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Variable Flood Discharge Constrains Autochthonous Organic Carbon Preservation in Deltas: Insights From Physical Experiments

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Key Points:

- Variable flood discharge increases deltaic slopes, which in turn leads to smaller deltas with smaller wetland areas
- Enhanced channel mobility and steeper slopes reduce the ability for large-scale shoreline movement to occur
- Variable discharge reduces the potential for autochthonous carbon storage in the subsurface

Supporting Information:

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

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Abstract Many global and regional climate models predict shifts in the frequency and magnitude of precipitation events. It is unclear how this transition will influence delta and wetland development. We address this knowledge gap via two reduced-scale physical delta experiments: one with constant discharge and the other with variable discharge. Floods with a peak discharge equal to three times the baseflow reduce the mean total delta-top area by a factor of two and a half and increase slopes by a factor of two. Enhanced channel mobility increases delta top slopes and limits large-scale shoreline movement, which reduce wetland planform. There is a 108% difference in the volume of preserved organic material in the subsurface between the variable and constant discharge conditions. Morphometric differences between systems constructed under constant versus variable discharge highlight the potential impact on ecologically sensitive and economically important coastal wetlands, with implications for the ability to sequester carbon.

Plain Language Summary Many climate models predict an increase in the variability of extreme precipitation and flood events. However, it is unclear how this will affect the development and sustainability of coastal deltas and wetlands. We compare observations from two delta experiments: one with constant river flood discharge and another with variable flood discharge. Our findings show that variable flood discharge results in steeper delta slopes, leading to smaller delta and wetland areas. This smaller wetland area leads to a reduction in the amount of organic material that can be stored in the subsurface.

1. Introduction

The predicted increase in precipitation and high-magnitude flood frequency driven by ongoing climate change (Intergovernmental Panel on Climate Change, 2023) has implications for deltaic environments. These landscapes are shaped by wetlands interacting with sediment and water sourced from rivers, in addition to coastal processes such as wave and tidal action (Edmonds & Slingerland, 2010; Lauzon & Murray, 2018; Nienhuis et al., 2020). With regards to river processes, variable discharge influences channel morphology, sediment transport, and patterns of deposition (e.g., Plink-Björklund, 2015), thereby altering delta morphodynamics (Barefoot et al., 2021; Chadwick & Lamb, 2021; Esposito et al., 2018; Ganti et al., 2016; Plink-Björklund, 2015). Experimental and field studies have demonstrated that channels constructed under highly variable discharge conditions exhibit greater mobility and more dynamic morphologies than those formed under low discharge variability (Barefoot et al., 2021; Esposito et al., 2018; Leenman et al., 2025). This increased channel mobility raises questions regarding the resilience of deltaic systems and has implications for the continued stability of coastal wetlands.

The ecological and biogeochemical functions of deltaic wetlands, which offer vital ecosystem services, depend on sediment delivery. However, climatic and anthropogenic influences pose risks to these ecosystems. Rising seas threaten to outpace vertical accretion of wetlands, leading to land loss (Li et al., 2024). Human activities such as construction of dams and artificial levees can significantly reduce sediment delivery to the topset of coastal deltas (Edmonds et al., 2023; Nienhuis et al., 2020), further exacerbating the already fragile stability of these coastal wetlands. While the impacts of enhanced discharge variability on wetlands are not fully constrained on any timescale, here we focus on timescales equal to or exceeding those linked to delta lobe construction and

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abandonment (typically 10^2–10^3 yrs) (e.g., Chamberlain et al., 2018; Chu et al., 2006; Pang & Si, 1979; Saito et al., 2000).

The longitudinal extent of deltaic coastal wetlands is constrained by their elevation relative to mean high tide (Kirwan et al., 2023; Morris et al., 2002). We hypothesize that high river discharge variability can destabilize this equilibrium, influencing the spatial distribution and mobility of wetlands over time. These dynamics have implications for organic carbon preservation, as wetlands are a substantial source of organic-rich deposits (Chmura et al., 2003) that contribute to carbon sequestration within deltaic stratigraphy. While previous studies document the effects of discharge variability on channel mobility (e.g., Barefoot et al., 2021; Leenman et al., 2025; Wu et al., 2025), the impact of such variability on the preservation of organic-rich strata within deltaic environments remains unclear. Earlier experimental studies found that deltas constructed under variable discharge exhibit more mobile channels, greater floodplain reworking, steeper slopes, and more stable shorelines (Barefoot et al., 2021; Esposito et al., 2018), all of which we hypothesize should influence the areal extent of wetlands on deltas and their preservation as carbon rich deposits in the subsurface.

