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**Key Points:**

- Marsh deposition decreases delta slope, creating feedbacks that alter the spatial deposition of clastic material
- A small addition of marsh material, almost doubled the area near sea level, which has significant implications for coastal restoration
- The interaction of marsh and clastic deposition creates a delta hypsometry more akin to global deltas than experiments without marsh

**Supporting Information:**

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

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# Marsh Sedimentation Controls Delta Top Morphology, Slope, and Mass Balance

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**Abstract** Rising sea levels, subsidence, and decreased fluvial sediment load threaten river deltas and their wetlands. However, the feedbacks between fluvial and non-fluvial (marsh) deposition remain weakly constrained. We investigate how non-riverine, elevation-controlled deposition typified by marshes impacts sediment partitioning between a delta's topset, coastal zone, and foreset by comparing a delta experiment with proxy marsh accumulation to a control. Marsh accumulation alters fluvial sediment distribution by decreasing the slope in the marsh window by ~50%, creating a 78% larger marsh zone. Fluvial incursions into the marsh window trap 1.3 times more clastic volume. The volume exported to deep water remains unchanged. Marsh deposition shifts elevation distributions toward sea level, which produces a hypsometry akin to field-scale deltas. The elevation-lowering effect of marshes on an equilibrium delta shown here constitutes an unexplored feedback and an important aspect of coastal sustainability.

**Plain Language Summary** Low-lying coastal zones, often with abundant vegetation (wetlands), are threatened worldwide because of rising sea level and decreased sediment supply. Coastal sediment accumulation is a fundamental process that helps these regions keep pace with rising sea level. This sediment may be delivered directly from rivers, or as mud and plant material in wetlands (e.g., marshes and mangrove forests) and shallow bays. Our study shows that sediment accumulated in the second manner alters the elevation distribution of coastal regions and the spatial deposition of the river sediment. These results provide important information for plans to help sustain and restore coastal land area.

## 1. Introduction

River deltas and their marsh platforms host diverse ecosystems threatened by anthropogenic impacts to coastal areas, such as rising sea levels, subsidence, and leveeing of channels (Ericson et al., 2006). Organic material production, a critical form of sediment accumulation in many river deltas, is the primary driver of marsh platform growth (Nyman et al., 2006), whereas clastic sedimentation via rivers drives deltaic lobe growth (Edmonds et al., 2009). To successfully predict the long-term fate of these ecosystems, the interaction controlling delta and marsh growth must be understood (Paola et al., 2011). While much is known about surface processes in channelized portions of river deltas (Edmonds & Slingerland, 2008; Li et al., 2017; Smart & Moruzzi, 1971) and much is known about sediment accumulation in marshes (Allen, 2000; Kirwan & Murray, 2007; Morris et al., 2002), the manner in which they interact remains largely uninvestigated.

Aerial imagery and the stratigraphic record show evidence of delta-marsh interaction in modern and ancient systems, and it is well known that deltaic channel deposits are sensitive to the deposition of fine-grained and organic material in floodplains (Bohacs & Suter, 1997; Esposito et al., 2017; Hoyal & Sheets, 2009). For example, ~25% of the recent Mississippi River Delta (MRD) sedimentation was organic marsh material (by mass) (Holmquist et al., 2018; Sanks et al., 2020). Further, evidence preserved in strata suggests organic-rich deposition influenced deltaic processes over most of the Phanerozoic (Chesnut & Greb, 1992). Both modern and ancient records suggest that clastic inputs influence the stability and growth of the marsh platform, thus influencing coastal sustainability.

The influence of marsh sediment accumulation on long-term ($>10^3$ years) delta dynamics remains largely unknown. A fundamental aspect of this sedimentation is that it is not directly sourced from the river and accumulates in deltas globally. This mass is composed of both mineral and organic material, has a low bulk density, and supplements clastic river sedimentation that is focused near channel mouths and within the channel network

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(Sanks et al., 2020). The organic component is formed in-situ via primary production of plants and accumulates as a parabolic function of elevation relative to sea level, with maximum production occurring around mean high tide (Morris et al., 2002). As it stands, experimental deltas have not included a process for accumulating this sediment. Instead, sediment cohesion is sometimes used as a proxy for vegetation (Hoyal & Sheets, 2009; Li et al., 2017), but not always (Ganti et al., 2016). Vegetation hydrodynamics have also been studied in an experimental delta through the use of alfalfa (Piliouras et al., 2017), though the deltas formed in this study were too steep to be accurate representations of coastal deltas.

