ABSTRACT: We investigate the asymmetrical development of deltas in terms of a high-angle-wave instability in the shape of a shoreline due to breaking-wave driven alongshore sediment transport. Demonstrating the strong wave-angle dependence of shoreline evolution, numerical modeling suggests that the characteristics of the wave climate can play an integral role in the morphological evolution of wave-influenced deltas. Systematic analysis demonstrates that delta development style, including asymmetrical evolution, depends on wave climate characteristics and the relative rate of sediment input. Although the ‘river delta asymmetry index’ presented by Bhattacharya and Giosan (2003) can predict asymmetrical behavior in natural cases, the simulated asymmetric development is poorly explained by this index, probably because the simplified modeling approach does not adequately resolve river mouth dynamics. However, the simulation results suggest that wave-angle distributions can constitute a first-order control on the plan-form expression of wave-influenced deltas.

1 INTRODUCTION

Deltas form where rivers deliver their sediment to open water; the competition between sediment delivery by the river and marine forces that rework this sediment determines the morphology of deltas. While many studies have explored how the balance of these forces affects the cross-shore evolution of deltas (e.g. Swenson et al 2005), there have been relatively few quantitative investigations of the plan-view evolution of deltas. Here, we apply numerical modeling and a new understanding of shoreline evolution due to alongshore sediment transport to study the plan-view evolution of deltas that are strongly influenced by alongshore sediment transport. When there is a regional net direction of alongshore sediment transport, this often leads to an asymmetrical development of a delta, where depositional styles differ on either side of a river mouth (Bhattacharya & Giosan 2003). Although the relative rates of sediment delivery to the coast versus alongshore sediment fluxes help determine the context for a delta’s form, the results presented here suggest that the wave-angle distribution can play a first-order role in the plan-view morphology and asymmetrical development of wave-influenced deltas.

2 ASYMMETRICAL WAVE-INFLUENCED DELTAS

Classically, the plan-view expression of deltas has been understood via a tripartite model, whereby the relative strength of river, waves, and tides determines delta morphology (Galloway 1975). In this paper, we focus our attention on ‘wave-influenced’ deltas, where tidal forces are relatively weak and wave reworking of sediments at the coast controls the morphological evolution of the deltaic coast, as opposed to the ‘wave-dominated’ distinction meaning the delta does not protrude seawards. For example, Wright and Coleman (1973) investigated the transition from river-dominance to wave-dominance in terms of a balance between river forces and wave forces. In their classification, the Danube Delta would not be considered ‘wave-dominated’. However, the St. George and Sulina lobes of the Danube delta exhibit a multitude of features, such as beach ridges and spits, indicating that wave reworking controls sediment movement at the shoreline (Giosan 1998, Giosan et al. 2005). Accordingly, we would consider these lobes of the Danube delta ‘wave-influenced’.

Bhattacharya & Giosan (2003) presented new conceptual models of the asymmetric evolution of
wave-influenced deltas, introducing a ‘river delta asymmetry index’, $A_{BG}$ (subscript added here for clarification purposes), the ratio between net alongshore transport at the river mouth ($m^3/yr$) and river discharge ($Q_m$, $10^6 m^3/month$). For a series of natural examples, this index performs well, asymmetrical delta development appears to require $A_{BG} > \sim200$. However, this index does not appear to be able to distinguish between all observed behaviors; for instance it is unable to discern between ‘asymmetric’ and ‘deflected’ cases presented by the authors.

Numerical investigations by Ashton & Murray (2005) suggest instabilities associated with alongshore sediment transport could also play a significant role in the asymmetrical development of wave-influenced deltas. Building upon recent understanding of a fundamental instability in shoreline shape when waves approach with particularly oblique (‘high’) angles ($\sim43^\circ$ in deep water) (Ashton et al. 2001), numerical simulations reproduce a range of delta morphologies as the characteristics of the wave-angle climate are varied. In this case, asymmetric behavior develops on the downdrift side of the river mouth as this portion of the delta coast becomes dominated by high-angle waves after the delta lobe’s aspect ratio (regionally cross-shore extension versus alongshore width) increases. As a result, simulations show migrating fields of shoreline undulations (or ‘alongshore sandwaves’) and spits that extend downdrift of the river mouth.

