

Incision Sets the Growth Rate of Delta Channel Networks

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Abstract: River deltas support large human populations and diverse ecosystems, but many are increasingly threatened by relative sea-level rise and sediment deprivation. Delta growth is widely viewed as a depositional process driven by sediment accumulation. However, the distributary channels that deliver sediment across deltas often extend before major episodes of subaerial land growth. Recent field observations suggest that, in many systems, these channels extend basinward by incision rather than deposition. Here, drawing on incisional growth theory, we derive an analytical solution that links channel-tip progradation to network topology, channel geometry, and river discharge. Analysis of observations based on this framework suggests that channel-tip progradation rates scale linearly with flow velocity at channel mouths, revealing an unexpectedly constant dimensionless ratio between the two—the progradation number—across deltas of widely varying sizes and growth rates. These findings suggest that incision is a predominant mechanism driving distributary channel growth and provide a simple framework for predicting channel-network expansion in delta restoration.

Main Text

River deltas are depositional landforms that serve as major coastal sinks for terrestrial sediment and associated materials, including nutrients and biomass^{1–3}. This accumulation builds fertile land that supports agriculture and diverse ecosystems, as well as coastlines that sustain about 50% of the world's population^{4–6}. Yet accelerating relative sea-level rise, sediment deprivation, and human modifications to channels, including leveeing and dredging, are causing land loss in many deltas^{1,2,7–10}. To sustain these vulnerable coastal landscapes, delta and wetland restoration projects are increasingly being implemented^{7,9,11–13}, with cost-effectiveness remaining a central concern¹⁴. A key question is how quickly these restoration projects can deliver tangible, demonstrable land-building benefits¹⁵. Addressing this question requires understanding how distributary channels, whose flow and geometry can be modified through engineering, relate to the growth of deltaic land^{8,16}.

Traditional assessments of delta growth have focused mainly on the rate at which deltas accumulate sediment^{1,17–21}. This perspective often implicitly assumes that the delta's distributary channel networks (DCN) and the radially averaged subaerial shoreline prograde at similar rates^{22–26} (Fig. 1). However, bathymetric observations show that distributary channels, especially their tips or mouths, can extend tens of kilometers beyond the firmly established land²⁷ (Fig. 1), as in topset-dominated systems such as the Wax Lake Delta²⁷ and the Head of Passes in the Mississippi Delta²⁸. Channel growth and subaerial land growth are not necessarily synchronous^{27,29,30}. These networks nevertheless provide the primary pathways for water, sediment, and nutrients to reach the receiving basin and interdistributary floodplains^{31–33}, even where the delta topset is partly or entirely subaqueous^{34–36}. Their expansion therefore sets the pace of broader land-building processes^{16,37}, making predictive models of distributary network growth essential for understanding delta progradation^{18,29,30,34,38–40}. Previous studies have examined how distributary network topology and morphology respond to external forcing^{41,42}, including river discharge^{43,44}, sediment supply^{18,42}, wave activity^{42,45}, and tidal currents^{46,47}. Yet what controls the rate of channel-tip progradation remains unclear^{35,44}.

The central challenge is that distributary channels in many topset-dominated deltas are incised into the surrounding sediments^{34,39,40,48,49}. Models that treat channel extension as a depositional process do not represent this incised channel morphology, while the predictive performance of incisional models across natural delta networks remains poorly constrained³⁵. A predictive framework for incisional growth is therefore needed, particularly given the global prevalence of topset-dominated delta networks under modern sea-level highstand conditions^{23,40,50}. Here, we derive an analytical model for distributary channel network growth using incisional theory and test it against a new compilation of network growth rates spanning rapidly and slowly growing deltas. We find an unexpectedly simple linear relationship between the channel-tip growth rate and mouth flow velocity and define their dimensionless ratio as the Progradation Number. This relation provides a

unified predictive framework for delta channel network growth, with implications for delta modeling, restoration, and rock record reconstruction⁵¹.

Theory and Results

Incisional Theory for Distributary Channel-Tip Growth and Its Test. Building on a simplified morphodynamic model of a distributary network³⁵, we describe channel-tip growth using an incisional sediment mass balance (Exner equation). We consider systems in which the channel thalweg lies below the surrounding delta-front sediments or mouth bar, as is typical of a topset-dominated delta (e.g., Fig. 2b,c). In this setting, basinward channel extension (Supplementary Fig. S1b) requires sediment erosion at the advancing tip. When a channel tip advances a distance Δx [L], the volume of sediment eroded is $\Delta V = \Delta x W H_b (1 - \lambda_0)$ [L³], where W is channel width [L], H_b is mouth bar height [L], and λ_0 is bed porosity [-]. For a volumetric sediment erosion rate E_v [L³/T] over a time interval Δt [T], this balance gives $\Delta V = \Delta x W H_b (1 - \lambda_0) = E_v \Delta t$. Defining the channel-tip progradation rate as $u_p = \Delta x / \Delta t$ [LT⁻¹] and the erosion rate per unit width as $E = E_v / W$ [L²T⁻¹], the incisional Exner equation becomes³⁵

$$u_p = \frac{\Delta x}{\Delta t} = \frac{E}{H_b (1 - \lambda_0)} = \frac{q_{sc} - q_{r-in} - \Delta q_t}{H_b (1 - \lambda_0)} \quad (1)$$

where q_{sc} is the sediment transport capacity of the flow near the distributary channel mouth, q_{r-in} is the riverine input sediment flux and Δq_t is the net landward tidal-current sediment flux, all expressed per unit width [L²T⁻¹]. We use u_p as a characteristic tip growth rate, distinct from shoreline progradation or subaerial land growth (see Fig. 2 and Supplementary Fig. S1).

For channels actively prograding by incision, sediment transport capacity (q_{sc}) greatly exceeds the incoming sediment fluxes ($q_{sc} \gg q_{r-in} + \Delta q_t$). Equation (1) simplifies to $u_p \approx q_{sc} / H_b (1 - \lambda_0)$, showing that tip advance is governed by the sediment erosion capacity relative to the thickness that must be eroded. Applying an empirical power-law relation between sediment transport capacity and water discharge per unit width, $q_{sc} = k' q^\beta$, then leads to $u_p \approx k' q^\beta / H_b (1 - \lambda_0)$.

To make the physical basis of this scaling relation explicit, we use a generalized sediment transport relation^{52,53} that incorporates sediment properties and hydrodynamic forcing: $q_{sc}^* = \alpha_0 (\tau_x^* - \tau_c^*)^\beta / C_f$, where $q_{sc}^* = q_{sc} / (RgD^3)^{0.5}$ is the dimensionless sediment transport capacity, R is the submerged specific gravity of sediment ($R=1.65$ for quartz in fresh water), g is the gravitational acceleration [LT⁻²], D is the characteristic bed grain size [L], C_f is the dimensionless resistance coefficient [-]; $\tau_x^* = \tau_x / (\rho RgD)$ is the dimensionless shear stress, $\tau_x^* = \tau_x / (\rho RgD)$ is the shear stress [ML⁻¹T⁻²], the subscript $x=b$ for bed shear stress and $x=c$ for critical shear stress of sediment incipient motion. The

parameters α_0 and β depend on transport conditions^{52,53}. Substituting this relation into simplified sediment mass balance yields

$$u_p = \frac{(RgD^3)^{0.5} q_{sc}^*}{H_b(1-\lambda_0)} = \frac{\alpha_0 (RgD^3)^{0.5} (\tau_b^* - \tau_c^*)^\beta}{C_f H_b(1-\lambda_0)}. \quad (2)$$

We next connect the local hydrodynamics to discharge, network topology and channel geometry. We define the water discharge per unit total outlet width as $q = Q / \sum_{i=1}^N W_i$, where Q is the water discharge at the delta apex, W_i is the width of outlet i , and N is the number of channel outlets. Because some flow can escape into interchannel areas^{54,55}, we introduce a discharge-retention ratio κ , such that $\sum Q_i = \kappa Q$ where $\kappa < 1$ represents loss of confinement in the deltaic channels³³. The local mouth flow velocity u thus satisfies $uH \approx \kappa q$, where H is characteristic water depth [L] above the mouth bar. Following the linearized drag approximation^{35,56-59}, $\tau_b \approx \rho \Lambda u$ where $\Lambda = C_f U$ is the dimensional resistance coefficient [LT⁻¹] and U is a characteristic flow velocity. Thus, $\tau_b^* \approx \frac{\Lambda u}{gRD} = \frac{\kappa q \Lambda}{gRHD}$.

