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Supplementary Information for

More extensive land loss expected on coastal deltas due to rivers jumping course during sea-level rise

Austin J. Chadwick[1], Sarah Steele[1], Jose Silvestre[1], Michael P. Lamb[1]
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

Corresponding author: Austin Chadwick
Email: Austin.chadwick23@gmail.com

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Supplementary Text

Details of experimental setup. The laboratory experiment was conducted in the Caltech River Ocean Facility, the same facility used by Ganti et al. in previously published delta experiments (1, 2). The experimental flume consisted of a 7-m-long, 14-cm-wide fixed-width river section that flowed into a 5-m-long, 3-m-wide unconfined ocean basin (Fig. 3a). Water and sediment were supplied at the upstream end and sea level was controlled using a programmable standpipe at the downstream end. The basin was initially free of sediment, and over several hours the flow naturally deposited sediment to form a river delta. The experiment was designed to feature backwater-scaled avulsions and sea-level changes dynamically similar to those on lowland deltas in nature (3). To reproduce backwater-scaled avulsions, we implemented a variable flood regime following the example of Ganti et al. (1, 2); water and sediment input oscillated between a low-flow and high-flow discharge, each of which produced significantly different normal flow depths (Table S1). Low- and high-flow durations were selected to be significantly shorter than the time required to adjust the channel to normal flow conditions to ensure backwater effects were persistent (4). Sediment supply was co-varied with water discharge to produce the same riverbed slope for both flow events (Table S1). The riverbed slope was shallow enough to allow subcritical flow ($Fr < 1$) and single-thread channels. To achieve sediment transport at such gentle slopes, we used low-density sediment: crushed, non-cohesive walnut shells ($1300\ \mathrm{kg/m^3}$) with near-uniform particle diameter ($0.7\ \mathrm{mm}$). Flow depth and slope resulted in a backwater length-scale of $L_b = H_n/S = 1.8\ \mathrm{m}$ (Table S1). Over the course of the experiment, we systematically raised sea level at four different rise rates ($\sigma = 0, 0.25, 1, \mathrm{and}\ 4$ mm/hr) in four phases (Phases A, B, C, and D). Rise rates were selected to span the range of dimensionless rise rates $0 < \sigma^* < 1$ (Table S2) which is common on natural deltas (5, 6) (Table S3). Although we did not incorporate subsidence into the experiment, delta response to uniform subsidence is expected to be mechanically similar to that of sea-level rise (7–9). Each phase was allowed to continue long enough to allow for many avulsions (Table S2). Phases were also kept brief enough such that the offshore basin did not deepen by more than a factor of two; this allowed us to mitigate the effect of changing basin depth and shoreline autoretreat on land loss (6, 10), and therefore better isolate the effect of sea-level rise rate.

Details of experimental data collection. Plan-view images of the delta were collected every minute using six overhead cameras mounted above the experimental facility. Photos from each camera were concatenated to ensure a wide field of view that extended beneath railings in the facility. The water was colored using a fluorescent green dye that allowed for visual distinction between subaerial and submerged land—even for shallow ($\sim 1\ \mathrm{cm}$) water depths— under ultraviolet light fixtures. Before starting a flow event we inserted ~ 0.5 gallons of dye into the end tank. The flow was then run at a very low discharge ($Q \sim 0.002\ \mathrm{L/min}$) with no sediment feed for ~ 12 hours of standby, which allowed the dye to disperse evenly throughout the basin without mobilizing sediment or disturbing the delta. The imagery was used to map river avulsions and the extent of dry and drowned land over the course of the experiment. Subaerial land was mapped within the shoreline, following the boundary of fluorescent green water and the brown sediment surface. Drowned land was mapped between the shoreline and the topset-foreset break; during sea-level rise, the shoreline retreated landward from the topset-foreset break (Fig. 3a-b). We identified avulsions as the establishment of a new channel that captured the majority of flow through consecutive flow events, accompanied by the partial or complete abandonment of the old channel, following previous work (2, 11). Avulsion location and time were measured as the location and time when the levee breach in the old channel initiated. Manual identification of avulsions involved a degree of subjectivity; still, our measurements for avulsion location have an uncertainty of less than one channel width and much less than the backwater length-scale, and measurements for avulsion time have an uncertainty of roughly one minute (1). We computed avulsion length (L_A) as the distance along the parent channel from the river mouth to the avulsion location, and computed avulsion frequency f_A using the definition $f_A \equiv 1/T_A$, where T_A is the time between the current avulsion event and the previous avulsion event.

