Response of river-dominated delta channel networks to permanent changes in river discharge

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[1] Using numerical experiments, we investigate how river-dominated delta channel networks are likely to respond to changes in river discharge predicted to occur over the next century as a result of environmental change. Our results show for a change in discharge up to 60% of the initial value, a decrease results in distributary abandonment in the delta, whereas an increase does not significantly affect the network. However, an increase in discharge beyond a threshold of 60% results in channel creation and an increase in the density of the distributary network. This behavior is predicted by an analysis of an individual bifurcation subject to asymmetric water surface slopes in the bifurcate arms. Given that discharge in most river basins will change by less than 50% in the next century, our results suggest that deltas in areas of increased drought will be more likely to experience significant rearrangement of the delta channel network. **Citation:** Edmonds, D., R. Slingerland, J. Best, D. Parsons, and N. Smith (2010), Response of river-dominated delta channel networks to permanent changes in river discharge, *Geophys. Res. Lett.*, *37*, L12404, doi:10.1029/2010GL043269.

1. Motivation

[2] An immediate impact of climate change and human modifications to river catchments is that the long-term average discharge of most rivers will change appreciably over the next century [*Nohara et al.*, 2006; *Palmer et al.*, 2008]. On rivers that terminate in marine or lacustrine basins, this hydrological change also will impact their deltas, and yet no framework exists for predicting the adjustments deltas may undergo as discharge changes. Relative sea-level rise is already threatening the world's deltas [*Blum and Roberts*, 2009; *Syvitski et al.*, 2009], and that problem could be further compounded if permanent changes in discharge also dramatically alter delta landscapes, which provide wetlands, biodiversity,, and homes to a significant part of the world's population [*Coleman*, 1988; *Day et al.*, 2007]. Studies to date have focused on identifying which deltas are at risk [*Day et al.*, 1995; *Ericson et al.*, 2006] and how they might respond to perturbations such as sea-level rise [*Jerolmack*, 2009]. But, how deltaic distributary networks will respond to changes in river discharge remains unknown.

[3] As the long-term average river discharge (Q) changes, the most dramatic response of a deltaic channel network, apart from a full avulsion caused by delta-lobe switching [*Coleman*, 1988], is abandonment or initiation of distributary channels. This scenario could be expected because the number of bifurcations in a distributary network correlates positively with the input Q and inversely with the power in the marine environment [*Syvitski and Saito*, 2007]. However, it is unclear whether an individual delta's response to changes in Q would follow the same trend between Q and channel number observed from the *Syvitski and Saito* delta compilation.

[4] Past work has shown that the splitting of discharges at channel bifurcations is subject to fairly stringent stability conditions. Two distributaries with identical downstream boundary conditions and a given upstream Shields stress (Θ) distribute water and sediment asymmetrically because this is a stable equilibrium configuration [*Wang et al.*, 1995; *Slingerland and Smith*, 1998; *Bolla Pittaluga et al.*, 2003; *Miori et al.*, 2006; *Zolezzi et al.*, 2006; *Bertoldi and Tubino*, 2007; *Edmonds and Slingerland*, 2008; *Kleinhans et al.*, 2008]. For a given Θ, upstream channel roughness, and channel aspect ratio, there exists only one asymmetric discharge ratio (Q_r) for which the downstream bifurcate channels are stable to small perturbations. While suggestive, these results cannot predict cases where there are significant changes in the incoming Q because the perturbations induced in these studies were local and small-scale. Furthermore, these studies considered isolated bifurcations, whereas in natural delta networks the bifurcations are interconnected. For instance, the presence of a bifurcation produces a backwater slope that extends upstream [*Edmonds and Slingerland*, 2008], and its absence could affect the water surface slopes of other reaches, thereby propagating the original perturbation throughout the entire delta network.

[5] To address these shortcomings, this paper presents the first numerical study of the response of distributaries within a self-formed, river-dominated delta to changes in Q at the delta head. Results show a threshold behavior. For a change in Q less than about 60%, a decrease causes more network reorganization than an equal magnitude increase in Q. However, above this 60% threshold, an increase in Q creates new channels at about the same rate as channels are lost with decreasing Q.