For actively prograding networks in which $\tau_b^* \gg \tau_c^*$, Equation (2) reduces to

$$u_p = \frac{\alpha q^\beta}{H_b} = \frac{\alpha}{H_b} \left(Q / \sum_{i=1}^N W_i \right)^\beta \quad (3)$$

$$\text{where } \alpha = \frac{\alpha_0 (RgD^3)^{0.5}}{C_f (1-\lambda_0)} \left(\frac{\kappa \Lambda}{gRHD} \right)^\beta.$$

Although wave and tidal dynamics are not explicitly resolved, their effects on channel network growth are implicitly represented through network topology (N) and channel geometry (W and H_b). For example, waves can redistribute sediment across the shoreline and reduce the number of outlets, whereas tidal forcing can widen the channel mouths⁴⁷, thereby changing discharge per unit width. Equation (3) therefore provides a general framework for examining these controls on channel-tip growth.

We assess the incisional model by its fit to the observations and whether systematic differences between smaller and larger networks remain in the fitted relation. Although the coefficient and exponent in Equation (3) have physical meanings and may vary among systems, we estimate both freely by fitting the incisional model to the full dataset to seek a universal network-growth law. We test the model using nine natural delta-network units, with water discharge, outlet number, individual outlet widths, and mouth-bar height, compiled from published sources or derived from publicly available bathymetric and satellite datasets for testing^{22,23} (see Methods).

Field observations strongly support the incisional growth scaling relation. The power law relation between $u_p H_b$ and q has $R^2=0.97$ (Fig. 3a), reconciling the observed

growth rates of small and large networks in a universal relation. Here, $u_p H_b$ represents the bulk sediment volume that must be eroded per unit outlet width per unit time as the channel tip advances. The resulting scaling links riverine forcing, modulated by network topology and channel width, to the sediment erosion required for network growth across the sampled deltas.

Simpler formulations based on Q or Q/N alone show weak negative relationships with u_p , rather than the hypothesized positive dependence. The q -only formulation also accounts for channel width (Q/NW) and yields a weak positive relationship, but retains substantial scatter and systematic separation between smaller and larger networks (Extended Data Fig. 1). These comparisons further support the full scaling in Equation (3), which incorporates the mouth bar height (H_b), as the simplest adequate formulation among those tested (Fig. 3a). Alternative scalings based on sediment supply as the primary control perform less well than discharge-based scaling (Discussion and Supplementary Fig. S2). More strikingly, the freely fitted exponent of the power-law relation between $u_p H_b$ and q , $\beta=1.07$, is unexpectedly close to unity, indicating a surprisingly linear relation.

Discovery and Implications of the Dimensionless Progradation Number. The unexpectedly linear relation reveals a remarkable simplification: the ratio $u_p H_b / q$ is dimensionless, and approximately constant across sampled networks (Fig. 3b). We define this dimensionless ratio as the “Progradation Number”, $\mathbf{Pr} = u_p H_b / q = (1.86 \pm 0.48) \times 10^{-6}$ (95% confidence interval). Rearranging yields $\mathbf{Pr} = u_p / U_m$ where $U_m = q / H_b = Q / (NWH_b)$ is a nominal mouth flow velocity, calculated from mean apex discharge, network topology, and channel outlet geometry. The observed $\mathbf{Pr}$ therefore indicates that channel tips advance at approximately two millionths of this nominal mouth flow velocity, corresponding to ~ 59 m/yr for $U_m = 1$ m/s (Fig. 3a). An exhaustive subset analysis further supports the stability of this relation and its predictive performance, in which power-law fits obtained using subsets of data (half) result in almost the same linear relations with similar predictive capacity to the one obtained from using the complete dataset (Supplementary Text S1).

To examine a possible physical origin of this dimensionless number and provide a theoretical rationale for the constant $\mathbf{Pr}$, we consider the case $\beta=1$ for cohesive sediment erosion^{60–62} and Equation (3) reduces to

$$u_p = \frac{q}{H_b} \frac{\alpha_0 \kappa}{1 - \lambda_0} \frac{U}{H} \left(\frac{D}{gR} \right)^{0.5} \quad (4)$$

To connect active, episodic incision with the long-term rates and mean discharge used in the empirical scaling, we average the channel propagation rate over a time interval T , $\overline{u_p} = \int_0^T u_p dt / T$, and neglect the channel-tip advance outside periods of floods (denoted by T_F). The average progradation rate is expressed as

$$\overline{u_p} = \frac{\int u_p(t) dt}{T} \approx \frac{\int_{T_F} u_p(t) dt}{T} = \frac{1}{T} \int_{T_F} q dt \frac{\alpha_0 \kappa}{H_b (1 - \lambda_0)} \frac{U}{H} \left(\frac{D}{gR} \right)^{0.5}. \quad (5)$$

If we define flood intermittency as the fraction of the total water volume during flood periods $I_f = \int_{T_F} q dt / \int q dt = \int_{T_{Q>BF}} Q dt / (\bar{Q} T)$ and use the temporally averaged mouth flow velocity $U_m = \int q dt / T / H_b$, we can obtain the following expression for the Progradation Number

$$\mathbf{Pr} = \frac{\overline{u_p}}{U_m} = \frac{\alpha_0}{(1 - \lambda_0)} \kappa I_f \frac{U}{H} \left(\frac{D}{gR} \right)^{0.5}. \quad (6)$$

Based on this derivation, the observed constant **Pr** could arise from relatively limited variation in the product of I_f , the dimensionless $(U/H) \sqrt{D/(gR)}$, and the prefactor $\alpha_0 \kappa / (1 - \lambda_0)$. The deltas compiled in this work indeed have a similar discharge coefficient of variation (C_v), supporting limited variation in I_f . Furthermore, sediment properties (α_0 , β , D) in delta settings are relatively similar, with grain size (D) varying over a narrow range. Sand (0.06-2 mm) is typically associated with energetic channelized flow and wave activity, and many channel tips show a transition from sandy channels to muddier mouth bars and surrounding deposits^{34,63}. These shared hydrological and sediment characteristics may therefore help explain why **Pr** remains nearly constant across the sampled deltas.

