Laboratory Investigation on Effects of Flood Intermittency on Fan Delta Dynamics

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Abstract To simplify the complex hydrological variability of flow conditions, experiments on delta evolution are often conducted using a representative channel-forming flood flow and results are related to field settings using an intermittency factor, defined as the fraction of time in flood. Although this factor provides an approximation of dominant flow conditions and makes modeling deltas easier by turning their complex hydraulics into a single representative value, little is known about how this generalization affects delta processes. We conducted experiments with periodic flow conditions to determine the effects of intermittent discharges on fan deltas. For each run, the magnitude of floods was held constant, but the duration changed, thus varying the intermittency factor, between 1 and 0.2. Floods consisted of higher water and sediment discharge, while base flow periods had lower water discharge and sediment input ceased, causing the system to become erosional during these periods. We find that as the duration of floods decreases, the delta topset is larger in area with a shallower slope due to reworking on the topset during base flow conditions. During base flows, the experimental system adjusts toward a new equilibrium state that in turn acts as the initial condition for subsequent flood periods. These results suggest that the adjustment timescale is a factor in determining the behavior of deltas and their channels. We conclude that both periods of flood when most of the sediment is supplied to the system and periods of base flow when topset sediment is reworked contribute to delta dynamics.

1. Introduction

Deltas are depositional systems that form where rivers discharge into standing bodies of water. These landforms are home to large populations of people, as well as provide habitat to diverse species of flora and fauna (Gosselink, 1984). Additionally, deltas protect against coastal land loss, which is especially significant during this current era of sea level rise and reduced riverine sediment supply (Nicholls & Mimura, 1998; Syvitski et al., 2005). However, in field settings, it is difficult to obtain a meaningful data set that covers the full evolution of a delta because these landforms evolve over large spatial and temporal scales. Instead, researchers utilize numerical models and laboratory experiments to investigate the controls on delta dynamics, which can then be related back to natural landscapes (Edmonds & Slingerland, 2007; Fagherazzi et al., 2015; Hoyal & Sheets, 2009; Kim et al., 2006; Kim & Jerolmack, 2008; Reitz et al., 2010). As a community, we rely heavily on physical and computational modeling of these important natural systems to understand how deltas form and evolve over time. It is crucial that we thoroughly investigate all the assumptions that go into simplifying models of these complex systems.

One of the more important simplifying assumptions is the notion of a dominant discharge (one that controls both the long-term morphology and that transports the most sediment over time, in the sense of Wolman & Miller, 1960), which allows the system to be modeled by a single characteristic discharge that is applied in terms of an intermittency factor (I) representing its frequency of occurrence (Paola et al., 1992; Parker et al., 1998). The dominant discharge assumption presumes that changes in delta morphology mainly occur during this flood event. However, recent findings on fluctuating sediment transport in depositional systems raise questions about this simplifying assumption. Shaw and Mohrig (2014) examined evolution of subaqueous channels at the delta front of the Wax Lake Delta, located on the coast of Louisiana. Using repeat bathymetric surveys, they observed that channels evolved differently during periods of low versus high discharge events. During floods, sediment that deposited on the topset caused delta progradation as well as aggradation in the channels, while erosion occurred at the channel sidewalls. Periods of base flow were marked by minimal channel bed aggradation and channel lengthening produced by erosion at the channel ends. The data in Shaw and Mohrig (2014) show that tidal influence during base flows can increase the
sediment-transporting shear stresses enough to cause bedload and suspended load transport. However, comparing the gauge height at Amerada Pass in the Atchafalaya Bay with the sediment-transport shear stresses indicates that even before the tide starts to fall, the shear stress rises above the critical value necessary to transport sediment. Their bathymetric data also indicate significant reworking of the sediment surface during base flow and were comparable to the volume of sediment deposited during floods, challenging the conventional notion that most of the sediment transport and morphologic adjustment occur during the formative discharge.

Several recent experimental studies have used periodic input conditions. Pilouras et al. (2017) conducted experiments at \( I = 0.33 \) with sediment feed turned off completely during interflow periods and found that floods caused channel aggradation, while interflow base flows created topographic relief due to channel incision. The discharge fluctuations in these experiments were important for limiting vegetation colonization and maintaining the distributary network of the delta. Also, Ganti et al. (2016) investigated the role of backwater hydraulics on river delta size by comparing experimental deltas produced with constant discharge with one produced over multiple flood cycles with \( I = 0.27 \), where sediment and water discharge values were selected to maintain constant transport slopes between high- and low-flow events. Their experiments showed that deltas with constant discharge conditions were not affected by backwater hydraulics, while the delta with multiple floods produced a deposit with a characteristic delta lobe size that was dependent on the backwater conditions. They concluded that unsteady transient flow conditions were required to produce deltas where backwater conditions controlled avulsion dynamics. Finally, Esposito et al. (2018) explored the role of variable flow dynamics on resulting alluvial stratigraphy through a set of laboratory experiments. In their experiments, sediment and water discharge alternated between high and low values to simulate flood cycles; however, sediment concentration remained constant through the experiment. They found that variable flows increased the lateral mobility of channels, with increased channel aggradation and overbank erosion. These studies highlight the importance of intermittency in delta dynamics, and while collectively they examined a range of I values, individually they only a single value of I was used in each study. Since natural conditions display variable values of I, there is a need to understand exactly how intermittency affects delta growth.

