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What makes a delta wave-dominated?

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ABSTRACT

River deltas, low-lying landforms that host high concentrations of human population and ecosystem services, face a new, and mostly unknown, future over the coming decades and centuries. Even as some deltas experience decreased sediment supply from damming, others will see increased sediment discharge from land-use changes. There are proposals to actively use riverine sediment supply to build new land and counteract delta loss. We present a novel approach to understanding the morphology of deltas by quantifying the balance between river inputs and the largely overlooked ability of waves to spread sediments along the coast. Defining a fluvial dominance ratio—river sediment input versus the potential maximum alongshore sediment transport away from the delta mouth—allows a quantitative assessment of this sediment transport balance. For a series of deltas on Java, Indonesia, that exhibit a large range of sediment loads but have a homogeneous drainage lithology and wave climate, and for more eclectic global examples, shoreline deflection increases along with this fluvial dominance ratio. The fluvial dominance ratio also predicts the observed transition from cuspate, wave-dominated deltas to fluvially dominated deltas with protruding, crenulated shorelines. Not only does this approach provide a more quantitative foundation for paleoenvironmental reconstructions and delta management, perhaps more importantly, this simple metric of fluvial dominance has a predictive application in determining potential morphology of deltas created by engineered sediment diversions.

INTRODUCTION

Deltas are dynamic depositional landforms, sensitive to changes in both the terrestrial and marine environments (Syvitski and Milliman, 2007; Nienhuis et al., 2013). Quantitative predictive tools for delta morphology are currently particularly relevant given that many deltas receive only a fraction of their historical fluvial sediment supply (Syvitski et al., 2009), climate change and sea-level rise will significantly modify the marine environment (Ericson et al., 2006), and new human-built deltas are proposed for coastal defense (Paola et al., 2011). Here we present a metric that estimates whether a delta would be fluvially dominated or wave-dominated for any given sediment supply and wave climate, allowing a quantitative assessment of wave influence on deltas and providing means to understand how delta morphology may respond to major environmental changes. We then test the metric on a set of small deltas on the island of Java, Indonesia, that have a homogeneous climate and similar watershed geology, as well as on other sample deltas from across the world.

BACKGROUND

In the absence of waves and tides, channel leveeing and bifurcation lead to the development of crenulated shorelines typical of fluvial dominance, with plan-view morphologies determined by sediment size (Orton and Reading, 1993; Caldwell and Edmonds, 2014) and cohesion (Edmonds and Slingerland, 2009). Wind waves discourage accumulation of fine-grained sediment at the delta mouth, and tend to sculpt delta shorelines into a cuspate shape consisting of sandy shorelines composed of shoreline-parallel beach ridges (Curray et al., 1969). Waves also affect the river mouth jet by increasing bottom friction, thereby enhancing plume spreading and limiting the growth of river mouth bars (Nardin et al., 2013). By suppressing the formation of mouth bars, waves alter delta distributary networks, and channel length statistics can be used to quantify the importance of waves (Jerolmack and Swenson, 2007). Other metrics have been developed that compare deltas in terms of the relative importance of delta-shaping processes (Wright and Coleman, 1973; Galloway, 1975; Mikhailova, 1995; Bhattacharya and Giosan, 2003). Although these previous studies provide much insight into the origin of the variability in delta morphology, they do not address mechanistic links between fluvial and marine sediment fluxes, making prediction and testing difficult.

Modeling studies (Komar, 1973; Ashton and Giosan, 2011) of wave-influenced deltas demonstrate a straightforward feedback between fluvial sediment delivery and the shoreline orientation near a delta's mouth; delivery of sediment to the nearshore zone increasingly deflects (reorients) the shoreline, and this deflection increases alongshore transport away from the mouth until a steady state is reached. This steady state develops early and is maintained as a delta grows (Ashton and Giosan, 2011). Obliquity in the wave approach generates a littoral transport difference between the updrift and downdrift delta flanks and can result in asymmetrical delta development with the potential for the formation of barrier islands, spits, and migrating alongshore sand waves on the downdrift flank (Bhattacharya and Giosan, 2003; Ashton and Giosan, 2011).

