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Long-term Cumulative Effects of Intra-annual Variability of Unsteady River Discharge on the Progradation of Delta Lobes: A Modeling Perspective

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Key Points:

- Numerical modeling assuming river discharge with intra-annual unsteadiness reproduced the zig-zag growth pattern observed in natural delta
- A tipping point was found in the delta area growth trajectory beyond which the delta area declines during periods of low discharge
- Predicted delta progradation for unsteady discharge scenarios differed when waves and variable sediment capture ratio were considered

Abstract

Rivers, regardless of their scales and geographic locations, are characterized with natural and human-induced variability in their discharges. While previous studies have established the effects of both inter- and intra-annual variabilities of unsteady river discharge on delta morphological evolution, the long-term cumulative effects of intra-annual unsteadiness on the progradation of delta lobe has remained hitherto elusive. To address this issue, numerical experiments using simplified unsteady discharge scenarios with recurrent intra-annual variability were performed in Delft3D and compared with those assuming constant bank-full discharge. A modified box model was further used to explore the effects of varying intra-annual unsteadiness on the progradation of delta lobes at reduced computational cost. While the overall trends of the progradation and the ultimate delta area created were found to be similar between the unsteady discharge scenarios and their corresponding constant bank-full discharge scenarios, the nuances of intermittent zig-zag variation in the Q8 lobe of the Yellow River Delta were well reproduced by model simulations assuming unsteady river discharge scenarios. In addition, long-term delta progradation predictions suggested the potential existence of a tipping point in the area growth trajectory beyond which the delta lobe area declines during periods of low discharge. When confounding factors such as waves and variable sediment capture ratio were further taken into consideration, simulation results for unsteady river discharge scenarios exhibit significant deviations from constant bank-full discharge scenarios. The implications of the modeling results for delta protection and restoration measures,

such as the water-sediment regulation scheme in the Yellow River and artificial channel diversions in the Mississippi River Delta, are also discussed.

1. Introduction

Deltas are the most populous areas and are among the most productive ecosystems in the world (Giosan et al. 2014). Despite their importance for human society and natural ecosystems, the world's deltas are "sinking" to the ocean due to sea-level rise, land subsidence and substantial decrease of sediment supply (Blum and Roberts 2009, Syvitski et al. 2009, Kirwan and Megonigal 2013). As one of the primary hydrodynamic forcing, river discharge plays an important role in shaping delta morphology (Galloway 1975, Syvitski and Saito 2007). Sediment load as well as grain size are highly dependent on the incoming river discharge (Nittrouer et al. 2011), and the estuarine jet dynamics which further dictates sediment transport and deltaic morphodynamics is also sensitive to the river discharge (Rowland et al. 2010, Canestrelli et al. 2014). At the same time, human activities at the upstream such as dam regulation have significantly altered river discharges and further affected the morphological evolution of deltas (Syvitski and Saito 2007, Bi et al. 2014, Bergillos et al. 2016). Given the increasing variability of river discharge under intensified human activities and climate change, understanding the potential effects of unsteady river discharge on delta morphological evolution thus becomes an imperative issue in the context of delta protection and restoration (Fagherazzi et al. 2015, Bergillos et al. 2016).

Generally, the evolution of river deltas comprises the abandonment of old delta lobes and creation of new (active) delta lobes due to river avulsion (Jerolmack and Swenson 2007, Ganti et al. 2016). The growth of the active river delta lobes is further shaped by the competing fluvial and marine forcings (Galloway 1975). Additional factors such as sediment grain size (Orton and Reading 1993, Caldwell and Edmonds 2014), vegetation (Nardin et al. 2016) and the unsteadiness of river discharge (Wright and Coleman 1973, Shaw and Mohrig 2014), have also been found to play an important role in controlling delta morphodynamics. Regarding the effects of unsteady river discharge on delta morphological evolution, some recent studies have explored the effects of inter-annual variability of river discharge on delta channel avulsion (Chatanantavet et al. 2012, Ganti et al. 2016) and delta growth rate (Rosen and Xu 2013). River floods and associated sediment pulses into the delta have been considered as the major factors that affect the growth of delta as well as the supported saltmarsh (Mudd 2011, Rosen and Xu 2013). Notably, a few studies have also studied the effects of intra-annual (seasonal) unsteadiness of river discharge on delta morphological evolution through field observation and numerical modeling (Guo et al. 2014, Shaw and Mohrig 2014, Guo et al. 2015, Gao et al. 2018). Among these studies, field observation conducted by Shaw and Mohrig (2014) in the Wax Lake Delta captured distinct deposition and erosion patterns for delta channel networks during periods of high and low river discharge, respectively. Guo et al. (2015) showed that seasonal variations of river discharge resulted in different morphodynamic equilibrium compared with that corresponding to constant bank-full discharge in their 1D estuarine morphodynamic simulations. Gao et al. (2018) proposed three regimes for the formation of river mouth bars at delta front under the combined effects of intra-annual unsteady river discharges and wave conditions. Notwithstanding the above-mentioned attempts to examine the effects of intra-annual unsteadiness of river discharge on delta morphological evolution, its long-term cumulative effects on delta progradation have remained hitherto elusive to our best knowledge. Furthermore, although some numerical studies have attempted to resolve the seasonal variability of river discharges by ad-hoc settings of upstream river boundary conditions (Van Der Wegen et al. 2011, George et al. 2012, Guo et al. 2015), it is still a common practice to assume a single constant bank-full discharge in relevant numerical and experimental studies on delta morphological evolution. The assumption of constant bank-full discharge is based on the premise that most of the water and sediments are delivered to the ocean during the infrequent flood events, so is the most significant morphological evolution. Therefore, the periods of low flow can be safely neglected (Hoyal and Sheets 2009, Geleynse et al. 2010). Given the above evidence on the potential effects of intra-annual variability, the validity of this assumption is also worth revisiting.

