Vegetation influence on delta evolution and dynamics under varying water- and sediment-discharge conditions

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Key Points

1. With no vegetation, deltas shift from few to many channels and global to local avulsions with increasing water discharge.
2. With high water or sediment discharge, vegetation tends to confine flow into existing channels, restricting creation of new channels.
3. With vegetation, increased sediment or water discharge results in a more stable channel network through frequent channel reoccupation.

Abstract

The dynamics and evolution of deltas and their channel networks involve interactions between many factors, including water and sediment discharge and cohesion from fine sediment and vegetation. These interactions are likely to affect how much vegetation influences deltas, because increasing sediment discharge increases aggradation rates on the delta and may result in sediment transport processes happening on timescales that are faster than those for vegetation growth. We explore how varying water and sediment discharge changes vegetation's effect on delta evolution. We propose two new insights into delta evolution under different discharge conditions. First, without vegetation, we observe a regime shift in avulsion dynamics with increasing water discharge, from a few active channels supplemented by overbank flow and undergoing episodic avulsion (with low discharge) to many active channels experiencing frequent partial avulsions (with high discharge). Second, with vegetation, increased aggradation results in more frequent switching of the dominant channels with increased sediment discharge, but also prevents vegetation from establishing in non-dominant channels resulting in more frequent channel reoccupation and therefore greater stability in channel network planform. These insights have important implications for understanding the distribution of water, sediment, and nutrients on deltas in the face of future changes in climate, human modifications of fluxes of sediment and water to the coast, and especially for restored or engineered deltas with controlled water or sediment discharges.

Plain Language Summary

Delta restoration projects may take the form of building new land through diverting water and sediment from a river or channel to a chosen location. The presence or absence of vegetation changes how deltas respond to different volumes of water (water discharge) and different amounts of sediment in the water (sediment discharge). We study the effect that the water and sediment discharge have on the behavior of channels on river deltas using a simple model. We find that deltas without vegetation and with lower water discharge have few channels and experience occasional large changes in channel location. However, with higher water discharge, deltas have many channels and experience frequent but small changes in channel location. On deltas with vegetation, we find that increasing the water discharge creates deltas with more stable channel networks, as vegetation makes creation of a new channel unlikely by confining water in channels and making the land outside of channels difficult to erode. Increasing the sediment discharge also increased channel stability deltas by burying young plants and preventing vegetation from growing in channels. This study will help us better understand how water and sediment discharge influences delta shape and channel behavior.

1. Introduction

The evolution of deltas and their distributary channel networks can be controlled by a number of factors, including the balance between river, wave, and tidal influences (e.g. Galloway, 1975; Syvitski et al., 2009; Nienhuis et al., 2015; Geleynse et al., 2011; Leonardi et al., 2015; Nienhuis et al., 2018), water and sediment discharge (Powell et al., 2012; Hoyal and Sheets, 2009; Orton and Reading, 1993; Edmonds et al., 2010), fraction of cohesive sediment (Caldwell and Edmonds, 2014; Hoyal and Sheets, 2009; Straub et al., 2015; Edmonds and Slingerland, 2009; Liang et al., 2015a; Tejedor et al., 2016) or cohesion from vegetation (Lauzon and Murray, 2018), base level rise (Chadwick et al., 2020; Jerolmack, 2009; Liang et al., 2016a; Martin et al., 2009; Ratliff et al., 2018), and many others. Recent research has focused on the role these factors play in shaping delta morphology and influencing autogenic timescales: the timescales at which deltas undergo cycles of channelization, channel extension and aggradation, avulsion and incision of a new channel (e.g. Hoyal and Sheets, 2009; van Dijk et al., 2009; Kim et al., 2006). Cohesion is thought to alter these timescales, decreasing channel mobility and avulsion frequency (Straub et al., 2015; Edmonds and Slingerland, 2009; Hoyal and Sheets, 2009; Caldwell and Edmonds, 2014; Liang et al., 2015a; Lauzon and Murray, 2018), favoring progradation even with high cross-levee slopes (Edmonds and Slingerland, 2009) and resulting in rugose shorelines.

Vegetation has many of the same cohesive-like effects as fine-grained sediment – elongating, deepening, and stabilizing channels and increasing shoreline rugosity – and may be even more effective at stabilizing channel networks, resulting in well-sorted sandy channel beds and potentially decreasing deltaic fine-grained sediment retention (Lauzon and Murray, 2018; Nardin and Edmonds, 2014). However, while recent research has begun to assess the cohesive effects of fine sediment under varied environmental conditions (e.g. Martin et al., 2009, Liang et al., 2016a,b), vegetation may be sensitive to environmental conditions in ways that cohesive sediment may not be. The influences of water and sediment discharge are particularly important to understand, as humans are increasingly modifying the distribution of water and sediment to the coast (e.g. Syvitski and Saito, 2007) which could have important implications for the evolution of natural deltas (e.g. Ericson et al., 2006; Anthony et al., 2014) and the success of engineered and restored deltas (e.g. Kim, 2012; Kim et al., 2009; Paola et al., 2011; Allison and Meselhe, 2010).