POTENTIAL LITTORAL TRANSPORT

As a result of the feedback between shoreline angle and alongshore sediment transport, a wave-influenced delta is at steady state when its shoreline is deflected such that there is a balance between wave-driven littoral transport away from the river mouth (Q_s) and the fluvial sediment retained nearshore (Q_r),

$$Q_r = Q_{s,r} - Q_{s,l}, \qquad (1)$$

where $Q_{s,r}$ and $Q_{s,l}$ are the littoral sediment flux directed to the right and left, respectively, of the river mouth (in kg s^{-1}; positive moving right looking offshore; Fig. 1A). As waves transport fine-grained river-borne sediments offshore and away from the littoral zone, muddy sediments are generally deposited as deltaic foresets below the shoreface toe. We therefore make the primary assumption that fine-grained sediments do not significantly affect the mass balance of the delta mouth (Geleynse et al., 2011). The littoral-grade fluvial flux that is retained nearshore is then roughly proportional to the sand fraction. We also assume that both the river channel and the wave-dominated shoreface prograde on top of a prodelta platform, and therefore the infilling depths for the fluvial and littoral systems are approximately equivalent.

Alongshore sediment transport is maximized when waves in deep water (at the toe of the shoreface) approach the shoreline at ~45° (Fig. 1C) (Ashton and Murray, 2006). Conceptually, there are two expectations for the interplay between fluvial sediment delivery and shoreline evolution as a consequence of this maximum in alongshore sediment transport. First, the tendency for fluvial input to deflect the coast as a delta grows is counteracted by waves, which tend to flatten the delta shoreline protrusion by moving sediment alongshore away from the river mouth. This phenomenon can be understood by considering an example of a delta exposed to waves approaching only head-on (i.e., crests and coast parallel). In this case, there is no net alongshore sediment transport until the shoreline is

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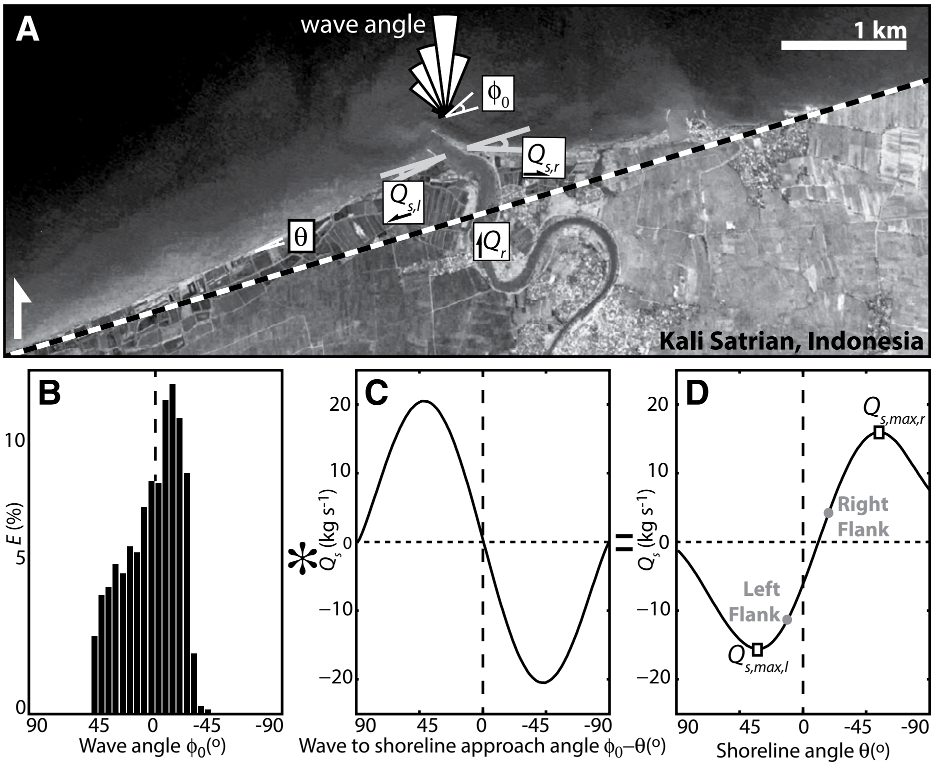

