strength and erosion resistance, in new tidal marshes remains poorly documented. Thus, limited insights exist into the main environmental drivers of sediment consolidation and into the role of vegetation. We hypothesize that sediment surface elevation in the intertidal zone, which determines tidal inundation frequency and duration, has an important influence on the drying-induced consolidation rate. Furthermore, the influence of sedimentation rate is difficult to predict, as it may be expected on the one hand that high sedimentation rates can increase self-weight consolidation, but on the other hand can prevent drying-induced consolidation, because the sediment gets buried before drying out (Brain et al. 2011). Oosterlee et al. (2020) showed that rapidly accreting sediments had a low bulk density, remained very fluid and were thus poorly consolidated in a tidal marsh restoration project. Such soft sediments are generally expected to be very vulnerable to erosion when subjected to hydrodynamic forces (Grabowski et al. 2011), but this remains poorly documented for newly forming tidal marshes. If we want to restore or create new, resilient tidal marshes for flood and shoreline erosion protection and other valuable ecosystem services such as carbon sequestration, it is important that their sediment beds become erosion resistant (McTigue et al. 2021; Schoutens et al. 2022). However, it remains unclear how spatial variations in tidal inundation and sedimentation rates within a tidal marsh restoration or creation site affect development of sediment strength and erosion resistance, where the presence of vegetation may also play a role.

Our aim is to improve the current understanding of the influence of tidal inundation and sedimentation rate on the development of tidal marsh sediment strength and erosion resistance in restored and newly created tidal marshes, as well as the influences of drainage, sediment, and vegetation on this development. For this, we measured sediment strength and erosion resistance of sediment layers with different accretion ages in a closely monitored restored tidal marsh with a controlled reduced tidal exchange (Cox et al. 2006; Maris et al. 2007) along the Scheldt estuary in Belgium. When this tidal marsh was created in 2006, initial bed elevation differences in the area led to differences in tidal inundation frequency and duration, and differences in sedimentation rate (Vandenbruwaene et al. 2011; Oosterlee et al. 2018; Maris et al. 2021). By also determining drainage characteristics and measuring sediment and vegetation characteristics, we were able to identify the effect of these variables on the development of sediment strength and erosion resistance.

Methods

Study area

We conducted our study at the tidal marsh of Lippenbroek, along the Scheldt estuary in Belgium (Fig. 1a). Lippenbroek is a previously embanked agricultural area, where the tide was reintroduced in March 2006 to allow the development of a tidal marsh ecosystem (Cox et al. 2006; Beauchard et al. 2011). A culvert system was installed in the dike between the restoration area and the estuary to create a controlled reduced tidal exchange, which is a form of regulated tidal exchange. This resulted in a tidal inundation regime that is similar to that in existing tidal marshes along the estuary, hence creating suitable conditions for tidal marsh development (Beauchard et al. 2011; Vandenbruwaene et al. 2011; Supporting Information Material: Study area). Underneath the sediment deposited after 2006 lies a strongly compacted relict agricultural soil, which restricts groundwater fluctuations to the top layer of the newly deposited sediment (van Putte et al. 2020). Regular monitoring campaigns are being executed at Lippenbroek to study how hydrodynamics, geomorphology, and ecology, among others, are evolving over time since the reintroduction of the tide (Maris et al. 2021).

Measurement locations and sampling depths

Since the tidal reintroduction in the area, surface elevation changes are being measured every 2 months using Surface Elevation Tables (SETs; Cahoon et al. 2002; Nolte et al. 2013) at 10 locations in the newly formed tidal marsh of Lippenbroek and at 3 locations in the pre-existing natural marsh nearby Lippenbroek, which is considered as a reference site for the newly formed marsh (Maris et al. 2021). At all measurement locations, sedimentation was the governing process of surface elevation changes, resulting in a gradual increase of surface elevation with time (Oosterlee et al. 2018). Therefore, assuming that other processes affecting surface elevation change were negligible compared to sedimentation, we approximated sedimentation rates by the increases of surface elevation.

For this study we selected measurement locations directly adjacent to eight surface elevation tables in the newly formed marsh of Lippenbroek and to the three surface elevation tables on the reference marsh (Fig. 1b). Tidal inundation frequency and duration of all measurement locations were calculated from the bed level elevations according to the methods described in Oosterlee et al. (2018) (Supporting Information Material: Calculations of tidal inundation variables), using the R package Tides (Cox 2014). The measurement locations were classified based on initial inundation frequency, as inundation characteristics are strong determinants of habitat development (Olff et al. 1997; Oosterlee et al. 2018): Measurement locations 1, 2, and 3 had a medium inundation frequency (50–80%) when the tide was introduced in 2006, measurement locations 4, 5, and 6 had a high inundation frequency (80–100%), and measurement locations 7 and 8 had a low inundation frequency (0–50%; Supporting Information Material: Tidal inundation and surface elevation change characteristics of measurement locations Supporting Information Table S1). These locations cover the whole range of relative elevations in the tidal frame that exists in Lippenbroek (Vandenbruwaene et al. 2011). Reference location 1 had a medium inundation frequency (50–80%), while reference locations 2 and 3 had a low inundation frequency (0–50%; Supporting Information Material: Tidal inundation and surface elevation change characteristics of measurement locations Supporting Information Table S1).

Since surface elevation changes have been intensively monitored at all selected measurement locations (Maris et al. 2021), we knew the dates when the sediment at specific present-day depths was deposited, and thus how old these sediment layers were. This allowed us to quantify the sediment strength for different sediment depths with different sediment age, and hence to study the rate of sediment consolidation. For several age categories of sediment (0–5, 5–10, and 10–15 yr old), we calculated their current depth in the sediment profile, using the recorded surface elevation change data (Fig. 1c; Maris et al. 2021). In this calculation we neglected the occurrence of erosion and sediment compaction (Supporting Information Material: Calculations of sampling depths).

Field measurements of erosion resistance proxies and sediment sampling

At all measurement locations, we took measurements of sediment strength, collected sediment samples, and recorded the vegetation species in August 2022. We measured sediment shear strength and penetration resistance, which are measures of sediment strength and can both be used as proxies for erosion resistance (Watts et al. 2003; Amer et al. 2017; Marin-Diaz et al. 2021). We measured shear strength of the sediment surface with a pocket shear vane tester (Eijkelkamp, The Netherlands) and shear strength from the depth of the upper boundary of the sediment layers of 0–5, 5–10, and 10–15 yr old (Fig. 1c) until 5.1 cm below that with a field inspection shear vane tester (Eijkelkamp, The Netherlands). We used a penetrologger (Eijkelkamp, The Netherlands) to measure penetration resistance of the sediment until the depth of the lower boundary of the 10–15 yr old layer at 1 cm intervals. Finally, we collected sediment samples with a gouge auger (Ø 8 cm; Eijkelkamp, The Netherlands) from the upper to lower boundary depths of the sediment layers of 0–5, 5–10, and 10–15 yr old. We took all measurements and samples in triplicate.

