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

4
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17

18 **Key Points:**

- 19
- 20 • Numerical modeling assuming river discharge with intra-annual unsteadiness
reproduced the zig-zag growth pattern observed in natural delta
 - 21 • A tipping point was found in the delta area growth trajectory beyond which the
22 delta area declines during periods of low discharge
 - 23 • Predicted delta progradation for unsteady discharge scenarios differed when
24 waves and variable sediment capture ratio were considered
- 25

26 **Abstract**

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

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

50

51 **1. Introduction**

52 Deltas are the most populous areas and are among the most productive ecosystems in
53 the world (Giosan et al. 2014). Despite their importance for human society and natural
54 ecosystems, the world's deltas are "sinking" to the ocean due to sea-level rise, land
55 subsidence and substantial decrease of sediment supply (Blum and Roberts 2009,
56 Syvitski et al. 2009, Kirwan and Megonigal 2013). As one of the primary
57 hydrodynamic forcing, river discharge plays an important role in shaping delta
58 morphology (Galloway 1975, Syvitski and Saito 2007). Sediment load as well as
59 grain size are highly dependent on the incoming river discharge (Nittrouer et al. 2011),
60 and the estuarine jet dynamics which further dictates sediment transport and deltaic
61 morphodynamics is also sensitive to the river discharge (Rowland et al. 2010,
62 Canestrelli et al. 2014). At the same time, human activities at the upstream such as
63 dam regulation have significantly altered river discharges and further affected the
64 morphological evolution of deltas (Syvitski and Saito 2007, Bi et al. 2014, Bergillos
65 et al. 2016). Given the increasing variability of river discharge under intensified
66 human activities and climate change, understanding the potential effects of unsteady
67 river discharge on delta morphological evolution thus becomes an imperative issue in
68 the context of delta protection and restoration (Fagherazzi et al. 2015, Bergillos et al.
69 2016).

70

71 Generally, the evolution of river deltas comprises the abandonment of old delta
72 lobes and creation of new (active) delta lobes due to river avulsion (Jerolmack and
73 Swenson 2007, Ganti et al. 2016). The growth of the active river delta lobes is further
74 shaped by the competing fluvial and marine forcings (Galloway 1975). Additional
75 factors such as sediment grain size (Orton and Reading 1993, Caldwell and Edmonds
76 2014), vegetation (Nardin et al. 2016) and the unsteadiness of river discharge (Wright
77 and Coleman 1973, Shaw and Mohrig 2014), have also been found to play an
78 important role in controlling delta morphodynamics. Regarding the effects of
79 unsteady river discharge on delta morphological evolution, some recent studies have
80 explored the effects of inter-annual variability of river discharge on delta channel
81 avulsion (Chatanantavet et al. 2012, Ganti et al. 2016) and delta growth rate (Rosen
82 and Xu 2013). River floods and associated sediment pulses into the delta have been
83 considered as the major factors that affect the growth of delta as well as the supported
84 saltmarsh (Mudd 2011, Rosen and Xu 2013). Notably, a few studies have also studied
85 the effects of intra-annual (seasonal) unsteadiness of river discharge on delta
86 morphological evolution through field observation and numerical modeling (Guo et al.
87 2014, Shaw and Mohrig 2014, Guo et al. 2015, Gao et al. 2018). Among these studies,
88 field observation conducted by Shaw and Mohrig (2014) in the Wax Lake Delta
89 captured distinct deposition and erosion patterns for delta channel networks during
90 periods of high and low river discharge, respectively. Guo et al. (2015) showed that
91 seasonal variations of river discharge resulted in different morphodynamic