Figure 1. A: Shoreline deflection by fluvial sediment input for the Kali Satrian delta in Indonesia. Example method of calculating maximum possible littoral transport, $Q_{s,max}$ (see the Data Repository [see footnote 1] for methods) by convolving the probability distribution of wave energy, E (~$H_0^{12/5}$) (B) with the littoral transport as a function of wave approach angle (C). This yields the littoral transport Q_s as function of the shoreline orientation θ in the current wave climate (D), demonstrating that the observed delta configuration has orientations such that Q_s is below $Q_{s,max}$ (square symbols in D). The dashed black line in A is the reference shoreline (θ = 0°) from which flank angle is measured.

deflected at the river mouth as the delta starts to prograde. Deflection of the shoreline increases sediment transport away from the mouth, and, if the fluvial sediment supply is less than the maximum potential littoral transport, the angle of shoreline deflection at the river mouth rapidly comes into steady state with the rate of fluvial input (Ashton and Giosan, 2011). Second, if fluvial sediment delivery is significantly large, there is no shoreline orientation that can transfer sediment away from the river mouth.

Thus, we hypothesize that a delta will be river-dominated when the fluvial sand flux (Q_r) is larger than the combined maximum possible littoral transport to the left and right of the river mouth ($Q_{s,max}$). This balance can be expressed nondimensionally as R, the fluvial dominance ratio:

$$R = \frac{Q_r}{Q_{s,max}}. \tag{2}$$

This fluvial dominance ratio yields two scenarios for both characteristic delta growth and plan-view morphology for a single distributary channel. In the case of $R < 1$, a configuration of shoreline angles exists that is capable of removing sediment alongshore as rapidly as it is delivered by the fluvial source. This leads to a cuspate delta with shoreline angles that are generally less than the maximizing angle (Fig. 1D). If $R > 1$, there is no deltaic shoreline angle that would be able to transport the provided fluvial sediment; the delta is fluvially dominated.

Equation 2 suggests a linear relationship between the retained fluvial flux Q_r and the fluvial dominance R: a doubling in fluvial sediment results in a doubling of the fluvial influence on the delta. The dependence of the wave climate on the fluvial dominance is more complicated. A spread in the wave approach reduces the ability for waves to diffuse the shoreline (Ashton and Giosan, 2011). Increased wave spread also changes the shoreline angle at which the transport maximum occurs (θ_{max}), such that deltas with a wide spread of wave approach angles will be more pointy for similar values of R (Fig. DR1 in the GSA Data Repository[1]).

Asymmetry in the wave climate marginally affects the maximum for Q_s, but displaces θ_{max} for both the left and right flank of the delta (Fig. DR1). As R approaches 1, asymmetry in delta morphology can develop (Bhattacharya and Giosan, 2003; Ashton and Giosan, 2011). The maximizing angle will be reached more easily along the downdrift coast; if this maximum is surpassed on one side, subsequent feedbacks will tend to trap more sediment on the updrift coast and drive that coast to larger angles that approach the transport-maximizing angle (Ashton and Giosan, 2011). A delta exposed to an asymmetric wave climate will therefore also be river-dominated once Q_r exceeds the sum of the left and right littoral transport maxima directed away from the river mouth (Fig. DR1).