This study aims to quantitatively assess how river discharge variability influences wetland extent, channel mobility, and the preservation of organic-rich strata within deltaic environments. To address this research gap, we conducted two physical delta experiments: one under steady discharge and the other under highly variable discharge. We quantified temporal changes in delta-top area and slope, key factors controlling wetland extent (Sanks, Zapp, Silvestre, Shaw, Dutt, & Straub, 2022). We apply these results to the Rio Grande Delta, which has historically experienced variable discharge (e.g., Blythe & Schmidt, 2018). Additionally, we measured the shoreline location as an indicator of channel mobility for each system, as lateral movement of channel position is often accompanied by corresponding changes in shoreline planform morphology (Kim et al., 2006; Martin et al., 2009; Straub et al., 2015). By quantifying these parameters, we investigate how discharge variability influences wetland stability, channel network dynamics, and the potential for autochthonous (in situ) organic carbon preservation in deltaic systems. These insights are critical for understanding how future discharge regimes may affect the resilience of deltaic wetlands and their role as long-term carbon reservoirs.

2. Methods

We investigate how variable discharge influences wetland and delta morphology, area, and preservation of carbon-rich strata using two reduced-scale physical delta experiments. One experiment was forced with a constant input flux, while the other was forced with variable discharge (Figure 1; Text S1, Figure S1, and Table S1 in Supporting Information S1). Experiments were conducted at the Tulane University Sediment Dynamics and Stratigraphy Laboratory and evolved autogenically under constant base-level rise. We refer to this constant base-level rise as pseudo-subsidence because it mimics spatially uniform subsidence patterns that allow for the creation of accommodation (Sheets et al., 2002). Water and clastic sediment were delivered to the experiments through an entrance channel, while a proxy material for non-riverine deposition (kaolinite clay) was simultaneously introduced via overhead deposition that accumulated on the delta-top following an elevation-based model. This model is representative of all organic-rich, non-riverine sedimentation within deltaic coastal environments (e.g., wetlands and tidal flats) (Morris et al., 2002; Sanks, Zapp, Silvestre, Shaw, Dutt, & Straub, 2022). We henceforth refer to this material as non-riverine sediment for simplicity. Experiments were paused to collect surface topography of the dry surface every 2 hr In the constant discharge experiment and every 2.2 hr In the variable discharge experiment. A hexagonal grid (cell area = 146.14 cm^2) was applied to the basin and cells with median elevations −9 to 5 mm relative to sea-level were defined as wetland. For simplicity and because our experiment did not include tides, we scaled this elevation window to channel depth, which is an internally derived and self-organized vertical scale. Elevations greater than 5 mm were defined as the area upslope of the wetland. A programmable carriage that moved in all Cartesian directions deposited the non-riverine sediment from overhead via a motion-activated sieve (Sanks, Zapp, Silvestre, Shaw, Dutt, & Straub, 2022) (See Text S1 in Supporting Information S1). Elevation windows −9 to −5 mm and 0–5 mm received non-riverine deposition ~0.9 times the base-level rise (~1.7 g/cell) and elevations between −5 and 0 mm received deposition ~1.8 times base-level rise (~3.4 g/cell). Error associated with deposition rates was approximately −33% and −19% in the constant discharge and variable discharge experiments, respectively (See Figure S2 in Supporting Information S1). Negative errors indicate less proxy material delivered to deposit than intended. After loading-induced compaction, deposition rates were at or below base-level rise rates, which allowed autogenic movement of the shoreline.