In this study, we focus on the effects of intra-annual (seasonal) unsteadiness of river discharge on the progradation of a single active delta lobe (subdelta) within its avulsion time scale (Figure 1a), i.e., when potential avulsion is yet to occur, and seek to answer two questions: (1) How will delta lobe area grow under unsteady river discharge with intra-annual variability as compared to the baseline scenario assuming constant bank-full discharge? and (2) How will the effects of unsteady river discharge depend on the parameterized degree of unsteadiness, with and without further incorporating other confounding factors such as waves and variable sediment capture ratio? Numerical experiments with simplified unsteady discharge scenarios with recurrent intra-annual variability were carried out using Delft3D, and compared with the corresponding constant bank-full discharge scenarios (termed "constant discharge scenarios" hereinafter). Afforded by its much reduced computational cost, a modified box model was also employed to thoroughly explore the effects of varying intra-annual unsteadiness on the progradation of delta lobes using extensive combinations of parameters of unsteadiness. The effects of further incorporating other confounding factors such as waves and variable sediment capture ratio are discussed as well. Finally, the implications of the modeling results for delta protection and restoration are discussed with reference to real-world examples.

2. Methods

2.1 Delft3D Model Setup

In this study, we used schematized numerical experiments with idealized geometry and modeling parameters assuming generic values as adopted in recent studies on estuarine-deltaic morphological processes (e.g. Geleynse et al. 2011, Fagherazzi et al. 2015). Delft3D, which is a process-based numerical model that solves hydrodynamics, sediment transport and morphodynamics in a coupled fashion (Lesser et al. 2004), was used as the modeling tool. The model adopted in this study is 2D depth-averaged. The computational domain followed those adopted in Edmonds and Slingerland (2010), which is rectangular (250 m × 2.5 m) with a river channel cutting through the shoreline and flowing into the receiving basin (Figure 1b), and the Chezy coefficient was set as the same constant value of 45 $m^{1/2}/s$. The initial depths of the receiving basin increase seaward and create gentle slopes ranging from 0.000267 to 0.000435, which are comparable to that adopted in Edmonds and Slingerland (2010). Notably, the geometry (width-to-depth aspect ratio) of the initial river mouth together with the Chezy coefficient determine the jet stability regime, which further affects sediment deposition in the river mouth and the formation of mouth bars and levees (Rowland et al. 2010, Mariotti et al. 2013, Canestrelli et al. 2014). However, this study focuses on the progradation of the whole delta, and the jet dynamics presumably only affects the very initial stage of the delta evolution. As such, we neglected the effects of varying the geometry of the initial river mouth and Chezy coefficient, and assumed constant values corresponding to stable jet condition throughout the numerical experiments conducted in this study.

The open boundaries include an upstream river boundary and three seaward boundaries. Unlike previous studies that assumed constant bank-full discharge, unsteady river discharge scenarios were imposed at the upstream river boundary (refer to the schematization of unsteady river discharge in Sec. 3.2). Same as Edmonds and

Slingerland (2010), a constant water level boundary conditions were prescribed at the three seaward boundaries, and equilibrium sediment concentration was prescribed at the upstream river boundary with uniform grain sizes of 65, 130 and 200 μm and a density of 2,650 kg/m^3. The initial bed sediment thickness for erosion is 10 m everywhere with identical sediment properties as the incoming sediments supplied at the upstream boundary. The bed load sediment transport formula is based on Van Rijn (1993). The computational time step was varied in each scenario to ensure numerical stability and accuracy. A spin-up time of 720 minutes was used in every scenario to attain fully developed hydrodynamic and sediment transport conditions before morphological evolution was allowed. Time-varying morphological scale factor (Van Der Wegen et al. 2011) was adopted in our model to accelerate the morphological evolution, i.e., 100 and 20 during periods of low and high discharges, respectively. The transition between low and high discharges is linear within one morphological day, allowing the adjustment of hydrodynamics during the period of transition and minimizing the sediment mass balance error caused by the transition. Key modeling parameters are listed in Table 1.

In this study, area measurement of the progradation of delta lobe was selected as an integral metric to explore the effects of unsteady river discharge on deltaic morphological evolution. After Delft3D simulations were completed, shoreline was defined using the Open Angle Method (OAM) proposed by Shaw et al. (2008). The method classifies grid cells into “land” and “open water” by the critical opening angle, which was set as 70° in this study. The area of the modeled delta lobe was further calculated as the area encompassed by the shoreline.