2. Numerical Model

[6] We used Delft3D (v. 3.28) to create self-formed delta channel networks. Delft3D simulates fluid flow and mor-

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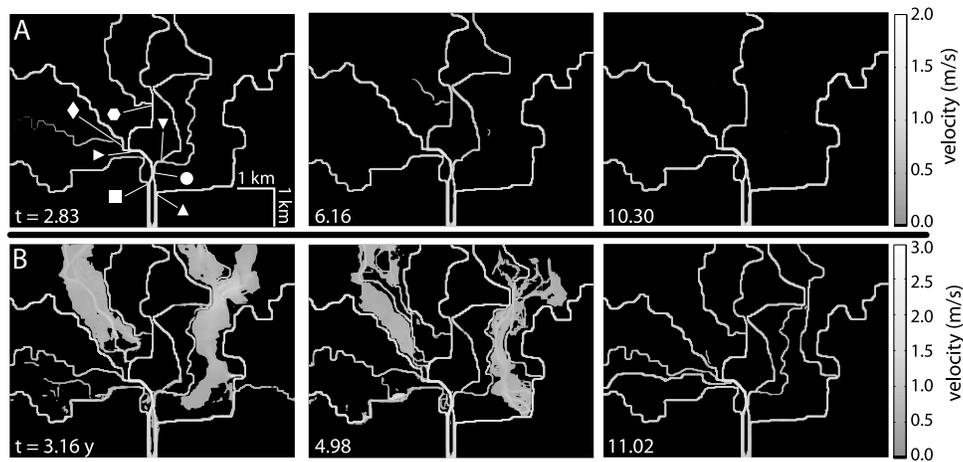
Figure 1. Maps of flow velocity computed in Delft3D from two experiments in simulation 1 showing network evolution as Q is: (a) decreased to 750 m^{3}s^{-1}; and (b) increased to 2500 m^{3}s^{-1}. t is elapsed time in years since Q began changing. As Q decreases, channels become abandoned, whereas when Q increases, water spills out of crevasses and onto the floodplain, sometimes creating a new distributary channel, although it may not persist (compare Figures 1b (middle) and 1b (right)). Even after the change in Q has stopped at $t \approx 5$ years, new distributary channels are created or abandoned, indicating a lag in the morphodynamic response of the system. Symbols in Figure 1a (left) refer to the bifurcations plotted in Figure 3.

phological changes and has been validated for a range of geomorphic applications [*Lesser et al.*, 2004]. Recently, Delft3D has been used to model the evolution of rivers and tidal deltas [e.g., *van Maren*, 2007; *Dastgheib et al.*, 2008; *Edmonds and Slingerland*, 2010]. Our self-formed delta simulations are depth-integrated and have a sediment-laden river entering a standing body of water devoid of waves, tides, and buoyancy forces, following the same setup and techniques given in *Edmonds and Slingerland* [2010]. Simulations 1 and 2 in the present paper are replicates of their runs *c* and *n*, respectively, except that the Q at the head of the delta herein is 1250 m^{3}s^{-1}. Simulations 1 and 2 have the same cohesive sediment sizes (30 μm) and slightly different noncohesive sediment sizes (225 and 350 μm, respectively), but both are provided here to demonstrate the variability in model predictions for similar initial boundary conditions. At the downstream boundaries we apply a steady, uniform water surface elevation boundary condition. The dynamics of the deltas are caused purely by the underlying physics of water and sediment transport, and because the channels are self-formed they are at bankfull discharge except where flow is re-routed due to channel creation or abandonment.