APPLICATION

We tested the application of the fluvial dominance ratio on 25 deltas on the north shore of Java, Indonesia (Fig. 2; Table DR1). Sedimentation on this shallow continental shelf generates a wide variety of delta morphologies, transitioning from cuspate wave-dominated deltas to fluvially dominated morphologies. The mountainous rivers on Java have some of the world's highest sediment yields (Milliman and Meade, 1983), enabling delta growth from small drainage basins. These deltas have similar wave climates, so the spectrum of delta forms appears to be related to large differences in the size of the drainage basins (Fig. DR2), particularly as minimal variation in lithology reduces the potential variability in terrestrial sediment characteristics such as type, size, and sorting, which can affect alongshore sediment transport rates (Komar, 1998). In addition, the Java Sea is microtidal (Ray et al., 2005), enabling us to focus on the interaction of waves and fluvial processes alone; as such, the northern Java coast presents an ideal test bed for studying the effects of sediment flux variation on wave-influenced delta morphology.

Using the BQART function (Syvitski and Milliman, 2007) (see the Data Repository for methods) to estimate the fluvial yield, we find that the angles of deltaic shoreline deflection increase as the computed sediment flux increases for these 25 deltas (Fig. 2A). The river-dominated deltas all have relatively large drainage basins and correspondingly large computed fluvial sediment flux. Using the CERC formula (Komar 1998; see the Data Repository) convoluted with directional wave climate data (Fig. 1), we determine the maximum potential littoral transport away from each delta. The fluvial dominance ratio R spans a significant range, from 0.05 for cuspate cases to >4 for river-dominated deltas (Fig. 2B). At approximately R = 1, there is a transition from single-channel deltas having smooth sandy coasts to multichannel deltas with more protruding, crenulated shorelines. Cuspate deltas typically have shoreline angles below the angle of maximum transport ($|\theta| < \theta_{max}$; black symbols in Fig. 2B).

[1]GSA Data Repository item 2015183, fluvial sediment flux and alongshore sediment transport calculation methods, wave climate distribution effects on alongshore sediment transport, and an overview figure and table of the selected deltas, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