Increasing water discharge can increase the number of bifurcations in delta channel networks (Syvitski and Saito, 2007; Edmonds et al., 2010). Delta slope is also (inversely) correlated with discharge and plays an important role in autogenic cycles (Powell et al., 2012). Increasing water discharge leads to a more organized channel system; channel mobility decreases and sediment transport capacity increases (Powell et al., 2012).

Increased sediment discharge increases deposition rates and can increase avulsion frequency and channel mobility as a result (e.g. Orton and Reading, 1993; Hoyal and Sheets, 2009; Bryant et al., 1995). Autogenic timescales generally decrease as sediment discharge increases relative to water discharge (Powell et al., 2012).

Changes in environmental conditions leading to increased deposition rates may have a significant effect on vegetation influence. Enhanced deposition may increase vegetation mortality, as plants are buried or uprooted (Pasquale et al., 2014; Perona et al., 2012), or make parts of the delta less suitable for vegetation colonization. If sediment transport processes act on timescales faster than those for vegetation growth, vegetation will likely not be able to influence delta morphology or dynamics (e.g. Murray and Paola, 2003; Pasquale et al., 2014; Perona et al., 2012).

We use the delta-building model DeltaRCM (adapted to include key vegetation effects by Lauzon and Murray, 2018) to investigate the effects of different environmental conditions (and therefore different climates) on vegetation's role in shaping delta evolution. We explore the effects of varying water and sediment discharges and test the hypothesis that high rates of sediment discharge will result in sediment transport processes that outpace the timescales of vegetation growth and establishment, therefore reducing the effects of vegetation on delta morphology and channel dynamics.

2. Methods

2.1 Model Description

DeltaRCM consists of a rule-based flow routing scheme and a set of sediment transport rules governing the behavior of water and sediment 'parcels' which build a small, river-dominated delta. In a previous study (Lauzon and Murray, 2018), we modified DeltaRCM to include the effects of vegetation to 1) reduce lateral transport of sediment and 2) increase flow resistance. A brief description of the model and our modifications are below, and a more detailed description of the vegetation rules can be found in Lauzon and Murray (2018). A more detailed description and an assessment of the hydrodynamic component of DeltaRCM can be found in Liang et al. (2015a,b). Model deltas have also been extensively compared to several observational, experimental, and numerical-model (Delft3D) datasets (Liang et al., 2015b; 2016a).

Each model run begins with a 5 m deep basin with an inlet channel of fixed width and depth on one side. In each time step, water and sediment "parcels" enter the domain through the inlet channel and are routed by a weighted random walk. Weights are determined by the average downstream direction (representing inertia), the water surface gradient (representing gravity), and a depth dependent resistance to flow. The proportion of sediment parcels which are sand

(f_{sand}) can be specified; remaining parcels are mud, and each has a different set of erosion and deposition rules. After the water parcels are routed, the depth-averaged flow field and then the water surface profile are updated, the sediment parcels are routed, and finally the bed elevations are updated. The model timestep, *dt*, is set so that a characteristic sediment volume, related to the volume of the inlet channel, enters the domain in each time step. Optimizing computational efficiency and model stability, this volume was determined by Liang et al. (2015a) to be:

$$dt = \frac{0.1\, N_0^2 V_o}{Q_s} \qquad (1)$$

where V_0 is the volume of one cell of the inlet channel, N_0 is the number of cells in the inlet, and Q_s is the input sediment discharge.

We incorporate two main effects of vegetation (represented as a fractional cover of each cell and representing emergent vegetation such as marsh grasses) into the model: 1) stabilizing channel banks, thereby reducing lateral transport, and 2) introducing friction, which increases resistance to flow. Lateral transport, previously dependent only on local slope and sand flux, now also decreases as vegetation cover increases. Flow resistance, previously only depth dependent, now increases with vegetation density representing friction and drag introduced by the plants.

Vegetation can establish in any cell near sea level (elevation > -0.5 m) with bed elevation change over the previous timestep less than 1% of the rooting depth of the vegetation. Fractional cover increases logistically between "flood" periods. We set the flood length equal to 3 days and the time between floods equal to 100 days, assuming about 10 days of bankfull flood per year. As the model represents bankfull flow, we increase fractional cover every n^{th} timestep where n is the number of timesteps in each flood. Mortality occurs during floods (that is, during each timestep) and is proportional to the magnitude of erosion and deposition events relative to the rooting depth of the vegetation.