Here, we investigate the influence of non-riverine accumulation on delta morphology and mass balance by comparing two physical experiments conducted at the Tulane University Sediment Dynamics Laboratory. We incorporate proxy-marsh sediment accumulation in an experimental river delta, an important advance in experimental sedimentology and coastal restoration. We compare this experiment to a previous, identical experiment that formed without marsh sedimentation. This setup is ideal to understand the interaction of ecogeomorphic processes in coastal wetlands and physical processes of river deltas due to the ability to assess long-term behavior at reduced time and length scales, control on forcing conditions (Table 1), precise measurements, and autogenic dynamics (Paola et al., 2009). By analyzing the experiments over long timescales relative to autogenic dynamics, we can interpret any differences as direct results of marsh deposition.

## 2. Materials and Methods

### 2.1. Experimental Setup and Data

We investigate two experimental deltas formed under identical boundary conditions. The only difference is that the control experiment evolved without explicit marsh sedimentation, while the treatment experiment evolved with a marsh proxy (Table 1). Thus, any changes between the two experiments can be attributed directly to the addition of marsh.

Both experiments were run for 560 hr (~10 times the compensation timescale), which captures many channel avulsions and inherent stochasticity of the system (Wang et al., 2011). Thus, time series explored in this work can be considered ergodic and emergent dynamics within these time series are robust. LiDAR scans of the basin were collected every one (control) or two (treatment) hours while the experiments were paused. Aerial imagery was taken every 15 min.

The deposit was sectioned from distal to proximal along strike every 10 cm. We use image processing to obtain a stratigraphic marsh fraction roughly every 10 cm in strike (Figure S1 in Supporting Information S1), which was interpolated across the basin using Bayesian kriging techniques to estimate the marsh and clastic volume sequestered in the basin (Text S2 in Supporting Information S1).

### 2.2. Marsh Proxy

The marsh proxy introduces non-riverine deposition to the treatment experiment (Figure 1a). In total, the mass of marsh proxy added to the system is 8% of the riverine sediment input and makes up 15% of the final deposit volume. While we discuss this proxy in terms of organic sedimentation, it may also represent fine-grained deposition from non-riverine processes (e.g., tides, waves, and storms) in tidal flats and wetland platforms. For simplicity, the marsh proxy simulated only the sediment properties of organic material, neglecting some physical properties of vegetation (e.g., stem density). We use kaolinite (clay) as the marsh proxy, which has a low initial bulk density (~90% porosity when deposited in water), uniform deposition upon settling, and relatively high settling velocity when surfactant (0.01% Jet Dry to water input) is added. Further, a distinctly different grain size and color from the riverine sediment makes it ideal to analyze in aerial imagery (Figure 1a) and stratigraphy (Figure S1 in Supporting Information S1).

To first order, marshes accumulate as a function of elevation relative to sea level (rsl) (Baustian et al., 2012; Cahoon et al., 1995; Kirwan et al., 2010; Morris et al., 2002). This generalization simplifies many complex processes of marsh ecology (Morris et al., 2002) and trapping of fine sediment (Li et al., 2009), yet the vast swaths of coastal marsh within decimeters of sea level show that this is a dominant, emergent control. We adapt the marsh production model from Morris et al. (2002), which shows an optimum accumulation rate near rsl and suboptimal accumulation above and below. Experimental elevations were scaled to the emergent channel depth

**Table 1**
*The Experimental Conditions for Both the Control (No Marsh) and Treatment (Marsh) Experiments Used for Comparison in This Study*

| Boundary condition | Control | Treatment |
|---|---|---|
| Sediment Mixture | Hoyal and Sheets (2009) | Hoyal and Sheets (2009) |
| Realtive Sea Level Rise ($RSLR_b$) | 0.25 mm/hr | 0.25 mm/hr |
| Riverine Sediment Discharge ($Q_s$) | 1.41 kg/hr | 1.41 kg/hr |
| Riverine Water Discharge ($Q_w$) | $1.72*10^{-4}$ $m^3/s$ | $1.72*10^{-4}$ $m^3/s$ |
| In-situ Marsh Deposition ($Q_m$) | None | 200 g/2-hr (average); 3.7 g/hex (max production); 1.7 g/hex (stable/unstable) |

from the control experiment (~14 mm). Hence, generating three elevation zones that received marsh: −9 to −5 (unstable), −5 to 0 (maximum production), and 0 to 5 mm rsl (stable), and collectively represent the marsh window. The maximum production zone received enough kaolinite to accumulate ~1 times the base relative sea level rise rate ($RSLR_b$; 0.5 mm/2-hr). The unstable and stable zones received enough sediment to accumulate ~0.5$RSLR_b$ (Figure 1b).