2.2 Schematization of Unsteady River Discharge and Model Scenarios

To properly introduce the unsteady river discharge with intra-annual variability, a simplified hydrograph with recurrent annual stepped flood pulses similar to the stepped hydrograph adopted in previous studies (e.g. Van Der Wegen et al. 2011, George et al. 2012, Mao 2012) was used to generate the unsteady river discharge scenarios (see Figure 2). Notably, the adopted hydrograph contains only a single peak within a water year, rather than multiple flood events. This is justified as high river discharges in most rivers usually occur during a relatively short period within the wet season. Ten water years with recurrent annual flood pulses were simulated to attain fully-developed deltas subject to the unsteady river discharges with intra-annual variability. Different combinations of high and low flows as well as duration of high flow were adopted for different unsteady discharge scenarios (Table 2). The Julian date of the onset of the high flow for every single water year was chosen as the 226th day of the water year, which is independent of the time interval between two consecutive high-discharge events in neighboring years.

Scenarios with constant river discharge (B01-03) were run as baseline scenarios to compare with the model simulation results of unsteady river discharge scenarios. The constant river discharges of these three scenarios assumed high flow of their corresponding unsteady river discharge scenarios, namely, 1,000, 1,600 and 2,500 m^3/s. The modeling period of the constant discharge scenario was adjusted such that same amount of sediments as the corresponding unsteady river discharge scenario was delivered to the computational domain. The morphological scale factor for constant discharge scenarios was set as 20.

2.3 Development of the Modified Box Model

Box models based on sediment mass balance are often used to explore the first-order morphological behavior of sediment supply and delta progradation (Wolinsky et al. 2010b, Lorenzo-Trueba et al. 2012) at much reduced computational cost. In this study, the box model developed by Wolinsky et al. (2010b) was modified to incorporate the effects of unsteady river discharge (Figure 1c). The governing equations for the box model read,

$$A\frac{dH}{dt}+H\frac{dA}{dt}=\frac{f_c}{c}\cdot q_s \tag{1}$$

where A (m^2) is delta area; H (m) is average deposition thickness; t (s) is time; c is dimensionless volumetric sediment concentration; f_c is dimensionless sediment capture ratio; q_s (m^3/s) is sediment supply. The derivation of Eq. (1) is documented in the supporting information.

The schematized unsteady river discharge with recurrent annual flood pulses (Figure 2) can be written as pulse wave function in Fourier series form,

$$q_w(t)=\left(D_w+\sum_{n=1}^{\infty}\frac{2}{n\pi}\sin(\pi n D_w)\cos\left(2\pi n\left(\frac{t-t_w}{T}-\frac{D_w}{2}\right)\right)\right)\cdot(q_{w\max}-q_{w\min})+q_{w\min} \quad (2)$$

where q_w (m^3/s) is river discharge; T (s) is water year (365 days); t_w (s) is the Julian date of the onset of maximum discharge measured in seconds; duty cycle $D_w=\tau_w/T$ (τ_w (s) is the duration of high river discharge pulse) represents the ratio of high pulse duration to water year; $q_{w\max}$ (m^3/s) and $q_{w\min}$ (m^3/s) are the high and low discharges, respectively. Notably, when D_w=1, Eq. (2) is degenerated to a constant discharge scenario.

Sediment supply was further related to river discharge using sediment rating curve. Assuming a commonly adopted power-law relationship between river discharge and sediment supply (Syvitski et al. 2000), q_s can be written as,

$$q_s=\alpha\cdot q_w^{\ \beta} \quad (3)$$

where α and β are regression coefficients for sediment rating curve.

Following Wolinsky et al. (2010a) which considered the combined effects of subsidence and sea-level rise on delta aggradation, deposition thickness, H can be written as,

$$H=H_0+R\cdot t \quad (4)$$

where H_0 (m) is the initial deposition thickness; R (m/s) is the rate of change in delta deposition thickness. In this study, the rate of change in delta deposition thickness R was assumed to be constant over time.

After substituting Eq. (4) into Eq. (1), the semi-analytical solution to Eq. (1) reads,

$$A = \frac{Q_t}{c \cdot \left(H_0 + R \cdot t\right)} \tag{5}$$

where Q_t is cumulative sediment storage defined as,

$$Q_t = \int_0^t \left(f_c \cdot q_s \right) dt' \tag{6}$$

where t' is a dummy variable. Notably, when f_c and q_s are assumed to be constant, Eq. (6) is degenerated to Wolinsky et al. (2010a)'s solution of the box model under constant sediment supply and sediment capture ratio,

$$A = \frac{\frac{f_c \cdot q_s}{cH_0} \cdot t}{1 + \frac{R}{H_0} \cdot t} \tag{7}$$

3. Model Results

3.1 Delft3D Modeling Results in the Progradation of Delta Lobes

Figure 3 shows the modeled delta lobes at the end of each Delft3D simulation for a number of representative model scenarios. As shown by the solid circles and triangles in Figure 4a, regardless of the grain size, the delta lobe area ratios between unsteady discharge scenarios and corresponding constant discharge scenarios fluctuate slightly around unity, provided that the same amount of sediment is delivered into the computational domain and wave effects are excluded. In such cases, unsteady river discharge scenarios create comparable ultimate delta lobe area relative to constant discharge scenarios at the end of the modeling periods, which justifies the employment of a constant simplified bank-full discharge when modeling long-term the progradation of delta lobes.