2.2 Experimental set-up

We use a model grid of 120 by 240 50 m^2 cells, and a sediment composition of 50% sand, as Lauzon and Murray (2018) demonstrated that vegetation has a less significant effect on the delta morphology and channel dynamics of deltas with higher proportions of mud, which are therefore already cohesive. We run a set of experiments to explore the effects of varying sediment (Q_s) and water (Q_w) discharge. For both sets of experiments, parameters were selected to be in line with those previously used for DeltaRCM (Liang et al., 2015a; 2016a,b), to be varied enough to be expected to influence delta evolution (e.g. an increase in discharge of at least 60%; Edmonds et al., 2010), and to be reasonable enough for inferences to be made to experimental and natural deltas (Syvitski and Saito, 2007). Details of experimental set-ups can be found in Table 1.

The discharge experiments are run with Q_w values of 1000 and 2000 m^3/s and Q_s values of 0.5, 1, and 2 m^3/s, both with and without vegetation, resulting in 12 unique model inputs. As the timestep depends on Q_s and the inlet size (N_0; Equation 1), which varies with Q_w, the discharge experiments are run until the same total amount of sediment has entered the model domain, which occurs after fewer timesteps for higher Q_w (Table 1). All experiments are run in triplicate, resulting in 36 total model simulations. We present averaged data wherever possible, and values for individual model simulations can be found in Table 2.

2.3 Data Analysis

To capture the dynamics of the channel network over time we measure the decay in channel planform overlap (Wickert et al., 2013). Using channel maps (determined using a velocity threshold equal to the minimum velocity for sediment transport) for the second half of each run, we measure the overlap in the channel network using a varying time lag. To eliminate differences in the channel network due to delta growth, we consider only the channels within the delta area at the initial time (halfway through the run). We fit an exponential decay function to the channel planform overlap data to obtain a decay constant M. M is a measure of how quickly the spatial configuration of the channel network changes. A high value suggests little similarity in the configuration of the channel network through time and would be a signature of frequent avulsions to new channels or frequent switching between existing channels. Using the same channel maps, we measure the decay in the fraction of the delta surface unreworked by the channel network to obtain a decay constant R, which approximates the rate dry cells are converted to wet cells. A high value suggests highly mobile channels, reflecting channel migration and/or avulsions to new (rather than previously occupied) channels.

By summing the channel maps analyzed above, we measure the fraction of time that each cell which is ever part of the channel network remains part of the channel network (Liang et al., 2016a). Again, we consider only those cells that were within the delta area at the halfway point and consider the second half of the run. These channel maps also allow us to qualitatively assess the spatial distribution of the channel network across the delta. We also calculate the average number of channels on the delta by counting the number of channels along the arc of a semicircle that has an area equal to 2/3 of the delta area at each time step. We average this over the second half of the model run to obtain an average number of channels for the delta.

We complement these measures of channel dynamics with an analysis of sediment distribution across the delta. Shoreline roughness (equal to the shoreline length divided by the square root of the delta area; $L_{shore}/\sqrt{A}$; Wolinsky et al., 2010) provides a measure of the evenness of the distribution of sediment across the delta by the channel network, with more stable channel networks tending to build more lobed deltas. To understand patterns in aggradation on the delta surface, we consider the cumulative distribution function of subaerial delta elevations. We use detrended elevations for this, which we obtain by subtracting the trend in delta slope imposed by the model (a function of sediment composition). We also examine maps of these detrended elevations to assess spatial patterns in aggradation. Finally, we measure the distribution of mud and sand across the delta by vertically averaging the stratigraphy to obtain a sand fraction for each cell of the model domain (Liang et al., 2016a).

3. Results and Discussion

The results we present below, taken together, suggest the following insights about how changing water and sediment discharge affect channel dynamics and how channels and vegetation interact. 1) Without vegetation, increasing Q_w results in a regime shift from a few active channels undergoing infrequent large avulsions to many channels undergoing frequent but small-scale avulsions. However, 2) with vegetation, both high Q_s or high Q_w lead to increased channel network stability through consistent channel reoccupation because 3) vegetation is both unable to fill in partially abandoned channels under those conditions and offers greater resistance to the creation of new channels.

3.1 Dynamics on unvegetated deltas

For unvegetated runs, channel mobility (as measured by R, the decay rate for remaining unreworked fluvial surface) increases with increasing Q_w (Figure 1a), suggesting that increased Q_w enhances channel migration and increases avulsion frequency (converting dry cells on the delta surface to channels more quickly). Increased Q_w tends to increase channelization (Powell et al., 2012), and we find that at high Q_w the number of channels is the same for all values of Q_s and is higher than that for low Q_w (Figure 1b), as flow is distributed more evenly across the delta and increasingly through channels instead of overbank flow. The increased number of channels results in a lower value of M, corresponding to slower decay in channel planform overlap (Figure 1c), suggesting more similarity in the configuration of the channel network through time with higher Q_w. (There is no relationship between M and Q_s.)