To apply the marsh proxy, LiDAR scans taken while the experiment was paused provide the median elevation of hexagonal grid cells covering the basin (146.14 $cm^2$; 7.5 cm sides; Figure 1c). Depending on the median elevation of the cell, we deposit either 3.4 (maximum production zone) or 1.7 g (stable and unstable zones) of

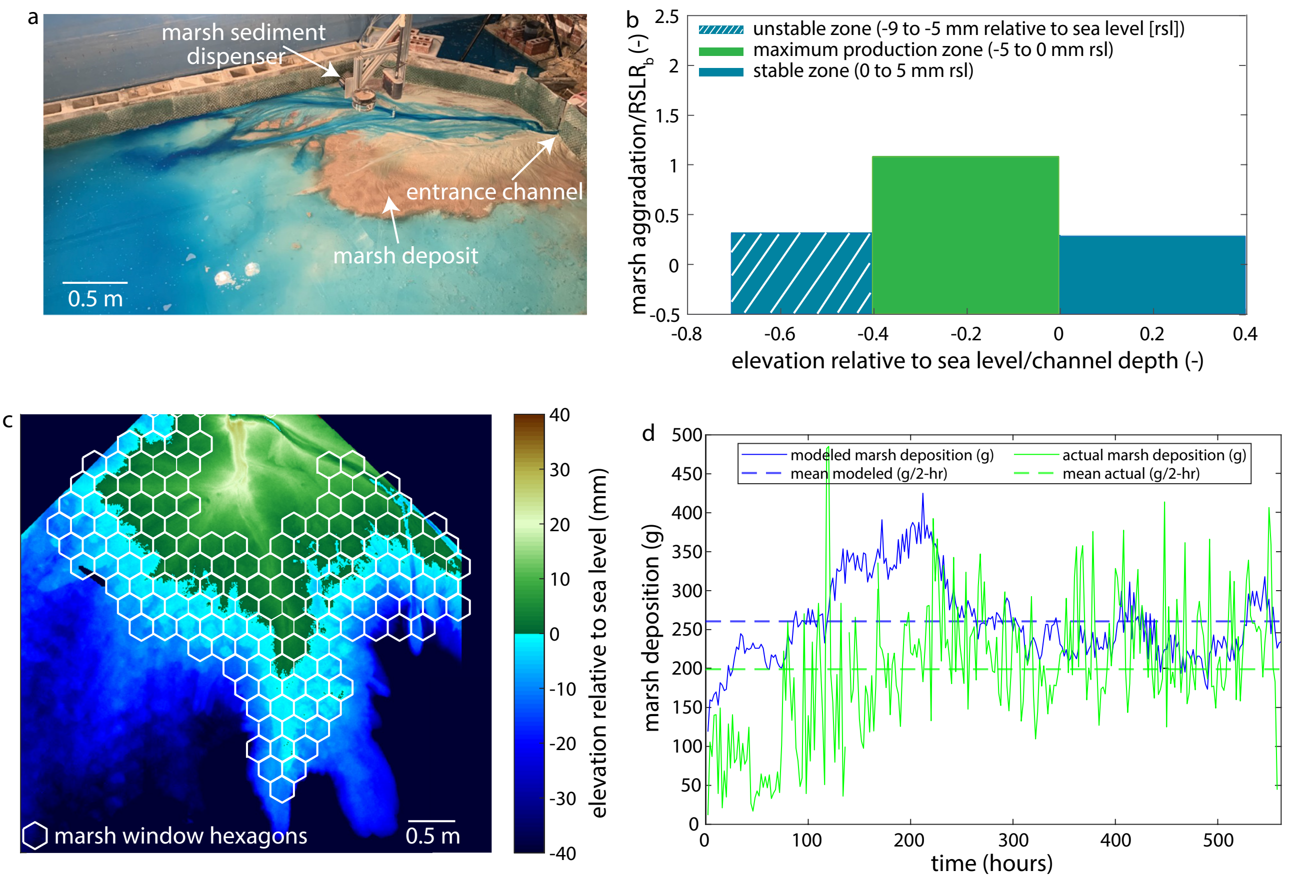


**Figure 1.** (a) The silver cart (top of image) holds the marsh dispenser, which deposits kaolinite at the center of each hexagonal grid (c) with an average elevation in the marsh window every 2 hr. The brown sediment is the kaolinite marsh proxy. (b) The model, adapted from Morris et al. (2002), used to determine the marsh zone. (c) The hexagonal grid imposed upon a LiDAR scan of the basin (hour 250). (d) Modeled versus actual marsh deposition (g) each deposition cycle during the experiment with the average ~200 g/2-hr shown as a green dashed line.