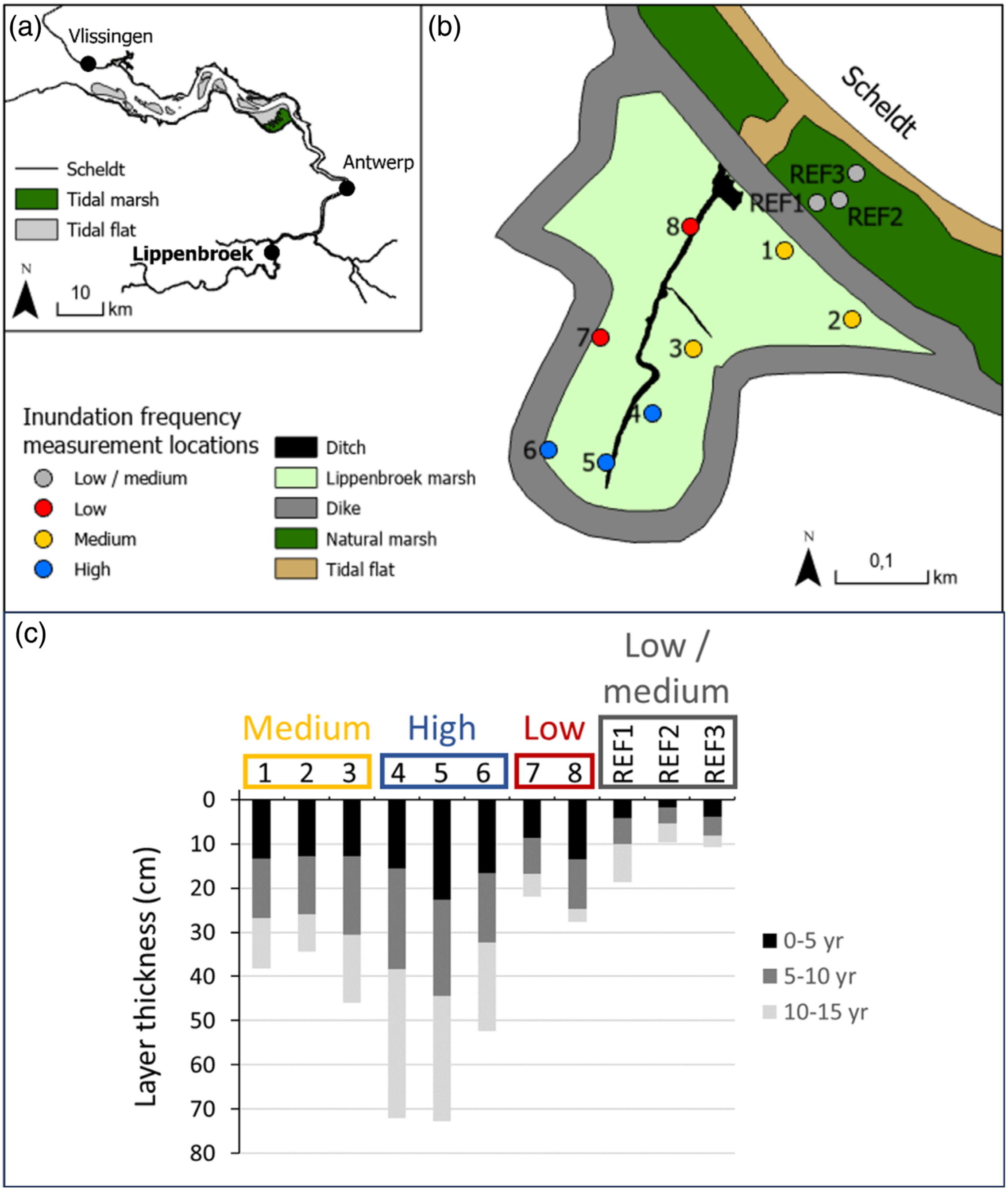

Fig. 1. (**a**) Location of Lippenbroek, a new tidal marsh developed on previously embanked land, along the Scheldt estuary in Belgium. (**b**) Measurement locations in the newly formed marsh of Lippenbroek and at the adjacent reference marsh along the Scheldt estuary. Gray locations indicate the reference locations with an initially medium (REF1) or low tidal inundation frequency (REF2 and REF3), red, yellow, and blue locations indicate the locations at the newly formed marsh with an initially low, medium, and high inundation frequency, respectively. (**c**) The depths of the sediment layers of 0–5 (black), 5–10 (dark gray), and 10–15 (light gray) years old for all measurement locations, based on surface elevation change data. The colors indicate the initial inundation frequency in 2006.

Laboratory measurements on sediment properties and belowground biomass

We weighed all sediment samples, that were taken from the upper to lower boundary depths of the sediment layers of 0–5, 5–10, and 10–15 yr old, in the laboratory, after which they were frozen, freeze dried, and re-weighed. By dividing the dry weight of the samples by their volume, we calculated their dry bulk density. We sieved the samples over a 1 mm sieve to remove and determine belowground biomass (live and dead combined). We then determined the fine fraction content (< 63 μm) and median grain size (D_{50}) of all samples using laser diffraction (Mastersizer 2000, Malvern, UK). We measured organic matter content with the loss on ignition method (Heiri et al. 2001), for which the samples were heated at 550°C for 4 h.

Flume measurements on erosion resistance of sediment samples

We tested sediment erosion resistance in the fast flow flume, of which the working principle is extensively described by Marin-Diaz et al. (2022). A few adjustments were made to this flume (Supporting Information Material: Fast flow flume), and flow velocity in the flow channels was 4.3 m s^{-1}. Such a high flow velocity simulates the flow velocities over a marsh that can be reached during a dike breach under storm surge conditions (Kamrath et al. 2006; Albers 2014).

To test erosion resistance under fast water flow in this flume, we collected triplicate erosion test samples (40 cm long × 13 cm wide × 20 cm deep) in April 2023 (i.e., winter state of vegetation) at a selection of measurement locations (2, 6, 7, 8, and REF1). This selection was based on inundation frequency class and present vegetation: location 2 with medium inundation frequency and common reed, location 6 with high inundation frequency and common reed, locations 7 and 8 with low inundation frequency and common reed and grass, respectively, and reference location 1 with medium inundation frequency and grass. Once the erosion test samples were placed in the flume, we measured their erosion resistance (Supporting Information Material: Fast flow flume).

Data analyses

We used the geoprocessing tool "Near" in ArcGIS Pro, version 3.0.2, to calculate the distances between measurement locations in the newly formed marsh of Lippenbroek and the main creek and the culverts in the dike. We excluded the measurement locations on the reference marsh from this analysis, since these points are inundated by and drain to the Scheldt estuary, so are not affected by the creeks and culverts in the newly formed marsh.

We performed all statistical analyses in R version 4.2.1 (R Core Team 2021). To calculate averages of the variables per measurement location we used the dplyr package (Wickham et al. 2022). We applied linear regressions to test relationships between environmental, sediment, and vegetation characteristics and sediment strength variables. For the relationships of erosion depth and surface shear strength (both measured at the sediment surface) with sediment depth and age, we used depth and age of the surface (0 cm and 0 yr, respectively). For the other sediment strength variables, we used average depth and age of the tested sediment layers. We extracted the slope of linear regressions between depth and shear strength, penetration resistance, and bulk density as a measure for the depth increase of these variables. For shear strength and bulk density we used the data of the sediment layers (0–5, 5–10, and 10–15 yr old) and average layer depths for these computations, while for penetration resistance we used all penetration resistance data (with an interval of 1 cm) and all 1 cm interval depths. Then we performed a linear regression between environmental characteristics and these depth increases to study how environmental characteristics affected the increases of shear strength, penetration resistance, and bulk density with depth. When the p value of linear regressions was below 0.050, we classified it as significant.

Results

Effect of inundation frequency, sedimentation rate, and drainage on sediment strength and erosion resistance

When considering data of all measurement locations, average sedimentation rate (herein approximated by increase of surface elevation) between 2006 and 2021 related positively to inundation frequency in both 2006 (Fig. 2a) and 2021 (Fig. 2b).

Of the environmental characteristics that we studied, inundation frequency in 2006 and 2021 most often significantly affected sediment strength variables (Fig. 3; Supporting Information Material: Statistics of linear regressions Supporting Information Table S2). When we considered data of all measurement locations, inundation frequency in 2021 showed a significant negative relationship with surface shear strength, and inundation frequency in both 2006 and 2021 showed significant negative relationships with shear strength, penetration resistance, and bulk density (Fig. 3). Erosion depth related positively to the average sedimentation rate between 2006 and 2021, while shear strength related negatively to the average sedimentation rate.

When we excluded data of the reference marsh, most of the relationships between environmental characteristics and sediment strength variables were similar to those when we included all data (Fig. 3; Supporting Information Material: Statistics of linear regressions Supporting Information Table S2). However, the relationships between surface shear strength and inundation frequency in 2021, between erosion depth and average sedimentation rate, and between shear strength and average sedimentation rate were non-significant when excluding data of the reference marsh. When excluding data of the reference marsh, distance to a creek branch negatively affected surface shear strength and bulk density, and distance to the culverts negatively affected shear strength (Fig. 3).