An increase in similarity in the channel network through time may seem to be at odds with an increase in channel mobility, but we suggest both can be explained by separating spatial and temporal variability in the channel network. We propose a regime shift from a few active channels that distribute sediment regionally via overbank flow and periodically undergo large-scale (global) avulsions at low Q_w to many channels distributed across the delta with limited overbank flow and frequent small-scale (local) avulsions at high Q_w. Such as shift would increase R (as channel migration and/or more frequent, but local, avulsions would be required to distribute flow across the delta in the place of overbank flow) while also decreasing M (as smaller-scale avulsions would result in smaller changes in the configuration of the channel network than abandoning and carving out an entire new channel). Considering the maps of the fraction of time that each channel cell remains a channel, we do see that deltas with low Q_w have fewer and shorter-lived channels which are not evenly distributed over the delta (Figure 2b,f,j), while deltas with high Q_w have relatively long-lived channels which are distributed over most of the delta area (Figure 2a,e,i).

The distribution of detrended elevations on the subaerial delta supports this proposed regime shift. The cumulative distribution function (CDF) of detrended elevations has a steeper slope for deltas with high Q_w; in other words, elevations across a delta with high Q_w are more similar than on deltas with low Q_w (Figure 3). For deltas with low Q_w, higher elevations are focused on certain areas of the delta along and near channel banks, suggesting regional distribution of sediment as described above (Figure 4a,c,e). For deltas with high Q_w, elevations are relatively constant across the delta as a more well-organized and extensive channel network distributes sediment more evenly across the delta (Figure 4b,d,f).

3.2 Dynamics on vegetated deltas

We find that both Q_w and Q_s influence channel dynamics on vegetated deltas. For low values of Q_w, channel mobility (*R*) on vegetated deltas is lower than mobility on unvegetated deltas for low and medium values of Q_s (Figure 1a). However, channel mobility on vegetated deltas for the highest Q_s we tested is comparable to that on an unvegetated delta, suggesting that vegetation's ability to decrease channel mobility is, as expected, reduced with high Q_s (e.g. Murray and Paola, 2003). However, for high values of Q_w, channel mobility is not strongly influenced by Q_s. For vegetated deltas, at high Q_s, R values remain comparable at high Q_w to those at low Q_w. In other words, the tendency for vegetation to stabilize channels by introducing roughness on channel banks is not inhibited by high Q_w. Reworking of the delta surface likely occurs at similar rates for low and high Q_w because the increased resistance to flow in vegetated areas likely makes avulsions to previously abandoned channels—in which increased sedimentation rates prevent vegetation from becoming established—more likely than the incision of new channels through vegetated areas. This is further supported by the average number of channels (Figure 1b). With high Q_w, vegetated deltas have fewer channels (4.46 ± 0.99) than unvegetated deltas (5.9 ± 0.39).

When vegetation is present, the number of channels decreases with increasing Q_s at low Q_w (Figure 1b). At high Q_w, the number of channels does not depend on Q_s. The number of channels remains constant for vegetated deltas with high Q_s for both values of Q_w. This suggests that at high Q_w, increased water flow results in increased erosion and deposition events in channels, preventing the establishment of vegetation and favoring reoccupation of a few channels regardless of Q_s, whereas at low Q_w, vegetation's ability to establish in channels depends on Q_s.

M is not determined by Q_s at low Q_w but decreases with increasing Q_s at high Q_w (Figure 1c). This suggests that with vegetation, there is more similarity in the configuration of the channel network through time with increasing Q_s at high Q_w. While we might expect *M* to increase with Q_s as rapid avulsions spread sediment across an aggrading delta, the decrease in *M* may be due to consistent channel reoccupation during avulsions. Aggradation and increased channel switching frequency that prevents vegetation from establishing in less active channels, combined with the fact that vegetation offers resistance to incising new flow paths, results in frequent channel reoccupation.

If the channel network is distributed evenly across the delta surface, as channel frequency maps suggests is true for vegetated deltas with high Q_w (Figure 2), consistent channel reoccupation would still facilitate the even distribution of sediment across the delta necessary for the high aggradation rates typical of high Q_s. Channels do appear to be less long-lived for vegetated deltas with high Q_w than for unvegetated ones (Figure 2). This also explains why we do not see the same trend at low Q_w, as the increased organization of the channel network that comes with high Q_w is necessary to facilitate even distribution of sediment across the delta.

Detrended delta elevations tend to be lower on vegetated deltas than unvegetated ones (between 15-30% of elevations are below 0.25 m on vegetated deltas, compared to only 5% on unvegetated ones), though deltas with high Q_w still tend to have steeper slopes or more similar elevations than those with low Q_w (Figures 3 and 4). The distribution of elevations shifts to the left with decreasing Q_s, representing lower elevations. Differences in elevation distributions with different Q_w and Q_s conditions are larger on vegetated deltas than unvegetated ones.

With increasing Q_w, more even distribution of channels across the delta surface results in a decreased tendency for vegetation to increase shoreline roughness. Shoreline roughness is typically higher for vegetated than unvegetated runs (Figure 1d); however, the magnitude of the difference decreases with increased Q_w.

