BREAKING-WAVE-DRIVEN SEDIMENT BYPASSING OF RIVER MOUTHS: MECHANISMS AND EFFECTS ON DELTA EVOLUTION

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Abstract: River mouths along sandy coastlines are influenced by alongshore transport of littoral sands. Here we simulate river mouth morphology under oblique wave approach with the numerical model Delft3D. Specifically, we study the mechanisms of alongshore sediment bypassing at river mouths. We find that bypassing rates are strongly dependent on river discharge and wave energy. River mouths deflect in the presence of littoral sediment transport when waves refract into the jet and subaqueous shoals. This wave refraction leads to a zone of low energy and sediment transport updrift of the river mouth, decreasing its ability to bypass littoral sediment. Because of this wave-refraction effect, the fraction of alongshore sediment transport that is bypassed can be explained by the ratio of jet momentum flux versus wave momentum flux. Quantifying environmental controls on river mouth morphology and alongshore sediment bypassing rates will give insight into the potential evolution of deltaic coastlines in a changing environment.

Introduction

River mouths are dynamic, complex regions shaped to various degrees by waves, tides and fluvial processes. Along a sandy coastline, a river mouth may act as a groin and completely or partially limit the bypassing of littoral sediments (Wright 1977). Here we study the mechanisms by which littoral sediment can bypass the river mouth and how wave and river mouth dynamics affect bypassing rates. On short timescales, sediment bypassing is important for managing river mouths. On longer timescales, sediment bypassing controls the migration of river mouths (Fig. 1) and the morphology and sedimentary architecture of deltaic systems (Bhattacharya and Giosan 2003; Giosan 2007). Modeling the effect of waves and river mouth jet properties on alongshore sediment bypassing rates allows us to explore the origins of delta asymmetry and channel orientation and offers insights into the spatial distribution of fluvial versus littoral sediment deposition.

Alongshore sediment bypassing is reflected in the morphology of river mouths (Fig. 1). We define the extent of alongshore sediment bypassing as the fraction (β) of updrift littoral sediment transport that is transported downdrift across the river mouth. In the absence of fluvial sediment supply, the channel is deflected

(Fig. 1b) when sediment transport bypassing the river mouth ($\beta \cdot Q_s$) is less than the net alongshore sediment transport rate delivered to the river mouth (Q_s). Like tidal inlets (see Fitzgerald 1982), this bypassing fraction may fluctuate over time, and because the river mouth itself can migrate, an event like spit breaching could episodically increase bypassing. Alongshore sediment bypassing of tidal inlets has been well studied (Bruun and Gerritsen 1959, 1961; Bruun 1978; Fitzgerald 1982; Fitzgerald et al. 2000; Kraus 2002; Tung et al. 2009) and mechanisms of tidal inlet bypassing can offer insight into mechanisms that might similarly influence bypassing of river mouths.