The growth rate of river deltas is known to decrease with age; thus, newly formed, juvenile deltas grow more rapidly than older ones^{35,64}. The linear relation also offers a unified mechanistic explanation for distributary-channel progradation across scales, from small, rapidly-growing to large, slowly-growing delta networks. Given a constant water discharge, $u_p = \mathbf{Pr} Q / (NWH_b)$ predicts slower channel-tip advance as the total cross-sectional area of the network mouths (NWH_b) increases. This increase can occur through three mechanisms: 1) channel bifurcations that add outlets N , as in the Selenga Delta²³, 2) widening of distal channels (W), as in the Amazon Delta, and 3) channel deepening (H_b), as at the Head of Passes in the Mississippi Delta²⁸ and the Amazon Delta⁶⁵.

The same relation also accommodates quasi-steady channel-tip progradation (scale-invariant)²⁴ when $Q/(NWH_b)$ remains approximately constant. This explains the sustained, quasi-steady growth of the Lafourche delta²⁴, which contradicts the slowing predicted by depositional models⁶⁶. Specifically, the stable number of channels (N) over 1000 years of progradation²⁸ may have helped maintain relatively stable discharge in a near-constant total cross-sectional channel area at the coast (NWH_b). This interpretation is compatible with the alternative view that simultaneous bottomset aggradation allowed the Lafourche Delta to expand into a shallower basin²⁵, implying potentially stable Q and H_b and therefore maintaining a constant progradation rate. The progradation number **Pr** thus provides a

unified incisional framework for interpreting not only rapidly and slowly growing distributaries but also sustained, quasi-steady network growth.

Discussion

The Progradation Number Captures Network-Scale Growth of Distributary Channels. Long-term changes in channel geometry and network topology, including contraction of channel area, in-channel deposition, and avulsions, will drive variable progradation rates among individual channels⁷⁶. **Pr** implicitly accounts for these processes insofar as they modify the effective total coastal cross-sectional area (NWH_b), the model's core geometric control. Despite substantial variability among individual channel tips, **Pr** captures the mean progradation rate well, suggesting that the growth rate of a single characteristic channel-tip, if it locates at the frontier of the delta network, can approximate distributary network growth. Accordingly, although the Mekong and Amazon deltas exhibit a range of individual channel progradation rates, the mean rate across channels agrees with incisional-model predictions (Fig. 3). Where spatial heterogeneity is particularly strong, a nested formulation that includes sub-channel networks may be more appropriate. For example, the Selenga Delta developed multiple lobes in response to spatially variable subsidence associated with tectonic subsidence heterogeneity⁴⁸, and the two prograding lobes considered here each agree with the model predictions (Fig. 3).

Incisional Channel-Tip Progradation is Decoupled from Bulk Delta Deposition. Channel-tip progradation through incision may seem counterintuitive because delta building is generally framed as a mass balance between sediment supply and accommodation^{8,11,19,23–27}. Sediment supply is positively correlated with water discharge and, in turn, with the channel progradation rate^{62–64}, but its relationship with channel progradation is nonlinear and highly uncertain (Supplementary Fig. S2). The difference between channel-tip progradation by incision and overall delta growth by deposition may reflect the different spatial scales of the two processes. The channel-tip is much smaller than the broad subaqueous delta platform (pre-delta deposit), so the sediment volume required for channel progradation is small relative to total sediment supply (Fig. 4). Our calculations based on observations and depositional models (Methods) indicate that only 1% (0.1%–10%) of the sediment supply is needed to construct levees in prograding channels, even after accounting for relative sea-level rise (RSLR) (Fig. 4). As a result, channel network progradation can greatly outpace average shoreline growth. At the Wax Lake Delta, for example, the average channel tip progradation rate is 79 m/yr, more than twice the average shoreline progradation rate of about 30 m/yr^{30,61}. Channels can therefore prograde far beyond the delta shoreline, or region of subaerial exposure, helping set the morphology of the emergent delta. The controls on channel-network expansion can therefore differ from those governing depositional land growth.

Based on our observations, this incisional style of channel progradation typically occurs in topset-dominated deltas, where the channel mouth is significantly deeper than the delta front and surrounding pre-delta seafloor deposits. Channels must therefore “bulldoze” through existing deposits to extend basinward. In this setting, mouth-bar erosion rate,

determined by mouth-flow velocity, sets the maximum potential basinward expansion rate (Fig. 3). Since channel extensions require relatively little sediment supply for levee construction (Fig. 4) and channel-tips may erode into locally derived bed material at the delta front, channel extension rates are likely insensitive to upstream sediment supply.

Sediment mass balance nevertheless governs total delta volume, including both the subaqueous platform and subaerial land. Sediment supply and depositional models remain crucial for foreset-dominated delta progradation (Fig. 1a), such as in the Yellow River Delta²² and for deltaic land building more broadly. Indeed, bulk sediment accumulation remains the primary focus of many restoration projects and stratigraphic studies^{17,67}.

Implications for Delta Restoration Projects. River delta progradation often reflects many interacting controls, including sediment supply, RSLR, waves, and tides. However, the incisional model derived and tested here suggests that a simple relation may capture channel-tip progradation rates. Our results indicate that local hydrodynamics, inferred from river discharge, network topology, and outlet geometry, can predict channel growth remarkably well. This finding supports channel incision, driven primarily by local flow conditions, as a first-order control on the development of distributary channel networks. Once deep incisional channels are established, levee aggradation and marsh accumulation can proceed where sediment is available. This framework has important implications for coastal restoration because tracking the extent of subaqueous channelization, rather than only the emergent subaerial delta land, may provide an early, predictable indicator of how delta channel networks respond to restoration.

For sediment diversions and delta restoration projects, the proposed relation also provides a basis for assessing how changes in average discharge could influence the pace of distributary channel network growth. This is important for restoration strategies aimed at maximizing land building because higher water discharge can rapidly extend the subaqueous channel network and disperse sediment over a broader area, even if the aggradation of levees and islands may take additional decades¹⁵. Conversely, disproportionately high sediment discharge may promote rapid aggradation but over a more limited area. Where both water and sediment are constrained, the magnitude and ratio of water and sediment discharge may therefore be tuned to balance channel network expansion and adjacent land building at similar rates, potentially maximizing restoration efficiency. This work provides a foundation for developing a more refined framework for tuning water and sediment discharge in delta restoration.

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Methods

Progradation Calculation Based on the Depositional Model

Based on the sediment mass conservation equation, i.e., the Exner equation, the growth of deltaic land or channels is treated as a depositional process in which sediment deposition controls progradation:

$$u_p = \frac{dx}{dt} = \frac{f_{re} Q_s}{P_d D_b (1 - \lambda_0)} - \frac{L}{D_b} \times RSLR \quad (S1a)$$

$$Q_{s-demand} = \left(u_p + \frac{L}{D_b} \times RSLR \right) P_d D_b (1 - \lambda_0) = f_{re} Q_{s-supply} \quad (S1b)$$

where u_p is the progradation rate; x is the longitudinal coordinate extending from the apex to the shoreline; t is the time; Q_s is sediment discharge; f_{re} is the fraction of incoming riverine sediment retained to construct the delta or channels; D_b is the basin depth; λ_0 is the porosity; L is a characteristic length that measures the inundated land of each unit relative sea level rise (RSLR); P_d represents the horizontal extent of the depositional front. If Equation (S1) applies to deltaic land building, P_d represents the perimeter of the deltaic shoreline^{17,19,68} whereas, for channel-levee progradation, it should scale with the total width of the deltaic channel levees¹⁸(Fig. 2a and Supplementary Fig. 1a). Because this combined levee width is much smaller than the deltaic shoreline perimeter, less retained sediment is required to sustain a given progradation rate. Therefore, when applying Equation (S1) to

channel growth predictions, the first term on the right-hand side of Equation (S1a) is usually much greater than the second term, which represents delta land/channel lost due to relative sea-level rise. Fig. 4 further shows that sediment demand for prograding channel levee construction is one to two orders of magnitude smaller than supply. In other words, sediment supply is more than sufficient to offset the effects of relative sea-level rise.