This consistent reoccupation hypothesis is qualitatively supported by the delta stratigraphy. The effect of high Q_s to increase channel aggradation and avulsion (by increasing cross-levee slopes through aggradation), encouraging even distribution of sediment across the delta, appears to result in less strong channelization of flow (less evidence of levee formation; Figure 4), especially when vegetation is present. This is supported by the decrease in the prevalence of sandy channel deposits with increasing Q_s (Figure 5c, g, k). The detrended elevation maps show evidence of pronounced levees suggesting long-lived channels for deltas with low Q_w but not for high Q_w (Figure 3).

4. Potential for Future Work

Our results raise some interesting questions that could be answered by future work.

In natural delta systems, multiple species and types of vegetation (e.g. aquatic plants or trees in addition to marsh grasses) exist in close proximity. In addition to each type of vegetation having different properties and levels of cohesive influence, both competition and facilitation effects could occur which would introduce more spatial and temporal variability in vegetation influence and may enhance or inhibit vegetation's overall level of influence. We have purposefully chosen to include only a simple representation of vegetation dynamics, with one type of vegetation, as a first examination of the basic question of how the effects of vegetation vary with water and sediment discharge conditions. With this question in mind, we incorporated only the cohesive effects of vegetation, though other dynamics such as organic sediment production may be important to consider in other contexts. Similarly, we provide a starting point for future research by considering ranges in water and sediment discharge, but our model deltas develop under constant discharge conditions (i.e., they could be considered at equilibrium). Natural deltas are subject to changes in discharge over time due to changing environmental conditions or human alteration of water or sediment fluxes to the coast (Syvitski and Saito, 2007), and so may be expected to experience transient effects as they respond to changing conditions which would not be captured by our equilibrium deltas. In addition to long-term trends in discharge, natural deltas experience stochastic variations in flow, which would likely have a different effect on vegetation than the constant flood height represented in our model. However, we have provided a foundation by identifying different behaviors in the delta channel networks across different experimental set-ups, which are consistent with experimental studies with changing discharge trends (but no vegetation; e.g. an increase in water discharge increasing the number of channels; Edmonds et al., 2010).

5. Summary and Implications

In agreement with previous research, we find that increasing Q_w increases the number of channels on unvegetated deltas (Edmonds et al., 2010), and (at low Q_w) channel mobility increases with Q_s (Powell et al., 2012; Orton and Reading, 1993; Hoyal and Sheets, 2009) and vegetation's ability to decrease channel mobility is decreased (e.g. Murray and Paola, 2003). We also propose two new insights into the evolution of delta channel networks under different discharge conditions: 1) a regime shift in avulsion dynamics, without vegetation, from a few active channels supplemented by overbank flow and undergoing episodic global avulsions at low Q_w to many active channels experiencing limited overbank flow and frequent local avulsions at high Q_w; and 2) that while vegetation's ability to establish in less active channels is decreased by more frequent channel switching and aggradation under high Q_s conditions, vegetation is still able to stabilize the channel network by favoring reoccupation of abandoned channels over incising new channels through vegetated areas.

The proposed insights into channel dynamics under high Q_w and Q_s conditions have important implications for deltaic channel-island exchange. As vegetation may reduce fluxes between channels and islands (e.g. Nardin and Edmonds, 2014), vegetation's effectiveness at channelizing flow under different sediment and water discharge conditions, and vegetation's tendency to remain established outside of channels even under high Q_w and Q_s conditions, will affect sediment and nutrient fluxes to islands (Hiatt and Passalacqua, 2015). On a larger scale, a shift from more lobate delta growth with low Q_w to more fan-like growth with high Q_w has implications for the delivery of sediment and nutrients across the entire delta through potential changes in network connectivity (e.g. Tejedor et al., 2016; Passalacqua, 2017). These implications will be particularly important for restored or engineered deltas, which are subject to natural delta processes after initial construction (Paola et al., 2011), or for diversions with controlled water and sediment discharges. If restoration efforts aim to build new deltaic land, they will need to consider the implications of discharge and sediment load on channel network configuration and dynamics, including the influence of vegetation.

Acknowledgements

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	f_{sand} (%)	Q_w (m^3/s)	Q_s (m^3/s)	N_0	# of timesteps	dt (hrs)	Time (years)
LWLS	50	1000	0.5	4	5000	≈ 11	≈ 230

LWMS	50	1000	1	4	5000	≈ 5.5	≈ 115
LWHS	50	1000	2	4	5000	≈ 3	≈ 60
HWLS	50	2000	0.5	8	1250	≈ 44	≈ 230
HWMS	50	2000	1	8	1250	≈ 22	≈ 115
HWHS	50	2000	2	8	1250	≈ 11	≈ 60

Table 1. Experimental setup. Experiments are run with and without vegetation.