Details of lobe-averaged model implementation. For both the experimental and field data, the lobe-averaged model (Eqs. 4-6) was implemented in a three-step approach. First , Eq. (5) was solved for avulsion frequency (f_A) using an iterative scheme (5) and input estimates of $Q_s,\ c_0,\ L_A$, $B,\ H,\ S, N$, and σ (Tables S1-S2). Second, f_A was plugged into Eq. (4) to estimate land loss (A_{lost}). Third, A_{lost} was plugged into Eq. (3) to estimate the area of persistently dry land (A_{dry}). Evaluation of Eqs. (3-4) also requires input estimates of total delta-plain area (A) and perimeter (P)—including both dry and drowned land; these values were computed using the landscape-averaged model (Eq. 1) for the experiment, and compiled from previous work (12) for the field data. The fractions of sediment deposited on persistently dry land (F_{dry}), deposited on intermittently drowned land (F_{lost}), and farther offshore ($F_{offshore}$) (Fig. 3e) were estimated by taking the ratio of terms in Eq. (5),

$$F_{dry} = \left(\frac{A_{dry}}{A}\right)\frac{f_A\left(L_A - \frac{1}{2}D\right)BH}{Q_s/c_0}, \quad \text{(S1)}$$

$$F_{lost} = \left(\frac{A_{lost}}{A}\right)\frac{f_A\left(L_A - \frac{1}{2}D\right)BH}{Q_s/c_0}, \quad \text{(S2)}$$

$$F_{offshore} = \frac{f_A DB\left(H_b + \frac{1}{2}z\right)}{Q_s/c_0}. \quad \text{(S3)}$$

Uncertainty in model predictions arose from uncertainty in lobe number (N); stochastic variability in the avulsion threshold (H) and avulsion length (L_A) (6, 13, 14); and gradual changes in the basin depth (H_b) as sea-level rose and fell (5, 15). Uncertainty in Eq. (5) was estimated using the variance formula,

$$s_{f_A} = \sqrt{\left(\frac{\partial f_A}{\partial n}s_n\right)^2 + \left(\frac{\partial f_A}{\partial H}s_H\right)^2 + \left(\frac{\partial f_A}{\partial L_A}s_{L_A}\right)^2 + \left(\frac{\partial f_A}{\partial H_b}s_{H_b}\right)^2} \quad \text{(S4)}$$

where s_{fA} is uncertainty in modeled avulsion frequency, and s_H, s_{LA}, and s_{H_b} represent the standard deviation in the avulsion threshold (± 1.1 mm), avulsion length (± 0.28 m), and basin depth (± 2 cm) observed across the entire experiment (Table S2). The term s_n represents uncertainty in $n = \frac{N+1}{2}$ based on a characteristic number of lobes between four and six ($N = 5 \pm 1$), consistent with field observations (16–19) and flume experiments (15, 20). Next, the variance formula was again used to propagate uncertainty in Eqs. (3-4) presented in Fig. 3d-e,

$$s_{A_{lost}} = \sqrt{\left(\frac{\partial A_{lost}}{\partial n}s_n\right)^2 + \left(\frac{\partial A_{lost}}{\partial f_A}s_{f_A}\right)^2} \quad \text{(S5)}$$

$$s_{A_{dry}} = s_{A_{lost}} \quad \text{(S6)}$$

where $s_{A_{lost}}$ and $s_{A_{dry}}$ represent uncertainty in modeled intermittent land area and persistently dry land area, respectively.

Details of landscape-averaged model implementation. For field data, landscape-averaged model predictions were compiled from previous work (12) (Table S3). For the experiment, landscape-averaged model predictions were calculated by solving Eq. (1) for the total delta-plain area (A) numerically using finite differences. Landscape-averaged land loss (A_{lost}) shown in Fig. 3e was estimated using a scaling analysis of Eq. (1): to first order, the area of lost land (A_{lost}) is equal to the rate of land loss times the duration of relative sea-level rise (T_{rise}), i.e. $A_{lost} \sim -\frac{dA}{dt}T_{rise}$. Combining this with the landscape-averaged model (Eqs. 1-2) and rearranging gives

$$A_{lost} = \left(\frac{Q_{s,need} - Q_s}{c_0 H_b}\right) T_{rise}, \quad \text{(S6)}$$

where T_{rise} is estimated by the experimental phase duration (Table S2). Thus, landscape-averaged models predict that the area of land loss is directly proportional to the deficit between the sediment available (Q_s) and the sediment needed to vertically accrete the entire delta plain at pace with sea level ($Q_{s,need}$; Eq. 2).