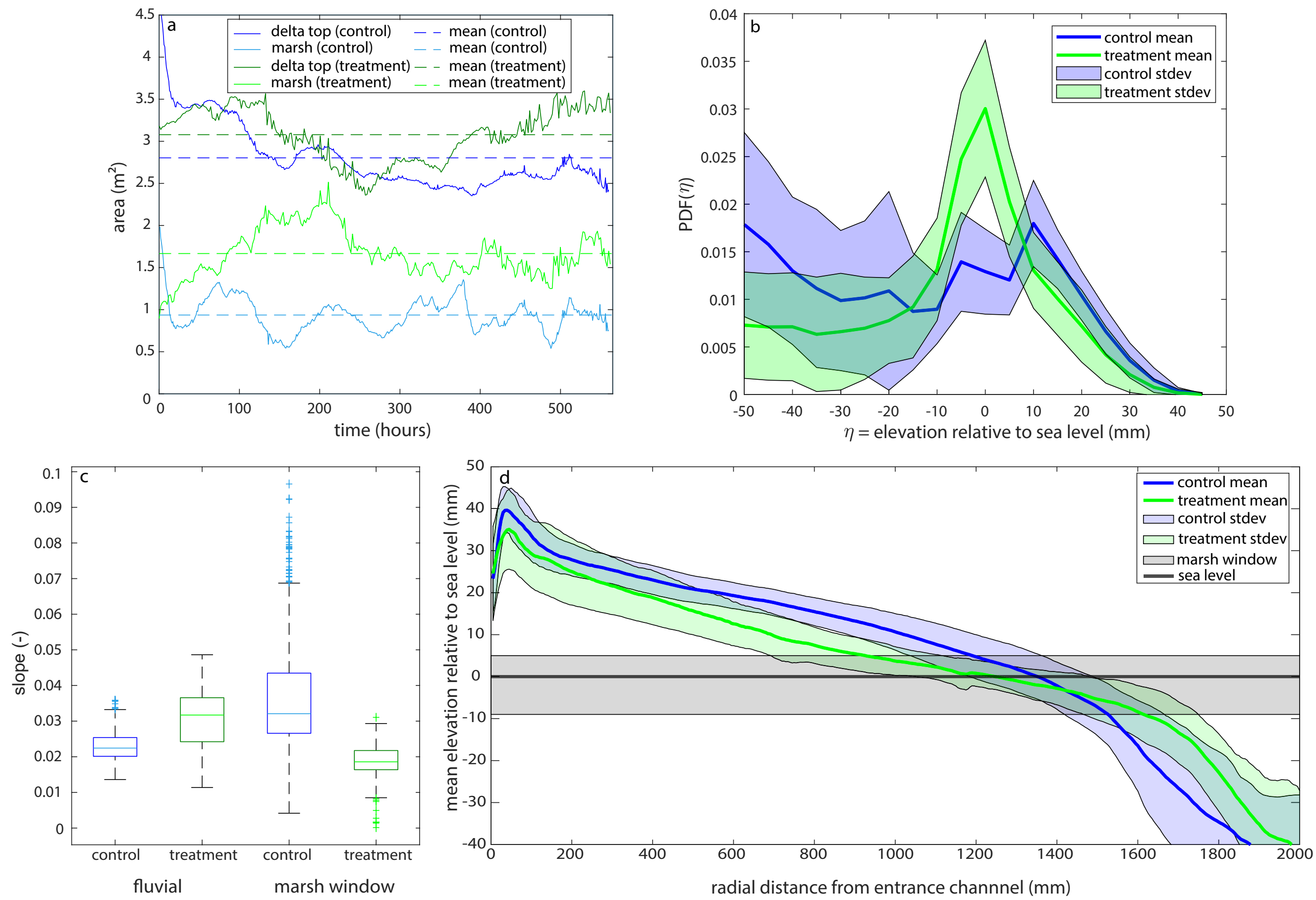


**Figure 2.** (a) Delta top (≥−9 mm rsl) and marsh window (−9–5 mm rsl) area for the control and treatment through time. (b) Time-integrated mean probability density of elevations relative to sea level, with one standard deviation shown for both experiments. (c) Box plots showing the time distribution of fluvial (>5 mm rsl) and marsh window delta slopes. (d) Mean elevation (mm) as a function of radial distance from the entrance channel (mm) integrated over space and time, with one standard deviation shown for both experiments.