This paper presents results from an experimental study on fan delta evolution with periodic water and sediment input conditions in order to investigate the competition between flood vs. base flow controls on fan morphology as a function of flood intermittency, which are usually ignored under the dominant discharge assumption. We present shoreline migration data, topset slope change, degree of fluvial channelization, and magnitude of topset reworking over flood and base flow periods in order to understand (1) the effect of a base flow period on fan delta morphodynamics and (2) the cumulative effect of multiple base flow periods over flood cycles across a range of intermittency factors. We employ a sediment volume ratio that characterizes the morphologic changes occurring during flood and base flow periods to compare with the intermittency factor of the dominant discharge. We note that the experimental fan delta characterizes a steep, coarse-grained, high-Froude-number, fan delta environment without sediment cohesion and backwater effects. However, we hypothesize that the identified processes of topset reworking during base flow are also applicable to low-gradient river deltas.

2. Methods

A series of experiments were conducted to determine the effects of different intermittency factors on fan delta evolution and their internal dynamics. A variety of different sediment supplies can occur in natural systems during base flow; however, since we wish to examine the effects of base flow periods on delta deposit morphology, we decided to turn off the sediment input completely to maximize these effects. This base flow condition represents a limiting case in which the system transitions from transporting below capacity in the river (as is common in supply-limited, gravel-bed rivers) to transporting near capacity within the delta. From previous work, we expect that during base flow, when the sediment supply from the river declines, the delta will become erosional and the topset slope will decrease (Parker et al., 1998; van Dijk et al., 2009; Whipple et al., 1998), producing a periodically erosional system like fan deltas. However, as intermittency factors decrease, the time available for the landscape to adjust between the flood and base flow periods will be shorter. Each experimental run contained flood periods that were followed by a period of base flow to
model hydrological variability in the natural system, such as seasonal changes in flow due to processes like snowmelt. Specifically, the water and sediment input conditions were square-wave functions, with higher values during the floods, which would be almost instantaneously lowered when base flow periods started (Figure 1). During the floods, water discharge was set to 0.1 l/s and sediment supply rate was 0.001 l/s, and during base flows, water discharge was halved to 0.05 l/s and sediment supply rate was turned off. We chose a base flow water discharge of half the flood value because gauge data from the Wax Lake Delta in Louisiana indicate that yearly summer base flows are approximately 40–50% of winter peak values (Shaw & Mohrig, 2014).

Past numerical studies assume an intermittency value of $I = 0.02$–0.05 (Parker et al., 1998; Swenson et al., 2005) since characteristic bankfull floods occur on average every 1–2 years (Leopold & Maddock, 1953). These flows are thought to do the most geomorphic work, a product of recurrence frequency and amount of sediment transported (Wolman & Miller, 1960). However, a study by Wright and Parker (2003) took another approach to calculating intermittency for the Mississippi River. Instead of determining the fraction of time the hydrograph was above bankfull discharge, they calculated the fraction of time required to transport the total annual sediment load under bankfull conditions. The results of their calculation indicate that the intermittency for the lower Mississippi River and Atchafalaya River is approximately $I = 0.35$ (Kim et al., 2009), which is in the range of intermittency values investigated in this current study. We conducted four experimental runs with different intermittency factors: $I = 1.0$ for continuous flood conditions, $I = 0.50$ with cycles of 1 hr of flood followed by 1 hr of base flow, $I = 0.33$ with cycles of 0.50 hr of flood followed by 1 hr of base flow, and $I = 0.20$ with cycles of 0.25 hr of flood followed by 1 hr of base flow (Figure 1).

We designed experimental runs to include flood durations that were relatively shorter than that of the autogenic timescale of the system under continuous flood conditions, where the autogenic timescale describes the natural cycle of sediment storage and release of the delta system and is observed by periods of topset flooding alternating with periods of channelization. From overhead images of the continuous flood experiment ($I = 1.0$), we determined the autogenic timescale of the system to be 72 min. From this observation, we set the flood and base flow duration to 1 hr each in the $I = 0.5$ experiment. For the lower intermittency factor experiments, we held the base flow period constant at 1 hr but decreased the flood duration so that it was shorter than the autogenic timescale, which is typical of most natural deltas (Aslan et al., 2005). Each experimental run included 5 hr of total cumulative flood time so that the total amount of sediment delivered to the system for each experiment was constant; however, as the intermittency factors decrease, the total duration of each experiment increased as more time was spent base flow periods.

Experiments were conducted in the Sediment Transport and Earth-surface Process (STEP) basin at the University of Texas at Austin. We utilized a 3-m by 2-m section of the basin with a flat rigid bottom surface with no subsidence (Figure 2). Water and sediment were mixed and input at a single point through a rock-cage to dissipate momentum of the flow as it entered the system. Both water and sediment discharges were
computer controlled to ensure accurate inputs. Above the flat basement floor of the basin, we laid down an initial 4.5-cm substrate layer \((h_s)\) of coarse sand for the delta to build out onto (Figure 2). Base level \((z)\), controlled by computerized weir, was held constant throughout all experiments at a depth of 2 cm above the coarse sand substrate layer, and continuously monitored by a sensor. In order to visualize the effects of changing intermittency on fan delta sediment transport and stratigraphic development, the input sediment mixture had a bimodal grain size distribution. We used a mixture of 70% silica sand (white) to 30% crushed walnut shell (brown) by volume. These proportions of sediment had been used in previous experiments, using crushed coal instead of walnut shell, to produce clear stratigraphy (e.g., Heller et al., 2001, Kim et al., 2006, Martin et al., 2009). The silica sand and crushed walnut used in these experiments both had a median grain size of approximately 150 \(\mu m\); however, due to the contrast in their density (silica sand at 2,650 kg/m\(^3\) and crushed walnut at 1,300 kg/m\(^3\)), their transport rates are different (Viparelli et al., 2015). For typical channelized flow during these experiments, the silica sand traveled as bedload only, while the crushed walnut was transported as bedload and in partial suspension. These modes of transport were confirmed from simple rouse number calculations.