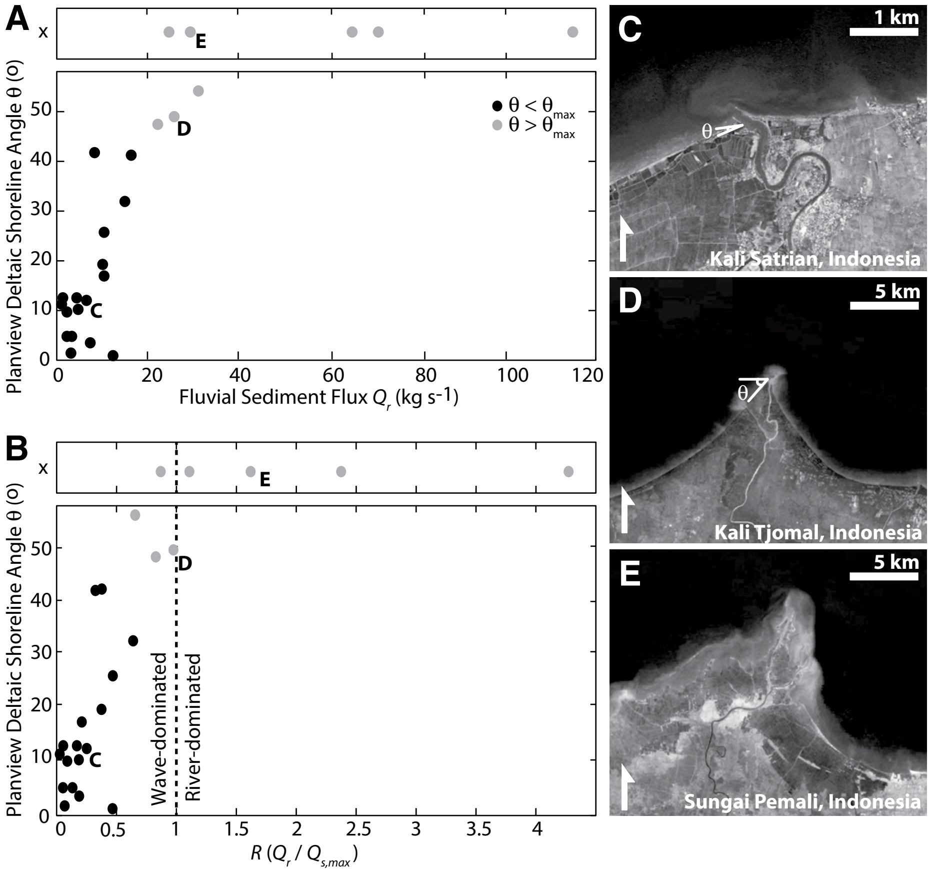

Figure 2. A: Average plan-view deltaic shoreline angle versus fluvial sediment flux (Q_r). B: Versus fluvial dominance ratio *R*. Note that river-dominated deltas do not generally have smooth shoreline orientations and are therefore plotted independently (denoted with an x). Deltas with gray symbols have shoreline angles >θ_{max}. C–E: Examples corresponding to the letters plotted in A and B. The angle definition in C and D shows the plan-view deltaic shoreline angle θ. River-dominated deltas (E) have no characteristic shoreline angle. Note that a diversion on the Sungai Pemali in 2005 created a new river-dominated delta lobe close to the original delta lobe.

We also compute the fluvial dominance ratio R for several well-documented deltas: the Senegal ($R \approx 0.04$), the Sao Francisco (Brazil, $R \approx 0.3$), the Tinajones lobe of the Sinu (Colombia, $R \approx 2$), and the Belize lobe of the Mississippi (United States, $R \approx 7$) (Fig. 3). Deltas with larger R increasingly protrude from the coast, transitioning toward river dominance for $R > 1$.

Interestingly, the Tinajones delta, with clearly defined beach ridges and a smooth shoreline indicative of wave dominance, has an estimated $R \cong 2$, which suggests fluvial dominance. Aerial photographs show that between A.D. 1938 and 1945, when this historic delta was formed by an avulsion (Suarez, 2004), the single-thread channel (which carried the entire fluvial flux) was river-dominated and prone to mouth bar formation. After two bifurcations leading to three simultaneously active channels, fluvial sediment delivery to each channel accordingly reduced to approximately one-third of the original Q_r. However, the littoral drift potential remains the same at every river mouth. This example suggests that, through bifurcation, a marginally river-dominated delta (lobe) could transition into wave dominance (e.g., the modern Chilia lobe of the Danube Delta, Romania; Filip and Giosan, 2014). This discharge splitting ultimately reaches a spatial limit when distributary shorelines interact with one another (Wolinsky et al., 2010).

Our approach also applies to the expected behavior of engineered river diversions, such as those suggested for the Mississippi Delta (Kim et al., 2009b). Estimates of the development of a full diversion of the Mississippi River are based on the assumption that the ensuing morphology will resemble a fan shape much like the modern Wax Lake delta (Louisiana, USA; Kim et al., 2009a). Indeed, for the modern Belize lobe of the Mississippi River, our computation of $R \approx 7$ suggests that a diversion of the full Mississippi would likely take a fluvially dominated form; however, this fluvial dominance is not necessarily an indication of a weak wave climate, but rather that the Mississippi River drains a large continental area and has a correspondingly large sediment discharge.