kaolinite. The marsh sediment dispenser (a sieve) is attached to a cart that moves about the basin. On average, the sieve is 0.60 m above the sediment surface, though this varies through time and space as sediment accumulates on the delta. Deposition is promoted by using a ButtKicker™ to vibrate the sieve (black box left of sieve in Figure 1a), triggering kaolinite to deposit evenly within the cell (Movie S1 in Supporting Information S1). While we deposit with great spatial precision, the proxy mass is under-distributed by ∼50% (Figure 1d; ∼60 g/2-hr less than modeled). Thus, if we met the target rates, effects quantified here would have likely been accentuated. While less accurate than anticipated, the spatial deposition of sediment is consistent with the model from Morris et al. (2002) (Figure 1b). Thus the in-situ deposition of kaolinite provides a reasonable proxy for marsh accumulation, as shown by significantly altered morphology and clastic deposition between the experiments.

## 3. Results

### 3.1. Delta Morphology

A significant difference between treatment and control is observed in the area within the marsh window (−9 to 5 mm rsl) and the delta top (≥−9 mm rsl). The marsh window was 0.936 ± 0.202 $m^2$ in the control, but larger in the treatment at an average size of 1.67 ± 0.288 $m^2$ (Figure 2a). Similarly, the delta top was smaller in the control at an average size of 2.80 ± 0.383 compared to 3.08 ± 0.316 $m^2$ for the treatment (Figure 2a). Considering the average delta top area, the treatment experiment was 10% larger than the control experiment, while the treatment marsh window was 78% larger.

**Table 2**
*The Clastic Volume Balance and Trapping Efficiency of Different Delta Regions for the Control and Treatment (Treat.) Experiments*

| Delta region | Area ($m^2$) [control] | Area ($m^2$) [treat.] | Clastic volume ($m^3$) [control] | Clastic volume ($m^3$) [treat.] | Trapping efficiency (%) [control] | Trapping efficiency (%) [treat.] |
|---|---|---|---|---|---|---|
| delta top (≥−9 mm rsl; ≥50% of time) | 2.73 | 2.96 | 0.363 | 0.355 | 55.0 | 53.7 |
| fluvial (>5 mm rsl; > 90% of time) | 0.880 | 0.352 | 0.121 | 0.0413 | 18.3 | 6.25 |
| marsh window (−9 to 5 mm rsl; ≥10% of time) | 2.87 | 4.28 | 0.339 | 0.453 | 51.4 [63.9[a]] | 68.6 [73.2[a]] |
| off shore (<−9 mm rsl; ≥50% of time) | N/A | N/A | 0.297 | 0.306 | 100 | 100 |

*Note.* Treatment marsh sedimentation is excluded from volume.
[a]The trapping efficiency calculated using the volume of clastic sediment delivered to the marsh window instead of the clastic sediment delivered to the delta top. Refer to Text S2 in Supporting Information S1 for equations and further explanation.

The elevation distribution shows an increase in elevations within the marsh window in the treatment experiment (Figure 2b), suggesting a change in slope relative to the control. Slopes are calculated radially from the entrance channel by fitting a linear regression through the mean elevations of 5 mm wide radial transects. We observe a 20% larger slope in the fluvial region (>5 mm rsl) for the treatment (3.0%) as compared to the control (2.3%). Interestingly, the slope in the marsh window is significantly reduced from 3.7% in the control to 1.9% in the treatment experiment (Figure 2c).

The mean elevation as a function of radial distance from the entrance channel shows that the addition of the marsh proxy alters the elevation distribution of the delta top (Figure 2d). The treatment experiment has an increase in marsh window elevations and a decrease in the area of elevations in the fluvial region. The relative elevations in the fluvial region are also smaller (by about one channel depth on average). Further, the delta top slope decreases upon entrance to the marsh window in the treatment, which allows the marsh to persist over a greater distance.