Although all experimental systems reported here are net-depositional, it is important to note that they all have high topographic slopes and are highly erosional during base flow periods because sediment supply is completely cut off during these times. Therefore, these deltas are more similar to fan deltas and/or alluvial fans with coarse sediment compared to those observed in natural low-gradient coastal delta systems. Additionally, the deltas in these experiments are also highly simplified compared to their natural counterparts, lacking vegetation and cohesive sediments, which would decrease their degree of erodibility (Edmonds & Slingerland, 2010; Hoyal & Sheets, 2009; Shaw et al., 2013; Tal & Paola, 2010; Thorne, 1990). Furthermore, our experimental deltas were not influenced by backwater hydraulics, which have been shown to produce erosion during high-flow conditions (Chatanantavet et al., 2012; Chatanantavet & Lamb, 2014; Lamb et al., 2012; Nittrower et al., 2011, 2012). Using the experimental design here, we aim to understand the fluviodeltaic processes of sediment reworking during base flow periods, which has been missing from the previous physical and computational modeling studies.

Figure 2. Schematic of experimental basin. (a) A three-dimensional schematic of the 3 m × 2 m basin used in this study. Water and sediment are mixed and fed through a rock cage at the point labeled \(Q_{in}\). The experimental deposit built out on an initial substrate of coarse sand with thickness \(h_s = 4.5\) cm. The base level throughout the experiment was held constant at \(z = 2.0\) cm. (b) Downbasin dip view of experiment. The dashed line denotes upper portion of topset where slope \((S)\) measurements were made.

Figure 3. Image processing technique. (a) Raw unprocessed overhead image of the experiment with inlet on the left side of the image. (b) Thresholded binary image used to measure topset area (black). (c) Image of extracted wetted topset area using thresholding method.
Throughout the experiments, fan delta evolution was tracked and recorded by taking time-lapse overhead images at 20-s intervals (Figure 3). At the end of the final base flow and flood period for each experiment, topography was measured using a laser sensor affixed to an automated cart system that scanned the entire deposit with a horizontal grid resolution set to 5 mm (in downbasin direction) by 2 mm (in cross basin direction) with a submillimeter vertical resolution. Following each experiment, the basin was completely drained of water and the deposit was allowed to dry overnight to prepare for stratigraphic slicing. A single slice was made along the centerline dip from inlet to shoreline. High-resolution images were taken of the exposed stratigraphy to characterize the deposit.

In order to observe changes in fan delta dynamics, we captured the total topset area, shoreline position, and wetted area fraction of the topset from the overhead time-lapse images (Figure 3). We preprocessed the images by correcting for lens distortion and converting the images to binary using thresholding techniques (Figure 3b; Tal & Paola, 2010). Topset area and shoreline calculations were made on these black and white binary images. Additionally, to characterize the degree of channelization on the delta, we used a similar thresholding technique to extract the area of the topset inundated with flow to determine wetted area fraction, which is the topset area covered with flowing water divided by the total topset area (Figure 3c). The wetted area fraction ranges in value from 0 to 1, where a value of 1 indicates that the topset is entirely covered with sheet flow while small values indicate more channelized flow over the delta. Finally, to estimate the timescale of the autogenic cycle, we calculate the power spectral density of the time series of the wetted area fraction starting at 2 hr of flood time to allow for the initial growth of the delta to the end of each experiment with a sampling frequency of every 10 min. Using methods outlined in Powell et al. (2012) and Carlson et al. (2018), we determine the periodicity of the wetted area fractions from the highest peaks of periodograms based on the power spectral density derived using a discrete Fourier transform.

We investigate the role of flood intermittency on the internal dynamics of the deposit by characterizing the stratigraphy along the centerline dip, where the stratigraphy records sedimentation events at the shoreline (Kim & Jerolmack, 2008). Although during periods of channelization on the delta surface, the channels may be directed to either side of the centerline dip and thereby not recorded in the stratigraphy, we verified from overhead time-lapse images that the channels will laterally migrate to occupy the centerline dip for some part of channelized period, thus providing a record of sedimentation for that period. Therefore, even though the centerline dip only provides a representative stratigraphy of the system, it offers a satisfactory record of the sedimentation of the system. We perform a similar analysis to that employed by Kim and Jerolmack (2008) to determine the period of fine versus coarse grain sedimentation at the delta shoreline using time series techniques. To complete this analysis, we convert color images of the centerline dip stratigraphy to gray scale, where the white (high gray scale intensity) represents the coarse grain sand deposits and the dark (low gray scale intensity) represents the fine-grain walnut shell deposits (Figures 4a and 4b). We crop the

Figure 4. Stratigraphy analysis. (a) Stitched images of centerline dip for all experimental runs. (b) Grayscale intensity cropped image of stratigraphy from \( I = 0.20 \). (c) Plot of intensity versus distance from shoreline form \( I = 0.20 \). (d) Plot of autocorrelation versus lag distance for \( I = 0.20 \).
image to the 40 pixels (~4 mm) of the center of the deposit thickness along the most distal 300 mm (Figure 4b). We then average the gray scale intensity for the 40 pixels of deposit thickness to get a single value of intensity versus distance (Figure 4c). With this intensity value, we calculate the autocorrelation coefficient to determine the period of sedimentation (Figure 4d).