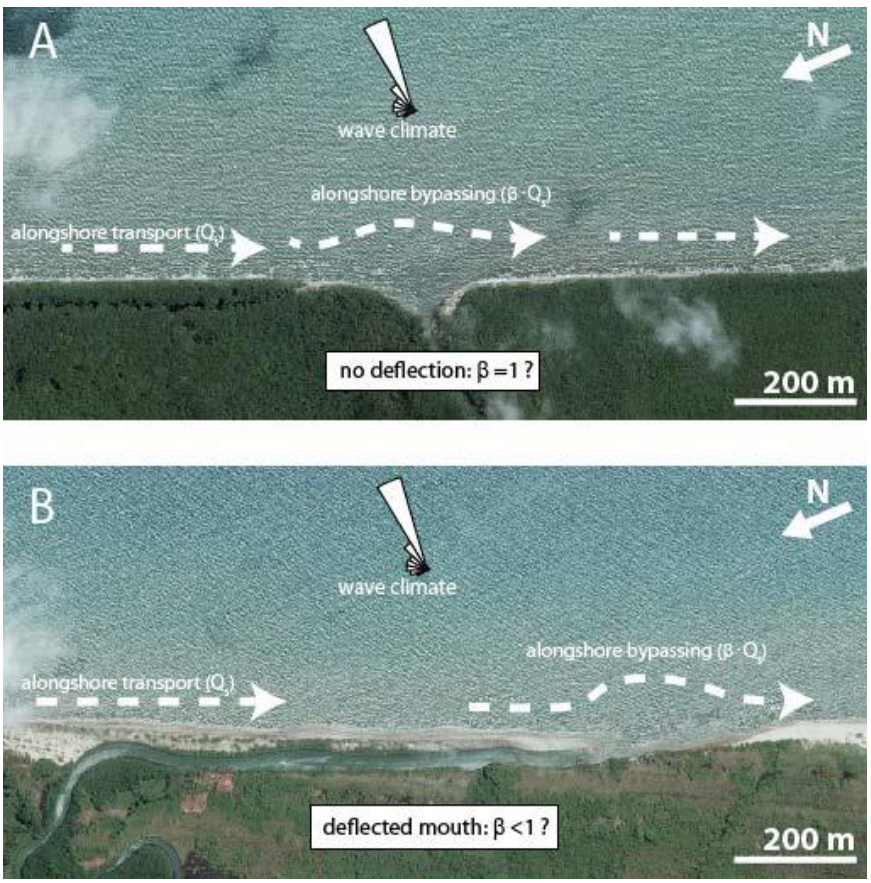

Figure 1: Two river mouths along the Caribbean coast of Nicaragua, experiencing a similar wave climate (and correspondingly, a similar alongshore sediment flux). The river mouth in A (coordinates: + 14.65, -83.29) is not deflected, implying that alongshore sediment is able to bypass the river mouth. The river mouth in B (coordinates: +14.41,-83.22) is strongly deflected: processes occurring at the river mouth limit bypassing of alongshore sediments. Q_s is the alongshore littoral

transport rate (kgs^{-1}), β is the fraction of Q_s that bypasses the river mouth, the wave rose represents the angular distribution of incoming wave energy, and the dashed arrows show the direction of net alongshore transport.

Sediment is typically bypassed in tidal inlets through bars on the ebb shoal, which accumulates sediment continuously or in discrete bypassing events. Bar bypassing is observed most frequently in shallow inlets that tend towards closure (Fitzgerald 1982). Bypassing of sediment can also occur episodically, for instance when the deflected inlet throat breaches through the subaqueous ebb shoal or, in a more extreme scenario, breaches the barrier spit (Fitzgerald 1982). Bruun and Gerritsen (1961) developed a sediment bypassing criterion based on the ratio between the alongshore sediment transport rate and the maximum water discharge during spring tide. High ratios likely lead to a deflected inlet. If the ratio is low, sediment can freely bypass, and littoral transport would not be able to steer the inlet (Bruun and Gerritsen 1961). Wave energy is strongly correlated with bypassing via alongshore sediment transport (Komar 1971; Fitzgerald 1982), but also via the effect of waves on the morphology of the ebb shoal (Olabarrieta et al. 2014). Recent research suggests that the presence of waves on the ebb shoal enhances the ability of the tidal inlet to bypass sediments (Olabarrieta et al. 2014).

Similarly to tidal inlets, we expect bypassing through river mouths to be strongly dependent on river discharge, river mouth jet dynamics, and river mouth morphology (Bhattacharya and Giosan 2003; Giosan 2007). The presence of waves causes the river mouth jet to decelerate but also increase mixing and re-suspension of sediments. Crescentic river mouth bars form close to the river mouth (Wright 1977; Nardin et al. 2013). River mouths deflect when obliquely incident waves and alongshore sediment transport construct updrift swash bars that force the channel downdrift (Wright 1977).