Effect of inundation frequency, sedimentation rate, and drainage on consolidation

When we considered data of all measurement locations, the increase of sediment strength variables with depth (here assumed to be indicators of sediment consolidation) related

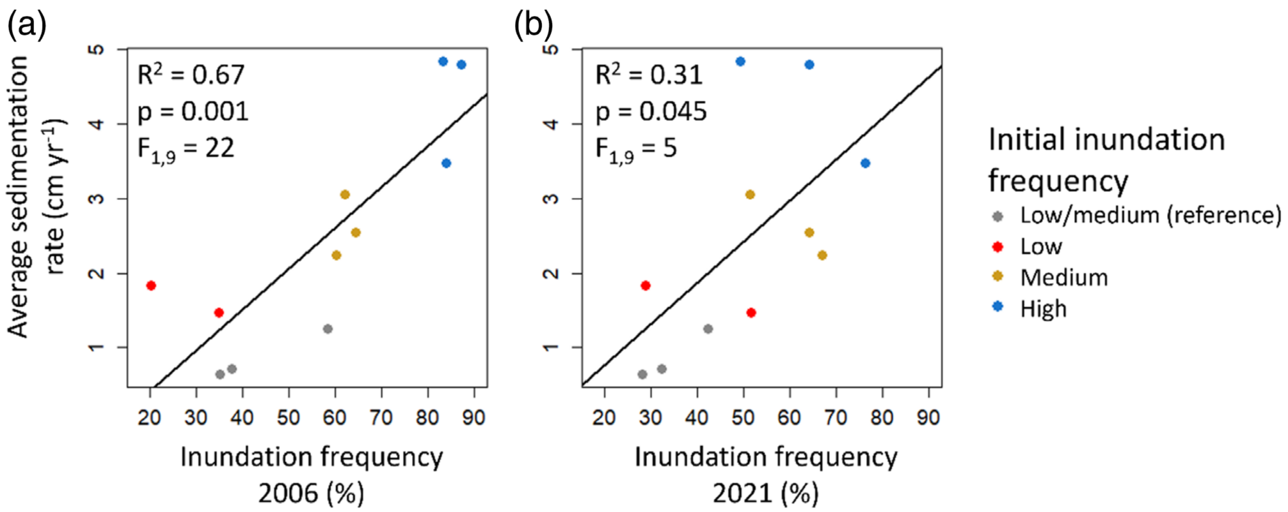

Fig. 2. Relationships between average sedimentation rate between 2006 and 2021 and inundation frequency in 2006 (**a**) and inundation frequency in 2021 (**b**). The colors of the points indicate the initial inundation frequency in 2006. The black lines indicate a significant ($p < 0.050$) linear regression.

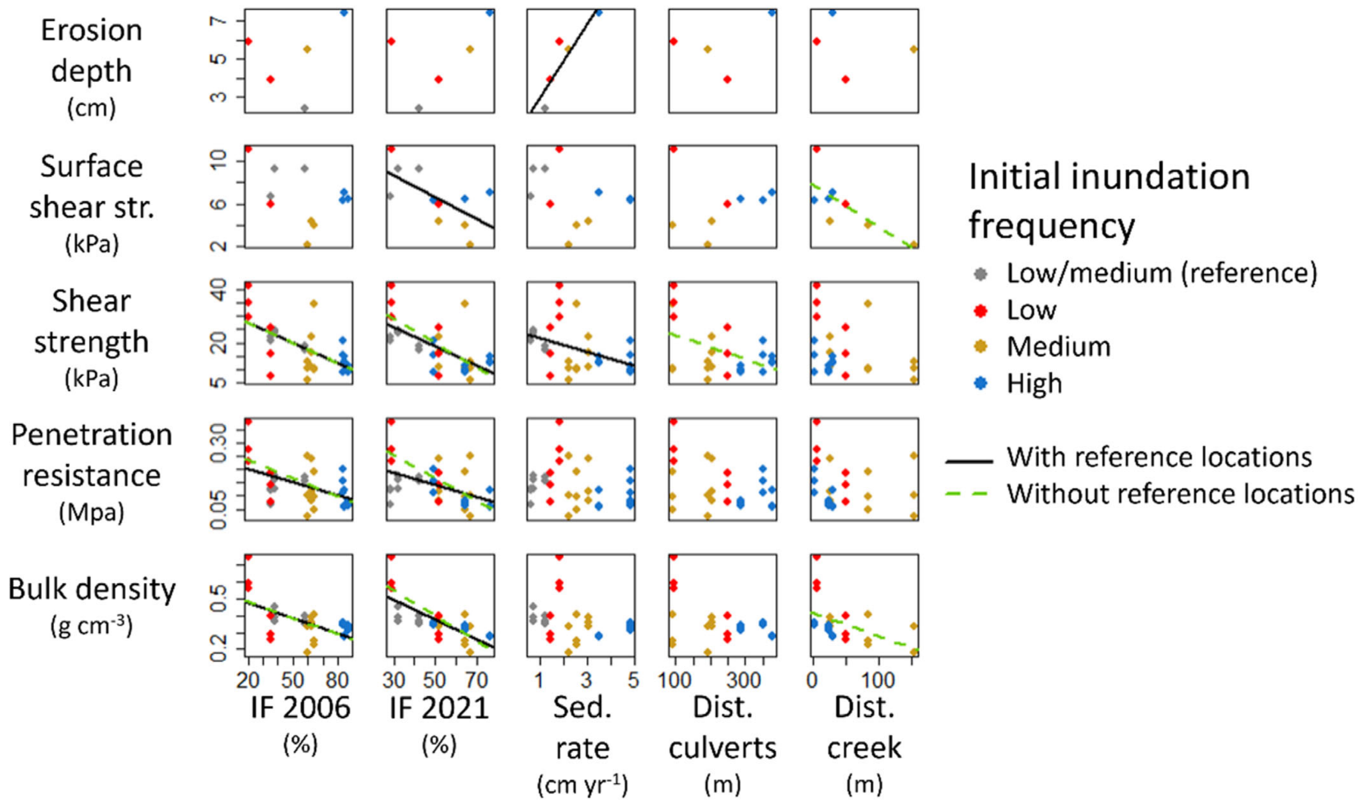

Fig. 3. Relationships between sediment strength variables (*y*-axis; erosion depth was measured after 3 h) and environmental characteristics (*x*-axis; inundation frequency in 2006, inundation frequency in 2021, average sedimentation rate between 2006 and 2021, distance to the culverts, and distance to a creek branch). Linear regressions of erosion depth after 3 h and surface shear strength are only based on surface layer data, because these variables were only sampled at the surface, while the linear regressions of shear strength, penetration resistance, and bulk density are based on data of all three sampled depths. Points represent an average of three replicates, and in the case of penetration resistance also of all measurements done within that sediment layer. A black, continuous linear regression line indicates a significant ($p < 0.050$) linear regression between two variables when all data is included, a green, dashed linear regression line a significant linear regression when data of the reference marsh is excluded. The absence of a line indicates a non-significant linear regression. The colors of the points indicate the initial inundation frequency in 2006. Note that data from the reference marsh was excluded from the linear regressions with distance to the culverts and distance to a creek branch, because these locations do not inundate or drain through the creek or culverts.