3. Results

3.1. Delta Progradation

Throughout the four experimental runs, each with varying intermittency factors, we tracked changes in delta morphology. We measured shoreline progradation by calculating the total subaerial topset area (A) from overhead images collected during the experiment. Topset area versus experimental runtime for each value of intermittency portrays a similar trend, where each delta initially rapidly progrades; however, this rate of progradation decreases as the delta increases in size (Figure 5a). Furthermore, we observe that the progradation rate with respect to total experimental runtime increases with increasing intermittency factor as the system cycles through shorter flood periods indicating it takes more time for the same amount of sediment to be delivered to the delta. The curves for the experiments with intermittent flows (I < 1) in Figure 5a show how most of the delta growth occurs during floods when sediment supply is turned on; however, there is a small yet finite amount of progradation that occurs during the base flow periods, indicating a reworking of previously deposited sediments. From the overhead images, we observe that any previously deposited walnut sediment, our fine-grain proxy, on the topset is transported downslope toward the shoreline during base flow periods.

Because the assumption of dominant discharge applies a single characteristic flow value to describe a delta system thereby inferring that delta dynamics and morphology are controlled by continuous flood input conditions, we plot the topset area versus the time in flood condition to compare the delta progradation with different intermittency factors (Figure 5b). By comparing the different experimental runs, we observe that the rate of topset progradation increases with decreasing intermittency. As a result, the total topset areas at the cumulative flood time of 300 min increases as the duration of each flood decreases, that is, the intermittency factor decreases.

To further examine the role intermittency plays on delta shoreline progradation, we compare the growth of topset area (A) for each intermittent experiment with data from the experiment with steady input conditions (I = 1.0). To make this comparison, we plot the topset area versus time for the steady experiment in which we inserted artificial base flow periods of non-activity using the assumption that flow below this characteristic value does not contribute to delta growth, and therefore, dA = 0. We plot the steady experiment with imposed artificial base flow periods corresponding to those of the intermittent experiments with I = 0.50, 0.33, and 0.20 and compare with raw data from those experiments (Figures 5c, 5e, and 5g). For each experimental run, we observe that the intermittent runs produce a larger delta as compared with the I = 1.0 run.

We also measure the progradation rate for each experimental run by calculating the change in topset area over a 10-min period. Similar to the topset area in Figures 5c, 5e, and 5g, we compare the measured progradation rate for each intermittent run with that of the steady flow run with imposed artificial zero progradation base flow periods corresponding to the times of the base flow in the intermittent runs (Figures 5d, 5f, and 5h). Figures 5d, 5f, and 5h verify that the progradation rates during the base flow periods are positive and nonzero in the intermittent runs. In general, by comparing progradation rates during the floods, we observe smaller progradation rates for deltas produced with intermittent flow conditions versus steady. This trend is well observed during the early stages of the runs with higher I values. Later stages of the runs and the I = 0.20 run show more comparable shoreline progradation rates during the floods between the continuous flood run and the intermittent flood runs and/or even higher shoreline progradation rates in the intermittent runs. During the base flow periods of these later stages of the runs, reworking is fluctuating in magnitude but in general becomes smaller, and thus, progradation rates are smaller (Figures 5f and 5h).

3.2. Delta Topset Slope

Since the same total volume of sediment was delivered by the end of each experimental run, if the delta topset area increased with decreasing values of intermittency factor, then by conservation of mass, the mean topset slope (S) should have decreased to compensate. To test this idea, we extract radial downbasin
Figure 5. Topset progradation. (a) Topset area versus physical runtime for experimental runs of different intermittency factors. (b) Topset area versus time in flood condition for experimental runs of different intermittency factors. (c, e, and g) Topset area versus time for experimental run $I = 0.50$, $0.33$, and $0.20$, respectively, each compared with $I = 1.0$ with imposed base flow periods with $dA = 0$ corresponding to the times of base flow in the intermittent runs. (d, f, and h) Progradation rate versus time for experimental run $I = 0.50$, $0.33$, and $0.20$, respectively, each compared with $I = 1.0$ with imposed base flow periods with $dA/dt = 0$ corresponding to the times of base flow in the intermittent runs.
3.3. Fluvial Dynamics

In the experiment with continuous flood conditions ($I = 1.0$), the wetted fraction displays an internal periodicity (Figure 7a) related to the autogenic avulsion cycle (Kim & Jerolmack, 2008) where the delta alternates between periods of sheet flow and channelized flow (Figure 7b). The power spectral density of the times series of the wetted area fraction produces an estimate of the autogenic timescale of 72 min. For the experimental runs with intermittent flows, the periodicity of the wetted area fraction varies with flood frequency (Figures 7b–7d), where generally, the wetted area fraction increases during the start of a flood, when water discharge is high, and decreases during the start of base flows, when water discharge is halved. Although this pattern of changes in the wetted fraction is generally true, there are observed variations within each flood and base flow periods, especially for longer floods associated with higher intermittency factor runs and for periods into the later time of each run. We calculate the periodicity of the wetted area fractions for the intermittent runs to be 122 min for $I = 0.50$, 88 min for $I = 0.33$, and 72 min for $I = 0.20$. In each case, the time for returning to a stage with low wetted fraction is approximately the time of a single total combined flood and base flow cycle. Similarly, we calculate the sedimentation periodicity from the centerline dip stratigraphy using an autocorrelation method. For the continuous flood run ($I = 1.0$), we calculate the period of fine grain sedimentation to be 68 min, whereas the period is substantially longer for the intermittent experiments with values of 184, 205, and 175 min, for intermittency factors of $I = 0.50$, $I = 0.33$, and $I = 0.20$, respectively.