Details of revising sediment estimates for field data. The sediment supply a delta needs to sustain its current area is given by Eq. (2). Past landscape-averaged estimates have evaluated Eq. (2) using modern measurements of dry-land area for A; this implies that all available sediment can be deposited on persistently dry land (i.e., $A = A_{dry}$). We revised these estimates by accounting for sediment deposition in both the area of persistently dry land (A_{dry}) and the area of intermittently drowned land (A_{lost}) by plugging in $A = A_{dry} + A_{lost}$ in Eq. (2). The additional term A_{lost} was computed using the lobe-averaged model (Eq. 4). Importantly, A_{lost} depends on the frequency of river avulsion and diversion (Eq. 5); to assess delta sustainability under different diversions scenarios, we estimated the needed diversion frequency ($f_{A,need}$) to sustain current dry-land area without changing the available sediment supply (i.e., the border between shaded and unshaded regions in Fig. 4b). This was done by combining Eq. (4-5) and Eq. (2) under the condition that there is exactly enough sediment to maintain the delta area ($Q_s = Q_{s,need}$), and rearranging for avulsion frequency, which gives

$$f_{A,need} = n\left(\frac{\sigma}{S}P\right)\left(\frac{Q_s}{\sigma} - A_{dry}\right)^{-1}. \quad \text{(S7)}$$

To plot the boundary shown in Fig. 4b we calculated Eq. (S7) for the scenario of 1 m sea-level rise in 100 years ($\sigma = 1$ cm/yr) using characteristic values for field data ($A_{dry} = 1\text{e}4\ \text{km}^2$, $S =$ 7.4e-5, $n = 2.5$; Table S3) and estimated delta perimeter using $P = \sqrt{A_{dry}}$.

Table S1. Variable flood regime of the experiment

	Low flow	High flow
Water discharge [liters/min]	14.4	20.4
Sediment supply [g/min]	30.4	69.4
Normal-flow depth, H_n [mm]	7.5	11.7
Flow duration [min]	22	8
Normal-flow transport slope, S [$-$]	0.0042	0.0042
Backwater length-scale, $L_b = H_n/S$ [m]	1.8	$-$
Froude number, Fr [-]	0.59	0.43

Table S2. Phases of the experiment

		Phase A	Phase B	Phase C	Phase D
EXPERIMENTAL DESIGN	Dimensionless sea-level rise rate, σ^* $[-]$	0	0.08	0.33	1.33
	Sea-level rise rate, σ [mm/hr]	0	0.25	1	4
	Flood-averaged sediment supply [g/min]	40.8	40.8	40.8	40.8
	Run time [hr]	0-43.5	43.5-82	82-101	101-105
	Duration, [hr]	43.5	38.5	19	4
	Number of low flows $[-]$	87	77	38	8
	Number of high flows $[-]$	87	77	38	8
MEASURED DURING EXPERIMENT	Number of avulsions $[-]$	10	22	16	2
	Average avulsion frequency, f_A [hr^{-1}]	0.5	0.9	1.0	2
	Average avulsion length, L_A [m]	1.3±0.28			
	Approximate lobe thickness, H [mm]	2.3±1.1			
	Approximate number of lobes, N $[-]$	5±1			
	Approximate lobe width, B [m]	0.2			
	Solids fraction of sediment deposit, c_0 $[-]$	0.7			

Lobe width (B) was estimated based on width of the active channel, as flood deposition was negligible during the experiment. Lobe thickness (H) was measured in a companion experiment (2). For simplicity we adopted a characteristic number of lobes in the range $N = 5 \pm 1$, consistent with field observations (16–19) and flume experiments (15, 20). This range is consistent with our experiment, based on estimating the number of lobes by the ratio of the delta width (~1 m) to the lobe width (~0.2 m). The solids fraction of the sediment deposit was calculated as $c_0 = (\rho_{bulk} - \rho_{water})/(\rho_{part} - \rho_{water})$ using direct measurements of the deposit's bulk density ($\rho_{bulk} = 1210\ \mathrm{kg/m^3}$), the water density ($\rho_{water} = 1000\ \mathrm{kg/m^3}$), and the sediment particle density ($\rho_{part} = 1300\ \mathrm{kg/m^3}$).

Table S3. Field data used in this study.