Because these simulations neglect complex rivermouth dynamics, the striking asymmetrical behaviors arise only from presence of the instability in shoreline shape. Below, we take a more systematic approach to compare and contrast the asymmetrical behavior expressed in the quantitative model with that presented by Bhattacharya & Giosan’s (2003) field-based model of asymmetrical model development.

3 NUMERICAL MODELING

Delta evolution is simulated using a numerical model which evolves the shoreline based upon gradients in alongshore sediment fluxes. This ‘one-contour-line’ approach assumes that the sandy shoreface sediment remains within the shoreface, and that cross-shore fluxes of sand beyond the shoreface depth, $D$, can be considered negligible compared to gradients in alongshore flux in the evolution of the coastline. The numerical model, summarized below, is described in greater detail by Ashton and Murray (2006a). The model discretizes equations for alongshore sediment flux and cross-shore sediment conservation similar to other one-contour-line models (e.g. Hanson & Kraus, 1989), with the unique ability to simulate a coast of arbitrary sinuosity and numerically accommodate unstable high-angle waves.

Within the model, the plan-view domain is discretized into cells filled with a fractional quantity of sediment, $F$, representing the plan-view excursion of the shore in each cell (Figure 1). Cells with $F = 0$ represent the open ocean, and cells with $F = 1$ are fully subaerial; the line of cells between the ocean and land with $0 < F < 1$ represents the shoreline. Deep-water waves with given height, $H$ (m), and period, $T$ (s), and approaching angle, $\phi_0$ (angle of wave crest) are refracted onshore using assumed shore-parallel contours until the waves break due to depth limitation. The CERC equation determines alongshore sediment fluxes ($Q_s$, $m^3/s$) between adjacent cells:

$$Q_s = KH_b^{5/2} \cos(\phi_b - \theta) \sin(\phi_b - \theta),$$

where $H_b$ is the breaking wave height (m), $\phi_b$ is the orientation of the breaking wave crests, $\theta$ is the shoreline orientation, and $K$ is an empirical constant dependent on sediment characteristics (typically $\sim0.4 m^{1/2}/s$ for quartz density sand with a porosity of 0.6, although this value can vary greatly in nature) (Komar 1998, Rosati et al, 2002). The model has constant-flux boundary conditions, and allows large promontories to ‘shadow’ other regions of the coast from oblique waves (Figure 1). An additional process of barrier overwash maintains a minimum barrier width (Ashton & Murray 2006a). Shoreface depth is held at 10 m in all simulations.
Every simulated day, the deep-water angle of approaching waves, \( \phi_{\text{w}} \), changes and can be any angle between 0° and 90°; this represents one of the main distinctions between this model and traditional one-contour-line approaches. Wave-approach angles are selected randomly from a probability distribution function defined by two variables, \( U \), the fraction of high-angle waves, and \( A_w \), the wave climate ‘asymmetry’ representing the fraction of waves approaching from the left, looking offshore. When \( A_w = 0 \), all waves approach from the left, when \( A_w = 0.5 \), waves approach equally from both directions. In all simulations, \( U < 0.5 \), representing a low-angle dominated climate; these simulations study the effect of active deposition at the shoreline, not the large-scale self-organization of the coast predicted when \( U > 0.5 \). Because an increased proportion of low-angle waves increases the effective ‘diffusivity’ of shoreline evolution (Ashton & Murray 2006a,b), increases in \( U \) represent a reduction in the effective shoreline diffusivity, reducing the ability for waves to flatten a bump in the coast.

To simulate deltas, we represent the effects of riverine deposition in an extremely simplified manner. At a fixed point in the alongshore direction, an equal quantity of sediment, determined from the rate of sediment influx (\( Q_b \), Mt/yr), is added each time step. \( Q_b \) represents the rate of delivery of riverine bedload sediment, assuming that the finer-grained fraction typically held in suspension (mud) either bypasses the shoreface as it is advected by the river plume or is winnowed from the shoreface by wave action, eventually moving offshore.

The simplified approach here remains in keeping with our goal of simplifying the model dynamics to a point that the simulated behavior can be well-understood (e.g. Murray 2002). Simulations are run for a set of representative input variables, and are not calibrated to reproduce any one particular deltaic environment. As with a physical experiment, results could be rigorously scaled for direct comparison to a natural setting.