Delta lobe area growths over time for representative scenarios were further compared in Figure 4b, along with their corresponding constant discharge scenarios, to illustrate the temporal patterns in delta progradation. Specifically, delta lobe area exhibits continuous smooth growth for constant discharge scenarios, whereas that for unsteady river discharge scenarios exhibits a zig-zag growth pattern over the modeling period. The zig-zag pattern is consistent with the dynamic change that delta lobe area surges during periods of high river discharge and levels off during periods of low river discharge in a natural delta lobe in the Yellow River Delta (see Sec. 4.1).

3.2 Modified Box Model Predictions of Delta Progradation

Afforded by its much reduced computational cost, the modified box model was adopted in this study to investigate the effects of unsteadiness of river discharge and other confounding factors such as variable sediment capture ratio on the progradation of delta lobes. Before proceeding to the box model predictions, the parameters in the box model including H, c, α, β, and f_c were first derived from the setting and simulation processes of the Delft3D model (see supporting information). The evolution of delta lobe area predicted by the box model was further validated against model predictions from Delft3D model. As the two representative cases presented in Figure 5, the predictions of the box model for unsteady river discharge scenarios agree satisfactorily with the corresponding numerical results, and reproduced the zig-zag growth pattern in delta lobe area.

Once validated, the box model was further used to predict long-term progradation of delta lobe for one synthetic scenario that served as the representative of the various model scenarios, which was also used as the baseline scenario to explore the effects of varying intra-annual unsteadiness on the progradation of delta lobe in Sec. 4.2. In the synthetic scenario, the parameters of scenario R14 were adopted, including the regression coefficients for sediment rating curve (α=4.23×10^{-9}, β=2.38), the dimensionless volumetric sediment concentration (c=0.6), initial deposition thickness (H_0=1.34 m), the high and low river discharges ($q_{w\max}$=1,600 m^3/s, $q_{w\min}$=100 m^3/s), the duty cycle for river discharge (D_w=0.11) and the Julian date of the onset of maximum discharge (t_w=226th days). The rate of change in deltaic deposition thickness was assumed as a typical value of R=7 mm/yr to represent the combined effects of subsidence and sea-level rise on delta aggradation, and the sediment capture ratio was assumed a constant value of f_c=0.9 as it is commonly assumed to be around unity in numerical modeling without tides and waves (Wolinsky et al., 2010a). When other parameters are given, the sediment capture ratio could be calibrated against the observed area growth data in natural delta lobes. The parameters listed above were adopted in the subsequent box model simulations unless otherwise specified.

Figure 6 shows the box model prediction of long-term progradation of delta lobe.

The overall trend reveals that the delta undergoes continuous progradation over the entire modeling period, albeit in a zig-zag fashion consistent with preceding cases. An up-close look at the delta lobe area growth captures different growth patterns at different stages of the evolution. Specifically, at the initial stage of the progradation of delta lobe (the left inset in Figure 6), the delta lobe area grows rapidly during periods of high river discharge and levels off during periods of low river discharge. As the delta lobe area continues to grow, the deposition thickness increases continuously, resulting in an ever-increasing accommodation space with which the limited sediment supply during the periods of low river discharge is hard to keep up. This is also predictable from the sediment mass balance equation (Eq. (1)), i.e., when the accommodation space $A \cdot R > f_c / c \cdot q_s$, rate of change in delta area $dA/dt < 0$. Once the tipping point is passed, the delta lobe area drops during periods of low river discharge, even though it still increases rapidly during periods of high river discharge (the right inset in Figure 6).

4. Discussion

4.1 Validation of Model Predictions with Remote Sensing Data of Natural Delta Lobe

Kong et al. (2015) reported linear correlation between observed annual sediment supply and the associated annual change of delta area at the Yellow River Delta through remote sensing analyses. As the typical hydrograph of the Yellow River at the Lijin Station (the nearest gauge station to the river mouth in the main course of the

Yellow River) features a concentrated high flood pulse created by the water-sediment regulation scheme (WSRS), it provides an ideal case for validation, i.e., to explore the existence of empirical evidence of the simulated growth pattern of delta lobes under unsteady river discharge scenarios in natural delta lobes. Notably, a natural channel shift occurred in 2007 inside the Q8 lobe. However, since the channel shift is still inside the lobe (Zhang et al. 2018), it still provides an ideal case for validation (see Figure S1 in the supporting information). We analyzed the remote sensing images of the Q8 lobe (Figure 7) where the current river mouth is located, and identified the respective shorelines (see supporting information for details). The area of the Q8 lobe (the black rectangle in the enlarged map on the right of Figure 7) was further calculated.