Methods

To investigate the natural extent and mechanisms of bypassing, we apply the coupled (depth averaged) hydrodynamic and morphodynamic model Delft3D-SWAN (Deltares 2014). The model is able to construct river mouth morphology from the combined action of alongshore transport and a river mouth jet. Using the model, we can calculate bypassing fractions and explore jet properties— emergent characteristics that co-develop with the river mouth morphology.

We model river mouth morphology with a domain modified from List and Ashton (2007), using a small (30 km alongshore by 5 km cross-shore) wave domain with a fine grid resolution nested into a larger (180 km alongshore by 90km cross-shore) and coarser wave domain. There is a shelf-break at 40 m water depth and at a distance of 80 km cross-shore, approximating the open-ocean conditions at

Duck, North Carolina. These dimensions were chosen to limit boundary artifacts that appear in the flow domain for obliquely approaching waves (List and Ashton 2007). The flow domain is 6 km alongshore by 5 km cross-shore, with a fine (25 m by 25 m) resolution close to the river mouth (Fig. 2). We extend morphologic change of the flow domain into the small wave domain to create a stable and fully developed alongshore current at the updrift and downdrift flow boundaries.

We run the morphodynamic model for 13 days after 1 day of hydrodynamic spin-up. With a morphological scaling factor of 90, simulations approximate 3.2 years of morphological change. Simulations with scaling factors of 30 and 70 showed similar results. To limit the side effects of the model spin-up, we adjust the initial river mouth geometry to the discharge conditions using hydraulic geometry. Bankfull channel depth and width are a function of discharge (Parker 1978). Discharge is varied between 50 m^3s^{-1} and 2000 m^3s^{-1}. We do not include fluvial sediment.

The modeled wave properties are varied between 0.5 m significant wave height and 4 s wave period to 2 m and 15 s, using a constant wave approach angle of 40° from shore-normal and a directional spread of 10°. The simulations spectrally resolve the wave-action balance equations to account for wave-current interactions and include refraction, depth-induced breaking and dissipation (Booij et al. 1999). The depth-averaged flow is forced by wave-induced radiation stresses and a discharge boundary condition applied at the river mouth boundary (Fig. 2). The flow drives bed load and suspended load fluxes, which are calculated using the equations of van Rijn (van Rijn 1993).

The sediment composition of each grid cell is tracked using 75 vertical layers of 10 cm. We divide the initial bed into two classes of sediment: one “updrift” class of 200.00 µm fine sand located in the updrift half of the domain, and one “downdrift” class of 200.01 µm fine sand in the other half of the domain downdrift from the river mouth. Modeled in this way, sediment acts as a tracer, allowing us to easily compute the fraction of updrift sediment that migrated downdrift past the river mouth.

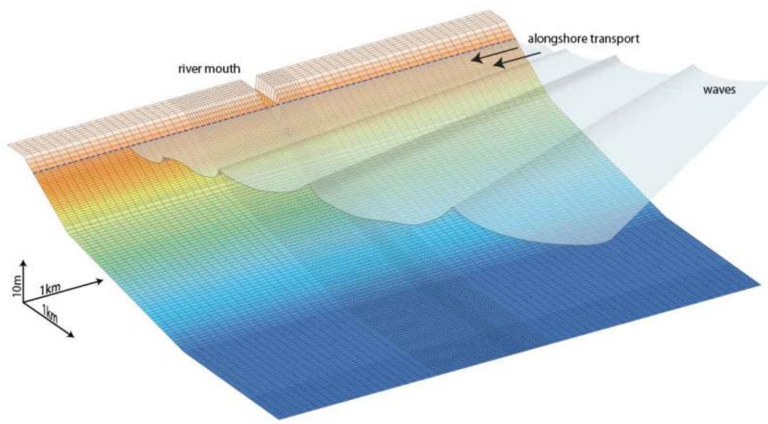

Figure 2: A schematic of the flow domain. The colors indicate the bed level, with the dotted line at sea level. The wave domains extend further alongshore and cross shore.