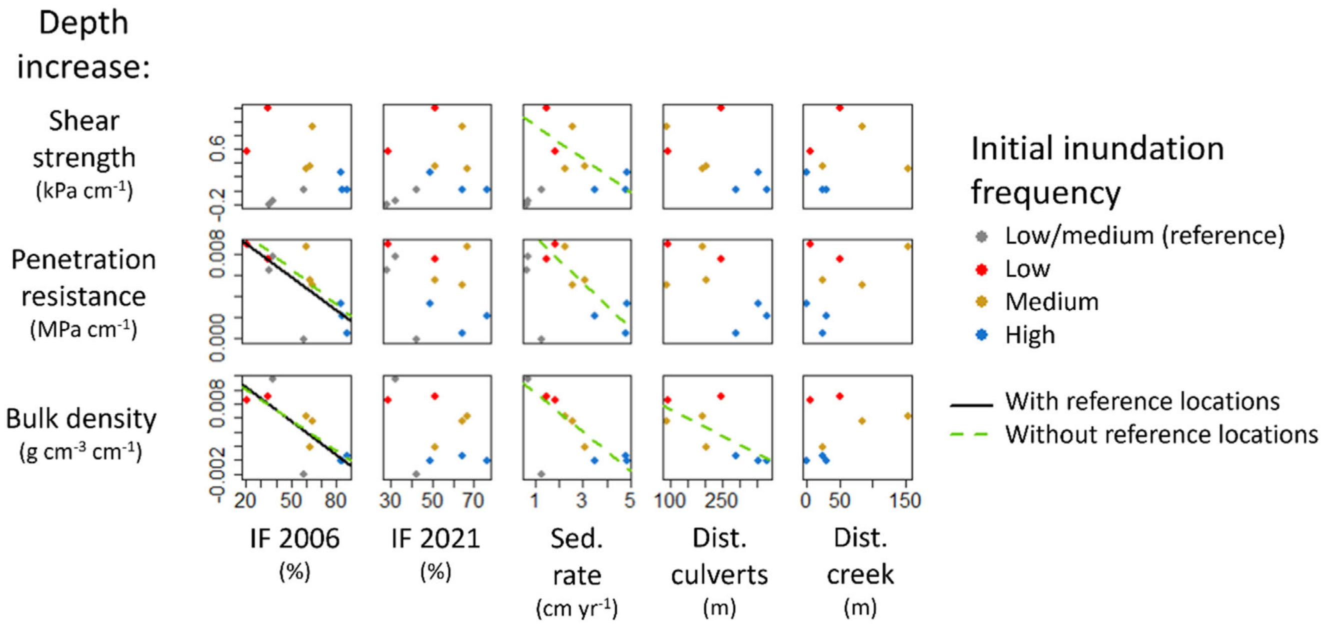

Fig. 4. Relationships between the increase of sediment strength variables with depth (*y*-axis) and environmental characteristics (*x*-axis; inundation frequency in 2006, inundation frequency in 2021, average sedimentation rate between 2006 and 2021, distance to the culverts, and distance to a creek branch). Points represent an average of three replicates. A black, continuous linear regression line indicates a significant ($p < 0.050$) linear regression between two variables when all data is included, a green, dashed linear regression line a significant linear regression when data of the reference marsh is excluded. The absence of a line indicates a non-significant linear regression. The colors of the points indicate the initial inundation frequency in 2006. Note that data from the reference marsh was excluded for the linear regressions with distance to the culverts and distance to a creek branch, because these locations do not inundate or drain through the creek or culverts.

most often significantly to the inundation frequency in 2006. Significant negative relationships existed between inundation frequency in 2006 and the increase of penetration resistance with depth and of bulk density with depth (Fig. 4; Supporting Information Material: Statistics of linear regressions Supporting Information Table S3). None of the other environmental characteristics that we studied significantly affected the depth increase of any of the sediment strength variables.

However, when we only studied relationships within the newly formed marsh (excluding data from the reference marsh), we found that the depth increases of shear strength, penetration resistance, and bulk density related negatively to the average sedimentation rate between 2006 and 2021 (Fig. 4; Supporting Information Material: Statistics of linear regressions Supporting Information Table S3). When excluding data from the reference marsh, the increase of bulk density with depth and distance to the culverts were also negatively related. No significant relationships existed with inundation frequency in 2021 and with distance to a creek branch, either with or without the reference marsh data (Fig. 4).

Effect of sediment and vegetation characteristics on sediment strength and erosion resistance

Of all sediment characteristics, bulk density and water content were the most important factors affecting surface shear strength, shear strength and penetration resistance (Fig. 5; Supporting Information Material: Statistics of linear regressions Supporting Information Table S4). Surface shear strength, shear strength, and penetration resistance related positively to bulk density, while all these variables related negatively to water content. A significant negative relationship between bulk density and water content also existed. The median grain size, D_{50}, showed positive relationships with shear strength, penetration resistance, and bulk density, while fine fraction and organic matter content showed negative relationships with shear strength and penetration resistance. Organic matter content and belowground biomass significantly decreased bulk density. Shear strength and penetration resistance increased significantly with age, while erosion depth did not significantly relate to any of the other variables (Fig. 5).

Discussion

To restore or create new, resilient tidal marshes, especially in the context of nature-based flood and shoreline erosion protection, it is important that they develop erosion resistant sediment beds. However, it remained unclear how sedimentation rates, especially when very high due to high tidal inundation frequency and duration, affect development of sediment strength and erosion resistance within restored/newly created tidal marshes. Our results from a unique, long term and closely monitored field site showed that lower tidal inundation frequency, lower sedimentation rate, and better drainage positively affect

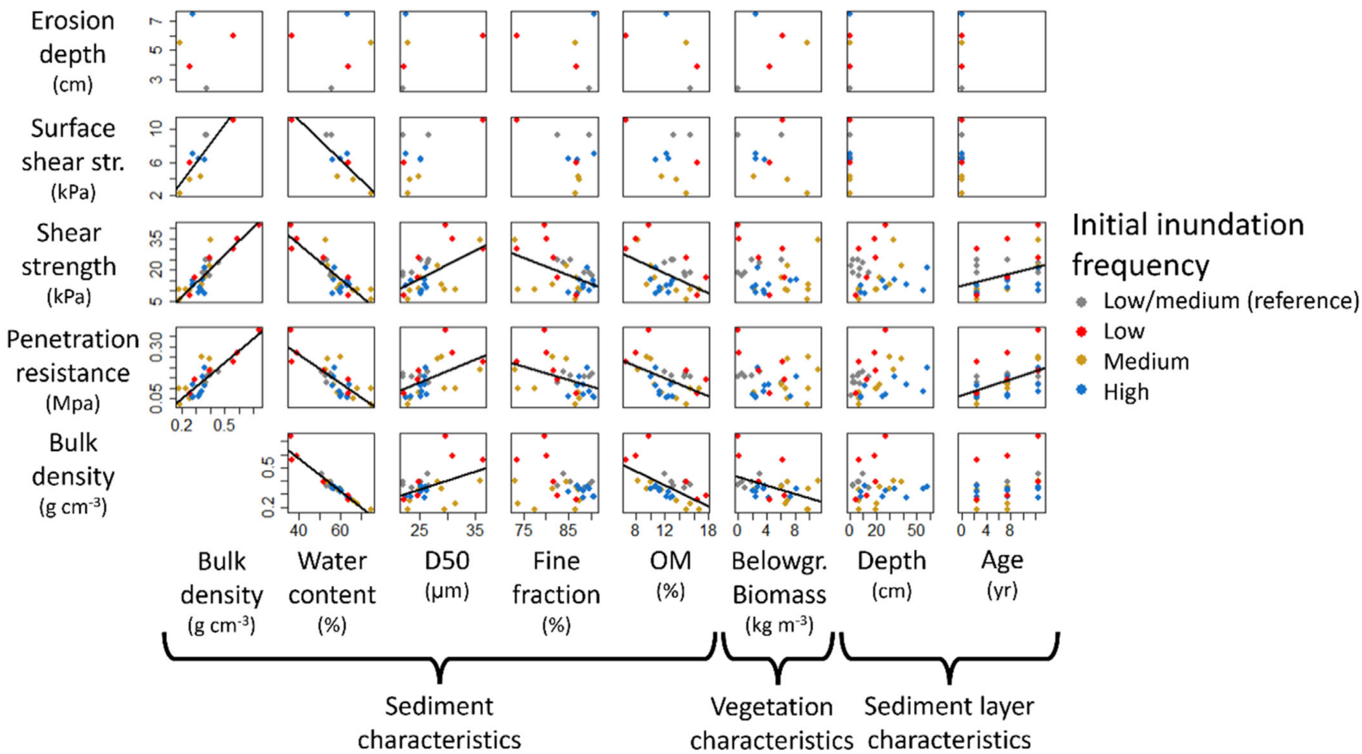

Fig. 5. Relationships between sediment strength variables (*y*-axis; erosion depth was measured after 3 h) and sediment characteristics (*x*-axis; bulk density, water content, median grain size (D_{50}), fine fraction content, organic matter content (OM), belowground biomass, sediment depth, and sediment age). The linear regressions of erosion depth after 3 h and surface shear strength are only based on surface layer data, because these variables were only sampled at the surface, while the linear regressions of shear strength, penetration resistance, and bulk density are based on data of all three sampled depths. Points represent an average of three replicates, and in the case of penetration resistance also of all measurements done within that sediment layer. A linear regression line indicates a significant ($p < 0.050$) linear regression between two variables, the absence of a line a non-significant linear regression. The colors of the points indicate the initial inundation frequency in 2006.

consolidation and the associated increase in sediment strength. In addition, we showed that somewhat coarser sediments contribute to strong marsh sediments (Fig. 6).