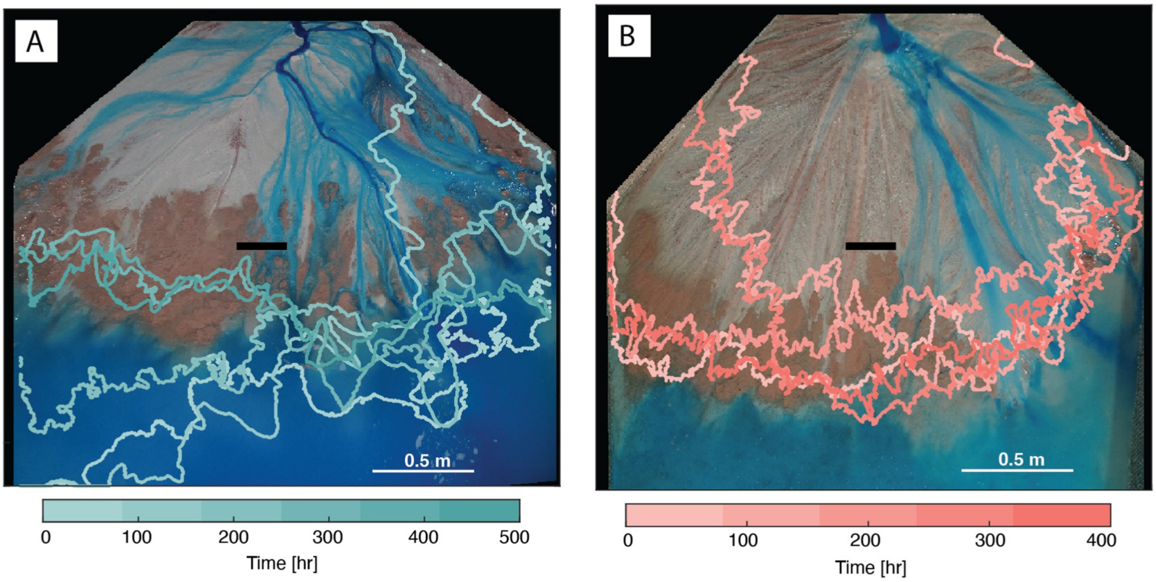

Figure 1. Shoreline location at 100-hr intervals for (a) Constant discharge and (b) Variable discharge experiments overlain on images of the experiments. Flow is dyed blue to aid visualization of flow paths. Image of variable discharge experiment taken during baseflow conditions. The visible extent of the total delta top (>−9 mm) is partially obscured by blue ocean water. Note the increased presence of coarse material (red sediment) on the terrestrial delta top in the variable discharge experiment compared to the fine-grained overbank material (white sediment) in the constant discharge experiment. Horizontal black lines represent strike-sections in Figure 4.

All other boundary conditions were held the same in the two experiments. For the variable discharge experiment, the discharge of water and sediment during flood was three times that of low flow periods (baseflow). Sediment discharge generally increases faster than linear relative to water discharge (e.g., Nittrouer et al., 2008), but the ratio of sediment to water discharge was kept constant over the flood-to-interflood cycle for simplicity (Esposito et al., 2018). The average discharge of water and sediment during a flood-baseflow cycle was identical to the constant discharge experiment. To achieve this, the baseflow discharge was ∼83% of the discharge in the constant discharge experiment. Each cycle lasted 66–59 min at baseflow and 7 min at flood. The ratio of flood-to-interflood duration and flood to baseflow discharge were motivated by yearly floods on the Mississippi River (e.g., Allison et al., 2013), but we emphasize that scaling experimental floods to field systems is challenging. Rather than attempting to scale our experimental landscape to any modern system, our aim was to quantify the implications of forcing an experimental fluvial network with a variable hydroclimate (Paola et al., 2009).

The fluvial clastic sediment mixture used in the experiments was based on a cohesive mixture developed by Hoyal and Sheets (2009) and consisted of particles ranging from 1 to 1,000 microns in diameter with a with a mean size of 67 microns. A small amount of polymer was added to the sediment mixture to enhance sediment cohesion, which aids in channel formation. Imagery and surface topography were also captured during active run cycles (15 min Intervals for imagery and every 45 min for topography). Strike-oriented sections of the resulting delta deposits were made at 10-cm intervals from distal to proximal to quantify the spatial distribution and volume of proxy organic material preserved in the subsurface. We used Bayesian kriging to calculate the volume of preserved non-riverine sediment in experiments (Text S1 in Supporting Information S1).

3. Results

3.1. Delta-Top and Wetland Morphology

We first focus on a comparison of delta-top area in the two experiments. We compare the total delta-top area (>-9 mm), but also the area upslope of the wetlands (>5 mm) and the area of the wetlands (−9 to 5 mm) to quantify the response to floods in different geomorphic zones. We then measure delta-top slopes as this parameter influences the sensitivity of the delta-top to large shoreline fluctuations. Lower slopes are more sensitive to shoreline fluctuations and yield more wetland area, resulting in greater preservation of organic matter in the subsurface at any one time.