The applicability of Equation (S1) is severely limited when the system is poorly constrained. For instance, the sediment discharge, if not measured over sufficiently long periods, can have uncertainties of up to two orders of magnitude; furthermore, the combined retention and porosity factor, $f_{rel}/(1-\lambda_0)$, is also challenging to constrain across deltas and requires careful calibration using multi-year satellite imagery or detailed numerical models^{69–72}. Due to the inherent challenges of quantifying sediment deposition, obtaining a globally applicable relation for progradation based on depositional sediment conservation remains challenging¹.

Field Observations of Delta Channel Networks

The remotely sensed data, including distributary network topology, channel lengths, and widths, were extracted using RivGraph⁷³, supplemented by manual digitization where image resolution limited automatic extraction. Determining progradation rates and mouth-bar height or bankfull depth requires identifying channel-mouth locations and local channel geometry, as described below.

For progradation rates, we used published values from the references whenever available, provided that the measurement methods were documented and consistent with those used here. Channel-tip progradation rates can be determined directly from tip displacement between successive bathymetric maps divided by the elapsed time²⁸. However, this is difficult when repeated bathymetric surveys are unavailable, and not all primary distributary channels are surveyed. Flow tracers can instead indicate flow divergence, which can be used to determine channel-mouth positions and their displacement over time²⁷. We also estimated channel advance from satellite imagery. We first obtained the trajectories of the channel centerlines, identified their cross points with the delta shorelines, and then divided the displacement of these intersections between successive dates by the elapsed time to determine average progradation rates. These measurements describe the advance of channel–shoreline intersections and serve as a proxy for channel advance.

We obtain mouth bar heights whenever detailed bathymetry (channel longitude profile) is available; otherwise, we use bankfull depths near the mouth, which measure the levee-thalweg differences as an approximation. We obtain bankfull depths from local cross-sectional measurements, documented in references and public databases.

Data availability: The compiled dataset is not included in this preprint and will be made publicly available in Supplementary Information upon publication of the peer-reviewed article.

Code availability: No custom code was generated for this study.

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Author contributions

HM and JS conceived the study. HM, TD, JS, LV, AT and MC compiled the database. HM derived the analytical formula and analyzed the data. HM and TD drafted the manuscript with substantial input from JS, AT, AM, EF. All authors contributed to the discussion and interpretation of the results.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information is available for this study. **Correspondence and requests for materials** should be addressed to Hongbo Ma or John Shaw.

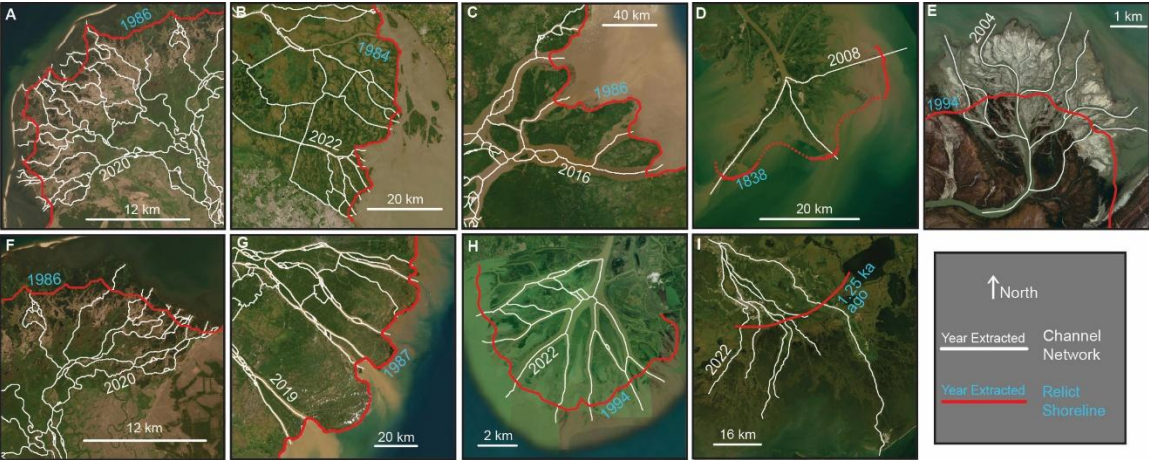


Fig. 1. Prograding distributary channel networks. The mapped channel networks (white) extend beyond earlier shorelines (blue), illustrating progradation. **a**, The western lobe of the Selenga Delta in Lake Baikal, Russia. **b**, The southeastern part of the Paraná Delta, Argentina. **c**, The Amazon Delta, Brazil. **d**, The Head of Passes in the Mississippi Delta complex, USA. **e**, The Syrdarya Delta in the Aral Sea, Kazakhstan; **f**, The eastern lobe of Selenga Delta in Lake Baikal, Russia. **g**, The Mekong Delta, Vietnam. **h**, The Wax Lake Delta, USA. **i**, The Lafourche Delta, USA.

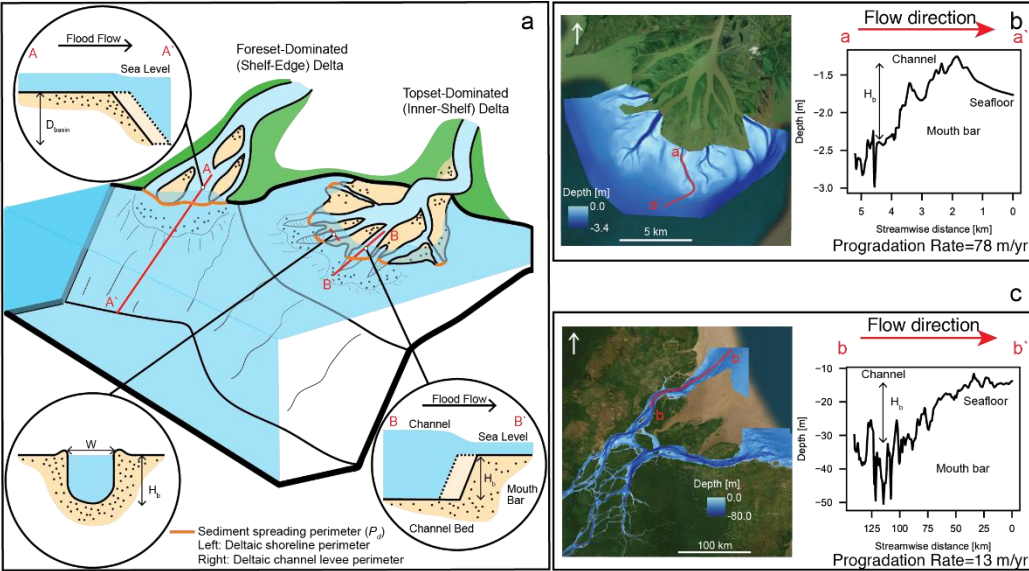


Fig. 2 Sketch of delta progradation: conceptual models and field examples. a, Progradation of a foreset-dominated delta (A-A') and topset-dominated delta (B-B'). **b,** The bathymetry and longitudinal profile of a channel mouth in the Wax Lake Delta, showing mouth bar height H_b . **c,** The bathymetry and longitudinal profile of a channel mouth in the Amazon Delta, showing bar height H_b . Both profiles show clear incisional features.