92 equilibrium compared with that corresponding to constant bank-full discharge in their
93 1D estuarine morphodynamic simulations. Gao et al. (2018) proposed three regimes
94 for the formation of river mouth bars at delta front under the combined effects of
95 intra-annual unsteady river discharges and wave conditions. Notwithstanding the
96 above-mentioned attempts to examine the effects of intra-annual unsteadiness of river
97 discharge on delta morphological evolution, its long-term cumulative effects on delta
98 progradation have remained hitherto elusive to our best knowledge. Furthermore,
99 although some numerical studies have attempted to resolve the seasonal variability of
100 river discharges by ad-hoc settings of upstream river boundary conditions (Van Der
101 Wegen et al. 2011, George et al. 2012, Guo et al. 2015), it is still a common practice
102 to assume a single constant bank-full discharge in relevant numerical and
103 experimental studies on delta morphological evolution. The assumption of constant
104 bank-full discharge is based on the premise that most of the water and sediments are
105 delivered to the ocean during the infrequent flood events, so is the most significant
106 morphological evolution. Therefore, the periods of low flow can be safely neglected
107 (Hoyal and Sheets 2009, Geleynse et al. 2010). Given the above evidence on the
108 potential effects of intra-annual variability, the validity of this assumption is also
109 worth revisiting.

110

111 In this study, we focus on the effects of intra-annual (seasonal) unsteadiness of river
112 discharge on the progradation of a single active delta lobe (subdelta) within its
113 avulsion time scale (Figure 1a), i.e., when potential avulsion is yet to occur, and seek

114 to answer two questions: (1) How will delta lobe area grow under unsteady river
115 discharge with intra-annual variability as compared to the baseline scenario assuming
116 constant bank-full discharge? and (2) How will the effects of unsteady river discharge
117 depend on the parameterized degree of unsteadiness, with and without further
118 incorporating other confounding factors such as waves and variable sediment capture
119 ratio? Numerical experiments with simplified unsteady discharge scenarios with
120 recurrent intra-annual variability were carried out using Delft3D, and compared with
121 the corresponding constant bank-full discharge scenarios (termed “constant discharge
122 scenarios” hereinafter). Afforded by its much reduced computational cost, a modified
123 box model was also employed to thoroughly explore the effects of varying
124 intra-annual unsteadiness on the progradation of delta lobes using extensive
125 combinations of parameters of unsteadiness. The effects of further incorporating other
126 confounding factors such as waves and variable sediment capture ratio are discussed
127 as well. Finally, the implications of the modeling results for delta protection and
128 restoration are discussed with reference to real-world examples.

129

130 **2. Methods**

131 **2.1 Delft3D Model Setup**

132 In this study, we used schematized numerical experiments with idealized geometry
133 and modeling parameters assuming generic values as adopted in recent studies on
134 estuarine-deltaic morphological processes (e.g. Geleynse et al. 2011, Fagherazzi et al.
135 2015). Delft3D, which is a process-based numerical model that solves hydrodynamics,

136 sediment transport and morphodynamics in a coupled fashion (Lesser et al. 2004),
137 was used as the modeling tool. The model adopted in this study is 2D depth-averaged.
138 The computational domain followed those adopted in Edmonds and Slingerland
139 (2010), which is rectangular (250 m × 2.5 m) with a river channel cutting through the
140 shoreline and flowing into the receiving basin (Figure 1b), and the Chezy coefficient
141 was set as the same constant value of 45 m^{1/2}/s. The initial depths of the receiving
142 basin increase seaward and create gentle slopes ranging from 0.000267 to 0.000435,
143 which are comparable to that adopted in Edmonds and Slingerland (2010). Notably,
144 the geometry (width-to-depth aspect ratio) of the initial river mouth together with the
145 Chezy coefficient determine the jet stability regime, which further affects sediment
146 deposition in the river mouth and the formation of mouth bars and levees (Rowland et
147 al. 2010, Mariotti et al. 2013, Canestrelli et al. 2014). However, this study focuses on
148 the progradation of the whole delta, and the jet dynamics presumably only affects the
149 very initial stage of the delta evolution. As such, we neglected the effects of varying
150 the geometry of the initial river mouth and Chezy coefficient, and assumed constant
151 values corresponding to stable jet condition throughout the numerical experiments
152 conducted in this study.