[7] We initially computed simulations 1 and 2 until all distributary channels reached the edges of the computational domain and the deltas reached equilibrium, defined as no further change in bed elevation in the domain. By allowing the channels to reach the edges of the computational domain, we removed progradational processes and focused on how changing Q affected the network upstream of the shoreline. We then used each equilibrium configuration as the initial condition for ~10 changing-discharge experiments. In each experiment, the Q at the delta head was linearly changed by −100% to +100% of the initial Q over a period of ~5 years. The simulations were computed until the deltas achieved a new equilibrium, usually after an additional 10 years. If time was properly scaled, Q would change over many decades because the channels are continually at bankfull discharge, which occurs intermittently in real sys-

tems. Tests showed that the results did not change if Q was changed linearly for a longer period (e.g. 15 years). During the simulation, the sediment transport rates at the upstream boundary are always in equilibrium with the incoming Q. In response to changes in discharge, the distributary channels could flood overbank, deepen, shallow, narrow, or widen. Bank erosion occurs if dry grid cells adjacent to the channel are wetted, eroded, and then incorporated into the channel.

3. Results

[8] In response to decreasing incoming Q, bifurcations in the network disappear at a linear rate with Q (Figures 1a and 2). Abandoned channels are preferentially filled with
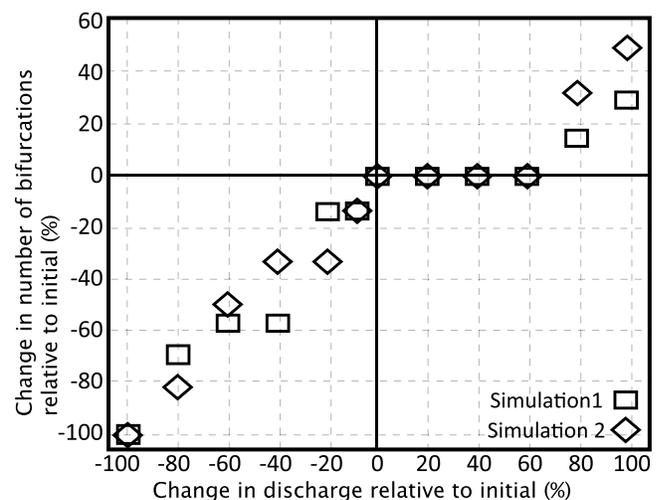
Figure 2. Change in the number of bifurcations as a function of changing Q. For the same percentage change in Q up to a value of 60%, only a Q decrease results in a change in the number of bifurcations. The number of bifurcations increases only when the rise in Q exceeds a threshold of about 60%.
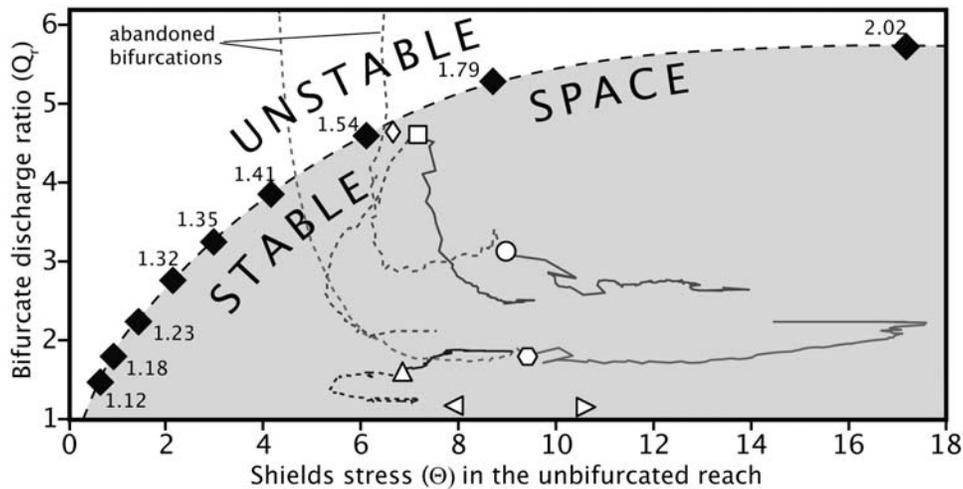
Figure 3. Stability diagram for bifurcations with asymmetric downstream boundary conditions. The long dashed line is the inferred solution between numerical experiments, plotted as solid black diamonds. The number adjacent to each diamond is the water surface slope ratio between bifurcates for that solution. See text for modeling details. All other shapes correspond to the initial positions of bifurcations from simulation 1, which are located in stable space prior to any change in Q (see Figure 1 for their locations in the network). For select bifurcations, their trajectory in Θ–Q_r space is shown in response to a decrease to 750 m^{3}s^{-1} (shorter dashed lines) or an increase to 1750 m^{3}s^{-1} (solid lines) in Q. All other bifurcations from simulations 1 and 2 conform to these general trajectories. Each trajectory line represents similar amounts of time, but possesses different lengths because the bifurcations move through Θ–Q_r space at different celerity.