The shorelines extracted before and after the flood pulse in 2002 show that the Q8 lobe prograded rapidly near the river mouth after the flood pulse (Figures 8a and 8b), whereas the flood pulse in 2003 led to the growth of the Q8 lobe to the southeast of the lobe (Figure 8e and 8d). As a result, the delta lobe area increases significantly after the flood pulses in both years (Figures 8c and 8f). During the WSRS periods in the Yellow River, excessive sediments associated with the river discharge pulses are delivered to the delta during relatively short durations, which create subaerial delta rapidly. The nuances of the intermittent zig-zag variation are well reproduced in the temporal growth pattern of the simulated unsteady river discharge scenarios (Figures 4b and 6), which is also consistent with a recent finding on the seasonal shoreline evolution under the influences of WSRS (Fan et al. 2018). For juvenile deltas such as the Wax Lake Delta, according to Carle et al. (2015), who studied the land accretion and vegetation community change in the Wax Lake Delta following the historic 2011 Mississippi River flood, a rapid land gain of 6.5 km^2 occurred during a two-month flood period in the Delta, equivalent to ~1/5 of the total delta area. The surge of the delta area during the relatively short flood period in the Wax Lake Delta again is consistent with the zig-zag growth pattern of delta area described above.

4.2 Effects of Varying Intra-annual Unsteadiness on Delta Progradation

Figure 6 shows that, as the delta lobe area keeps growing, it may pass a tipping point and begin to decline during periods of low river discharge. Afforded by the computational efficiency of the box model, the progradation of delta lobes with extensive combinations of Q_r, which is defined as the ratio between the low and high river discharges $q_{w\min}$ and $q_{w\max}$, and duty cycle D were tested to identify conditions at which the decline of delta lobe area during periods of low river discharge occur. Notably, D=0 and D=1 or Q_r=1 correspond to constant low and high river discharges, respectively. The constant river discharge prevents the decline of delta lobe area for these two exceptional cases. The high river discharges were set as 1,000, 1,600 and 2,500 m^3/s in the subsequent simulations. As shown in Figures 9a-9c, the shaded area in the Q_r versus D parameter space, which represents when decline of delta lobe area during periods of low river discharge occurs, increases with increasing modeling period. The trend is consistent with the reasoning that, regardless of growth rate, the likelihood that the delta lobe area and hence the accommodation space grows too large for the limited sediment supply during periods of low river discharge to fill, i.e., the decline of delta lobe area, increases with time.

The boundaries separating the decline and no-decline cases as two different regimes of unsteadiness on the Q_r versus D parameter space are shown as the dark lines in Figure 9d. Notably, the boundaries for different $q_{w\max}$ and identical evolution time coincide with each other (not shown here for clarity). As shown in Figure 9d, the occurrence of delta lobe area decline during periods of low river discharge was found to be dependent on Q_r and D as expected. The delineated boundaries also suggest that, for a certain D, the decline of delta lobe area during periods of low river discharge can be prevented through the regulation of Q_r to be above some threshold value. Similarly, for a certain Q_r, regulation of D to be below some threshold value would result in the same effect. Further analyses showed that the likelihood that the delta lobe area declines during periods of low flow increases with increasing rate of change in deltaic deposition thickness R (Figure S3 in the supporting information).

In the context of reservoir discharge regulation, given the adopted stepped hydrograph, the fixed total volume to be released downstream, Q_w, within one water year can be written as,

$$Q_w = q_{w\max} \cdot D \cdot T + q_{w\min} \cdot (1 - D) \cdot T \tag{8}$$

where Q_w is the total volume discharged within one water year. Manipulation of Eq. (8)

leads to

$$(1-Q_r)=\frac{\left(\dfrac{Q_w}{q_{w\max}\cdot T}\right)-1}{(D-1)} \tag{9}$$

For a fixed total volume Q_w, once the high flow $q_{w\max}$ is determined, Eq. (9) dictates a hyperbolic relationship between D and Q_r (gray lines in Figure 9d). For a host of varying $q_{w\max}$, the corresponding hyperbolas intersect with the predetermined boundaries at different locations, and the portion of the hyperbolas above the respective intersection represents the conditions for no-decline.

4.3 Effects of Variable Sediment Capture Ratio on Delta Progradation

In the previous discussions on the box model, the sediment capture ratio was assumed to be constant over time. However, sediment retention in fluvial-deltaic systems is influenced by factors such as vegetation, hydrological connectivity and wave conditions (Swenson et al. 2005, Nardin and Edmonds 2014, Hiatt and Passalacqua 2015). These factors can be seasonally variable, resulting in varying sediment capture ratio accordingly. For example, the arrival of the floods to the delta lobe might or might not be coincident with high vegetation coverage in the flood plain of the delta lobe. As such, we incorporated a time-varying sediment capture ratio in the box model, which was also written in pulse wave function (Figure 10a) as river discharge without loss of generality,

$$f_c(t)=\left(D_f+\sum_{n=1}^{\infty}\frac{2}{n\pi}\sin(\pi n D_f)\cos\left(2\pi n\left(\frac{t-t_f}{T}-\frac{D_f}{2}\right)\right)\right)\cdot\left(f_{c\max}-f_{c\min}\right)+f_{c\min} \tag{10}$$

where t_f (s) is the Julian date of the onset of maximum sediment capture ratio; duty cycle $D_f=\tau_f/T$ (τ_f (s) is the duration of high sediment capture ratio) represents the ratio of pulse duration to water year; $f_{c\max}$ and $f_{c\min}$ are high and low sediment capture ratios, respectively. Notably, t_w relative to t_f quantifies the phase relationship between the cycles of unsteady river discharge and variable sediment capture ratio, and the periodic variation of river discharge is synchronous with sediment capture ratio when $t_w=t_f$.