153

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

158 Slingerland (2010), a constant water level boundary conditions were prescribed at the
159 three seaward boundaries, and equilibrium sediment concentration was prescribed at
160 the upstream river boundary with uniform grain sizes of 65, 130 and 200 μm and a
161 density of 2,650 kg/m^3 . The initial bed sediment thickness for erosion is 10 m
162 everywhere with identical sediment properties as the incoming sediments supplied at
163 the upstream boundary. The bed load sediment transport formula is based on Van Rijn
164 (1993). The computational time step was varied in each scenario to ensure numerical
165 stability and accuracy. A spin-up time of 720 minutes was used in every scenario to
166 attain fully developed hydrodynamic and sediment transport conditions before
167 morphological evolution was allowed. Time-varying morphological scale factor (Van
168 Der Wegen et al. 2011) was adopted in our model to accelerate the morphological
169 evolution, i.e., 100 and 20 during periods of low and high discharges, respectively.
170 The transition between low and high discharges is linear within one morphological
171 day, allowing the adjustment of hydrodynamics during the period of transition and
172 minimizing the sediment mass balance error caused by the transition. Key modeling
173 parameters are listed in Table 1.

174

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

180 which was set as 70° in this study. The area of the modeled delta lobe was further
181 calculated as the area encompassed by the shoreline.

182

183 **2.2 Schematization of Unsteady River Discharge and Model Scenarios**

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

198

199 Scenarios with constant river discharge (B01-03) were run as baseline scenarios to
200 compare with the model simulation results of unsteady river discharge scenarios. The
201 constant river discharges of these three scenarios assumed high flow of their

202 corresponding unsteady river discharge scenarios, namely, 1,000, 1,600 and 2,500
203 m³/s. The modeling period of the constant discharge scenario was adjusted such that
204 same amount of sediments as the corresponding unsteady river discharge scenario was
205 delivered to the computational domain. The morphological scale factor for constant
206 discharge scenarios was set as 20.

207

208 **2.3 Development of the Modified Box Model**

209 Box models based on sediment mass balance are often used to explore the first-order
210 morphological behavior of sediment supply and delta progradation (Wolinsky et al.
211 2010b, Lorenzo-Trueba et al. 2012) at much reduced computational cost. In this study,
212 the box model developed by Wolinsky et al. (2010b) was modified to incorporate the
213 effects of unsteady river discharge (Figure 1c). The governing equations for the box
214 model read,

$$215 \quad A \frac{dH}{dt} + H \frac{dA}{dt} = \frac{f_c}{c} \cdot q_s \quad (1)$$

216 where A (m²) is delta area; H (m) is average deposition thickness; t (s) is time; c is
217 dimensionless volumetric sediment concentration; f_c is dimensionless sediment
218 capture ratio; q_s (m³/s) is sediment supply. The derivation of Eq. (1) is documented in
219 the supporting information.

220

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

$$223 \quad q_w(t) = \left(D_w + \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin(\pi n D_w) \cos\left(2\pi n \left(\frac{t-t_w}{T} - \frac{D_w}{2}\right)\right) \right) \cdot (q_{w\max} - q_{w\min}) + q_{w\min} \quad (2)$$

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

230

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

$$234 \quad q_s = \alpha \cdot q_w^\beta \quad (3)$$

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

236

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

$$240 \quad H = H_0 + R \cdot t \quad (4)$$

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

244

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

$$246 \quad A = \frac{Q_t}{c \cdot (H_0 + R \cdot t)} \quad (5)$$

247 where Q_t is cumulative sediment storage defined as,

$$248 \quad Q_t = \int_0^t (f_c \cdot q_s) dt' \quad (6)$$

249 where t' is a dummy variable. Notably, when f_c and q_s are assumed to be constant, Eq.