### 3.2. Sediment Balance

To limit delta-marsh interaction, the fluvial region discussed below encompasses only the area above 5 mm relative to sea level (rsl) for at least 90% of the experiment. The marsh window is the area ≤5 and ≥−9 mm rsl for greater than 10% of the experiment. Thus, the marsh window begins exactly where the fluvial zone ends. The delta top is the area that is ≥−9 mm rsl for at least 50% of the experiment, which captures average conditions. Off-shore is <−9 mm rsl for at least 50% of the experiment.

While each experiment had the same clastic sediment input, the spatial distribution of sediment accumulation is different. For volume balance and trapping efficiency equations refer to Text S2 in Supporting Information S1. The area in the fluvial region for greater than 90% of the control experiment is 0.880 $m^2$, which accumulates 0.121 $m^3$ of sediment throughout the experiment. The corresponding area of the treatment experiment is 0.352 $m^2$, which accumulates 0.0413 $m^3$ of clastic sediment during the experiment. Since the marsh extent is larger in the treatment experiment, more clastic sediment is trapped in this elevation window than in the control (Figure S2 in Supporting Information S1). Thus, the marsh window has a 68.6% trapping efficiency (clastic sediment delivered to the delta top/clastic sediment accumulated in marsh) in the treatment, but a 51.4% trapping efficiency in the control (Table 2).

The area on the delta top is 2.73 $m^2$, accumulating a total volume of 0.363 $m^3$ of sediment. The corresponding area of the treatment experiment is slightly larger (2.96 $m^2$), but accumulates less clastic sediment (0.355 $m^3$). Compared to the total fluvial input (0.660 $m^3$), this yields similar delta top trapping efficiencies of 55.0% in the control and 53.7% in the treatment (Table 2). Hence, similar amounts of clastic sediment are transported past the marsh zone. We also find that roughly 85% of the marsh deposited was preserved in the resulting delta top stratigraphy, which accounts for 15% of the delta top volume. Though the total clastic sediment sequestrated here is similar in both experiments, marsh sedimentation augments the clastic sedimentation in the treatment experiment leading to the formation of a vastly different delta.

10.1029/2022GL098513

## 4. Discussion

The experiments show that marshes interact with deltas and have first-order impacts on morphology and sediment partitioning. We show that even a small addition of marsh proxy sediment (~8% of riverine mass) drastically impacts delta formation. Specifically, marsh deposition flattens the delta, alters location of maximum clastic deposition, and changes the delta hypsometry.

### 4.1. An Important Feedback

It is remarkable that an 8% addition of marsh mass creates a 78% increase in extent of the marsh window. This marsh sedimentation is essential to the long-term stability of the treatment experiment. Paradoxically, the addition of marsh proxy reduces total clastic sedimentation on the delta top, but simultaneously bridges the gap to create a delta spanning a similar extent. This illustrates an important and previously unexplored feedback between marsh and river delta sediment accumulation.

The emergent effect of the interaction between marsh and clastic sedimentation is the decreased slope of the subaerial marsh window. Because the treatment experiment has smaller slopes from the shoreline to the top of the marsh window and the shoreline location changes only slightly (Figure 2d), the area from the top of the marsh window to the apex must be smaller in the treatment experiment (Figures 2c and 2d). Marshes do not erode sediment from upstream to include within the marsh window, yet the lower slopes of a marsh in dynamic equilibrium with its delta effectively "steal" clastic sediment from higher elevations. For example, the fluvial area accumulated 3 times less clastic volume in the treatment experiment (Table 2). Instead, the remaining sediment trapped on the delta top is sequestered in the marsh window, which accumulates 1.3 times more clastic volume (Table 2) than the control. While marsh deposition changes the sediment balance between the marsh window and elevations above it, the clastic sediment partitioning of the topset and foreset remains similar. Even so, the decreased slope and associated feedbacks leads to variation in spatial clastic deposition in the treatment experiment as compared to the control.

Decreased delta top slopes have previously been shown to alter delta morphology and increase channelization (Parker et al., 1998). Decreased delta slopes are a function of grain size and cohesion (Edmonds & Slingerland, 2010; Caldwell & Edmonds, 2014; Li et al., 2017), as well as a function of the ratio of water to sediment discharge (Powell et al., 2012; Whipple et al., 1998; Wickert et al., 2013). Here we suggest a new mechanism for lowering delta top slope: non-riverine sedimentation in the floodplain. The slope break caused by marshes has been shown to influence avulsion locations (Ratliff et al., 2021). Hence, this process matters for modern-day and ancient river deltas, which often support large swaths of marsh.