How inundation frequency, sedimentation rate, and drainage affect consolidation

The higher the initial inundation frequency and thus the higher the average sedimentation rate were (Fig. 2; Oosterlee et al. 2018; Vandenbruwaene et al. 2011), the smaller was the increase of bulk density with depth (Fig. 4). It is assumed that an increasing bulk density with depth has been the result of consolidation (cf. Zhou et al. 2016), although differences in fine fraction and organic matter content with depth might also have played a small role (Supporting Information Material: Depth profiles of fine fraction and organic matter content Supporting Information Fig. S3). This suggests that little consolidation has taken place at locations with high tidal inundation frequency and sedimentation rates (Fig. 6). As discussed in Brain et al. (2011) and Colosimo et al. (2023), high sedimentation rates lead to reduced drying of the deposited sediment, because these sediments are buried by new sediment layers before they can dry out completely. This hinders the occurrence of drying-induced consolidation. Locations with high inundation frequency and duration also have less time to drain than high locations and thus remain wetter (Stagg and Mendelssohn 2010), which further reduces drying-induced consolidation.

Inundation frequency and sedimentation rate were strongly correlated (Fig. 2; Oosterlee et al. 2018; Vandenbruwaene et al. 2011), which makes it difficult to fully separate the effects of inundation frequency and sedimentation rate on consolidation. It is striking that bulk density at all sediment depths decreased significantly with initial and current inundation frequency (Fig. 3) while the increase of bulk density with depth only decreased significantly with initial inundation frequency and sedimentation rate (Fig. 4). Since differences existed in fine fraction and organic matter content between sites (Fig. 5), this could be a result of the effect of fine fraction and organic matter content on bulk density (Brooks et al. 2021; Fig. 6), which would have affected the absolute bulk density values but not the increase of bulk density with depth.

Locations farther away from the culverts (i.e., the tidal in- and outlet through which water drains from the marsh toward the estuary at low tides) had a smaller increase of bulk density

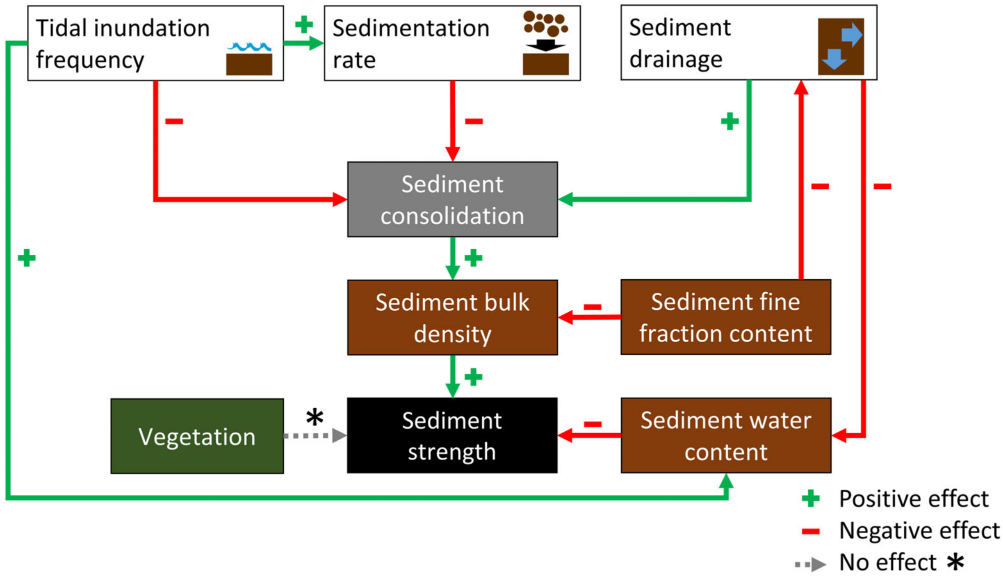

Fig. 6. Conceptual framework of this study showing the effects of environmental (white boxes), sediment (brown boxes), and vegetation (green box) characteristics, as well as of the consolidation process (gray box), on sediment strength (black box), and the relationships between them. Green, continuous arrows and pluses indicate positive effects, red, continuous arrows and minuses indicate negative effects, and gray, dashed arrows indicate the absence of an effect. *There was no measured effect of vegetation on sediment strength, possibly caused by the presence of vegetation at all locations or by the small sampling volume of belowground biomass. However, a potentially protective function of belowground biomass was observed in the flume measurements.

with depth (Fig. 4). This can be interpreted as locations farther away from the culverts are likely to experience slower and reduced sediment bed drainage as compared to nearby locations. Furthermore, this spatial variability in sediment drainage is likely to be especially large in a tidal marsh site on previously embanked cropland, due to the very consolidated relict agricultural soil that underlies the sediment deposited after reintroduction of the tide (van Putte et al. 2020). The resulting wetter conditions far away from the culverts (possibly also partially caused by the higher inundation frequency of some of these locations) are expected to reduce consolidation (Fig. 6; Colosimo et al. 2023; Dong et al. 2020).

How consolidation and drainage affect sediment strength and erosion resistance

Drying-induced consolidation leads to an increase in bulk density (Zhou et al. 2016; Colosimo et al. 2023) and our results showed that positive relationships exist between bulk density and sediment strength variables (shear strength and penetration resistance; Figs. 5, 6). The effect of drying-induced consolidation on sediment strength was also illustrated by the negative relationship between sediment strength variables and water content (Fig. 5), and corresponds with previous literature discussing how consolidation of clays and silts generally leads to increases in sediment strength and erosion resistance (Dade et al. 1992; Grabowski et al. 2011; Chen et al. 2012). The increase of penetration resistance with depth decreased with increasing initial inundation frequency (reference and newly formed marsh combined) and sedimentation rate (only newly formed marsh), and the increase of shear strength with depth also decreased with increasing sedimentation rate (only newly formed marsh; Fig. 4). This can be explained by the fact that shear strength and penetration resistance increase with consolidation and increasing bulk density (Vaz et al. 2001).

We found that the lower the sedimentation rate of a location, the greater the erosion resistance (Fig. 3), likely due to more consolidated soils at the locations with lower sedimentation rate (Fig. 6). However, all tested locations were relatively erosion resistant (< 8 cm erosion after 3 h under high flow velocity), which is assumed to mainly result from the dense root and rhizome network (Gyssels et al. 2005; Chen et al. 2012; Lo et al. 2017; Brooks et al. 2021) and the cohesive sediment (Grabowski et al. 2011; Brooks et al. 2021).

Shear strength related negatively to distance to the culverts, and surface shear strength and bulk density related negatively to distance to the creek that drains the marsh (Fig. 3). In addition to the effect of drainage on consolidation, the wetter conditions far away from the culverts or a creek branch could also directly lead to a smaller sediment strength (Fig. 6; Grabowski et al. 2011).

How sediment and vegetation characteristics affect sediment strength and erosion resistance

Previous studies showed that sediment strength increases with higher fine fraction and organic matter content as a result of increased cohesivity (Houwing 1999; Feagin et al. 2009; Ford et al. 2016; Lo et al. 2017; Brooks et al. 2021). In contrast, we found that shear strength and penetration resistance decreased with increasing fine fraction and organic matter content (Figs. 5, 6). When fine fraction contents are higher than 30–50%, erosion resistance starts to decrease, because of the decrease in bulk density (Mitchener and Torfs 1996; Grabowski et al. 2011). This could explain our observed negative relationship between fine fraction and sediment strength. A very high fine fraction content can also impair drainage (Brooks et al. 2021; Cao et al. 2021) and thereby lead to wetter sediments, which decreases sediment strength as well (Vaz et al. 2001; Grabowski et al. 2011). These wet sediment conditions could reduce organic matter decomposition, due to slower microbial activities, and thus lead to higher organic matter contents (Yousefi Lalimi et al. 2018). Locations with high fine fraction and water contents therefore often have high organic matter contents, and the observed negative relationship between sediment strength and fine fraction content could thus also be the reason for the negative relationship between sediment strength and organic matter content that we found.

Although belowground biomass has previously been found to increase erosion resistance (Gyssels et al. 2005; Chen et al. 2012; Lo et al. 2017; Brooks et al. 2021), we did not find a significant effect of belowground biomass on erosion resistance, shear strength, or penetration resistance (Figs. 5, 6). Vegetation was present at all locations (at most locations dense reed), so we might not have measured at a wide enough vegetation range to test this effect. Another potential explanation could be that belowground biomass was determined from the sediment samples with a diameter of 8 cm. This relatively small sampling volume, and thus the probability of sampling a large rhizome and a lot of roots or almost no roots at all, might have led to the absence of these relationships. However, we did observe a potentially protective function of belowground biomass when subjecting sediment samples to water flow in the flume. Once a few centimeters of erosion had taken place, a maze of roots covered the sediment surface, which might have prevented erosion from continuing much further. In addition, a greater erosion resistance of the deeper sediment layers themselves might also have contributed to this. This made the sediment generally erosion resistant to high flow velocities of 4.3 m s^{-1}.