We track the position of the river mouth to calculate the total volume of updrift sediment that has bypassed it. The computed bypassing fraction (β) is equal to (i) the total volume of updrift sediment in our flow domain downdrift from the channel, plus (ii) the cumulative volume of updrift sediment that exited the flow domain, divided by (iii) the cumulative total volume of littoral sediment that entered the domain at the updrift boundary. Wave and fluvial conditions are varied systematically to investigate their effect on river mouth morphology, channel deflection, and sediment bypassing rates.

Results

River mouth morphology

In our model simulations, we observe bypassing mechanisms analogous to bar bypassing, ebb shoal breaching, spit breaching that are observed in tidal inlets. Starting with a symmetric river mouth geometry (Fig. 3a), we found three distinct phases of morphological development that characterize a deflected river mouth. Initially, a strongly deflected jet and a moderately sized offshore bar develop (Fig. 3b, phase 1). The deflected jet provides an efficient littoral sediment bypassing pathway, moving the sediment through the river mouth into the downdrift littoral zone. Continuous updrift littoral sediment supply feeds a spit, deflecting the river mouth into the waves, reaching an orientation more perpendicular to the shoreline (Fig. 3d, phase 2). This coincides with faster downdrift migration rates of the channel and lower bypassing fractions. In the final phase, the channel elongates downdrift (Fig. 3e, phase 3). In all the model runs performed in this study, this last configuration of low bypassing rates and fast downdrift migration of the river mouth remained under constant forcing conditions.

Model simulations for different river mouth discharge conditions show that higher discharge channels take longer to deflect (Fig. 4). This timescale dependence is related to the updrift alongshore sediment flux filling up and steering the channel. Low discharge river mouths are generally less deflected, consistent with the observation from tidal inlets that narrow, low discharge tidal channels bypass more sediments (Bruun and Gerritsen 1959).

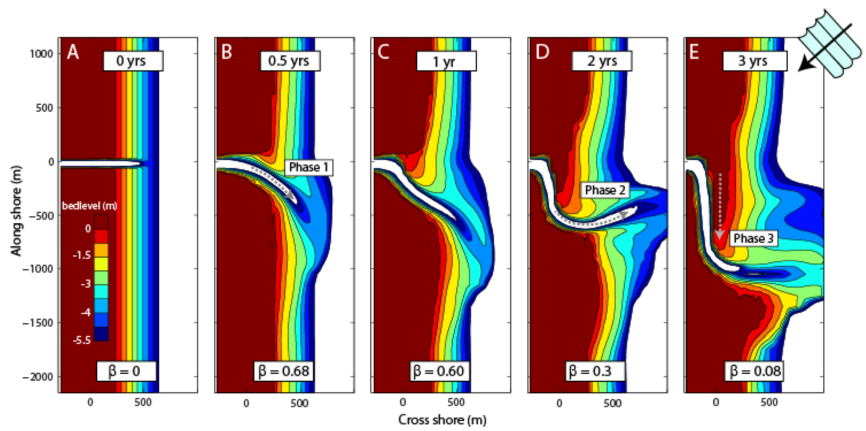

Figure 3: The simulated morphology of a deflected river mouth after 0, 0.5, 1, 2 and 3 years. The boxes indicate (cumulative) bypassing fractions (β). Discharge for these runs is 500 m^3s^{-1}; waves are set at 1.5 m, 10 s. The inset displays incoming deep-water wave angle. Colors indicate bed level.