Table 2. Data for individual triplicate model simulations used to obtain averaged values presented in Figure 1. Shoreline roughness and number of channels are averaged over the second half of the model simulation and presented with standard deviation. LWHSv1 and 2 have no values for *M*. Both modeled deltas formed lobes to the left side of the model domain during the first half of the run, leaving a large embayment on the right side which fills in during the second half of the run (Figure S1). Because M is calculated only considering channels that were within the delta area at the halfway point of the model run, and for the second half of the runs channels are concentrated on delta area that did not exist at that time, we do not include these values. LWHSv2 has no value for *R* because the Python Scipy tool "optimize curve fit" failed to find a solution to fit an exponential decay function to the data. This is probably because there was not enough data, for the same reason as we could not calculate *M* for LWHSv2.

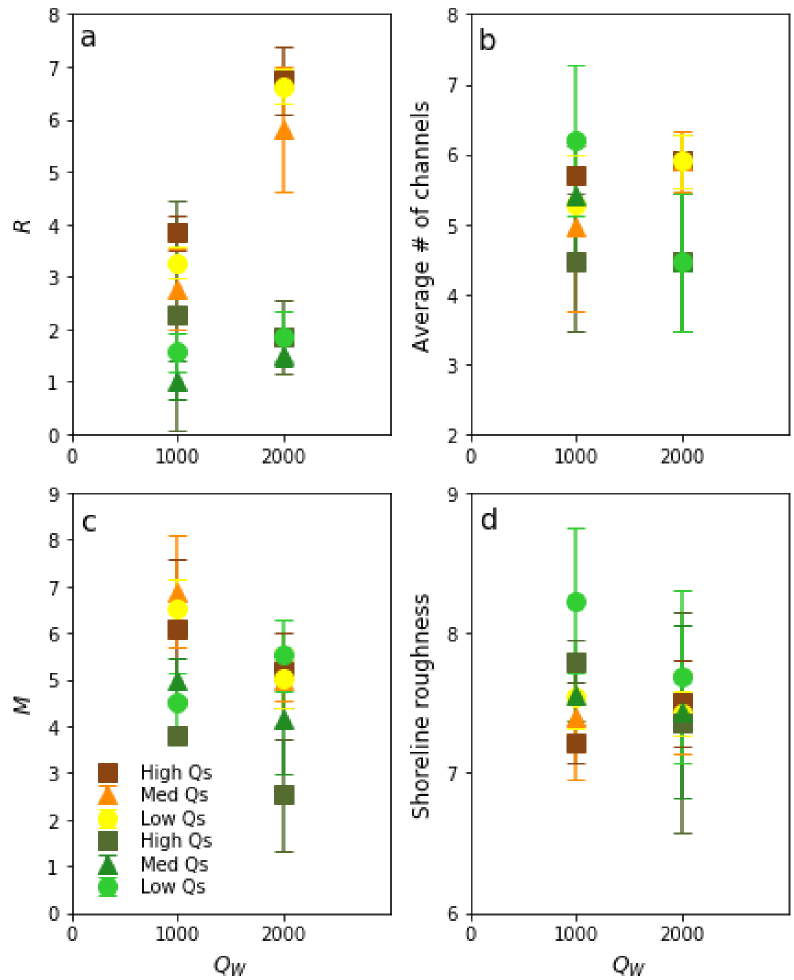

Figure 1. a) R (the rate of decay in remaining delta surface unreworked by the channel network), b) average number of channels, average over the second half of the run and counted along the arc of a semicircle with 2/3 of the delta's area c) M (the rate of decay in channel planform overlap), d) shoreline roughness (measured as shoreline length divided by the square root of delta area). Panels are plotted against Q_w, with Q_s represented by increasingly dark shades of orange (for unvegetated deltas) and green (for vegetated deltas). In panel c, there is only one value of M and 2 values of R for the $Q_w = 1000$, $Q_s = 2$ vegetated condition (explanation found in Table 2 and Figure S1).