	σ [mm/yr]	L_A [km]	L_b [km]	f_A [1/kyr]	Q_s [Mt/yr]	H_c [m]	H [m]	B_c [km]	B [km]	H_b [m]	N [-]	T_c [kyr]	σ^* [-]	A_{dry} [km^2]
Parana	3	210	295	0.6	79	11.8	8.2	1.3	50.8	40	5±1	3.6	2.3	1.4e5
Danube	0.2	95	125	0.5	67	6.3	5.0	1.3	50	50	5±1	0.9	0.1	2.5e4
Nile	4.5	210	254	—	120	16.2	—	0.2	9.6	120	5±1	0.5	0.4	1.0e5
Mississippi	2.3	490	480	0.8	400	21	12.5	0.7	26	80	5±1	1	0.3	3.6e5
Rhine-Meuse	1.6	51	45.5	0.7	3.1	5	2.3	0.7	28	18	5±1	3.3	2.6	3.3e3
Magdalena	2.9	67	63.2	—	220	6	—	1.1	44	200	5±1	0.1	0.1	6.3e3
Orinoco	2.6	78	133.3	1	150	8	2.1	2	80	110	5±1	0.9	0.7	2.8e4
Amazon	2.9	404	400	—	1200	12	—	3	120	50	5±1	0.8	0.5	2.5e5
Rhone	2.8	—	183.5	0.7	31	7.3	2.9	0.4	15.1	70	5±1	1	1	5.3e4
Yellow	1.7	31	35	142.9	1100	3.5	0.7	0.5	20	30	5±1	3.5e-3	4e-3	1.9e3
Brahmaputra	11.4	—	70	2	540	7	10	3.3	132	80	5±1	0.2	0.8	7.7e3

Relative sea-level rise rates (σ) are reported by Chadwick et al. (5) and reflect the sum of eustatic sea-level change (21) and coastal subsidence (22–26) estimated over the time that avulsions occurred. Avulsions occurred during the late Holocene period (last 7 ky), with the exception of the Yellow where pre-industrial historical avulsions are documented (13). Avulsion lengths (L_A) and backwater length-scales (L_b) are reported in (13, 27). Avulsion frequency (f_A), channel depth (H_c), and channel width (B_c) are reported in (28). Basin depths (H_b) are reported in (29). Sediment supplies (Q_s) are reported in (30), and are converted here to volumetric rates using a sediment density of $2650\ \mathrm{kg/m^3}$ and 40% porosity ($c_0 = 0.6$). Channel filling timescales are estimated as $T_c = H_c B_c L_b c_0 / Q_s$ following (4, 31). Data for the Danube are reported in (32). Deltas were assumed to be composed of four to six lobes ($N = 5 \pm 1$) with width of forty times the channel width ($B = 40B_c$), which are reasonable estimates (18, 19, 33, 34). Depositional thickness of the delta lobe at avulsion (H) is reported by Chadwick et al. (5) and dimensionless sea-level rise (σ^*) is calculated using Eq. (5). Area of persistent dry land (A_{dry}) is reported by Giosan et al. (12), or where unavailable was estimated by $\frac{1}{2}\pi L_b^2$ following Ganti et al. (1). Area of intermittently drowned land (A_{lost}) was calculated using Eq. (4). Empty table entries indicate data were not available.

Table S4. Land loss forecasts for field data that account for avulsions and delta lobes

	Intermittent land area, A_{lost} [km^2]	**Fraction of land lost, A_{lost}/A** [%]	**Sediment needed $Q_{s,need}$** [Mt]	**Predicted avulsion frequency** [1/kyr]
Parana	4.5e5 ± 7.5e4	76 ± 35	9.4e5 ± 1.2e5	0.6
Danube	4.9e4 ± 8.2e3	66 ± 25	8.5e4 ± 1.3e4	1.8
Mississippi	1.0e5 ± 1.7e4	22 ± 5	2.3e5 ± 2.7e4	1.6
Rhine-Meuse	2.3e4 ± 3.8e3	87 ± 53	4.1e4 ± 6.0e3	0.6
Orinoco	8.4e4 ± 1.4e4	75 ± 33	1.8e5 ± 2.2e4	7.2
Rhone	2.5e5 ± 4.2e4	83 ± 44	4.8e5 ± 6.6e4	—
Yellow	1.6e2 ± 2.7e1	8 ± 1	5.4e3 ± 4.3e1	189.3 ± 6.4
Brahmaputra	1.3e4 ± 2.2e3	63 ± 22	3.3e4 ± 3.5e3	—

Intermittent land area (A_{lost}) was calculated using Eq. (4). Fraction of land lost ($\frac{A_{lost}}{A} = \frac{A_{lost}}{A_{dry}+A_{lost}}$) was calculated using the predicted intermittent land area and the dry land area from Table S3. Needed sediment ($Q_{s,need}$) was calculated using Eq. (2) accounting for deposition in both persistent and intermittent land areas ($A = A_{dry} + A_{lost}$; Eq. 3). Predicted avulsion frequency was calculated using Eq. (5). Calculations were performed for a scenario of 1-m of sea-level rise over 100 years following Giosan et al. (2014), and where applicable show ± 1 standard deviation in uncertainty propagated from an estimated lobe number of $N = 5 \pm 1$ using Eq. S5. Empty table entries indicate field data necessary to perform calculations were not available (Table S3).

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