In order to examine which area of the topset is getting reworked by the flow, we calculate the flow occupation frequency for each run by determining how often the flow is active over the topset area. To calculate this quantity, we threshold overhead time-lapse images of the experiments so pixels with active flow are black while all other pixels are white. By summing all the occurrences of a pixel being black (occupied by flow) from a series of images through time, then dividing by the total number of images, we can ascertain the frequency each area of the topset is visited by flow. Figures 7e–7h show the occupation frequency maps, depicting
that the fraction of time each pixel is inundated with water for the first 15 min of the last flood period for each intermittency factor, with a sampling frequency of every minute. For all values of intermittency factor, the flow tends to occupy areas along or close to the centerline dip of the topset, avoiding regions to the sides. For constant flood ($I = 1.0$), we observe that the flow appears to occupy a wider topset area (Figure 7e), while as the intermittency decreases to $I = 0.50$ and 0.33, the active topset area narrows and the channels become more confined (Figures 7f and 7g). At $I = 0.20$, the pattern changes as the flow occupies a wider region; however, unlike the wide spanning region during the continuous flood, this

Figure 7. Topset wetted area fraction and recurrence frequency maps. (a–d) Topset wetted area fraction versus time for each experimental run with different intermittency factors. Data obtained from overhead images at sampling frequency of every 10 min. The dashed line indicates starting time for time series analysis to determine periodicity ($T$). Calculated periodicity of each run is labeled in its respective plot. The blue background shading denotes periods of flood, while the white indicates base flow. (e–h) Recurrence frequency maps of wetted topset area for the first 15 min of the last flood period for each experimental run. Sampling frequency for analysis is every minute. Intermittency factors decrease from top to bottom as shown in panels (a)–(d).
region contains multiple narrow active channel paths (Figure 7h). As indicated in the wetted area fraction time series, experiments with $I=0.50$ and $I=0.33$ show instantaneous increase in the value at the starting of the final flood period and gradual decrease after the initial moments of the flood period, while experiment with $I=0.20$ shows a continuous increase in the wetted area fraction over the final flood period.

4. Discussion

4.1. Topset Growth

We conducted a set of laboratory experiments to investigate the effects of varying hydrologic and sediment inputs on fan delta morphology. We find that with a decreasing value of flood intermittency factors, the resulting fan delta has a larger overall topset area with a shallower topset slope. In our experiments, during floods when sediment is supplied to the system, the fan delta exhibits rapid progradation. At the same time, the supplied sediment is used to aggrade the subaerial topset of the fan delta. On the other hand, during base flow periods the experiments show that there is not enough discharge to the fan delta to allow for total sheet flow, instead laterally migrating channels incise into the fan delta topset deposit, eroding previously deposited sediment, and transporting it to the shoreline. This reworking of sediment during low discharge produces a lower topset gradient; a deepening trunk channel connected to the fan delta apex will continue to transport sediment from the channel bed downbasin to the shoreline causing a smaller, yet not negligible, rate of progradation compared to times of flood. For the $I=0.20$ experiment, the delta grew to a total size of 1.22 m$^2$ of which it prograded a total of 0.10 m$^2$ during cumulative base flow periods and a total of

![Figure 8. Sheet flow versus channelized flow. Images from overhead time-lapse camera of delta experiments. Images from $I=1.0$ displaying channelized flow (a) taken at runtime = 170 min and sheet flow (b) taken at runtime = 205 min. Images from $I=0.20$ displaying channelized flow (c) taken at runtime = 950 min and sheet flow (d) taken at runtime = 900 min.](image-url)
1.12 m² during cumulative flood periods, indicating that 8% of delta aerial growth occurred during low flow when sediment was not being supplied to the system from upstream. Although the amount of sediment reworking during the base flow periods has a small relative rate of progradation compared to flood periods, when integrated over multiple cycles, the accumulated result on the surface morphology can be significant. Figure 5g shows about 0.2 m² difference in the topset area between the I = 1.0 and 0.2 experiments at the end of the run. Since 0.10 m² was caused by the base flow reworking, the remaining ~0.1 m² should be attributed to processes occurring at times other than the base flow periods. This result hints that the progradation was enhanced not only during the base flow periods but also during the flood periods. By the latter stages of the experiments we observed during flood periods more focused and channelized flows (Figure 9), which were organized over the multiple base flow periods. These focused flows may aid in transporting sediment through the fluvial topset depositing sediment beyond the shoreline more effectively during transitions between low and high flows (Figures 7e–7h).