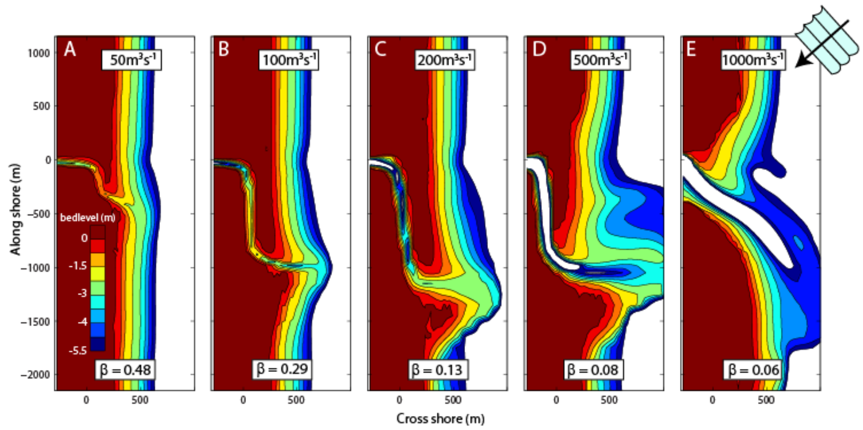

Figure 4: Simulated river mouth morphology after 3 years for fluvial water discharge varying from 50 m^3s^{-1} to 1000m^3s^{-1} and no fluvial sediment supply. Wave height is 1.5 m, wave period is 10 s and wave approach angle is 40° from shore-normal. The colors indicate the bed level.

Alongshore sediment bypassing

To better understand the observed relation between discharge and sediment bypassing, we examine breaking wave heights and associated alongshore sediment transport fluxes. High discharge, which corresponds to large subaqueous shoals and high jet velocities, lead to depth and current refraction of the waves and create a zone of low wave height updrift of the river mouth (Fig. 5). Sediment transport induced by wave breaking is limited and sediment is deposited updrift of the channel; the updrift bar accretes and the channel deflects (Fig. 5b). If on the other hand the river mouth shoal is small and the jet is weak, there is no significant wave refraction updrift of the river mouth (Fig. 5a). Bypassing occurs because littoral sediment is transported into the channel. Note that the zone of low wave heights downdrift of the river mouth is also associated with sediment accumulation: a refraction effect that is empirically observed in tidal inlets (Oertel 1977) and river mouths (Giosan et al. 2005; Giosan 2007).

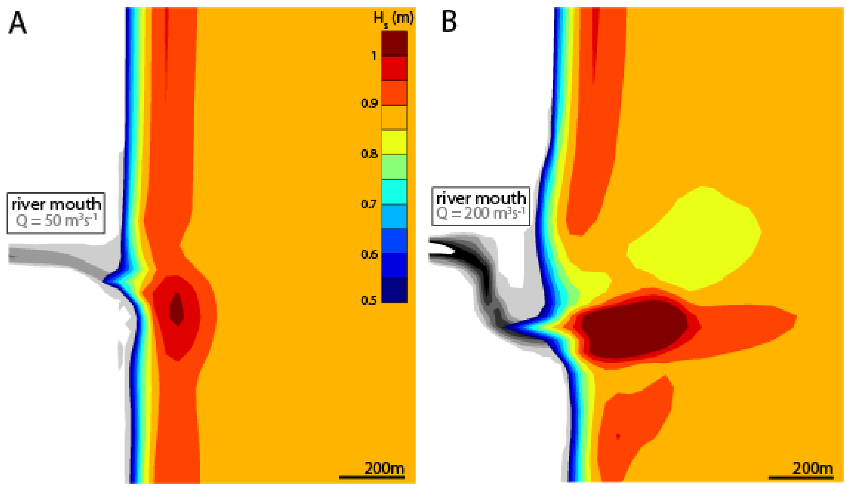

Figure 5: Significant wave height (H_s) close to the river mouth for different river discharges, a) 50 and b) 200. The zones of increased wave height occur alongshore (due to shoaling), and close to the river mouth (due to shoaling and wave current interactions), and are more pronounced for larger discharge. The channel morphology is showed in gray contours.