The ability to apply this model at deltas implicitly relies on several other assumptions. At natural deltas, deposition at the river mouth is typically complex, with other factors such as river avulsion, river mouth processes, multiple lobe interactions, and the seasonality of wave and river inputs playing important roles in the morphologic evolution (Wright & Coleman 1973, Giosan et al. 2005). Offshore deposition of fine-grained sediment must be sufficient to provide a platform over which the delta shoreface can prograde. However, if this deposition were too great, the prodelta could play a significant role in frictional wave attenuation, such as at the Mississippi River (Wright and Coleman 1973). If wave attenuation becomes dominant, the delta can no longer be considered wave-influenced, the model assumes prodelta deposition is neither too fast nor too slow.

4 RESULTS

As reported by Ashton & Murray (2005), the form of delta evolution changes as the inputs are varied. By systematically investigating the space occupied by the parameters \( A_w \), \( U \), and \( Q_b \), we identified five ‘prototype’ forms of the simulated deltas (Figure 2,3) as the inputs are varied (Figure 4). Many natural deltas exhibit similar behaviors to the prototypes (Ashton & Murray 2005).

4.1 Prototype deltas

In the model’s most expected behavior, the delta steadily progrades symmetrically about the river mouth, exhibiting a classic cuspate shape (Figure 2a). Similar behavior was modeled by Komar (1973), using waves approaching from one shore-normal (or one slightly oblique) wave approach angle. This behavior has long been the paradigm for delta evolution under the influence of waves. Although symmetrical wave climates favor this behavior, if sediment delivery rates are low, this classic depositional style can arise even with a distinct asymmetry to the wave climate (Figure 4).

For generally symmetric wave climates, a higher rate of sediment input or an increased presence of high-angle waves (larger \( U \)) can result in more complex behavior where spits extend offshore of the coast near the river mouth in both directions, resulting in a discontinuous shore (Figure 2b). Increasingly complex interactions emerge as new spits are formed near the mouth and move downdrift towards the flanks, affecting previously created spits.

When sediment delivery is relatively high and with a pronounced asymmetry to the wave climate (\( A_w \approx 0.6 \)), the dominance of high-angle waves is favored on the downdrift flank of the delta (Ashton and Murray 2005). As a result, high-wave-angle features such as migrating sandwaves and eventually offshore-extending spits begin to form along the downdrift coast (Figure 3a). Delta progradation increases the plan-view aspect ratio of the lobe, favoring the formation of spits, increasing the complexity of the downdrift coast over time.

For simulations with sediment fluxes between the extremes of the asymmetrical-spit delta and classic cuspate delta, an interesting behavior emerges. The delta develops a significant ‘bend’ in the downdrift
coast, yet offshore-extending spits do not form (Figure 3b). This region may experience transient alongshore pulses of sediment in the form of alongshore sandwaves, but generally the delta grows maintaining this geometry. This behavior appears for a significant number of parameter combinations (Figure 4), so we do not consider it merely a continuous form between the Komar and spit-dominated morphologies.

The final type of behavior represents a far less realistic manifestation of the numerical model. Deposition at the ‘river’ far outpaces the ability for along-
shore sediment transport to spread this sediment alongshore, forming a ‘tree’ shape (Figure 2c). In a natural delta, this rapid offshore extension would likely result in river avulsion towards the sides of the ‘delta’ or the development of many distributaries. The modeled behavior certainly does not resemble that of natural deltas, and we interpret these simulation results as an indication that the delta should be considered ‘river-dominated’. Although waves could affect evolution of a delta with these input variables, it likely would display morphologies and behaviors reflecting river domination (Galloway 1975). Therefore, these simulations do provide some insight as they help suggest a quantitative upper threshold on relative sediment input rates for wave-influenced deltas.

4.2 Parameter space dependence

The wave climate parameters and sediment influx determine the basic model behavior (Figure 4). Although most of the simulations are run with the same offshore wave height and period ($H = 1$ m and $T = 6$ s, respectively), simulations were run with different values to determine if modeled behavior were dependent on the particular input variables. To plot these different simulations in the same parameter space, we normalized the riverine sediment flux ($R$) by a maximum alongshore sediment flux. Because simulations use a full ‘climate’ of wave-approach directions, and not waves approaching from only one direction, determining this maximum flux is not straightforward. We computed the ‘maximum alongshore sediment flux’ using (1) and assuming a wave climate with $A_w = 1$ (fully asymmetric climate). Although variations in $U$ only have a slight effect on alongshore fluxes, simple computations reveal that alongshore fluxes are also maximized when $U = 1$.