the cohesive sediment via deposition. In contrast, as Q increases, channels experience overbank flow and creation of sediment crevasses, but new bifurcations are created only if the Q is increased by more than approximately 60% (Figures 1b and 2). We conclude that delta networks of the type studied here are less sensitive to increases than to decreases in discharge (Figure 2). When new channels are created, they carry between 20 and 60% of the increased Q, with the rest being redistributed within the remaining network. This threshold for channel creation occurs because the existing network has some capacity to carry additional Q, and only when that capacity is exceeded is flooding sufficient to create new channels. Interestingly, during the approach to that threshold, increases in Q never cause the abandonment of bifurcations, even though theoretical work suggests that such an increase in Θ could cause instability [*Bolla Pittaluga et al.*, 2003; *Miori et al.*, 2006; *Edmonds and Slingerland*, 2008].

[9] The central question that arises from these results is why delta networks and their bifurcations are more sensitive to decreases, rather than increases, in Q? The answer to this question, and the sensitivity of such delta networks, lies in the configurations of the bifurcate channels. Previous stability studies have focused on bifurcations that have symmetric downstream boundaries [*Bolla Pittaluga et al.*, 2003; *Miori et al.*, 2006; *Edmonds and Slingerland*, 2008], such as bifurcations with equal-length bifurcate channels that enter a lake. However, as will be shown for natural deltas, bifurcations in the numerical deltas respond to downstream boundary conditions that are asymmetric, with the ratio of average water-surface slopes between the two bifurcate channels in these experiments being 2.2 (n = 13), thus rendering comparisons to previous theory inappropriate. To explore the stability of bifurcations subject to asymmetric downstream

boundary conditions, we conducted additional experiments using Delft3D.

[10] This second set of modeling experiments in Delft3D simulated the conditions of a deltaic bifurcation with one upstream inlet, two downstream outlets, and fixed walls (see *Edmonds and Slingerland* [2008] who used an identical set-up). The model contained one cohesive (4 μm) and one non-cohesive sediment fraction (125 μm), a uniform Chezy roughness of 45 m$^{1/2}$s^{-1}, a channel aspect ratio of 16, and a uniform initial bathymetry. Grain size differences between these experiments and simulations 1 and 2 have little effect on the results, primarily because the sediments have the same user-specified cohesion properties. In this set of simulations (black diamonds in Figure 3), we prescribed different water-surface elevations at the downstream boundaries and then adjusted Θ at the upstream boundary (by changing Q) until we found the value below which the bifurcation was unstable (i.e. reverts to one channel) and above which it was stable (i.e. both bifurcates transmit water and sediment) This was repeated for additional asymmetric downstream water-surface elevations until a parameter space was defined. Θ is computed from the median grain size of all sediment fractions coming into the delta.