250 (6) is degenerated to Wolinsky et al. (2010a)'s solution of the box model under

251 constant sediment supply and sediment capture ratio,

$$252 \quad A = \frac{\frac{f_c \cdot q_s \cdot t}{cH_0}}{1 + \frac{R}{H_0} \cdot t} \quad (7)$$

253

254 **3. Model Results**

255 **3.1 Delft3D Modeling Results in the Progradation of Delta Lobes**

256 Figure 3 shows the modeled delta lobes at the end of each Delft3D simulation for a

257 number of representative model scenarios. As shown by the solid circles and triangles

258 in Figure 4a, regardless of the grain size, the delta lobe area ratios between unsteady

259 discharge scenarios and corresponding constant discharge scenarios fluctuate slightly

260 around unity, provided that the same amount of sediment is delivered into the

261 computational domain and wave effects are excluded. In such cases, unsteady river

262 discharge scenarios create comparable ultimate delta lobe area relative to constant

263 discharge scenarios at the end of the modeling periods, which justifies the

264 employment of a constant simplified bank-full discharge when modeling long-term
265 the progradation of delta lobes.

266

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

275

276 **3.2 Modified Box Model Predictions of Delta Progradation**

277 Afforded by its much reduced computational cost, the modified box model was
278 adopted in this study to investigate the effects of unsteadiness of river discharge and
279 other confounding factors such as variable sediment capture ratio on the progradation
280 of delta lobes. Before proceeding to the box model predictions, the parameters in the
281 box model including H , c , α , β , and f_c were first derived from the setting and
282 simulation processes of the Delft3D model (see supporting information). The
283 evolution of delta lobe area predicted by the box model was further validated against
284 model predictions from Delft3D model. As the two representative cases presented in
285 Figure 5, the predictions of the box model for unsteady river discharge scenarios

286 agree satisfactorily with the corresponding numerical results, and reproduced the
287 zig-zag growth pattern in delta lobe area.

288

289 Once validated, the box model was further used to predict long-term progradation
290 of delta lobe for one synthetic scenario that served as the representative of the various
291 model scenarios, which was also used as the baseline scenario to explore the effects of
292 varying intra-annual unsteadiness on the progradation of delta lobe in Sec. 4.2. In the
293 synthetic scenario, the parameters of scenario R14 were adopted, including the
294 regression coefficients for sediment rating curve ($\alpha=4.23\times 10^{-9}$, $\beta=2.38$), the
295 dimensionless volumetric sediment concentration ($c=0.6$), initial deposition thickness
296 ($H_0=1.34$ m), the high and low river discharges ($q_{w\max}=1,600$ m³/s, $q_{w\min}=100$ m³/s),
297 the duty cycle for river discharge ($D_w=0.11$) and the Julian date of the onset of
298 maximum discharge ($t_w=226$ th days). The rate of change in deltaic deposition
299 thickness was assumed as a typical value of $R=7$ mm/yr to represent the combined
300 effects of subsidence and sea-level rise on delta aggradation, and the sediment capture
301 ratio was assumed a constant value of $f_c=0.9$ as it is commonly assumed to be around
302 unity in numerical modeling without tides and waves (Wolinsky et al., 2010a). When
303 other parameters are given, the sediment capture ratio could be calibrated against the
304 observed area growth data in natural delta lobes. The parameters listed above were
305 adopted in the subsequent box model simulations unless otherwise specified.