Implications for tidal marsh restoration and creation

When restoring or creating tidal marshes by reintroducing the tides in previously embanked areas with high inundation frequency and duration, sedimentation rates may be very high. This can lead to very fluid sediments with low bulk densities (Oosterlee et al. 2020). In turn, this may result in high erosion risks if hydrodynamic forces are high (Grabowski et al. 2011) and will likely slow down vegetation establishment (Cao et al. 2021). Our study showed that locations in tidal marshes with low inundation frequency, low sedimentation rates, and good drainage experience most drying-induced consolidation, resulting in strong and erosion resistant sediment. Clay-silt-sand mixtures and vegetation (depending on the spatial scale) also increased sediment strength and erosion resistance. Therefore, to restore or create resilient tidal marshes for flood and shoreline erosion protection and other ecosystem services, the aim should be to:

1. Ensure that sedimentation rates will not be extremely high (as, e.g., up to 4 m yr^{-1} which was observed in a restored marsh with full tidal exchange along the Scheldt Estuary by Oosterlee et al. (2020)). This can be accomplished in two ways. *First*, by selecting areas with relatively high bed level for marsh restoration or creation, which would lead to a lower tidal inundation frequency and duration and thus to lower sedimentation rates (Oosterlee et al. 2018). If no areas with high sediment bed levels are available, it can be considered to increase the elevation with sediment nourishments (Vuik et al. 2019; Baptist et al. 2021), although care should then be taken that the nourished sediment is not too sandy and therefore easily erodible (Marin-Diaz et al. 2022). *Second*, by the implementation of a controlled reduced tide (using culverts through dikes or dams), the water depth and inundation frequency and duration in the tidal marsh can be reduced, also resulting in smaller sedimentation rates (Oosterlee et al. 2020).
2. Enhance drainage by digging creeks, ensure that possibilities for natural creek formation exist, or increase hydraulic conductivity of the compacted relict agricultural subsoil. The latter could be achieved by for example deep plowing (Brooks et al. 2015). Increasing hydraulic conductivity would stimulate drainage and hence lead to reduced sediment water contents, thereby stimulating consolidation (Dong et al. 2020; van Putte et al. 2020; Colosimo et al. 2023). The lower water content will also directly lead to more erosion resistant sediments because the cohesiveness will be higher (van Ledden et al. 2004; Grabowski et al. 2011). It is important to keep in mind that this lower sediment water content due to enhanced drainage is likely to increase organic matter decomposition (Yousefi Lalimi et al. 2018). If one of the marsh restoration or creation goals is carbon sequestration, this should be carefully weighed against the goal of erosion resistant marshes contributing to flood and shoreline erosion protection.
3. Select locations with a sufficient supply of clay and silt particles (5–10% clay particles of the available sediments to transition from non-cohesive to cohesive behavior according to van Ledden et al. 2004), but also of some sand. Clay and silt particles will enhance cohesion and thus erosion resistance (Grabowski et al. 2011), but the presence of some sand particles will prevent the clay and silt content to surpass 30–50%. This will prevent a decrease in erosion resistance (Mitchener and Torfs 1996; Grabowski et al. 2011).
4. Stimulate vegetation establishment, by ensuring that seed availability is high enough, that the sediment is suitable for

establishment, and that a “window of opportunity” for seedling establishment exists (Balke et al. 2014). If seed availability is not sufficient for vegetation establishment, planting or seeding could be considered (Hudson et al. 2021). Good sediment drainage will enhance vegetation establishment and growth (Mendelssohn and Seneca 1980; Cao et al. 2021). Seeds require disturbance free “windows of opportunity” for their initial establishment and to be able to grow large enough to withstand hydrodynamic disturbances (Hu et al. 2015).

5. Give the system enough time for vegetation establishment and consolidation, to ensure the development of erosion resistant sediment. A vegetated tidal marsh with erosion resistant sediment does not develop instantaneously when a dike is breached or when culverts are installed for marsh restoration or creation. This is expected to take at least 6 yr (Watts et al. 2003). Taking this into account, the tide should be reintroduced in restoration or creation projects a few years before the marsh is necessary or used for their flood and shoreline erosion protection benefits and ecological value.

In conclusion, if the goal is to restore or create tidal marshes for flood and shoreline erosion protection, we should aim for sites with relatively low inundation frequency, moderate sedimentation rates, and cohesive sediment mixtures of clay, silt, and sand, which are well drained and have potential for vegetation establishment. These conditions have a high likelihood of resulting in restored or created tidal marshes that contribute to nature-based flood and shoreline erosion protection.

Data availability statement

The data of this study are openly available in the research data repository 4TU: https://doi.org/10.4121/ee3a00ea-6557-43ef-8bd3-7aa28a79b6a1.

References

ABPmer. 2023. Coastal habitat creation scheme database. https://www.omreg.net/

Albers, T. S. 2014. Emergency closure of dike breaches: The effect and applicability of emergency measures. M.Sc. thesis. Delft Univ. of Technology.

Amer, R., A. S. Kolker, and A. Muscietta. 2017. Propensity for erosion and deposition in a deltaic wetland complex: Implications for river management and coastal restoration. Remote Sens. Environ. **199**: 39–50. doi:10.1016/j.rse.2017.06.030

Balke, T., P. M. J. Herman, and T. J. Bouma. 2014. Critical transitions in disturbance-driven ecosystems: Identifying windows of opportunity for recovery. J. Ecol. **102**: 700–708. doi:10.1111/1365-2745.12241

Baptist, M. J., and others. 2021. Salt marsh construction as a nature-based solution in an estuarine social-ecological system. Nat.-Based Sol. **1**: 100005. doi:10.1016/j.nbsj.2021.100005

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman. 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. **81**: 169–193. doi:10.1890/10-1510.1

Barciela-Rial, M., L. A. van Paassen, J. Griffioen, T. van Kessel, and J. C. Winterwerp. 2020. The effect of solid-phase composition on the drying behavior of Markermeer sediment. Vadose Zone J. **19**: e20028. doi:10.1002/vzj2.20028

Beauchard, O., S. Jacobs, T. J. S. Cox, T. Maris, D. Vrebos, A. van Braeckel, and P. Meire. 2011. A new technique for tidal habitat restoration: Evaluation of its hydrological potentials. Ecol. Eng. **37**: 1849–1858. doi:10.1016/j.ecoleng.2011.06.010

Brain, M. J., A. J. Long, D. N. Petley, B. P. Horton, and R. J. Allison. 2011. Compression behaviour of minerogenic low energy intertidal sediments. Sediment. Geol. **233**: 28–41. doi:10.1016/j.sedgeo.2010.10.005

Brooks, H., and others. 2021. Resistance of salt marsh substrates to near-instantaneous hydrodynamic forcing. Earth Surf. Process. Landf. **46**: 67–88. doi:10.1002/esp.4912

Brooks, K. L., H. L. Mossman, J. L. Chitty, and A. Grant. 2015. Limited vegetation development on a created salt marsh associated with over-consolidated sediments and lack of topographic heterogeneity. Estuaries Coasts **38**: 325–336. doi:10.1007/s12237-014-9824-3

Cahoon, D. R., J. C. Lynch, B. C. Perez, B. Segura, R. D. Holland, C. Stelly, G. Stephenson, and P. Hensel. 2002. High-precision measurements of wetland sediment elevation: II. The rod surface elevation table. J. Sediment. Res. **72**: 734–739. doi:10.1306/020702720734

Cao, H., and others. 2021. Salt marsh establishment in poorly consolidated muddy systems: Effects of surface drainage, elevation, and plant age. Ecosphere **12**: e03755. doi:10.1002/ecs2.3755

Cao, H., Z. Zhu, T. Balke, L. Zhang, and T. J. Bouma. 2018. Effects of sediment disturbance regimes on Spartina seedling establishment: Implications for salt marsh creation and restoration. Limnol. Oceanogr. **63**: 647–659. doi:10.1002/lno.10657

Chen, Y., C. E. L. Thompson, and M. B. Collins. 2012. Saltmarsh creek bank stability: Biostabilisation and consolidation with depth. Cont. Shelf Res. **35**: 64–74. doi:10.1016/j.csr.2011.12.009