The mean area upslope of the wetland zone was larger by a factor of three in the constant discharge experiment than in the variable discharge experiment. In the constant discharge experiment, the area upslope of the wetland exhibited a large-scale oscillation with an amplitude of ∼1.5 m^2 over a duration of ∼300 hr. In contrast, the area upslope of the wetland within the variable discharge did not experience any large-scale oscillations. Rather, the area upslope of the wetland experienced a steady increase from ∼0.5 to ∼1 m^2 and then remained relatively constant over the duration of the experiment (Figure 2a).

The wetland area in the constant discharge experiment also experienced a large-scale but inverse oscillation of ∼1.5 m^2 (Figure 2b). While the area upslope of the wetland experienced a decrease, the wetland area increased to ∼2.5 m^2 over a period of ∼200 hr before reaching an apparent dynamic equilibrium. This phase of growth was characterized by consistent wetland development under steady hydrological conditions. These oscillations result from episodic terrestrial sediment storage events likely driven by large-scale autogenic processes (e.g., compensation filling of accommodation facilitated by avulsions) within the system (e.g., Wang et al., 2011, 2024). In this case, punctuated relocation of the clastic transport system followed by long timescale network stability results in abandonment and drowning of old wetlands while new wetland platforms develop in other regions. In contrast, the variable discharge experiment exhibited a different pattern. Mean wetland area was smaller than the wetland area in the constant discharge experiment by approximately a factor of 2.5 and remained relatively constant. The relative absence of large-scale cyclicity highlights frequent clastic sediment redistribution caused by forcing conditions that were constantly changing and increased channel mobility that favored lateral migration over punctuated avulsions. In this case, variable discharge conditions reduced wetland growth. The mean total delta-top area in the constant discharge experiment was approximately 2.5 times larger than that of the variable discharge experiment (Figure 2c).

To calculate slopes, median elevation profiles were extracted along radial transects at 5 mm intervals and a regression performed on elevation versus radial distance for each timestep. The slope distributions across the delta-top exhibited differences between the two experiments, with consistently steeper slopes observed under variable discharge conditions. Upslope of the wetland zone, slopes were generally higher in the variable discharge experiment, with a median slope of 0.055 compared to 0.030 in the steady discharge experiment (Figure 2d). Within the wetland zone, the slopes were lower overall but demonstrated differences between the two experiments. The median wetland slope in the variable discharge experiment (0.040) was more than double that of the steady discharge experiment (0.018). Total delta-top area slope distributions further reflected the impact of highly variable discharge on delta surface morphology. The median slope in the variable discharge experiment was approximately 0.044, nearly double that of the constant discharge experiment (0.023). The total delta area slope distributions capture the bimodality of slope distributions between wetland area and the terrestrial area above the wetland, whose relative planform extents oscillate through time.

Fluctuations in terrestrial delta area in the two experiments must be linked to movement of shorelines, which drive changes in where wetlands accumulate and where organic-rich strata is found in the subsurface. We quantify this by performing a spectra analysis on time series of shoreline location (See Text S2; Figure S2 in Supporting Information S1). This has the dual advantage of informing us about the magnitude of shoreline movement and timescales of network stability. Long timescale transgressions are linked to episodes of local abandonment coupled to relative sea level rise, and mobile channel networks rapidly change the locus of deposition, resulting in shoreline stability. Spectral analysis (Multi-Taper method) was applied to time series of shoreline location to identify the longest timescales of statistically correlated shoreline movement, which produce the most significant transgressions or regressions. These longest timescales for the constant discharge and variable discharge experiments occur at $T = \sim 57$ hr and $T = \sim 37$ hr, respectively (Figure 3). Channel migration (lateral migration and avulsion) in the constant discharge experiment was governed by longer timescales, which allowed for longer periods of shoreline transgression (Figure 1a). In contrast, the variable discharge experiment exhibited more frequent shifts in shoreline position (Figure 1b).