$R$, the normalized riverine sediment flux, provides a rough, yet straightforward estimate of the river influx versus the capability of waves through alongshore sediment transport to remove this sediment from the river mouth. As opposed to other approaches comparing variables such as the relative ‘power’ of waves versus the river (Wright & Coleman 1973), we believe that the focusing on the fluxes allows a direct comparison of the influence of the processes.
Simulation results collected for a range of $R$ are plotted together (Figure 4). In general, the ‘classic’ behavior is favored for small river inputs (small $R$), when waves are more low-angle (small $U$), and when wave climates are symmetric ($A_w \sim 0.5$). Increasing asymmetry and the proportion of high-angle waves ($U$) tends to favor complex behaviors. Model results suggest that river dominance becomes the norm after $R > 2.5$, a sensible result as the ability for alongshore sediment transport to remove sediment should begin to be limited beyond $R \sim 2$ (with sediment moved away from the river mouth in both directions).

4.3 Comparisons with delta asymmetry index

To compare the model results with the asymmetrical deltaic behavior described by Bhattacharya & Giovan (2003), the input variables need to be placed in terms of $A_{BG}$, which is computed in terms of a riverine water flux divided by a mass flux for alongshore sediment transport. To do so, the bedload river flux in the model needs to be converted to an average monthly water discharge ($Q_m$).

Although several rating relationships for suspended sediment transport have been presented (e.g. Syvitski et al, 2000), few relationships relate bedload and discharge. Using values from Syvitski & Saito (in press), a reasonable linear relationship exists between discharge and bedload transport for wave-influenced deltas (Figure 5a). Note that the values presented by Syvitski and Saito (in press) do not represent measurements; rather, they are computed values, essentially a function of water discharge and the delta gradient. Essentially, the linear trend in Figure 4a reflects that these river-influenced deltas have similar gradients. This linear relationship between bedload flux and water discharge is not apparent when all deltas are considered (Figure 5b), suggesting that there is some significance to the linear relationship found for wave-influenced deltas.

Using this linear relationship and the known alongshore sediment fluxes, $A_{BG}$ can be computed for the simulations (Figure 6). The first interesting result is that despite the abstract, theoretical nature of the model and the crudeness of the relationship derived between discharge and bedload flux, the values for $A_{BG}$ in the model (up to $\sim 450$) fall within the same range as those reported for nature (up to $\sim 350$). Although the appearance of downdrift spits requires some degree of asymmetry, the variable $A_{BG}$ appears to have little ability to predict asymmetrical model behaviors.

5 DISCUSSION

Although it was unable to predict the modeled asymmetric behavior, $A_{BG}$ should not be dismissed, particularly as it performs well for natural examples. Rather, the results from Figure 6 suggest that some
of the modeled behavior arises for reasons unexplained by this simple metric. The model is limited at the river mouth as it does not resolve processes that occur there that play vital roles in the asymmetrical behaviors described by Bhattacharya & Giosan (2003) and Giosan et al. (2005), including wave/river plume interactions and complex morphodynamic feedbacks that allow for the storage on the subaqueous delta. Furthermore, as the simulations assume a fixed river location, they could not generate ‘deflected’ river mouths seen in nature. They also assume that the river does not impede sediment from bypassing the mouth. Although seasonal and longer-term fluctuations in driving forces have been shown to affect the morphodynamic evolution of natural deltas (e.g. Fraticelli 2006, Giosan et al. 2005), the model also assumes constant sediment inputs and regular, uncorrelated inputs of wave energy. Future research will aim to better resolve and represent river mouth processes and episodicity in driving forces.

6 CONCLUSIONS

One-contour-line simulations of wave-influenced delta evolution demonstrate a range of symmetric and asymmetric behaviors, determined by the characteristics of the wave climate and the relative sediment influx. The details of the wave climate distribution can play a first-order control on delta evolution, showing that the influence of waves cannot be adequately represented by the average ‘wave energy’. The simulated asymmetrical behavior does not arise from river mouth processes, these river mouth processes can result in asymmetrical development of natural deltas. However, as the asymmetrical behavior from both the wave-climate and river mouth processes occur when waves approach obliquely, driving strong alongshore sediment transport, it may be likely that both types of asymmetrical behavior could occur concurrently.

REFERENCES