Wave reworking of abandoned lobes of the Mississippi has resulted in the formation of barrier islands such as Grand Isle and the Chandeleur Islands. Breton Sound and Barataria Bay, two sites of proposed diversion (Kim et al., 2009b), are protected from waves by these barrier islands. A diversion of 25% of the current Mississippi River flux (Kim et al., 2009b) would be fluvially dominated. However, as sea-level rise continues to threaten the existence of barrier islands (Lorenzo-Trueba and Ashton, 2014), these sites might in the future become increasingly exposed to waves. The Brazos River delta (Texas), diverted in 1929, is an example where exposure to waves led to the growth of wave-sculpted shorelines (Rodriguez et al., 2000). The differences in morphologic expression for wave-dominated and fluvially dominated deltas have significant implications for the growth, ecological development, and the potential influ-

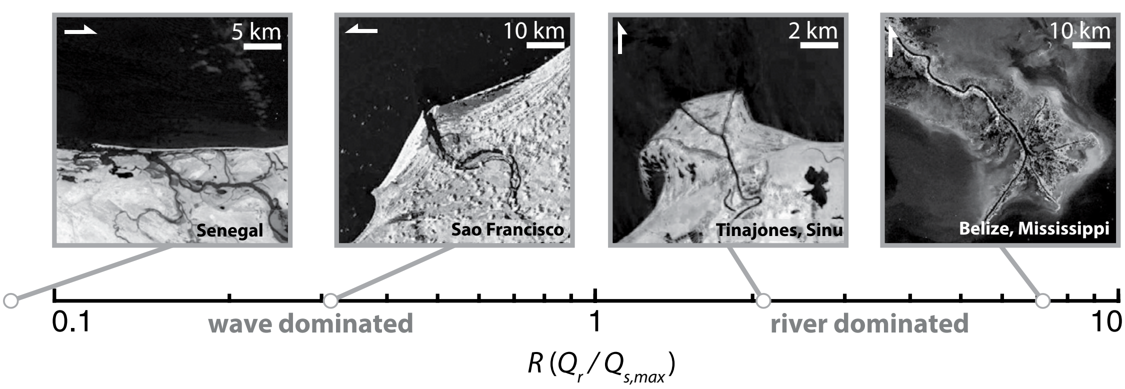

Figure 3. The fluvial dominance ratio *R* for sample world deltas (see text). Images from Google Earth™ and NASA. Values used are in Table DR3 (see footnote 1).

ence of vegetation on deposition for an engineered river diversion.

DISCUSSION AND CONCLUSIONS

The ratio of fluvial sediment flux to the alongshore transport maximum (R) predicts delta morphology in steady state. However, R is dependent on fluvial and wave characteristics, which have substantial temporal variability. Because time scales of delta distributary formation are O (50 yr) (Jerolmack and Swenson, 2007), we average across seasonal and interannual fluctuations. However, over longer time scales, discharge variation and avulsions can reduce sediment load and substantially alter delta morphology (Nienhuis et al., 2013).

Even as R represents a straightforward metric, note that its computation can be rather inexact, given the imprecise nature of sediment transport formulations. Calculation of fluvial sediment delivery is always an estimate; in our case, for the deltas on Java, computed fluxes are uncalibrated, and we use a best estimate for the sand fraction. Furthermore, the CERC coefficient for littoral sediment transport can vary widely (Komar, 1998). However, even given the inexact nature in its estimation, the orders of magnitude variability we see in the fluvial dominance ratio suggests that R can serve as a diagnostic tool.

The fluvial dominance metric proposed here can determine the steady state of growing deltas and aid in the future management of existing deltas and proposed sediment diversions. Using a process-based metric allows us to quantitatively relate deltaic morphology to shaping processes in the modern and the ancient, thus serving as a paleoenvironmental indicator. For example, we envision analyzing relict beach ridges and using modern or modeled wave data to calculate paleofluvial sediment fluxes, and vice versa. In consideration of the many threats to deltas in the coming centuries, our results suggest that deltas with highly deflected shorelines close to the transition between fluvial- and wave-dominated morphologies are particularly sensitive to variations in environmental driving conditions.

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