3.2. Preserved Subsurface Organic Carbon

In both experiments, the fraction of preserved organic-rich non-riverine sediment increases from the channel inlet to a peak before declining beyond the mean shoreline. The constant discharge experiment exhibits a more pronounced peak, reaching a maximum of approximately 0.23 at approximately 1.0 m downstream of the channel inlet (Figure 4d). In contrast for the variable discharge experiment, there is a lower peak fraction of non-riverine

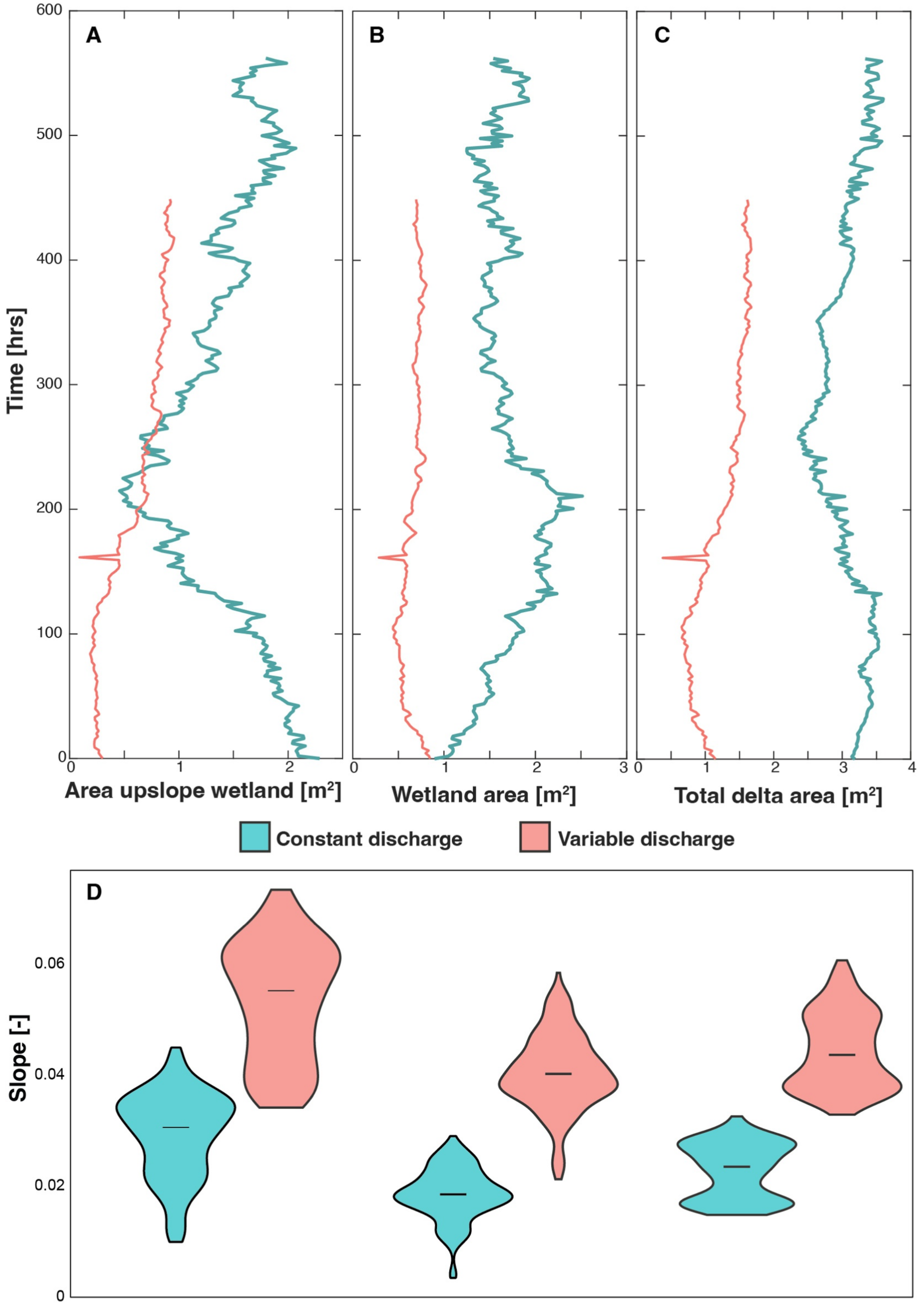

Figure 2. Time series of (a) area upslope of the wetland (b) wetland area, and (c) total area for the constant and variable discharge experiments. Slopes for each corresponding region are directly below each time series in panel (d). The horizontal line inside distributions represents median slopes.