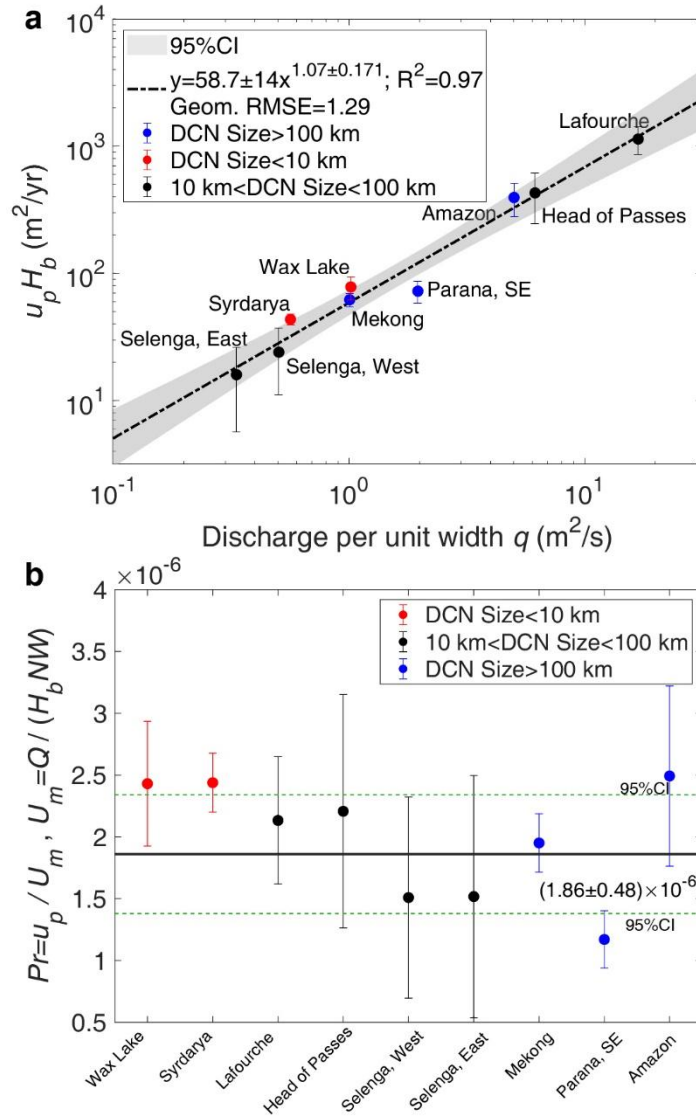


Fig. 3. A unified progradation rate predictor incorporating mouth-bar height or its bankfull-depth proxy. a, Accounting for mouth bar height reconciles all delta network expansions into a linear relation between the discharge per unit width $q=Q/NW$ and the product of the progradation rate and mouth bar height $u_p H_b$. The freely fitted exponent is approximately unity (linear), with $R^2=0.97$. Shading indicates the 95% confidence interval of the fitted relation. Notably, the linear relation also reveals a dimensionless progradation number $\mathbf{Pr}=u_p/U_m$, where $U_m=q/H_b=Q/(H_bNW)$ is the nominal mouth flow velocity, and this number $\mathbf{Pr}=(1.86\pm0.48)\times10^{-6}$ (in Panel b). With constant $\mathbf{Pr}$, the network progradation rate can be estimated as $u_p=\mathbf{Pr}Q/(H_bNW)$, given apex discharge and channel network properties (Q, N, W, H_b).

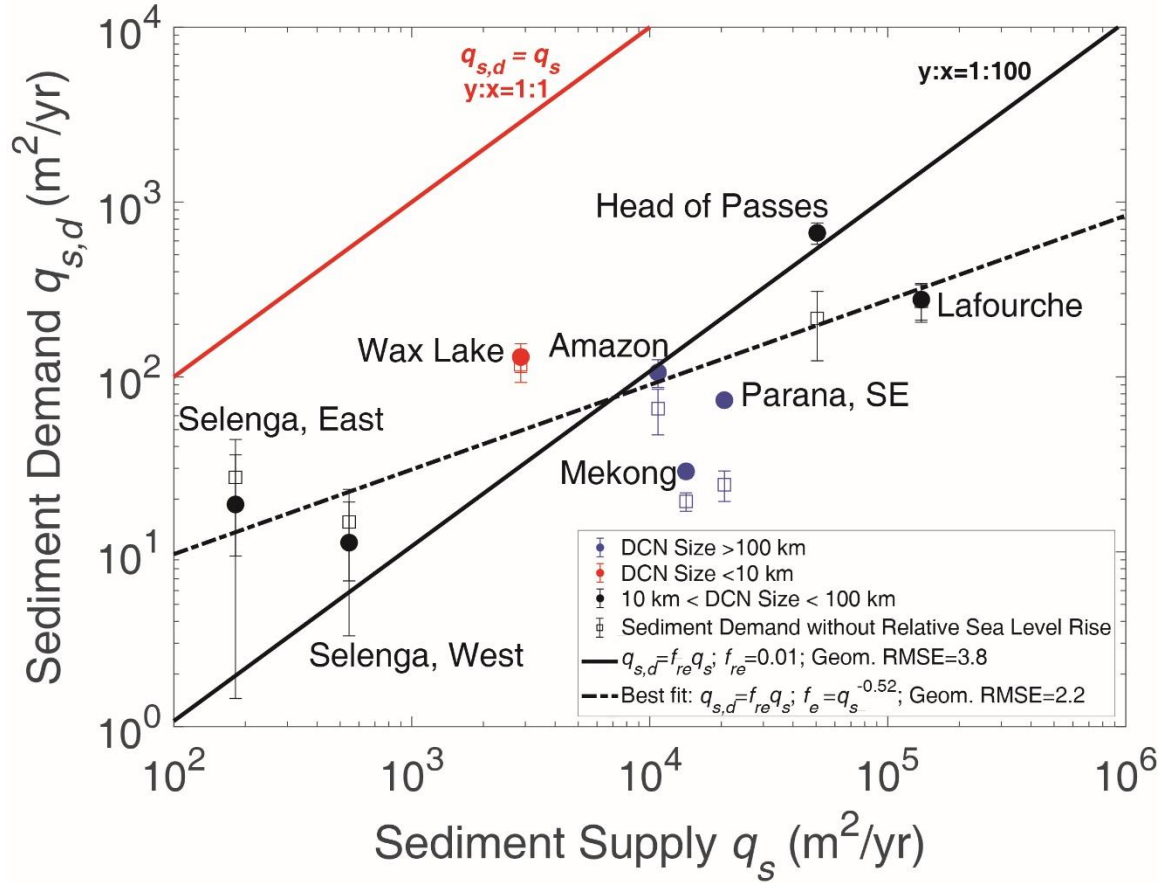
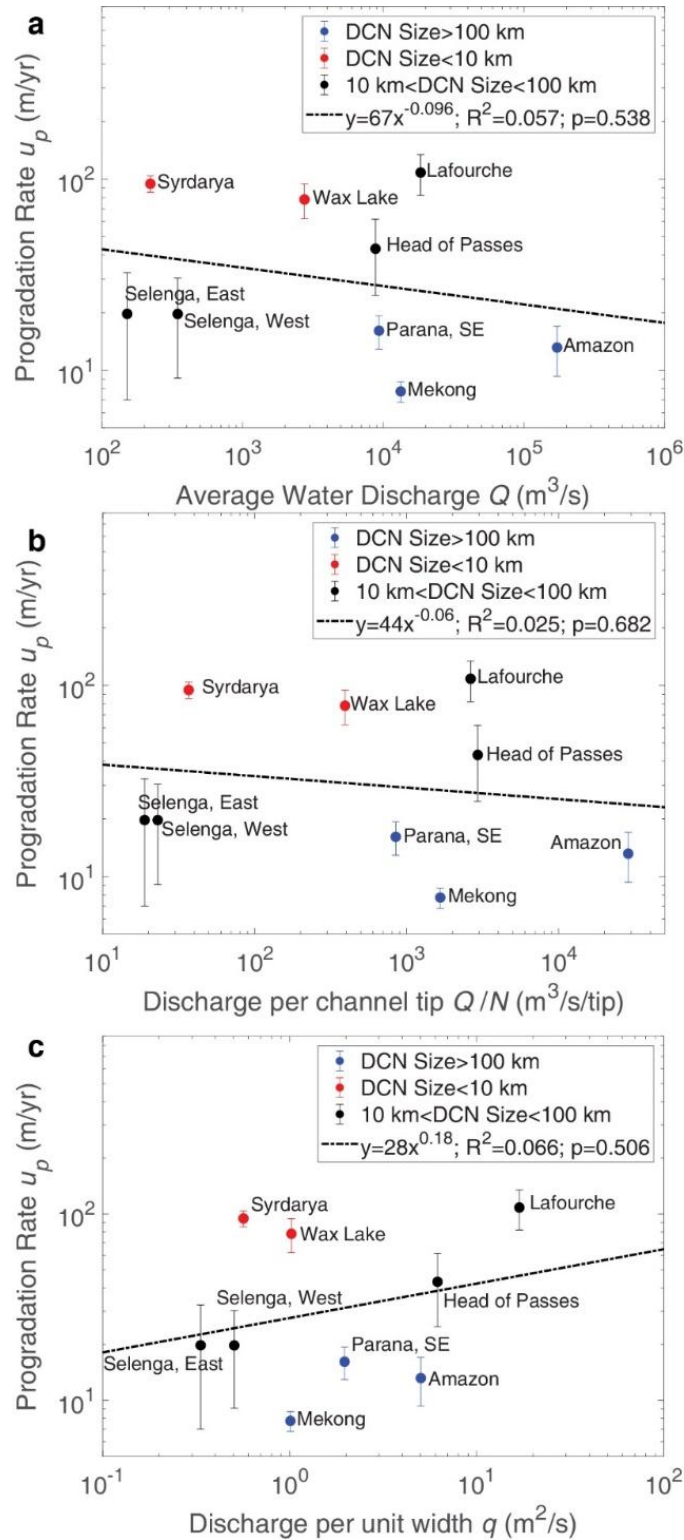