Colosimo, I., D. S. van Maren, P. L. M. de Vet, J. C. Winterwerp, and B. C. van Prooijen. 2023. Winds of opportunity: The effects of wind on intertidal flat accretion. Geomorphology **439**: 108840. doi:10.1016/j.geomorph.2023.108840

Cox, T. J. S. 2014. Tides: Quasi-Periodic Time Series Characteristics. https://cran.r-project.org/web/packages/Tides/Tides.pdf

Cox, T., T. Maris, P. De Vleeschauwer, T. De Mulder, K. Soetaert, and P. Meire. 2006. Flood control areas as an opportunity to restore estuarine habitat. Ecol. Eng. **28**: 55–63. doi:10.1016/j.ecoleng.2006.04.001

Crooks, S., J. Schutten, G. D. Sheern, K. Pye, and A. J. Davy. 2002. Drainage and elevation as factors in the restoration of salt marsh in Britain. Restor. Ecol. **10**: 591–602. doi:10.1046/j.1526-100X.2002.t01-1-02036.x

Dade, W. B., A. R. M. Nowell, and P. A. Jumars. 1992. Predicting erosion resistance of muds. Mar. Geol. **105**: 285–297. doi:10.1016/0025-3227(92)90194-M

Dong, Y., N. Lu, and P. J. Fox. 2020. Drying-induced consolidation in soil. J. Geotech. Geoenviron. Eng. **146**: 04020092. doi:10.1061/(asce)gt.1943-5606.0002327

Doody, J. P. 2013. Coastal squeeze and managed realignment in southeast England, does it tell us anything about the future? Ocean Coast. Manag. **79**: 34–41. doi:10.1016/j.ocecoaman.2012.05.008

Duarte, C. M., I. J. Losada, I. E. Hendriks, I. Mazarrasa, and N. Marbà. 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Change **3**: 961–968. doi:10.1038/nclimate1970

Fairchild, T. P., and others. 2021. Coastal wetlands mitigate storm flooding and associated costs in estuaries. Environ. Res. Lett. **16**: 074034. doi:10.1088/1748-9326/ac0c45

Feagin, R. A., S. M. Lozada-Bernard, T. M. Ravens, I. Möller, K. M. Yeager, and A. H. Baird. 2009. Does vegetation prevent wave erosion of salt marsh edges? Proc. Natl. Acad. Sci. USA **106**: 10109–10113. doi:10.1073/pnas.0901297106

Fivash, G. S., S. Temmerman, M. G. Kleinhans, M. Heuner, T. van der Heide, and T. J. Bouma. 2023. Early indicators of tidal ecosystem shifts in estuaries. Nat. Commun. **14**: 1911. doi:10.1038/s41467-023-37444-6

Ford, H., A. Garbutt, C. Ladd, J. Malarkey, and M. W. Skov. 2016. Soil stabilization linked to plant diversity and environmental context in coastal wetlands. J. Veg. Sci. **27**: 259–268. doi:10.1111/jvs.12367

French, P. W. 2006. Managed realignment—The developing story of a comparatively new approach to soft engineering. Estuar. Coast. Shelf Sci. **67**: 409–423. doi:10.1016/j.ecss.2005.11.035

Gourgue, O., and others. 2022. Biogeomorphic modeling to assess the resilience of tidal-marsh restoration to sea level rise and sediment supply. Earth Surf. Dyn. **10**: 531–553. doi:10.5194/esurf-10-531-2022

Grabowski, R. C., I. G. Droppo, and G. Wharton. 2011. Erodibility of cohesive sediment: The importance of sediment properties. Earth-Sci. Rev. **105**: 101–120. doi:10.1016/j.earscirev.2011.01.008

Gyssels, G., J. Poesen, E. Bochet, and Y. Li. 2005. Impact of plant roots on the resistance of soils to erosion by water: A review. Prog. Phys. Geogr. **29**: 189–217. doi:10.1191/0309133305pp443ra

Heiri, O., A. F. Lotter, and G. Lemcke. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. J. Paleolimnol. **25**: 101–110. doi:10.1023/A:1008119611481

Houwing, E.-J. 1999. Determination of the critical erosion threshold of cohesive sediments on intertidal mudflats along the Dutch Wadden Sea Coast. Estuar. Coast. Shelf Sci. **49**: 545–555. doi:10.1006/ecss.1999.0518

Hu, Z., J. van Belzen, D. van der Wal, T. Balke, Z. B. Wang, M. Stive, and T. J. Bouma. 2015. Windows of opportunity for salt marsh vegetation establishment on bare tidal flats: The importance of temporal and spatial variability in hydrodynamic forcing. J. Geophys. Res.: Biogeosci. **120**: 1450–1469. doi:10.1002/2014JG002870

Hudson, R., J. Kenworthy, and M. Best [eds.]. 2021. Saltmarsh restoration handbook: UK and Ireland. Environment Agency.

Kamrath, P., M. Disse, M. Hammer, and J. Köngeter. 2006. Assessment of discharge through a dike breach and simulation of flood wave propagation. Nat. Hazards **38**: 63–78. doi:10.1007/s11069-005-8600-x

Kirwan, M. L., and J. P. Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature **504**: 53–60. doi:10.1038/nature12856

Lo, V. B., T. J. Bouma, J. van Belzen, C. van Colen, and L. Airoldi. 2017. Interactive effects of vegetation and sediment properties on erosion of salt marshes in the Northern Adriatic Sea. Mar. Environ. Res. **131**: 32–42. doi:10.1016/j.marenvres.2017.09.006

Marin-Diaz, B., L. L. Govers, D. van der Wal, H. Olff, and T. J. Bouma. 2021. How grazing management can maximize erosion resistance of salt marshes. J. Appl. Ecol. **58**: 1533–1544. doi:10.1111/1365-2664.13888

Marin-Diaz, B., L. L. Govers, D. van der Wal, H. Olff, and T. J. Bouma. 2022. The importance of marshes providing soil stabilization to resist fast-flow erosion in case of a dike breach. Ecol. Appl. **32**: e2622. doi:10.1002/eap.2622

Maris, T., S. Baeten, T. van den Neucker, T. van den Broeck, and P. Meire. 2021. OMES rapport 2020 Intergetijdengebieden: Onderzoek naar de gevolgen van het Sigmaplan, baggeractiviteiten en havenuitbreiding in de Zeeschelde op het milieu. Geïntegreerd eindverslag van het onderzoek verricht in 2019, deelrapport Intergetijdengebieden (ECOBE 021-R276). Universiteit Antwerpen.

Maris, T., T. Cox, S. Temmerman, P. de Vleeschauwer, S. van Damme, T. de Mulder, E. van den Bergh, and P. Meire. 2007. Tuning the tide: Creating ecological conditions for tidal marsh development in a flood control area. Hydrobiologia **588**: 31–43. doi:10.1007/s10750-007-0650-5

Masselink, G., M. E. Hanley, A. C. Halwyn, W. Blake, K. Kingston, T. Newton, and M. Williams. 2017. Evaluation of salt marsh restoration by means of self-regulating tidal gate—Avon estuary, South Devon, UK. Ecol. Eng. **106**: 174–190. doi:10.1016/j.ecoleng.2017.05.038

McLeod, E., and others. 2011. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Front. Ecol. Environ. **9**: 552–560. doi:10.1890/110004

McTigue, N. D., Q. A. Walker, and C. A. Currin. 2021. Refining estimates of greenhouse gas emissions from salt marsh "blue carbon" erosion and decomposition. Front. Mar. Sci. **8**: 661442. doi:10.3389/fmars.2021.661442

Mendelssohn, I. A., and E. D. Seneca. 1980. The influence of soil drainage on the growth of salt marsh cordgrass *Spartina alterniflora* in North Carolina. Estuar. Coast. Mar. Sci. **11**: 27–40. doi:10.1016/S0302-3524(80)80027-2

Mitchener, H., and H. Torfs. 1996. Erosion of mud/sand mixtures. Coast. Eng. **29**: 1–25. doi:10.1016/S0378-3839(96)00002-6

Mossman, H. L., M. J. H. Brown, A. J. Davy, and A. Grant. 2012. Constraints on salt marsh development following managed coastal realignment: Dispersal limitation or environmental tolerance? Restor. Ecol. **20**: 65–75. doi:10.1111/j.1526-100X.2010.00745.x

Nelson, J. L., and E. S. Zavaleta. 2012. Salt marsh as a coastal filter for the oceans: Changes in function with experimental increases in nitrogen loading and sea-level rise. PLoS One **7**: e38558. doi:10.1371/journal.pone.0038558

Nguyen, H. M., K. R. Bryan, and C. A. Pilditch. 2020. The effect of long-term aerial exposure on intertidal mudflat erodibility. Earth Surf. Process. Landf. **45**: 3623–3638. doi:10.1002/esp.4990

Nolte, S., E. C. Koppenaal, P. Esselink, K. S. Dijkema, M. Schuerch, A. V. de Groot, J. P. Bakker, and S. Temmerman. 2013. Measuring sedimentation in tidal marshes: A review on methods and their applicability in biogeomorphological studies. J. Coast. Conserv. **17**: 301–325. doi:10.1007/s11852-013-0238-3

Olff, H., J. de Leeuw, J. P. Bakker, R. J. Platerink, H. J. van Wijnen, and W. de Munck. 1997. Vegetation succession and herbivory in a salt marsh: Changes induced by sea level rise and silt deposition along an elevational gradient. J. Ecol. **85**: 799–814.