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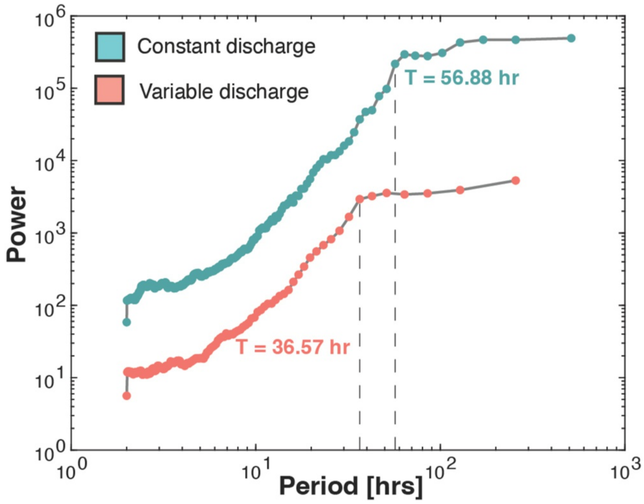

Figure 3. Power spectra of shoreline location for constant discharge (teal) and variable discharge (coral) experiments. Note higher power associated with the constant discharge experiment, resulting from increased shoreline roughness.

sediment preservation (~0.17) at approximately 1.8 m downstream of the channel inlet. The decline of the fraction occurs over a distance approximately five times longer (1.3 m) in the constant discharge experiment compared to the variable discharge experiment (0.30 m). The volumes of preserved non-riverine sediment were ~0.051 m^3 (total deposit volume 0.338 m^3) and ~0.015 m^3 (total deposit volume 0.350 m^3) for the constant and variable discharge experiments, respectively, a 108% difference.

4. Discussion

Previous work emphasized that wetlands are under threat from sea-level rise and subsidence (e.g., Li et al., 2024; Schuerch et al., 2018; Törnqvist et al., 2020). However, there is an additional component of climate change that is detrimental to the persistence of coastal wetlands. Here, we highlight river discharge variability and its effect on coastal wetlands and their ability to sequester organic-rich material as carbon in the subsurface. As climate studies project an increase in the frequency and intensity of precipitation and flooding events (e.g., Myhre et al., 2019; Tabari et al., 2020), our results suggest that these changes will cause global deltas on average to become steeper, smaller, have smaller wetland areas, and reduced shoreline movement, acknowledging that we do not consider influences from tides and waves. The results of this work provide insight into how climate-driven changes to the hydrologic flashiness of a system can alter the morphology of wetlands and deltas through modifications to channel and shoreline mobility, which reduce preservation of blue carbon (carbon stored by tidal wetlands, e.g., Adame et al., 2024) and impact wetland ecosystem services.

4.1. Geomorphic Controls on Morphology and Carbon Storage

Many of the morphometric differences observed in our two experiments mirror those quantified in prior physical delta experiments that evolved with and without floods but that lacked proxy non-riverine material (e.g., Barefoot et al., 2021; Esposito et al., 2018). Three key findings emerge from this study. First, high variability discharge impacts the area of delta-tops and their wetlands while also impacting the slopes of these regions. The variable discharge experiment exhibited a smaller and more spatially constrained delta-top and wetland area (~60% decrease) compared to the constant discharge experiment. Contrary to previous physical delta experiments that did not incorporate non-riverine material and which documented an increase in delta area resulting from high discharge variability (Barefoot et al., 2021; Esposito et al., 2018), we find the opposite trend when incorporating non-riverine sediment accumulation. Floods influence the redistribution of sediment onto adjacent floodplains, where sediment accumulates prior to reaching the shoreline. This process promotes the growth of the terrestrial delta top and increases slopes in comparison to constant discharge conditions under which channels confine and transport sediment directly to the shoreline and marine environment—even under relatively low slope conditions. Consequently, in the absence of wetlands, floods increase terrestrial area (Barefoot et al., 2021; Esposito et al., 2018).

In contrast, the slower migration of channels in the absence of floods permits portions of the delta-top to transition from terrestrial to marginal marine environments characterized by exceptionally low slopes and shallow water depths over submerged portions of the delta topset. Such low-slope and shallow regions are particularly conducive to the development of spatially extensive wetland platforms, which contribute to offsetting relative sea level rise, while clastic deposition builds new land in other areas of the delta. Previous work has demonstrated that variable discharge can inhibit levee development and promote avulsion (Barefoot et al., 2021). Likewise, in the variable discharge experiment, the steeper topset slopes arise due to flow loss to overbank regions, which are inefficient at sediment transport unless the topset slope is increased to compensate.