The box model was further used to investigate the effects of unsteady river discharge coupled with variable sediment capture ratio. The additional parameters in Eq. (10) were assigned values as follows: D_f=0.35, $f_{c\max}$=0.9 and $f_{c\min}$=0.3. The Julian date of the onset of maximum sediment capture ratio t_f was varied to generate different phase relationships between the cycles of unsteady river discharge and variable sediment capture ratio (Figure 10a).

Figure 10b shows the progradation of delta lobes for scenarios with different phase relationship between the cycles of unsteady river discharge and variable sediment capture ratio. Generally, the progradation of delta lobe follows similar zig-zag growth pattern as the scenarios with constant sediment capture ratio. Different area growth trajectories for the synchronous, overlapped and asynchronous scenarios are attributable to the cumulative sediment storage defined in Eq. (6). Specifically, when the periodic variation of river discharge is synchronous with sediment capture ratio, i.e., high river discharge and hence high sediment supply are coincident with high sediment capture ratio, more sediments are trapped in the delta lobe and thus result in greater delta area growth. The opposite happens when the periodic variations of river discharge and sediment capture ratio are completely asynchronous. The delta lobe area growth trajectory for the overlapped scenario falls in between the synchronous and asynchronous scenarios as expected.

4.4 Effects of Waves on Delta Progradation

In natural deltas, marine forcing such as storm-induced waves could be important to the progradation of delta lobes (Swenson et al. 2005). When river debouches into low energy environments, sediments tend to store in fluvial-deltaic systems and create subaerial delta; when the marine energy is strong, waves in combinations with currents may transport sediments offshore and restrict the formation of subaerial delta (Swenson et al. 2005). To further explore the coupling effects of unsteady river discharge and waves forcing on delta progradation, additional scenarios (Table 3) were run with waves added on top of the river discharge. The initial depths of the receiving basin were increased to the range of 2.5-6.5 m (increasing seaward) to dampen wave shoaling and maintain model stability. Scenarios W0 and B04W0, as the baseline scenarios to be directly compared with wave-added scenarios, were run without waves. Wave conditions were imposed at the offshore seaward boundary parallel to the initial shoreline. The wave-added and baseline scenarios were documented in Table 3, where the constant river discharge for scenarios B04W0-W3 were set as 1,300 m^3/s. Wave conditions were defined by significant wave height (H_s) and peak period (T_p) with the assumption of wave propagation perpendicular to the initial shoreline. For all wave-added scenarios, peak period is fixed at 5 s and significant wave heights are listed in Table 3, and fixed sediment grain size of 200 μm was adopted.

The stars in Figure 4a show that, when a relatively strong wave condition (H_s=0.8 m) was imposed, the area ratio became significantly smaller than unity, i.e., the created delta area became significantly smaller for unsteady discharge scenario than that for constant discharge scenario. With decreasing wave height, the area ratio increases toward unity. The contrast between no-wave scenarios and wave-added scenarios is presumably due to the transport of sediment offshore or alongshore by waves, which is further compounded by the varying modeling periods between the constant and unsteady discharge scenarios to ensure approximately same total sediment supply between the scenarios. Specifically, the modeling periods of the constant discharge scenarios (B04W1-W3) are shorter than the unsteady scenarios (W1-W3). As such, the wave reworking time would be longer for unsteady discharge scenarios and hence more wave-induced sediment transport out of the delta. This suggests that when waves are present, especially strong waves, extra care should be taken when adopting the constant bank-full discharge assumption for numerical modeling. Figure 11 further shows the comparison of temporal delta area growth under wave conditions. While the constant discharge scenario follows similar continuous smooth growth pattern as those without waves, unsteady discharge scenarios exhibit different temporal growth patterns. As illustrated in Figure 11, when wave energy is relatively strong (H_s=0.8 m), the zig-zag growth pattern vanishes. On the contrary, when wave energy decreases (H_s=0.4 m and 0.2 m), the zig-zag growth pattern returns.

It is worth pointing out that, for deltas with a relatively short avulsion time scale such as the Yellow River Delta, subsidence and sea level rise could not result in significant reduction in delta lobe area on such a short time scale (the initial evolution stage shown in Figure 6), whereas wave-induced erosion may exacerbate the sediment shortage during periods of low flow, and potentially lead to the decline of delta lobe area during periods of low flow (Figure 8). To further incorporate waves in the box model, a sink term of sediments was added in the box model as follow,

$$A\frac{dH}{dt}+H\frac{dA}{dt}=\frac{f_c\cdot q_s}{c}-S_w \tag{11}$$

where S_w (m^3/s) represents the wave-induced loss of sediments from the delta (Figure 12).