Fig. 4. Sediment demand for prograding channel levees, estimated based on observed progradation rate and mass-conservation law. Sediment demand for constructing the levees of prograding channels is estimated based on the sediment mass balance (see Equation S1b in Methods). Supply and demand are expressed per unit width. The solid circles incorporate the relative sea level rise (RSLR), whereas open squares assume RSLR = 0. The red solid line denotes sediment demand equal to total supply; the black solid line denotes demand equal to 1% of supply. The best-fit relation (dash-dot line) of the sediment supply to the demand data indicates that the sediment retention ratio f_{re} decreases as sediment supply increases. Geometric Root Mean Square Error (Geom. RMSE) indicates that the deviation ratio of model predictions to data is between a factor of 2 and 4. The depositional relations show greater multiplicative scatter than the incisional relation (Geom. RMSE=1.29; Fig. 3a).



Extended Data Fig. 1. Hierarchical tests of factors in the incisional model for accurately predicting the progradation rate of distributary channel networks. **a**, Average water discharge at the delta apex (Q) shows a weak negative relationship with the progradation rate of distributary channels. **b**, Water discharge normalized by the number

of outlets (Q/N) is also weakly anticorrelated with progradation rate and does not improve the explanation. **c**, Normalizing further by channel width, to obtain discharge per unit width, $q=Q/NW$, yields a weak positive correlation that only marginally improves predictive capacity for progradation rates; however, the resulting relation underestimates the higher progradation rates of smaller deltas and overestimates the lower progradation rates of larger deltas. These relations using remotely sensed data do not adequately describe progradation rates across the full range of network sizes within a single framework.

Supplementary Information

Incision Sets the Growth Rate of Delta Channel Networks

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Supplementary Information:

Text S1

Figs. S1 to S4

Supplementary Text S1. Exhaustive subset stability and internal cross-validation analysis

The power-law regression between the product of progradation rate u_p and mouth bar height H_b ($u_p H_b$) and water discharge per unit width q or $u_p H_b = \alpha_I q^{\beta_I}$ surprisingly results in a linear relation that is dimensionally homogeneous and consequently leads to a constant dimensionless number $Pr = u_p H_b / q = u_p / (q / H_b) = u_p / U_m = (1.86 \pm 0.48) \times 10^{-6}$, i.e. the linear relation between the network growth rate and nominal mouth flow velocity, where $\alpha_I = (1.86 \pm 0.48) \times 10^{-6}$ and $\beta_I = 1.07 \pm 0.17$ (mean $\pm$ 95% confidence interval).

We conducted an exhaustive subset analysis to assess the sensitivity of the fitted coefficient and exponent to network-unit selection. From the nine network units, we enumerated all possible combinations of five units, giving $C(9,5)=126$. For each subset, we fitted the power-law relation in log space and obtained the estimated coefficient $\tilde{\alpha}_I$ and $\tilde{\beta}_I$, and their 95% confidence intervals. We also evaluated predictions for the four network units excluded from each fit.