Second, increased discharge variability reduces the distances and timescales over which shorelines can transgress or regress. The reduction in large-scale shoreline movement (Figure 3) results from the combination of increased slopes and enhanced mobility of channels. Conversely, the accumulation of organic matter under constant discharge reduces the delta-top slope. Coupled with reduced channel mobility, the shoreline in the constant

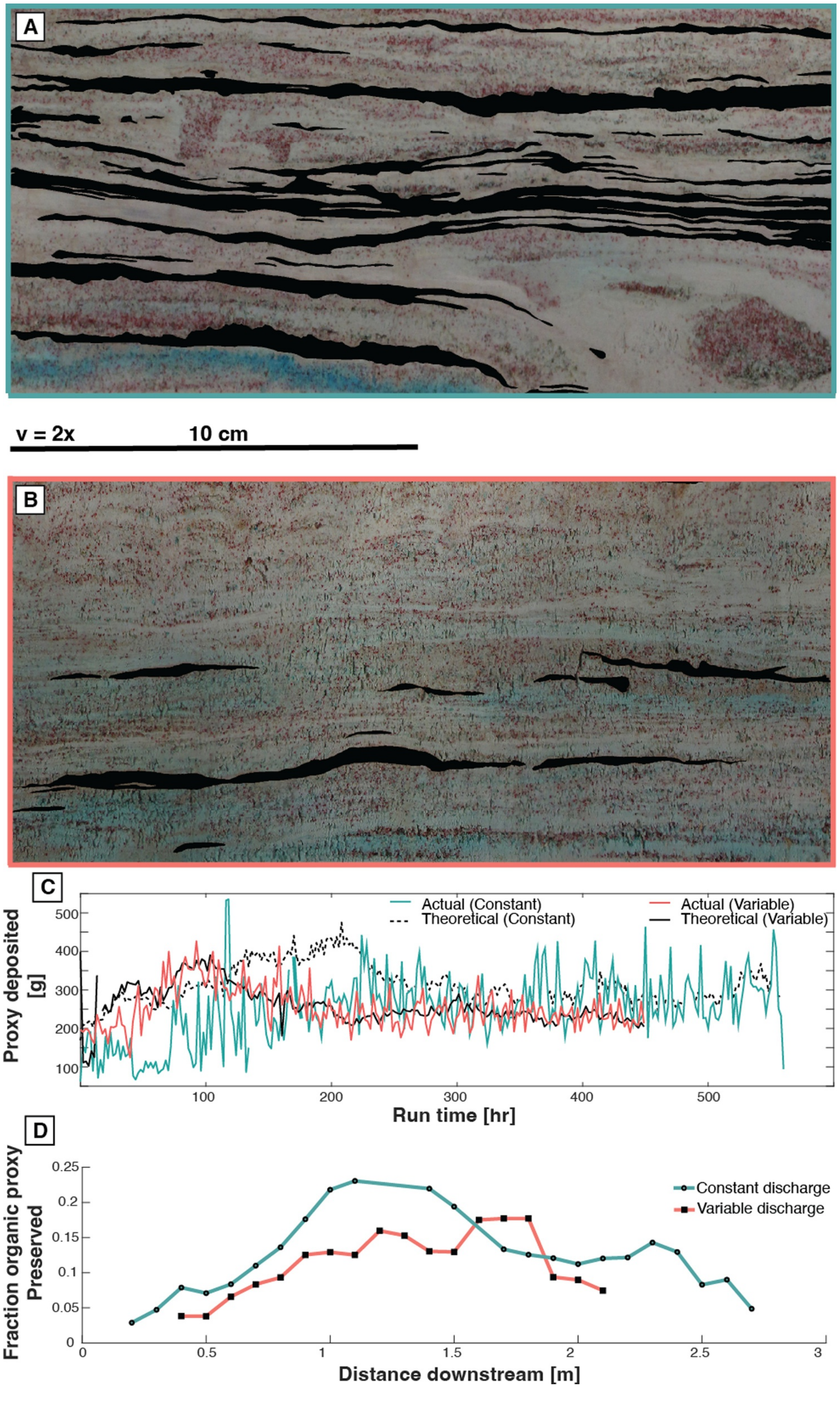

Figure 4. Stratigraphy for (a) Constant discharge and (b) Variable discharge experiments. Black areas represent preserved seams of non-riverine material. Note the increased presence of sandbodies in panel (a) compared to (b). (c) Proxy material deposition as a function of time. (d) Fraction of proxy material preserved as a function of distance downstream.

discharge experiment can experience larger-scale shoreline movement (Figure 1a) leading to long wavelength roughness of the shoreline. River-dominated deltas can contain large interdistributary bays that are shallow, low energy settings that can trap sediment (Elliott, 1974) and organic carbon. Thus, a system under variable discharge, which will be less prone to developing interdistributary bays, might experience reductions in carbon storage near the shoreline.