Assuming waves propagate perpendicularly to the delta lobe such that the longshore transport is proportional to sin2θ (Figure 12) according to the CERC formula (Komar 1971),

$$\frac{1}{2}S_w=K_1H_b^{5/2}\sin\theta\cos\theta=0.5K_1H_b^{5/2}\sin 2\theta \tag{12}$$

where K_1 is empirical constant, H_b is breaking wave height, and θ is wave angle.

Without loss of generality, we assume a constant width of delta (Figure 12), and the longshore transport (sediment loss from the delta lobe) increases with increasing delta area as dictated by the following function,

$$S_w = f\left(A\right) \tag{13}$$

Substitution of Eq. (13) into Eq. yields,

$$\frac{dA}{dt} + \frac{1}{\left(H_0 + R\cdot t\right)}\left(A\cdot R + f\left(A\right)\right) = \frac{1}{\left(H_0 + R\cdot t\right)}\frac{f_c}{c}q_s \tag{14}$$

It is straightforward that a similar tipping point can be defined as in the case without waves, i.e., $dA/dt < 0$ when $A\cdot R + f\left(A\right) > f_c/c\cdot q_s$.

4.5 Implications for Delta Protection and Restoration

In the context of delta protection and restoration, such as the WSRS in the Yellow River and artificial channel diversions in the Mississippi River Delta, the effects of unsteady river discharge and variable sediment capture ratio on delta progradation as we discussed above should be taken into consideration. For instance, the setting of the timing for artificial floods or the location of the channel diversions should avoid strong wave conditions to reserve more sediments in the fluvial-deltaic systems to replenish the already sediment-starved deltas as much as possible (Figure 5a). Moreover, if the artificial floods carrying excessive sediments are coincident with greater sediment capture ratio, e.g., when vegetation is flourished in the delta lobe, more sediment can be trapped to create land (Figure 11b). As for the setting of discharge when generating artificial floods, the decrease in the duration of the high river discharge and the increase in the ratio of low-to-high discharge tend to prevent the decline of delta area during periods of low river discharge (Figure 10d). The conditions for no-decline when the constraint of a fixed total volume discharged from the reservoir to the downstream is further incorporated have also been discussed and are not repeated here for brevity. Admittedly, the above discussions are subject to numerous simplifications and in principle only, which lays a foundation for future implementation in practice.

In this study, numerical experiments using simplified unsteady discharge scenarios with recurrent annual flood pulses were simulated for ten water years to attain fully-developed deltas for our examination. The effects of varying intra-annual unsteadiness on the progradation of delta lobes, i.e., the potential existence of a tipping point in the delta lobe area growth trajectory beyond which the delta lobe area declines during periods of low discharge, were further explored using box model for more extended periods of up to 50 years. Given the above modeling periods adopted as generic examples, the scientific issue and modeling framework proposed in this study, however, are not restricted to any specific timeframe. Instead, they are applicable to river-dominated delta lobes within their avulsion time scales that vary from delta to delta, e.g., decades for the Yellow River Delta versus centuries for the Mississippi River Delta. In other words, the same modeling analysis can be extended or shortened to a time period that is suitable for the delta lobe in question.

5. Conclusions

In this study, numerical experiments with schematized unsteady river discharge scenarios with recurrent annual flood pulses were performed using Delft3D and a modified box model to explore the long-term cumulative effects of intra-annual unsteadiness on the progradation of delta lobes. The major findings from this study are summarized as follows:

(1) Simulations assuming unsteady river discharge with intra-annual variability reproduced the zig-zag growth pattern that is also observed in natural delta lobe.

(2) The overall trends of the progradation of delta lobe and ultimate delta lobe area created were found to be similar between the unsteady river discharge scenarios and their corresponding constant discharge scenarios, when the effect of waves is excluded or relatively weak.

(3) A tipping point may exist in the delta lobe area growth trajectory beyond which the delta lobe area declines during periods of low river discharge. The occurrence of the delta lobe area decline was found to be related to river discharge ratio Q_r and duty cycle D, and their threshold values are dependent on the evolution time and the rate of change in deltaic deposition thickness R.

(4) When waves were taken into consideration, model predictions on unsteady river discharge scenarios exhibit significant deviations from constant discharge scenarios. When relatively strong wave conditions were imposed, the zig-zag growth pattern vanished and the created delta area became significantly smaller,

presumably due to the transport of sediment offshore or alongshore by waves.

(5) For deltas with a relatively short avulsion time scale such as the YRD, subsidence and sea level rise could not result in significant reduction in delta area in our study window, whereas wave-induced erosion may exacerbate the sediment shortage during periods of low flow, and potentially lead to the observed tipping point.

(6) The phase relationship between the cycles of river discharge and sediment capture ratio has significant effects on the progradation of delta lobe. Different area growth trajectories for the synchronous, overlapped and asynchronous scenarios were observed.

Using schematized numerical experiments, this study has offered some discussion on the long-term cumulative effects of intra-annual variability of unsteady river discharge on the progradation of delta lobes, which has implications for sustainable delta management. Further studies that account for more confounding factors are recommended in the future.

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Figure Captions

Figure 1. (a) Schematic of the evolution of delta lobes. (b) Configurations of the computational domain and open boundaries

in Delft3D model. (c) Schematic diagram of sediment balance for the box model. A is delta area; H is averaged deposition thickness; q_s is sediment supply to the delta; q_{out} is sediment bypassed the delta.