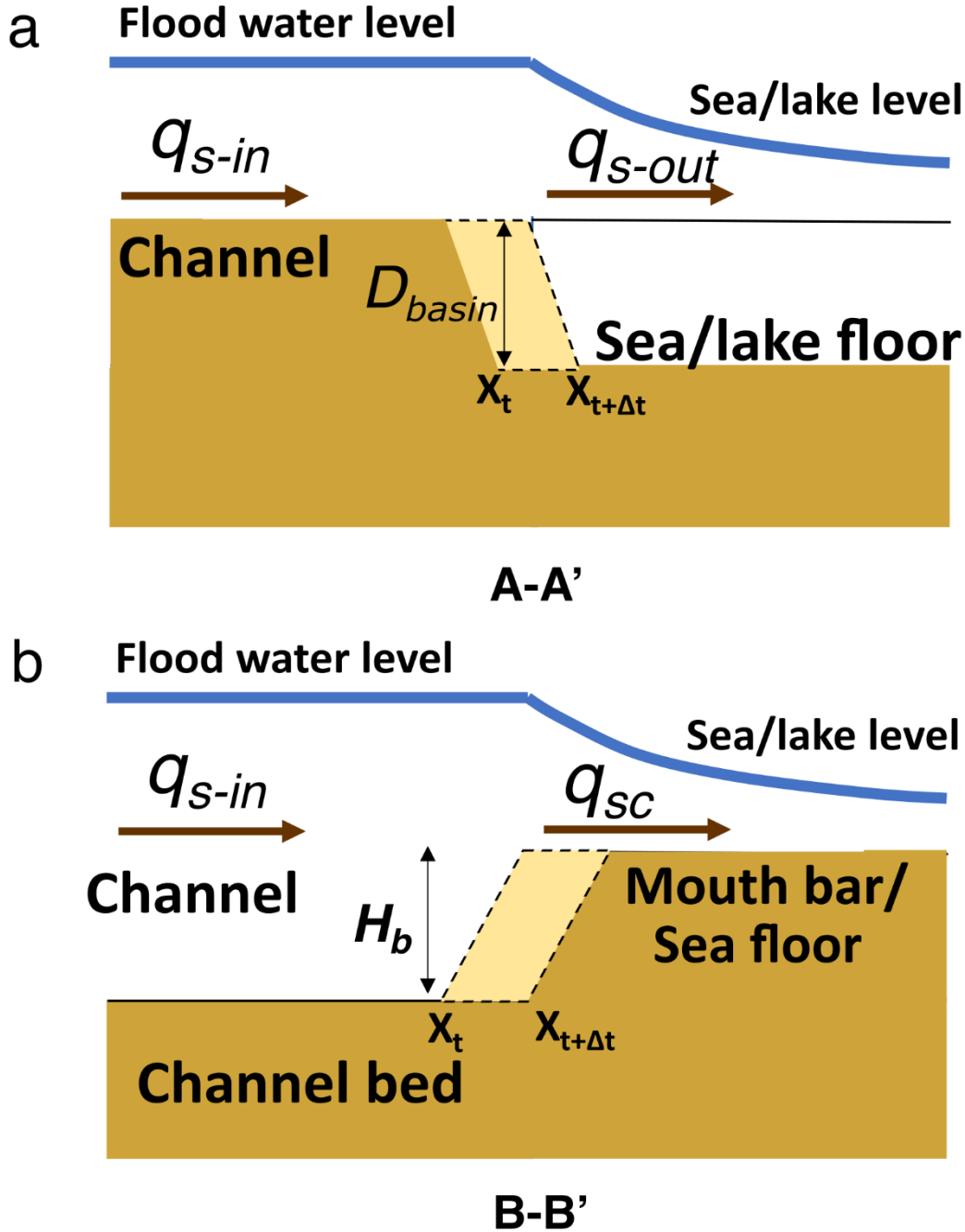
Two aspects of performance were assessed. First, we examined parameter stability using the distributions of $\tilde{\alpha}_I$ and $\tilde{\beta}_I$ across subsets (Supplementary Fig. S3a,b). We counted how often the full-dataset estimates fell outside the corresponding subset confidence intervals. These frequencies were treated as descriptive measures of subset stability. We also examined the distributions of R^2 and the regression slope-test p-value (Supplementary Fig. S3c,d).

Second, we evaluated the predictive ability of each subset relation for the four held-out network units using the discrepancy ratio (DR), defined as the ratio of the predicted value to the observed value: $DR = \text{predicted}/\text{observed}$. The 126 subsets provide 504 held-out predictions, representing repeated predictions for nine unique network units.

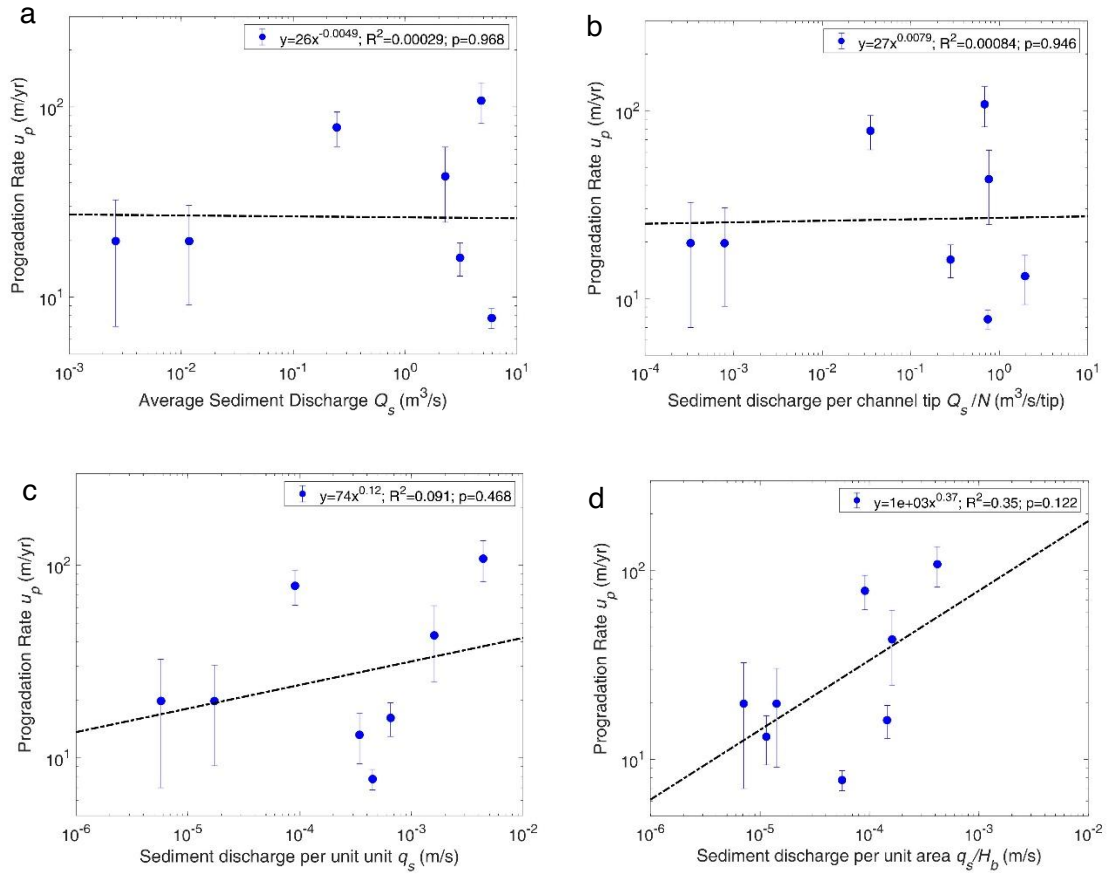
The power-law regression generally maintained strong fits despite the limited number of observations in each subset (Supplementary Fig. S3c,d). The distributions of estimated coefficients and exponents were broadly consistent with the full-dataset estimates (Supplementary Fig. S3a,b), further confirming the stability of the two values.

Among the 126 subsets, the full-dataset coefficient fell outside the corresponding subset confidence interval in four cases (3.17%), and the full-dataset exponent fell outside the corresponding interval in one case (0.79%). These exclusion proportions describe agreement with the full-dataset estimates; they are not null-hypothesis p-values.