### 4.2. Delta Hypsometry

Equilibrium hypsometry, or the elevation distribution on the delta top, shows enhanced areas of elevations near sea level where marsh sedimentation or similar processes are present (Figure 2b). Using the ETOPO Global Relief Model (NOAA) in Google Earth Engine, we explore this hypothesis for four large river deltas (MRD, Ganges Brahmaputra Meghna Delta (GBMD), Mekong River Delta, and Rio Grande River Delta). Despite coarse resolution and systematic errors in this digital elevation model (Minderhoud et al., 2019), comparison at the vertical scale of several meters is appropriate (Text S3, Figure S3 in Supporting Information S1). Scaling by channel depth (for comparison across scales) reveals the general hypsometry of these deltas (Figure 3).

The treatment experiment and global deltas show a peak in elevations between 0 and 0.5 channel depths above relative sea level (rsl). In both the treatment experiment and global deltas, >30% of all elevations between −1 and 3 channel depths lie between 0 and 0.5 channel depths rsl, while the control experiment only has 15% of elevations here. Rather, the control experiment shows its peak around 0.8 channel depths rsl due to increased slopes and associated reduced area near the shoreline. The marsh proxy organizes the treatment experiment's hypsometry to reflect the dominant hypsometric feature of delta systems. At a minimum, this suggests that proxies for non-riverine, elevation-based coastal accumulation can improve the fidelity of laboratory scale models. It also suggests that purely fluvial, lobe based delta deposition is insufficient to understand sedimentation in modern deltas. While organic deposition is a reasonable control on these systems, tidal flat and barrier island reworking should also fundamentally influence delta hypsometry and sediment partitioning in similar ways, because they

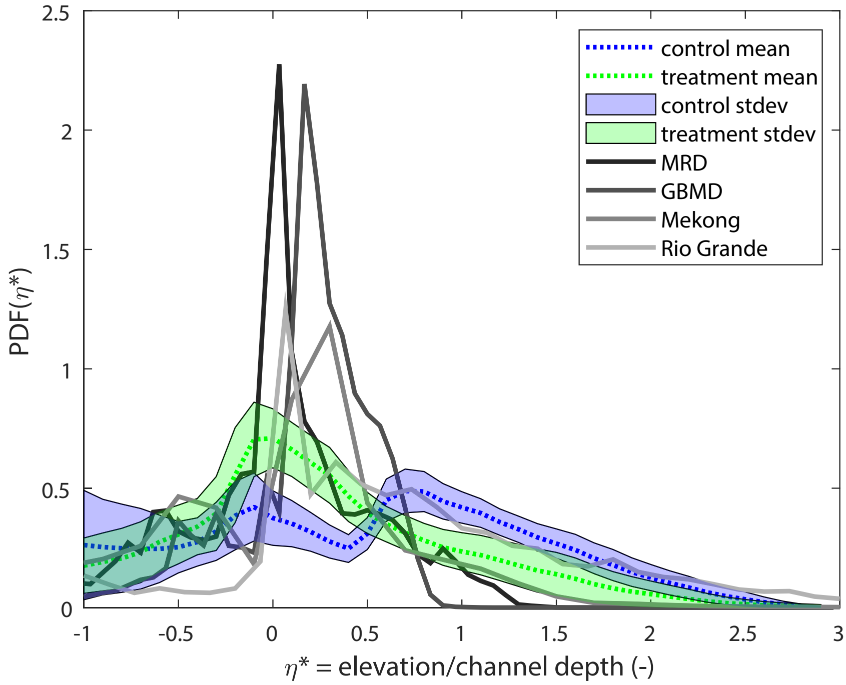


**Figure 3.** Probability density function showing hypsometry of control and treatment experiment and four global deltas (Mississippi River Delta [MRD], Ganges Brahmaputra Meghna [GBMD], Mekong, and Rio Grande). Elevations are normalized by channel depth ($\eta$*) for comparison across scales.

are also focused deposition near sea level. The point here is that despite many different accumulation processes and ecologies in these field-scale deltas, the proxy is successful in pushing the experimental hypsometry closer to field systems. Succinctly, the coupling of riverine and non-riverine sediment deposition appears to be essential in shaping global deltas.