Third, higher discharge variability results in less carbon burial. Both constant and variable discharge experiments showed maximum preservation of organic-rich, non-riverine sediment near the mean shoreline position. However, the preservation of organic-rich strata was more tightly constrained to regions near the mean shoreline in the variable discharge compared to the constant discharge experiment. The observed patterns in non-riverine preservation have important implications for understanding carbon cycling in deltaic systems and interpreting the stratigraphic record. The maximum preservation near the mean shoreline in both experiments is critical for long-term carbon storage and is consistent with prior sequence stratigraphic models demonstrating maximum thickness of organic-rich strata near the shoreline where biomass production rates match accommodation production rates (Bohacs & Suter, 1997; Diessel et al., 2000). The reduction in organic matter preservation in the high variability discharge experiment indicate that climate-driven changes in flood regimes could alter the efficiency and spatial distribution of sequestered carbon in marginal marine environments. However, some studies have posited that an enhanced input of allochthonous organic matter may lead to increased burial in coastal and offshore systems (e.g., Galy et al., 2015; Prieur et al., 2024). Our experiments do not account for allochthonous inputs to the system and further work could explore the ability of these floods to deliver organic carbon to offshore gravity-flow or deep-marine systems.

Although wetland area was smaller in the variable discharge experiment, which implies less deposition of non-riverine sediment, there is only a 3.0% difference in total mass deposited (∼200 g/run cycle) in both experiments (Figure 4c). While this seems paradoxical, error in deposition of the non-riverine sediment was higher in the constant discharge experiment compared to the variable discharge experiment (−34% difference in theoretical deposition for the first 450 hr). Additionally, increased channel mobility may have reworked and removed material from the system. We hypothesize the discrepancy in preservation of non-riverine material between experiments would likely be larger if we accounted for the measured deposition error of the proxy material in the two experiments. However, it would be difficult to constrain due to the dynamics of the systems and post-depositional compaction.

4.2. Application to Rio Grande Delta

Previous laboratory experiments (e.g., Sanks, Zapp, Silvestre, Shaw, Dutt, & Straub, 2022) have demonstrated that non-riverine sedimentation can produce slope breaks between low elevation wetland platforms and the higher alluvial valley inland. If we apply this to field settings, our experimental observations agree with the morphology of the Holocene Rio Grande Delta. Prior to damming, the Holocene Rio Grande Delta evolved under highly variable discharge (Blythe & Schmidt, 2018; Swartz et al., 2020). Modern hypsometric comparisons show relatively steep terrestrial delta area with a correspondingly smaller wetland platform area as opposed to other systems with less flashy hydrographs that show lower delta slopes and larger wetland platforms (Shaw et al., 2025).

5. Conclusions

In this study we quantified how flood discharge variability influences delta and wetland morphology and the preservation of organic material in the subsurface. While relative sea level rise can pose a risk to coastal wetlands globally, it is necessary to also recognize threats from allogenic controls that can often be overlooked, such as enhanced flood discharge variability resulting from a changing climate.

Our delta experiments incorporate a proxy for organic-rich, non-riverine sedimentation, which allows us to simultaneously capture the evolution of deltas and their blue carbon systems. Therefore, we identify three key findings in our study that can translate to real-world systems:

1. Variable discharge increases deltaic slopes, which in turn leads to smaller deltas with smaller wetland areas.
2. Enhanced channel mobility and steeper slopes reduce the ability for large-scale shoreline movement, such as transgression or regression, to occur.
3. Variable discharge reduces the potential for carbon storage in the subsurface.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Experimental data is available for TDWB 19-2 (Sanks, Zapp, Silvestre, Shaw, & Straub, 2022; Silvestre, 2025a) and TDWB 23-1 (Silvestre, 2025b, 2025c).

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