[11] The resulting stability diagram (Figure 3) shows the line that divides the stable and unstable space for a bifurcation subject to asymmetric downstream boundary conditions. When Q (or Θ) is increased, bifurcations from simulation 1 are invariably stable because through bed and width adjustments they move to a new configuration at a higher Θ that is deeper into stable space (solid lines in Figure 3). With decreasing Q, the bifurcations that plot closest to the stability line could be expected to become abandoned. This would be true if the local response at the bifurcation mirrored the changing boundary conditions, such that an increase in Θ at the delta head caused an
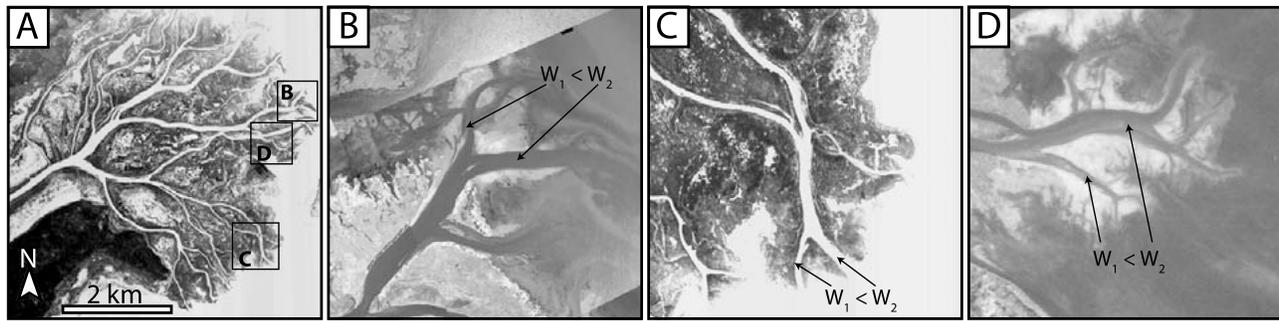
Figure 4. (a–d) Images of the Mossy delta, Saskatchewan, Canada, showing that bifurcations at the shoreline have asymmetric ratios in channel width (and therefore Q) before they become incorporated into the network. Figures 4a and 4c are from 2009 (copyright Digital Globe, Inc, obtained through National Geospatial-intelligence Agency commercial imagery program). Figures 4b and 4d are from 2003 and 1982, respectively (copyright Information Services Corporation, SK, Canada).

increase in Θ at all bifurcations. However, the response is more complex because the bifurcations are part of a network. For example, in some cases a decrease in Q at the delta head results in an increase, or no change, in the local Θ (see trajectory of upright triangle and square in Figure 3). Hence, the best predictor of which bifurcations will be abandoned does not depend on their location in stability space, the details of their planform geometry, or their position in the network, but rather on the size of the channel. Smaller channels are preferentially abandoned; of the bifurcations abandoned, 72% (n = 11) had a ratio of initial Q at the bifurcation relative to delta head of less than 0.25.

4. Application to Natural Deltas

[12] Based on these results, we suggest that natural delta networks should be more stable when subjected to increases, rather than decreases, in Q (and Θ) because most of their bifurcations possess asymmetric downstream boundary conditions. Deltaic bifurcations evolve from flow division around river mouth bars, and initially are approximately symmetric, but once perturbed they shift to the more stable asymmetric solution. Aerial photography from the Mossy delta in Saskatchewan, Canada [*Edmonds and Slingerland*, 2007], suggests that this shift happens while bifurcations are still at the delta front (Figure 4), causing bifurcate channels to prograde at different rates (provided the accommodation space is uniform) as they receive different amounts of sediment. Inevitably, these differing rates of progradation will cause asymmetric bifurcate channels that will be incorporated into the network as the delta continues to advance. This qualitative argument is also supported by water surface elevation data collected on the Mossy delta, where the average water surface slope ratio between bifurcate channels of eight different bifurcations was found to be 2.3 (for bifurcation locations, see Figure 1a numbers 1–8 in *Edmonds and Slingerland* [2008]).

5. Conclusions

[13] Numerical modeling experiments have permitted investigation of the integrated network effects of changing the long-term average discharge at the head of a delta. As discharge is increased, existing bifurcations always find new stable configurations to pass the increased flow. This ability

arises because most bifurcations possess asymmetric water surface slopes in their downstream arms, and this configuration is invariably stable to increases in discharge. If discharge increases exceed 60%, flooding and creation of new channels occurs. If discharge is decreased from the initial value, bifurcations are susceptible to instability and channels are abandoned in proportion to the magnitude of discharge decrease.

[14] For certain magnitudes of discharge change these results suggest that deltas in areas of increased drought will experience greater rearrangement of distributary networks than deltas in areas experiencing an increase in discharge. A more thorough investigation of parameter space, including the effect of tides, waves, and flow variability, is required to makes these results more generally applicable.

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