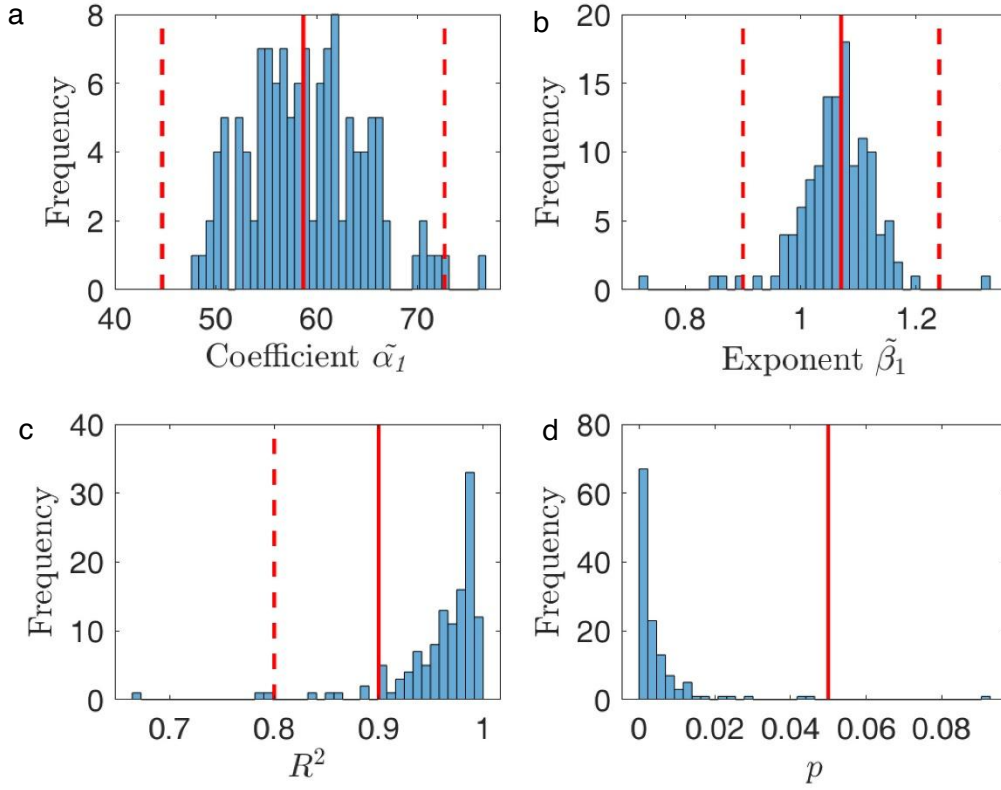
The discrepancy ratios indicate predictive consistency within the compilation. Their geometric mean was approximately 1.00, suggesting little overall multiplicative bias, and their geometric standard deviation was approximately 1.4. Approximately 69% of held-out predictions were within a factor of 1.4 of the observed values. Using the rounded values in Supplementary Table 1, 496 of the 504 predictions (98.4%) were within a factor of two of the observations (Supplementary Fig. S4). These results confirm internal cross-validations across the available network units.



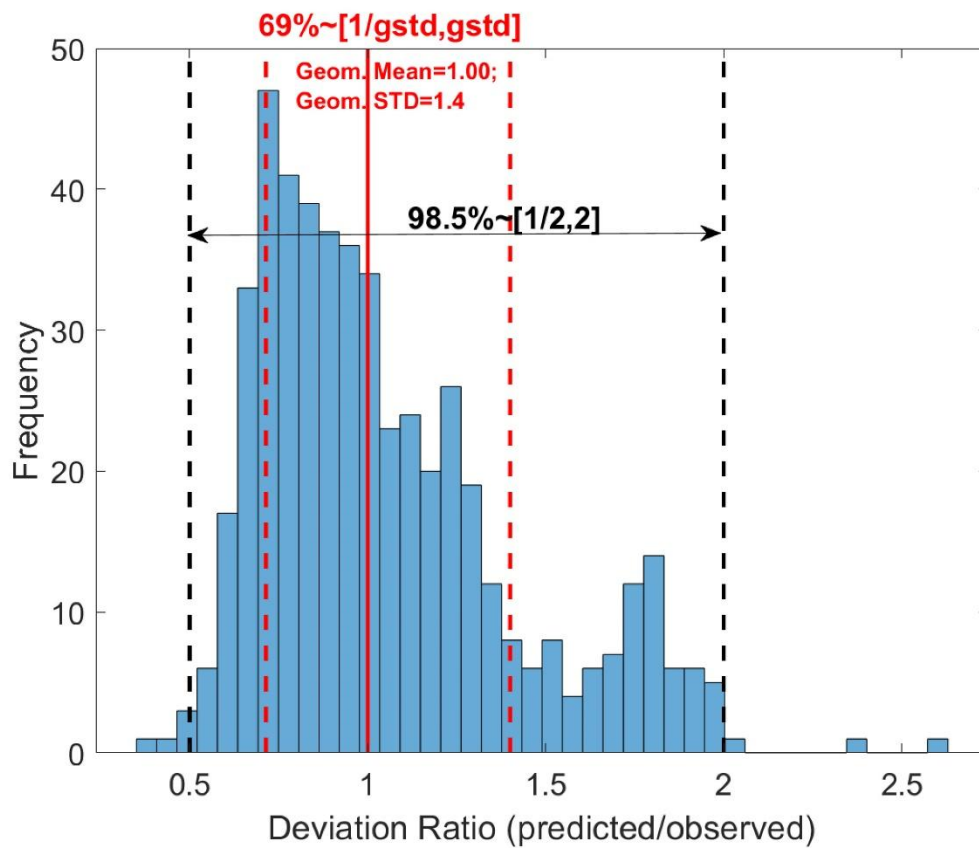
Supplementary Fig. S1. Sketch of channel progradation mechanisms. a, Gilbert-type distributary channel in a foreset-dominated delta. The channel bed is aggradational and lies above the receiving-basin floor, as in the Yellow River Delta. **b**. Distributary channel in a topset-dominated delta. The channel bed is incisional and lies below the mouth bar and adjacent seafloor. The positions x_t and $x_{t+\Delta t}$ indicate the advancing channel tip at successive times. D_{basin} denotes basin depth, corresponding to D_b in the text, and H_b denotes mouth-bar height. The labeled fluxes are incoming sediment flux q_{s-in} , outgoing sediment flux q_{s-out} , and sediment-transport capacity q_{sc} .



Supplementary Fig. S2. Relations between channel-tip progradation rate and sediment discharge. Progradation rate u_p is plotted against total sediment discharge Q_s (a), sediment discharge per channel outlet Q_s/N (b), sediment discharge per unit outlet width $q_s=Q_s/NW$ (c), and q_s/H_b (d). Sediment discharge is expressed volumetrically in these panels. All four fitted relationships have slopes that do not pass the p -test (not significantly different from zero).



Supplementary Fig. S3. Subset stability of the power-law regression. Distributions of fitted coefficients $\tilde{\alpha}_1$ (**a**), fitted exponents $\tilde{\beta}_1$ (**b**), log-space R^2 values (**c**), and regression slope-test p -values (**d**) from all 126 five-unit subsets of the nine-unit compilation. In **a** and **b**, solid red lines indicate the full-dataset estimates and dashed red lines indicate their reported confidence intervals. The reference lines in **c** mark $R^2=0.8$ and 0.9 ; the red line in **d** marks $p=0.05$.



Supplementary Fig. S4. Internal cross-validation of the subset regression relations. Distribution of discrepancy ratios, $DR = \text{predicted}/\text{observed}$, for 504 held-out predictions from the 126 five-unit subset fits. The geometric mean is approximately 1.00 and the geometric standard deviation is approximately 1.4. Red dashed lines mark $DR = 1/1.4$ and 1.4 , enclosing approximately 69% of predictions. Black dashed lines mark $DR = 0.5$ and 2 , enclosing 98.4% of predictions calculated from the rounded table. These are repeated held-out predictions for nine unique network units. Because the fitted relations used only 5 of 9 samples, their performance should be worse than that of the relation fitted to the full dataset.