Figure 9. Spatial distribution of deposition during final flood. (a–c) Maps of the difference in topography between the final flood and the final base flow period for all experimental runs. Maps are normalized by duration of flood so maps display deposition rate. (d–f) Overhead images of corresponding deltas at the time of transition from base flow to flood conditions.
### 4.2. Base Flow Erosion Versus Flood Deposition

The decrease in topset slope during base flow periods as compared to floods, as well as the finite progradation of the shoreline during base flows when no sediment is input to the system, suggests that sediment deposited during floods is being eroded and redeposited during the base flows. Furthermore, especially for the early stages of the experiments, lower progradation rates during floods in intermittent systems compared to those in the continuous flood run indicate a decrease in the efficiency to prograde the delta with lower values of $I$ (Figure 5), suggesting that there is a change in the amount of sediment allocated to shoreline progradation versus topset aggradation. This change in sediment allocation is likely due to conservation of sediment mass as the topset slope fluctuates due to intermittency effects. In order to quantify this idea and determine how the reworking of sediment during base flows changes with varying intermittency factor, we estimate the volume of sediment ($V_f$; positive value indicating deposition and negative corresponding to erosion) on the topset. During each type of flow, calculating the change in topset area ($\Delta A$) due to progradation from the overhead images at the beginning and end of each flow cycle multiplied by the base level depth ($z$) of the basin gives

$$V = z \Delta A$$  \hspace{1cm} (1)

Assuming that there is no loss of sediment to the ocean and that the topset slope near the shoreline is zero, this value provides an estimate of the volume of sediment transported to the shoreline from the fluvial system. In the case of base flow, where sediment supply is turned off, this volume represents the amount of sediment eroded from the topset contributing to cutting down the slope and is measured using equation (1) (Figure 10a):

$$V_E = z \Delta A_b$$  \hspace{1cm} (2)

where $V_E$ represents the total volume of base flow erosion and $\Delta A_b$ denotes the change in the delta surface area during a base flow period. On the other hand, during floods, where we know the total volume of sediment input to the system (sediment feed rate times duration of flood: $V_f = Q_s/(1 - \lambda) \times \Delta t$, where $Q_s$ denotes sediment supply rate, $\lambda$ denotes deposit porosity, and $\Delta t$ denotes a time duration), the volume ($V_f$; equation (1)) represents the fraction of the total volume ($V_f$) that contributes to progradation. Conversely, the amount of sediment deposited on the topset promoting aggradation of delta is calculated by subtracting the volume due to progradation from the total sediment volume input (Figure 10b). The total volume of deposition on the delta surface during the experiment can be written as

$$V_D = V_f - z \Delta A_f$$  \hspace{1cm} (3)

where $V_D$ represents the total volume of flood deposition on the delta surface and $\Delta A_f$ denotes the change in the delta surface area during a flood period.

Using the methods described above, we calculate the volume of sediment eroded from the topset during base flows and the volume of sediment deposited on the topset during floods for each intermittent experimental run. We estimate the porosity of the deposit by dividing the total volume of sediment input to the system, calculated using the sediment feed rate and the duration of flood time, by the total deposit volume, measured from laser topographic scans. The average porosity for all experimental
runs is 0.57. The ratios of the erosion volume during base flow to the flood deposition on the deltaic surface, $V_E/V_D$, show more reworking of the fluvial surface during base flow periods in the early stage of each run and also in the runs with lower intermittency factors (Figure 11). For the $I = 0.20$ experiment, the maximum ratio of $V_E/V_D (~0.6)$ occurred around 1-hr flood time and the ratio decreased significantly toward the end of the 5-hr flood time. The decreasing trend in $V_E/V_D$ is similar in all other runs. This result indicates the base flow is a major factor for shaping the deltaic morphology in these experiments especially in the early stages of fan delta evolution, which is related to the shallow surface slope developed over base flow periods.

Relating these results to natural delta systems will depend on the degree of sediment transport that occurs during base flows relative to their transport capacity, which along with backwater dynamics (Lamb et al., 2012; Nittrouer et al., 2012) will determine if the delta has periods of erosion, like fan deltas and the ones in these experiments, or deposition, like most lowland natural deltas. In these experiments, the total sediment volume of the topset deposition increases over time due to the increase in the fan delta topset area, while the progressively shallower topset slope also decreases shear stress and diminishes erosion during base flow periods. Interestingly, the topset-reworking rate (both erosion and deposition) is smaller with lower intermittency factors. It is most likely that runs with lower intermittency factors develop more channelized flows to guide floods through the channels to advance the shoreline faster but minimize the overbank flood deposition.