306

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

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

322

323 **4. Discussion**

324 **4.1 Validation of Model Predictions with Remote Sensing Data of Natural Delta**

325 **Lobe**

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

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

341

342 The shorelines extracted before and after the flood pulse in 2002 show that the Q8
343 lobe prograded rapidly near the river mouth after the flood pulse (Figures 8a and 8b),
344 whereas the flood pulse in 2003 led to the growth of the Q8 lobe to the southeast of
345 the lobe (Figure 8e and 8d). As a result, the delta lobe area increases significantly
346 after the flood pulses in both years (Figures 8c and 8f). During the WSRS periods in
347 the Yellow River, excessive sediments associated with the river discharge pulses are
348 delivered to the delta during relatively short durations, which create subaerial delta
349 rapidly. The nuances of the intermittent zig-zag variation are well reproduced in the
350 temporal growth pattern of the simulated unsteady river discharge scenarios (Figures
351 4b and 6), which is also consistent with a recent finding on the seasonal shoreline

352 evolution under the influences of WSRS (Fan et al. 2018). For juvenile deltas such as
353 the Wax Lake Delta, according to Carle et al. (2015), who studied the land accretion
354 and vegetation community change in the Wax Lake Delta following the historic 2011
355 Mississippi River flood, a rapid land gain of 6.5 km² occurred during a two-month
356 flood period in the Delta, equivalent to ~1/5 of the total delta area. The surge of the
357 delta area during the relatively short flood period in the Wax Lake Delta again is
358 consistent with the zig-zag growth pattern of delta area described above.

359

360 **4.2 Effects of Varying Intra-annual Unsteadiness on Delta Progradation**

361 Figure 6 shows that, as the delta lobe area keeps growing, it may pass a tipping point
362 and begin to decline during periods of low river discharge. Afforded by the
363 computational efficiency of the box model, the progradation of delta lobes with
364 extensive combinations of Q_r , which is defined as the ratio between the low and high
365 river discharges q_{wmin} and q_{wmax} , and duty cycle D were tested to identify conditions at
366 which the decline of delta lobe area during periods of low river discharge occur.
367 Notably, $D=0$ and $D=1$ or $Q_r=1$ correspond to constant low and high river discharges,
368 respectively. The constant river discharge prevents the decline of delta lobe area for
369 these two exceptional cases. The high river discharges were set as 1,000, 1,600 and
370 2,500 m³/s in the subsequent simulations. As shown in Figures 9a-9c, the shaded area
371 in the Q_r versus D parameter space, which represents when decline of delta lobe area
372 during periods of low river discharge occurs, increases with increasing modeling
373 period. The trend is consistent with the reasoning that, regardless of growth rate, the

374 likelihood that the delta lobe area and hence the accommodation space grows too
375 large for the limited sediment supply during periods of low river discharge to fill, i.e.,
376 the decline of delta lobe area, increases with time.

377

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

390

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

$$394 \quad Q_w = q_{w\max} \cdot D \cdot T + q_{w\min} \cdot (1 - D) \cdot T \quad (8)$$

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

396 leads to

$$397 \quad (1 - Q_r) = \frac{\left(\frac{Q_w}{q_{w\max} \cdot T}\right)^{-1}}{(D-1)} \quad (9)$$

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

403

404 **4.3 Effects of Variable Sediment Capture Ratio on Delta Progradation**

405 In the previous discussions on the box model, the sediment capture ratio was assumed
 406 to be constant over time. However, sediment retention in fluvial-deltaic systems is
 407 influenced by factors such as vegetation, hydrological connectivity and wave
 408 conditions (Swenson et al. 2005, Nardin and Edmonds 2014, Hiatt and Passalacqua
 409 2015). These factors can be seasonally variable, resulting in varying sediment capture
 410 ratio accordingly. For example, the arrival of the floods to the delta lobe might or
 411 might not be coincident with high vegetation coverage in the flood plain of the delta
 412 lobe. As such, we incorporated a time-varying sediment capture ratio in the box model,
 413 which was also written in pulse wave function (Figure 10a) as river discharge without
 414 loss of generality,

$$415 \quad f_c(t) = \left(D_f + \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin(\pi n D_f) \cos\left(2\pi n \left(\frac{t-t_f}{T} - \frac{D_f}{2}\right)\right) \right) \cdot (f_{c\max} - f_{c\min}) + f_{c\min} \quad (10)$$

416 where t_f (s) is the Julian date of the onset of maximum sediment capture ratio; duty
417 cycle $D_f = \tau_f / T$ (τ_f (s) is the duration of high sediment capture ratio) represents the ratio
418 of pulse duration to water year; f_{cmax} and f_{cmin} are high and low sediment capture ratios,
419 respectively. Notably, t_w relative to t_f quantifies the phase relationship between the
420 cycles of unsteady river discharge and variable sediment capture ratio, and the
421 periodic variation of river discharge is synchronous with sediment capture ratio when
422 $t_w = t_f$.