Figure 2. Schematized unsteady river discharge with recurrent annual flood pulses.

Figure 3. Modeled delta at the end of each Delft3D simulation for a number of representative model scenarios. Unsteady discharge scenarios and their corresponding constant discharge scenarios are displayed side-by-side.

Figure 4. (a) Delta area ratios between unsteady river discharge scenarios and corresponding constant discharge scenarios at the end of modeling periods; (b) Temporal delta area growth for unsteady river discharge scenarios versus constant discharge scenarios without wave conditions. t is time and A is delta area, which are normalized by the maximum evolution time $t_{\max}$ and maximum area $A_{\max}$.

Figure 5. Comparison of the box model predictions versus Delft3D modeling results

in delta progradation. t is time and A is delta area, which are normalized by the maximum evolution time $t_{\max}$ and maximum area $A_{\max}$ of the Delft3D modeling results.

Figure 6. The box model prediction of long-term delta progradation under unsteady river discharge and constant sediment capture ratio. t is time and A is delta area, which are normalized by the maximum evolution time $t_{\max}$ and maximum area $A_{\max}$.

Figure 7. Location of the Yellow River Delta and Q8 lobe (the black rectangle in the enlarged map on the right).

Figure 8. Changes of the Q8 lobe subject to the water-sediment regulation scheme (WSRS) in 2002 and 2003, respectively, from remote sensing images: (a) and (c) show the shoreline changes; (b) and (d) show the delta progradation around the river mouth and to the southeast of the lobe, respectively; (c) and (f) show the changes of delta area of the Q8 lobe.

Figure 9. Combinations of Q_r and D when decline of delta area during periods of low river discharge occurs (shaded area) for $q_{w\max}$=1,600 m^3/s for different modeling periods: (a) 10 years, (b) 30 years and (c) 50 years. (d) Boundaries (dark lines) separating the decline and no-decline cases as two different regimes of unsteadiness in the river discharge ratio Q_r versus duty cycle D parameter space; The hyperbolic

curves represent the relationship between Q_r and D (gray lines) for a fixed total volume discharged, Q_w and varying high flows, $q_{w\max}$.

Figure 10. (a) Schematic of different phase relationship between the cycles of unsteady river discharge and variable sediment capture ratio; (b) Predictions of delta progradation for scenarios with different phase relationship between the cycles of unsteady river discharge and variable sediment capture ratio. q_w is river discharge; f_c is sediment capture ratio; t_w is the Julian date of the onset of maximum river discharge; t_f is the Julian date of the onset of maximum sediment capture ratio.

Figure 11. Temporal delta area growth for unsteady river discharge scenarios versus constant discharge scenarios with wave conditions. t is time and A is delta area, which are normalized by the maximum evolution time $t_{\max}$ and maximum area $A_{\max}$; H_s is significant wave height.

Figure 12. Schematic of wave-induced longshore transport in delta lobes

Table 1. Modeling parameters of Delft3D

Modeling parameter	Value	Units
Cell size	25×25	m
Initial geometry of the river channel	250×2.5	m
Initial bed slope	0.000267~0.000435	-
Initial erodible sediment thickness	10	m
Chezy coefficient	45	$m^{1/2}/s$
Sediment grain size	65, 130, 200	μm

Table 2. Scenarios of unsteady river discharge and corresponding constant discharge scenarios used in the Delft3D model

Run ID	D_{50} (μm)	High flow (m^3/s)	Low flow (m^3/s)	Duration of high flow (d)	corresponding constant discharge scenarios
R01	200	1,000	100	30	B01
R02	200	1,000	100	40	
R03	200	1,000	100	50	
R04	200	1,000	100	60	
R05	200	1,000	200	30	
R06	200	1,000	200	40	
R07	200	1,000	200	50	
R08	200	1,000	200	60	
R09	200	1,000	300	30	
R10	200	1,000	300	40	
R11	200	1,000	300	50	
R12	200	1,000	300	60	
R13	200	1,600	100	30	B02
R14	200	1,600	100	40	
R15	200	1,600	100	50	
R16	200	1,600	100	60	
R17	200	1,600	200	30	
R18	200	1,600	200	60	
R19	200	1,600	300	60	
R20	200	2,500	100	30	B03
R21	200	2,500	100	40	
R22	200	2,500	100	50	
R23	200	2,500	100	60	
R24	200	2,500	200	40	
R25	200	2,500	300	40	
R09S1	65	1,000	300	30	B01S1
R09S2	130	1,000	300	30	B01S2

Table 3. Scenarios of unsteady river discharge coupled with waves and corresponding constant discharge scenarios

Run ID	D_{50} (μm)	High flow (m^3/s)	Low flow (m^3/s)	Duration of high flow (d)	Corresponding constant discharge scenarios	Significant wave height H_s (m)
W0	200	1,300	300	20	B04W0	-
W1	200	1,300	300	20	B04W1	0.2
W2	200	1,300	300	20	B04W2	0.4
W3	200	1,300	300	20	B04W3	0.8