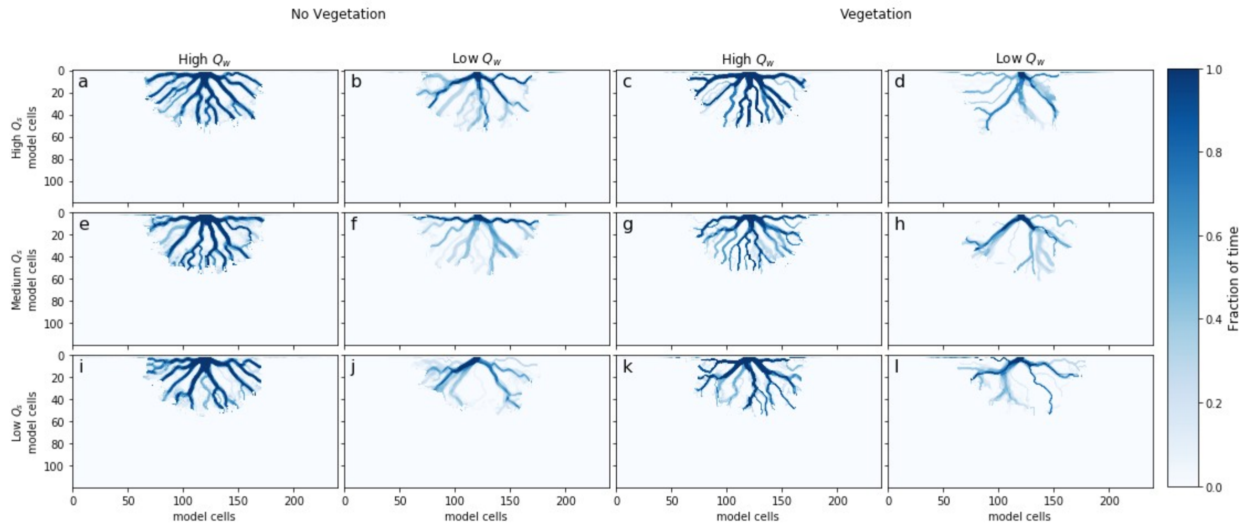

Figure 2 – Maps of the fraction of time any cell which is part of the channel network during the second half of the run remains part of the channel network. Cells with a value of zero are never channels, and cells with a value of 1 are always channels. For the top row (a–d) $Q_s = 2$ m^3/s, for the middle row (e–h) $Q_s = 1$ m^3/s and for the bottom row (i–l) $Q_s = 0.5$ m^3/s. The first two columns are unvegetated runs and the third and fourth are vegetated. The first and third columns have $Q_w = 2000$ m^3/s and the second and fourth have $Q_w = 1000$ m^3/s.

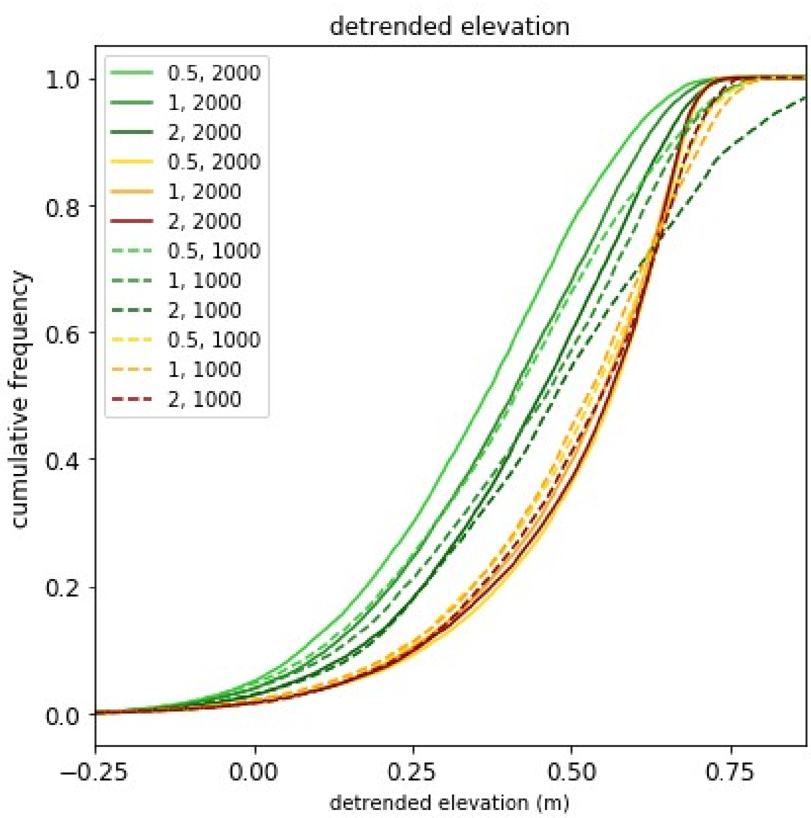

Figure 3. Cumulative distribution function of detrended subaerial delta elevations, averaged across triplicate runs. Shades of green represent vegetated deltas and orange/brown represents unvegetated deltas. Dashed lines are low Q_w and solid lines are high Q_w. Darker colors represent higher Q_s. Legent reads Q_s, Q_w.