423

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

430

431 Figure 10b shows the progradation of delta lobes for scenarios with different phase
432 relationship between the cycles of unsteady river discharge and variable sediment
433 capture ratio. Generally, the progradation of delta lobe follows similar zig-zag growth
434 pattern as the scenarios with constant sediment capture ratio. Different area growth
435 trajectories for the synchronous, overlapped and asynchronous scenarios are
436 attributable to the cumulative sediment storage defined in Eq. (6). Specifically, when
437 the periodic variation of river discharge is synchronous with sediment capture ratio,

438 i.e., high river discharge and hence high sediment supply are coincident with high
439 sediment capture ratio, more sediments are trapped in the delta lobe and thus result in
440 greater delta area growth. The opposite happens when the periodic variations of river
441 discharge and sediment capture ratio are completely asynchronous. The delta lobe
442 area growth trajectory for the overlapped scenario falls in between the synchronous
443 and asynchronous scenarios as expected.

444

445 **4.4 Effects of Waves on Delta Progradation**

446 In natural deltas, marine forcing such as storm-induced waves could be important to
447 the progradation of delta lobes (Swenson et al. 2005). When river debouches into low
448 energy environments, sediments tend to store in fluvial-deltaic systems and create
449 subaerial delta; when the marine energy is strong, waves in combinations with
450 currents may transport sediments offshore and restrict the formation of subaerial delta
451 (Swenson et al. 2005). To further explore the coupling effects of unsteady river
452 discharge and waves forcing on delta progradation, additional scenarios (Table 3)
453 were run with waves added on top of the river discharge. The initial depths of the
454 receiving basin were increased to the range of 2.5-6.5 m (increasing seaward) to
455 dampen wave shoaling and maintain model stability. Scenarios W0 and B04W0, as
456 the baseline scenarios to be directly compared with wave-added scenarios, were run
457 without waves. Wave conditions were imposed at the offshore seaward boundary
458 parallel to the initial shoreline. The wave-added and baseline scenarios were
459 documented in Table 3, where the constant river discharge for scenarios B04W0-W3

460 were set as $1,300 \text{ m}^3/\text{s}$. Wave conditions were defined by significant wave height (H_s)
461 and peak period (T_p) with the assumption of wave propagation perpendicular to the
462 initial shoreline. For all wave-added scenarios, peak period is fixed at 5 s and
463 significant wave heights are listed in Table 3, and fixed sediment grain size of $200 \mu\text{m}$
464 was adopted.

465

466 The stars in Figure 4a show that, when a relatively strong wave condition ($H_s=0.8$
467 m) was imposed, the area ratio became significantly smaller than unity, i.e., the
468 created delta area became significantly smaller for unsteady discharge scenario than
469 that for constant discharge scenario. With decreasing wave height, the area ratio
470 increases toward unity. The contrast between no-wave scenarios and wave-added
471 scenarios is presumably due to the transport of sediment offshore or alongshore by
472 waves, which is further compounded by the varying modeling periods between the
473 constant and unsteady discharge scenarios to ensure approximately same total
474 sediment supply between the scenarios. Specifically, the modeling periods of the
475 constant discharge scenarios (B04W1-W3) are shorter than the unsteady scenarios
476 (W1-W3). As such, the wave reworking time would be longer for unsteady discharge
477 scenarios and hence more wave-induced sediment transport out of the delta. This
478 suggests that when waves are present, especially strong waves, extra care should be
479 taken when adopting the constant bank-full discharge assumption for numerical
480 modeling. Figure 11 further shows the comparison of temporal delta area growth
481 under wave conditions. While the constant discharge scenario follows similar