Oosterlee, L., T. J. S. Cox, S. Temmerman, and P. Meire. 2020. Effects of tidal re-introduction design on sedimentation rates in previously embanked tidal marshes. Estuar. Coast. Shelf Sci. **244**: 106428. doi:10.1016/j.ecss.2019.106428

Oosterlee, L., T. J. S. Cox, W. Vandenbruwaene, T. Maris, S. Temmerman, and P. Meire. 2018. Tidal marsh restoration design affects feedbacks between inundation and elevation change. Estuaries Coasts **41**: 613–625. doi:10.1007/s12237-017-0314-2

R Core Team. 2021. R: A language and environment for statistical computing. R foundation for Statistical computing, https://www.R-project.org/

Ridgway, G., and M. Williams. 2011. Self-regulating tide gate: A new design for habitat creation, delivering benefits through evidence. Environment Agency.

Schoutens, K., and others. 2022. Stability of a tidal marsh under very high flow velocities and implications for nature-based flood defense. Front. Mar. Sci. **9**: 920480. doi:10.3389/fmars.2022.920480

Smolders, S., Y. Plancke, S. Ides, P. Meire, and S. Temmerman. 2015. Role of intertidal wetlands for tidal and storm tide attenuation along a confined estuary: A model study. Nat. Hazards Earth Syst. Sci. **15**: 1659–1675. doi:10.5194/nhess-15-1659-2015

Stagg, C. L., and I. A. Mendelssohn. 2010. Restoring ecological function to a submerged salt marsh. Restor. Ecol. **18**: 10–17. doi:10.1111/j.1526-100X.2010.00718.x

Temmerman, S., E. M. Horstman, K. W. Krauss, J. C. Mullarney, I. Pelckmans, and K. Schoutens. 2023. Marshes and mangroves as nature-based coastal storm buffers. Ann. Rev. Mar. Sci. **15**: 95–118. doi:10.1146/annurev-marine-040422

Temmerman, S., P. Meire, T. J. Bouma, P. M. J. Herman, T. Ysebaert, and H. J. De Vriend. 2013. Ecosystem-based coastal defence in the face of global change. Nature **504**: 79–83. doi:10.1038/nature12859

Torfs, H., H. Mitchener, H. Huysentruyt, and E. Toorman. 1996. Settling and consolidation of mud/sand mixtures. Coast. Eng. **29**: 27–45. doi:10.1016/S0378-3839(96)00013-0

van Ledden, M., W. G. M. van Kesteren, and J. C. Winterwerp. 2004. A conceptual framework for the erosion behaviour of sand-mud mixtures. Cont. Shelf Res. **24**: 1–11. doi:10.1016/j.csr.2003.09.002

van Putte, N., and others. 2020. Groundwater dynamics in a restored tidal marsh are limited by historical soil compaction. Estuar. Coast. Shelf Sci. **244**: 106101. doi:10.1016/j.ecss.2019.02.006

Vandenbruwaene, W., T. Maris, T. J. S. Cox, D. R. Cahoon, P. Meire, and S. Temmerman. 2011. Sedimentation and response to sea-level rise of a restored marsh with reduced tidal exchange: Comparison with a natural tidal marsh. Geomorphology **130**: 115–126. doi:10.1016/j.geomorph.2011.03.004

Vaz, C. M. P., L. H. Bassoi, and J. W. Hopmans. 2001. Contribution of water content and bulk density to field soil penetration resistance as measured by a combined cone penetrometer-TDR probe. Soil Tillage Res. **60**: 35–42. doi:10.1016/S0167-1987(01)00173-8

Vuik, V., B. W. Borsje, P. W. J. M. Willemsen, and S. N. Jonkman. 2019. Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. Ocean Coast. Manag. **171**: 96–110. doi:10.1016/j.ocecoaman.2019.01.010

Vuik, V., S. N. Jonkman, B. W. Borsje, and T. Suzuki. 2016. Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes. Coast. Eng. **116**: 42–56. doi:10.1016/j.coastaleng.2016.06.001

Wang, C., and S. Temmerman. 2013. Does biogeomorphic feedback lead to abrupt shifts between alternative landscape states?: An empirical study on intertidal flats and marshes. J. Geophys. Res.: Earth Surf. **118**: 229–240. doi:10.1029/2012JF002474

Wang, H., and others. 2017. Zooming in and out: Scale dependence of extrinsic and intrinsic factors affecting salt marsh erosion. J. Geophys. Res.: Earth Surf. **122**: 1455–1470. doi:10.1002/2016JF004193

Watts, C. W., T. J. Tolhurst, K. S. Black, and A. P. Whitmore. 2003. In situ measurements of erosion shear stress and geotechnical shear strength of the intertidal sediments of the experimental managed realignment scheme at Tollesbury, Essex, UK. Estuar. Coast. Shelf Sci. **58**: 611–620. doi:10.1016/S0272-7714(03)00139-2

Weisscher, S. A. H., A. W. Baar, J. van Belzen, T. J. Bouma, and M. G. Kleinhans. 2022. Transitional polders along estuaries: Driving land-level rise and reducing flood propagation. Nat.-Based Sol. **2**: 100022. doi:10.1016/j.nbsj.2022.100022

Wickham, H., R. François, L. Henry, and K. Müller. 2022. dplyr: A grammar of data manipulation. https://dplyr.tidyverse.org

Yousefi Lalimi, F., S. Silvestri, A. D'Alpaos, M. Roner, and M. Marani. 2018. The spatial variability of organic matter and decomposition processes at the marsh scale. J. Geophys. Res.: Biogeosci. **123**: 3713–3727. doi:10.1029/2017JG004211

Zhou, Z., M. van der Wegen, B. Jagers, and G. Coco. 2016. Modelling the role of self-weight consolidation on the morphodynamics of accretional mudflats. Environ. Model. Softw. **76**: 167–181. doi:10.1016/j.envsoft.2015.11.002

Zhu, Z., and others. 2020. Historic storms and the hidden value of coastal wetlands for nature-based flood defence. Nat. Sustain. **3**: 853–862. doi:10.1038/s41893-020-0556-z

Acknowledgments

This study is part of the project *The Hedwige-Prosper Polder as a future-oriented experiment in managed realignment: integrating saltmarshes in water safety* of the research programme "Living Labs in the Dutch Delta" which is financed by the Dutch Research Council (NWO) and co-financed by EcoShape and STOWA. We would like to thank Dimitri van Pelt for his help with finding the best method to take the sediment samples and Tom van den Neucker for showing us the locations of the surface elevation tables in the field. We thank Peter Herman for his useful input on the study design. We would like to thank Lydia Sloof, Zhengquan Zhou, Wout Coppens, Laurens Schroeders, Yuhang Tan, and Victoria Mason for their help with the data and sample collection in the field. We want to thank the Flemish Government and "De Vlaamse Waterweg" for financing the OMES project in which data is collected that was used for this study, and "Agentschap voor Natuur en Bos" for permission to perform the measurements at Lippenbroek. We are grateful to Dave Huijsman, Yvo Witte, and Aarnoud van de Burgt for designing and building the fast flow flume, and for their schematic drawing of the flume. We would like to thank two reviewers for their feedback on our manuscript.

Conflict of Interest

None declared.

Submitted 30 January 2024

Revised 26 July 2024

Accepted 16 August 2024

Associate editor: Ruth Reef