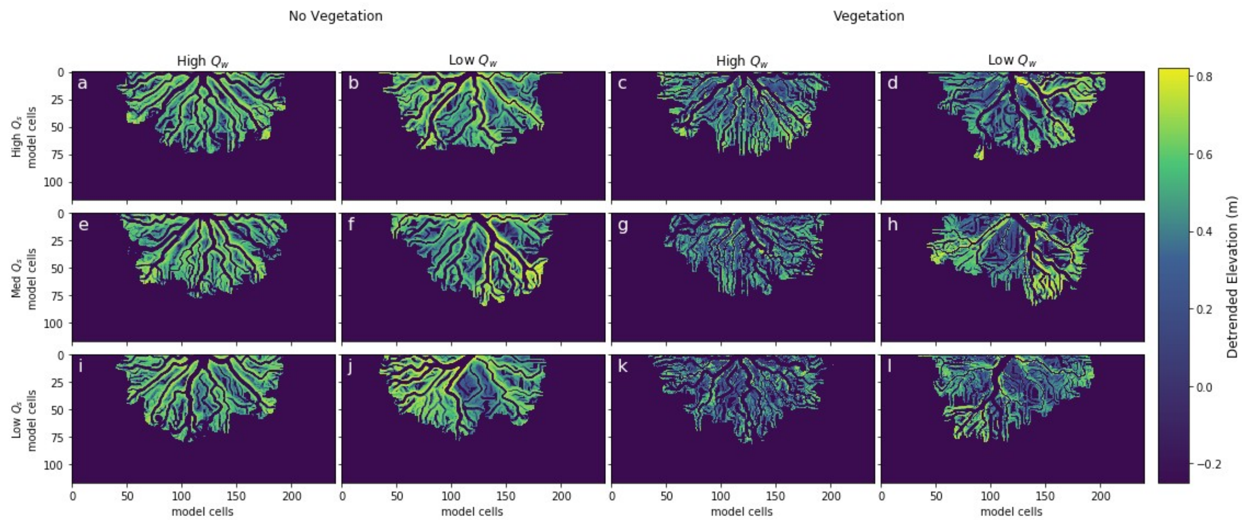

Figure 4 – Maps of the detrended elevations of each land cell within the delta area at the last timestep of the model simulation. For the top row (a–d) $Q_s = 2$ m^3/s, for the middle row (e–h) $Q_s = 1$ m^3/s and for the bottom row (i–l) $Q_s = 0.5$ m^3/s. The first two columns are unvegetated runs and the third and fourth are vegetated. The first and third columns have $Q_w = 2000$ m^3/s and the second and fourth have $Q_w = 1000$ m^3/s. All are examples from individual model simulations (not averaged).

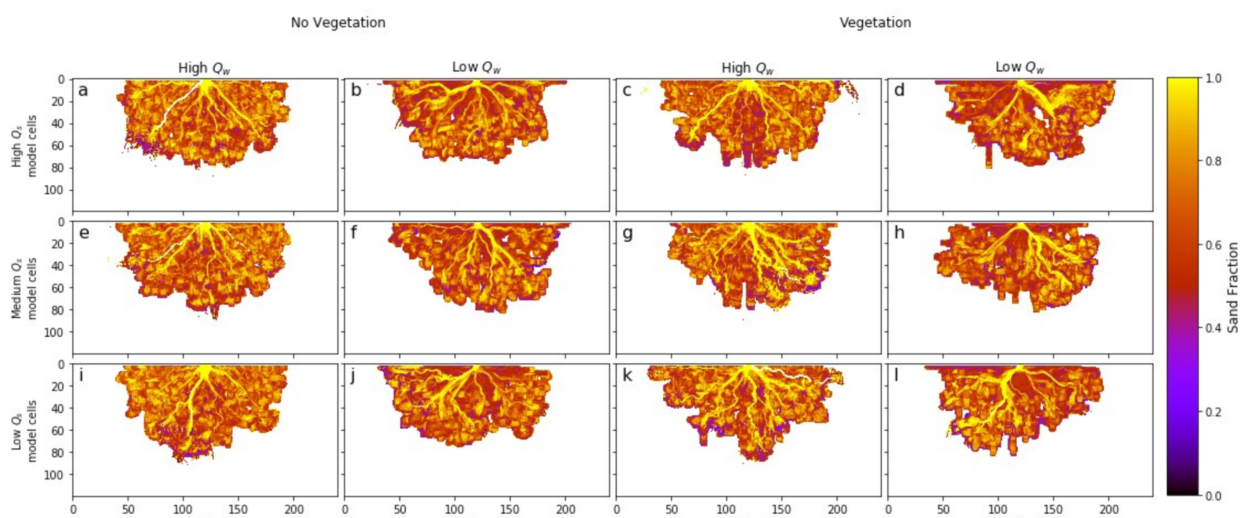

Figure 5 – Maps of vertically average fraction of sand present in each cell of the model grid near the end of the model run. Cells with a value of zero contain only mud, and cells with a value of 1

contain only sand. For the top row (a–d) $Q_s = 2$ m^3/s, for the middle row (e–h) $Q_s = 1$ m^3/s and for the bottom row (i–l) $Q_s = 0.5$ m^3/s. The first two columns are unvegetated runs and the third and fourth are vegetated. The first and third columns have $Q_w = 2000$ m^3/s and the data shown is from t = 1250 and the second and fourth have $Q_s = 1000$ m^3/s and the data shown is from t = 4750.

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