482 continuous smooth growth pattern as those without waves, unsteady discharge
 483 scenarios exhibit different temporal growth patterns. As illustrated in Figure 11, when
 484 wave energy is relatively strong ($H_s=0.8$ m), the zig-zag growth pattern vanishes. On
 485 the contrary, when wave energy decreases ($H_s=0.4$ m and 0.2 m), the zig-zag growth
 486 pattern returns.

487

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

$$495 \quad A \frac{dH}{dt} + H \frac{dA}{dt} = \frac{f_c \cdot q_s}{c} - S_w \quad (11)$$

496 where S_w (m^3/s) represents the wave-induced loss of sediments from the delta (Figure
 497 12).

498

499 Assuming waves propagate perpendicularly to the delta lobe such that the
 500 longshore transport is proportional to $\sin 2\theta$ (Figure 12) according to the CERC
 501 formula (Komar 1971),

$$502 \quad \frac{1}{2} S_w = K_I H_b^{5/2} \sin \theta \cos \theta = 0.5 K_I H_b^{5/2} \sin 2\theta \quad (12)$$

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

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

$$507 \quad S_w = f(A) \quad (13)$$

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

$$509 \quad \frac{dA}{dt} + \frac{1}{(H_0 + R \cdot t)} (A \cdot R + f(A)) = \frac{1}{(H_0 + R \cdot t)} \frac{f_c}{c} q_s \quad (14)$$

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

512

513 **4.5 Implications for Delta Protection and Restoration**

514 In the context of delta protection and restoration, such as the WSRS in the Yellow
 515 River and artificial channel diversions in the Mississippi River Delta, the effects of
 516 unsteady river discharge and variable sediment capture ratio on delta progradation as
 517 we discussed above should be taken into consideration. For instance, the setting of the
 518 timing for artificial floods or the location of the channel diversions should avoid
 519 strong wave conditions to reserve more sediments in the fluvial-deltaic systems to
 520 replenish the already sediment-starved deltas as much as possible (Figure 5a).
 521 Moreover, if the artificial floods carrying excessive sediments are coincident with
 522 greater sediment capture ratio, e.g., when vegetation is flourished in the delta lobe,
 523 more sediment can be trapped to create land (Figure 11b). As for the setting of
 524 discharge when generating artificial floods, the decrease in the duration of the high

525 river discharge and the increase in the ratio of low-to-high discharge tend to prevent
526 the decline of delta area during periods of low river discharge (Figure 10d). The
527 conditions for no-decline when the constraint of a fixed total volume discharged from
528 the reservoir to the downstream is further incorporated have also been discussed and
529 are not repeated here for brevity. Admittedly, the above discussions are subject to
530 numerous simplifications and in principle only, which lays a foundation for future
531 implementation in practice.

532

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

546

547 **5. Conclusions**

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

553

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

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

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

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

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

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

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

578

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

584

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732

733

734

735 **Figure Captions**

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

738

739

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

743

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

745

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

749

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

755

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

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

760

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

764

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

767

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

773

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

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

781

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

788

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

793

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

795

796 **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

797

798

799

800 **Table 2.** Scenarios of unsteady river discharge and corresponding constant discharge
 801 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	
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	B01
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	
R14	200	1,600	100	40	
R15	200	1,600	100	50	
R16	200	1,600	100	60	B02
R17	200	1,600	200	30	
R18	200	1,600	200	60	
R19	200	1,600	300	60	
R20	200	2,500	100	30	
R21	200	2,500	100	40	
R22	200	2,500	100	50	
R23	200	2,500	100	60	B03
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

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804 **Table 3.** Scenarios of unsteady river discharge coupled with waves and corresponding
 805 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

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