### 4.3. Slope Fluctuations

In fan delta experiments with constant water and sediment discharge such as the experimental run with $I = 1.0$, the fan delta self-organizes and evolves into a quasi-equilibrium state with a constant topset slope, set by the sediment-to-water concentration, that should fluctuate about a mean value as sediment is stored and released during autogenic cycles when the fan delta alternates between channelized and sheet flow (Kim & Jerolmack, 2008). When the input conditions are changed, as seen in previous experimental studies with deltas built over a range of different input parameters, the delta obtains diagnostically distinguishable steady states. In our experiments of intermittent flows, the input conditions change periodically between flood and base flow times, each with their own respective steady state. For intermittent flows, when the sediment and flow conditions change, the delta adjusts to its new steady state morphology. This transition to a new equilibrium is not instantaneous but requires a finite amount of time to transport sediment that evolves the system. The amount of time necessary for the system to adjust is largely controlled by the input parameters and initial conditions, which determine the rate of adjustment, and the initial state of the landform, which determines how much adjustment is needed to reach the new equilibrium. The results from these experiments indicate that as intermittency factors decrease, there is not enough time during the flood periods for the delta to fully adjust, as evident in the measured topset gradients, which decrease with decreasing intermittency factor. During the base flow periods, the system adjusts to a no sediment input condition by incising the topset thereby decreasing its topset gradient; however, during floods, supplied sediment causes the slope to build up (Figure 6). Because the flood duration decreases with smaller $I$ values, the slope is unable to aggrade as it did during the longer floods of the higher valued $I$ runs. This effect is time-cumulative and can become magnified as the not fully adjusted delta is the new initial condition for subsequent floods and base flows, which accounts of the overall lower topset gradient as the intermittency decreases. Chatanantavet and Lamb (2014) found similar results on backwater dominated deltas, where rivers that supplied sediment and water discharge to the deltas were in a constant transient state; however, due to backwater hydraulics their systems alternated between aggradation during low flows and riverbed scour during high flows. To further investigate this idea of delta adjustment, we analyze the spatial distribution of deposition during the final flood period using the laser topographic scans collected. Figures 9a, 9b, and 9c display maps of deposition on the delta topset by examining the time normalized difference in topography at the end of the final base flow period from the end of the final flood period. By comparing these maps with maps depicting the active channel network for the 15-min interval prior to the time of transition from base flow to flood (Figures 9d–9f), we can distinguish more focused deposition along the previously existing channels for lower intermittency factors. Specifically, in the $I = 0.20$ run (Figure 9c) we observe the best case of localized deposition, as well as some strong channel erosion. This focused deposition and erosion may explain why we observe larger slope fluctuations in the lower intermittency factor runs and less slope fluctuation in the higher intermittency runs where deposition is more disperse over the topset area.
4.4. Autogenic Processes

The flow intermittency can potentially affect the natural cyclic behavior of alternating channelized and sheet flow observed on fan deltas. In the continuous flood run ($I = 1.0$) we measured an autogenic cycle to be approximately 72 min (Figure 7), which nicely corresponds to the prediction based on the channel geometry and sediment supply rate to scale the fluvial autogenic process reported in Kim and Jerolmack (2008) and Reitz et al. (2010). This measured timescale is also consistent with the cycle of fine grain sedimentation (~68 min) measured from the stratigraphy (Figure 4); however, for the experiments with intermittent flow, the periodicity of channelized versus sheet flow of each system is tied to the imposed frequency of intermittency instead of the natural internal dynamics as shown in Figure 7. In the case of continuous flood experiments, the internal dynamics produces periods of channelized flow followed by sheet flow over the topset surface as the system alternates between sediment storage and release (Kim et al., 2006; Reitz et al., 2010). Conversely, for the intermittent flows examined in these experiments, the degree of wetted fraction on the topset surface is controlled by the upstream discharge conditions (Figures 7b–7d), where high wetted fraction comparable to sheet flow in the continuous flood run occurs during floods. The higher water discharge of the flood cannot be contained in the channels created on the shallow incised topset surface from the previous base flow period. Furthermore, the intermittent deltaic system would need to adjust to new equilibrium before a natural autogenic cycle can occur; however, we have found that for lower values of $I$, a dynamic steady state is never attained. These experiments are highly erodible due to high topset gradients and noncohesive sediment and this increase in erosion makes the periods of base flow seen in these experiments more influential on the overall delta dynamics as compared to a less erosive natural system, which may not experience the same magnitude of sediment reworking during times of base flow. However, as seen in Figure 11, the erosional reworking on the topset decreases with time. While we observe a strong control of change in fluvial pattern by the discharge fluctuation, the cycles of coarse and fine foreset deposits do not match well with the timescales of fluvial pattern changes. The periods calculated based on the final stratigraphy are 184, 205, and 175 min for $I = 0.50, 0.33$, and $0.20$, respectively. Although not every depositional cycle is included in the sliced stratigraphic section taken at the centerline dip, the channelization periods for the intermittent experiments are similar, indicating that internal dynamics regulate the pulse of this system. The autogenic process might return to regulate the morphodynamic evolution, but this is beyond the data limit that we have currently.

4.5. Intermittency: Future Directions

In addition to the high erodibility of these deltas, another simplification of this experiment that needs to be addressed when comparing to natural systems is the manner in which we imposed the intermittent input parameters. For each intermittent run of this experiment, we decreased the value of intermittency factor by holding the base flow period duration constant while decreasing the flood duration. Although we imposed an oversimplified periodic square wave to the input parameters, it does simulate the manner in which natural deltas tend to have shorter periods of high flow, where seasonal spring snowmelt or rainy season floods typically only occur for a small fraction of the year. For instance, an intermittency of $I = 0.1$ will have 36.5 days a year of a characteristic high water discharge. However, it is interesting to think how the effects of intermittency might change for systems that are flashy with many floods spread over the course of a year versus seasonal systems with a single high flow period. For the case of $I = 0.1$, this difference could mean 36 individual daylong floods distributed throughout the year versus a single 36 daylong sustained high flow. The results from this study suggest that there is not a linear relationship between the magnitude of sediment reworking and duration of flood periods as evident in the increased topset slope difference between base and flood flows with decreasing intermittency factor (Figure 6). The topset reworking diminishes with time similarly across a range of intermittency factors. However, the topset reworking is higher during the early part of the delta evolution with lower intermittency factors, which reduces topset slope more quickly and develops stronger channel flows. Therefore, the early stage of the delta evolution under different intermittent flood conditions is important in the overall delta morphology and channel organization. Further work is required to determine the direct effects of not only intermittency but also flood frequency on delta dynamics. Since the current experiments kept the base flow duration the same, determining the effects of intermittency driven by different duration of base flow on delta dynamics would be a great future topic.
Furthermore, these experiments presented here only examine the limiting case of zero sediment input during base flows, which we designed to maximize a highly erosive process. It has been observed in many natural deltas that flows below flood conditions are able to transport sediment loads. Ganti et al. (2016) ran experiments with a single intermittency value where sediment concentrations were varied in order to yield the same transport slope during low flows and high flows, producing a delta that was not erosive with a constrained topset slope. However, these experiments also simply the reality of the nonlinear sediment transport, where lower flows will generally have smaller sediment concentrations and conversely higher flows will generally have greater concentrations (van Rijn, 1984), suggesting that variable flow conditions can cause a system to transition from accretions to erosional as observed in the presented experiments. Furthermore, sediment flux of the system can be affected by regional tectonics and vegetation cover (Fielding et al., 2018), adding to the complexity when attempting to simulate natural systems. Future work is necessary to investigate the role of sediment flux during intermittent flows to make depositional or bypass system over a range of intermittencies.