### 4.3. Limitations

The kaolinite marsh proxy is not yet capable of discerning the effect of distinct ecologies or non-fluvial processes, meaning the proxy reflects any elevation-based, non-riverine coastal deposition. Our study differs fundamentally from those that consider the hydrodynamic or sediment transport effects of vegetation (e.g., stem density and roughness). Instead, it is the proxy's volume that alters delta slopes and zones of mass accumulation. Though the influence of vegetation properties on hydrodynamics has been shown to impact clastic sedimentation rates (Nardin & Edmonds, 2014), this interaction occurs on much shorter timescales (daily tidal cycle) than the timescales focused on here ($>10^3$). Similarly, the proxy is not able to capture erosional effects of wind and waves like marsh edge erosion (McLoughlin et al., 2015) or pond formation and expansion (Himmelstein et al., 2021). However, these processes also occur on shorter timescales than focused on here. If ecological, hydrodynamic, or erosional effects pushed sedimentation away from the elevation-based deposition model, then results may differ in ways that cannot be quantified here.

Our study is limited to the influence of non-riverine deposition on delta dynamics in an equilibrium system. We do not incorporate an acceleration of sea level rise rate (SLRR) thus, we cannot assess the limits of marsh to vertically aggrade or move laterally with changes in SLRR. The marsh proxy would likely interact dynamically with accelerating SLRR, and this can be assessed with future studies.

### 4.4. Implications

This work can be used to inform restoration and management plans on river deltas with significant marsh deposition. Successful restoration of deltaic wetlands hinges on understanding delta hypsometry and the temporal and spatial clastic sediment deposition rates. While marsh sedimentation is relatively continuous (once every 2 hr) in

10.1029/2022GL098513

the marsh window, it is important to note that this region accumulates primarily fluvial sediment. The extent of this region is increased due to the feedbacks between the river and marsh. Given the importance of channel-marsh interaction to the mass balance in the treatment experiment and in the absence of other clastic sediment distribution mechanisms (e.g., tides or storms), limiting channel-marsh interaction via leveeing could significantly alter the feedbacks observed here.

Engineered marsh platforms must be consistent with how the wetland platform would grow naturally (Paola et al., 2011). Modern deltas have elevation windows that matter for habitability (higher elevation, fluvial ridges) and others that matter for storm surge protection and biodiversity (lower elevation, wetlands). The presence of non-riverine deposition on the shallow platforms created via river diversions (or other restoration methods) will create mostly land at or near sea level. Millions of people globally rely on this region to mitigate flooding (Edmonds et al., 2020), thus the probability distribution of elevations (Figure 2b) will eventually have implications for the extent of storm surges and susceptibility to drowning. Similarly, the change in coastal accumulation rates seen in the treatment experiment has implications for the abiotic, fluvial deposit (i.e., fluvial ridges). Since the interaction between rivers and wetlands controls this area partitioning, it should be a significant control on modern deltas and any future river diversions created to support them.

## 5. Conclusion

We show that the addition of marsh proxy sedimentation in a delta experiment fundamentally alters the mass balance and hypsometry of the resulting delta. Specifically, we find a new control on delta top slope: non-riverine sedimentation. The decreased marsh window slope creates feedbacks that impact the spatial and temporal distribution of riverine sediment, leading to increased area near sea level. The interaction of river and marsh sediment in the treatment experiment leads to a morphological signature more consistent with modern-day river deltas than the control. Since coastal wetlands accumulate sediment to keep pace with relative sea level rise in the low-lying regions of deltas, they fundamentally flatten land near the coast creating the vast platforms seen globally. The lower slopes create feedbacks with clastic sediment deposition patterns that will help to inform future restoration plans, as these plans typically hinge on the successful distribution and retention of riverine sediment.

## Data Availability Statement

Data used to reproduce the results of this study are archived at: https://figshare.com/articles/dataset/TDWB_19_2_MassBalance_Morphology/19963034 and Sanks (2022a). These data must be downloaded and placed in the data folder of the GitHub repository (https://github.com/kmsanks/TDWB_19_2_MassBalance_Morphology). The repository contains the software used to reproduce the results of this study and is archived on both GitHub and in Zenodo (Sanks, 2022b). Data archiving of the raw experimental data is available for both TDB-18-1 (control; Straub & Dutt, 2022) and TDWB-19-2 (treatment; Sanks et al., 2022). Note, this data is not needed to reproduce any results from the study, but may be of interest for other researchers.

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