Our simulations suggest that strong jets and large shoals inhibit sediment bypassing. Depth refraction does not depend on the wave height. However, wave energy changes the timescale associated with bar growth and channel deflection. These controls on bypassing can therefore be summarized as a competition between the river mouth jet (which builds the shoals and generates a strong current for the waves to refract into), and ocean waves (which control the timescale over which spit building is occurring). We define a ratio J of the jet momentum flux (M_J) versus the onshore wave momentum flux acting on the river mouth (M_W) to capture these controls on bypassing:

$$J = \frac{M_J}{M_W} = \frac{\rho_w \cdot Q \cdot u}{S_{xx} \cdot W} = \frac{\rho_w \cdot Q \cdot u}{E[n(1+\cos^2\theta) - \frac{1}{2}] \cdot W}, \tag{2}$$

where ρ_w is the water density (kgm^3), Q is the river discharge (m^{3}s^{-1}) and u is the depth- and width-averaged river velocity (ms^{-1}), S_{xx} is the radiation stress per meter along shore (Nm^{-1}), W is the width of the river mouth (m), E is the wave energy density (Nm^{-1}) which equals $\frac{1}{16} \cdot \rho_w \cdot g \cdot H_s^{\ 2}$ (Dean and Dalrymple 1991), g is the vertical acceleration due to gravity (ms^{-2}), H_s is the significant wave height (m), n is the ratio of the group velocity and the phase velocity of the incoming waves, θ is the incoming wave angle.

In model simulations with varied wave height (0.5 m to 2 m), wave period (4 s to 15 s) and river discharge (50 m^3s^{-1} to 2000 m^3s^{-1}), we observe that the bypassing fraction is inversely related to the momentum flux ratio J (Fig. 6). When wave momentum flux is greater than jet momentum flux, bypassing occurs frequently. On the other hand if the jet momentum flux is relatively large, the river mouth deflects and the bypassing fraction is low.

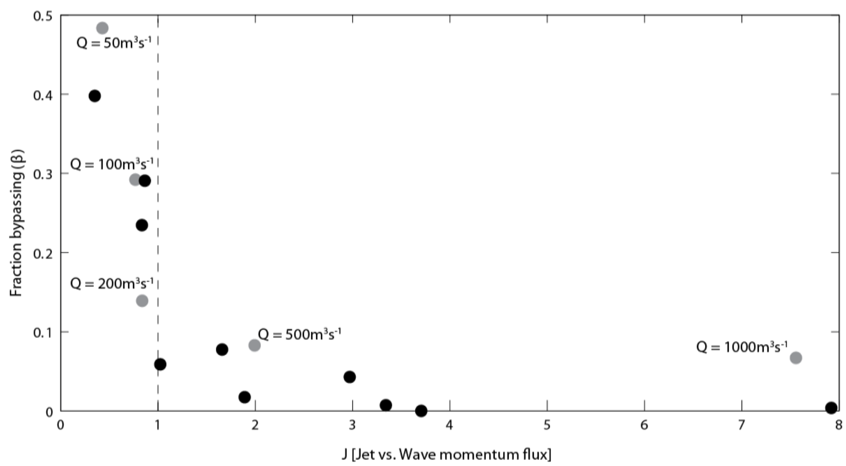

Figure 6: Calculated bypassing fraction for different ratios of jet vs. wave momentum flux. The gray markers correspond to the cases displayed in figure 4. The dashed line separates wave-dominated river mouths from jet-dominated river mouths.

Conclusions

In this study we modeled the morphology of river mouths in wave environments to investigate mechanisms of alongshore sediment bypassing. Under constant wave forcing and omitting fluvial sediments, modeled river mouths reach a state where the river mouth migrates and the channel elongates. In this state, the shoals and the river mouth jet cause waves to refract and generate a depositional environment updrift of the river mouth that limits bypassing and makes the river mouth itself deflect. Sediment bypassing is dominant in a regime of weak river mouth jets and strong waves. Previous studies (e.g. Bhattacharya and Giosan 2003) showed that river mouth deflection and delta asymmetry occur for low relative fluvial energy. Our simulations imply a contrasting relationship between fluvial discharge and river mouth deflection, where deflection is larger for higher discharge. Our simulations do not take into account fluvial sediment supply, which scales with fluvial discharge. This disparity between our modeling study and field examples is suggestive that fluvial sediment concentration is an important variable controlling delta dynamics.

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