These experiments are only the first steps toward understanding the effects of intermittent flows on delta dynamics. Because the results from this study provide only preliminary insight into intermittency, we are currently unable to relate these results directly to the field; however, we are able to qualitatively compare with other studies. We see similar results to those of Shaw and Mohrig (2014) from field observations of the evolving Wax Lake Delta along the coast of Louisiana (Figure 12a), where periods of high flow cause channel aggradation and delta progradation, while periods of low flow produce incision at the channel tips. Using the repeat bathymetric data from this study, we can quantify the amount of erosion and deposition occurring during high and low flows in a natural evolving system. Bathymetric data over an approximate 4-km² area was collected in July 2010 and March 2011 between a period of base flow and again in August 2011 after a large flood. We subtract these bathymetric maps to determine changes in topography, indicating sediment erosion or deposition (Figures 12b and 12c). We found that during the low-flow period between July 2010 and March 2011, the delta experienced net erosion (total erosion minus total deposition) of 2.87 × 10⁻⁴ km³, while during the flood that took place between March 2011 and August 2011, the delta had net deposition (total deposition minus total erosion) of 6.14 × 10⁻⁴ km³. By computing the ratio of erosion to deposition, as we did for the intermittent flows of this experiment, we get a value of 0.47. One of the experiments (i.e., I = 0.20) shows \( \frac{V_E}{V_D} \) values similar to that of Wax Lake Delta during the early stage. Knowing that the channel tips in Wax Lake Delta have been extended by ebb tidal current (Rossi et al., 2016), intermittent flood and base flow cycle alone might produce a \( \frac{V_E}{V_D} \) value smaller than the prediction. Although our experimental deltas were highly erosive and more akin to steep fan deltas, whereas the Wax Lake Delta features shallow slopes and tidal influence, we observe in both cases that sediment is reworked to some degree during low-flow conditions. Two estimations could be drawn from this comparison: (1) In terms of sediment transport during flood versus base flow, lower intermittency conditions for experiments reproduce more natural delta morphology and transport dynamics as seen in \( \frac{V_E}{V_D} \) values. (2) Even though it is hard to predict the exact rate, the Wax Lake Delta is likely to have higher topset reworking during its early stages of development with decreasing topset reworking as the delta grows. Note that Wax Lake Delta and other natural deltas would have reworking more focused within their

**Figure 12.** Wax Lake Delta maps. (a) Map of Wax Lake Delta with white boxed region denoting study area in coastal Louisiana, USA. (b) Elevation difference map from July 2010 to March 2011. (c) Elevation difference map from March 2011 to August 2011.
channel networks and at their shorelines. Future work is necessary to assert any definite conclusions on the effects of intermittency on field-scale lowland deltas; however, our study suggests that sediment reworking and channel incision during low/base flow times can contribute to shaping fluviodeltaic systems as those during flood times.

5. Conclusion
In summary, we conducted a set of experiments to investigate the controls of flood intermittency on delta process and form. Through varying the flood duration in our experiments, we found that as intermittency factors decrease, the overall delta topset becomes larger as the slope becomes shallower due to erosion of topset sediments being reworked basinward during base flow periods. As intermittency factors decrease, topset flow deposition and base flow erosion on the topset are smaller in magnitude, but the deltaic surface develops a higher topographic roughness (and/or strong channelization) by localized erosion and deposition compared to more widely distributed sedimentation and erosion in higher intermittency conditions. Furthermore, we find that for systems with low intermittency factors, the delta may be in a constant state of adjustment since flow fluctuations occur too frequently for the system to attain an equilibrium state. Additionally, because of this adjustment time between flows, the natural internal dynamics observed through the autogenic cycle may be obscured because during autogenic storage events, sediment that is deposited on the topset is reworked during base flow periods before the delta can reach its equilibrium slope. Finally, it is important to state that these experiments are a simplified case of intermittent flows and more work is needed to explore the functional relationship between variable flows and delta dynamics; however, this work provides evidence that the dominant discharge assumption, which does not consider base flow reworking, does not fully describe delta processes. This work confirms that periods of base flow are integral to delta evolution because they contribute to the overall evolution of the fluviodeltaic system through the reworking of sediment.

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References


