AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL077638

*Major Topic or Scientific Question: What makes a delta tide-dominated?
*New Scientific Knowledge: New tide-dominance theory quantitatively relates discharge and tides to the morphology of tide-dominated deltas
*Broad Implications: New theory can be used to assess long-term changes to river deltas driven into an uncertain future

Key Points:
- We propose a new tide-dominance ratio T that quantitatively and a priori defines tide-dominated deltas and predicts their morphology
- We test our new tide-dominance ratio on 72 river deltas and alluvial estuaries globally and find good correspondence
- We use the tide-dominance ratio to assess long-term morphologic change to river deltas caused by river discharge reductions

Supporting Information:
- Supporting Information S1
- Data Set S1

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Citation:
Nienhuis, J. H., Hoitink, A. J. F., & Törnqvist, T. E. (2018). Future change to tide-influenced deltas. *Geophysical Research Letters*, *45*, 3499–3507. https://doi.org/10.1029/2018GL077638

Received 21 FEB 2018
Accepted 1 APR 2018
Accepted article online 12 APR 2018
Published online 22 APR 2018

Future Change to Tide-Influenced Deltas

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Abstract Tides tend to widen deltaic channels and shape delta morphology. Here we present a predictive approach to assess a priori the effect of fluvial discharge and tides on deltaic channels. We show that downstream channel widening can be quantified by the ratio of the tide-driven discharge and the fluvial discharge, along with a second metric representing flow velocities. A test of our new theory on a selection of 72 deltas globally shows good correspondence to a wide range of environments, including wave-dominated deltas, river-dominated deltas, and alluvial estuaries. By quantitatively relating tides and fluvial discharge to delta morphology, we offer a first-order prediction of deltaic change that may be expected from altered delta hydrology. For example, we expect that reduced fluvial discharge in response to dam construction will lead to increased tidal intrusion followed by enhanced tide-driven sediment import into deltas, with implications for navigation and other human needs.

Plain Language Summary Due to global-scale construction of reservoirs and direct water withdrawal for irrigation, river discharge peaks that feed deltas are in many cases diminishing. Here we introduce a simple theory to estimate the response of tide-influenced deltas to river discharge change. First, we show that our theory successfully predicts the magnitude of downstream channel widening, a hallmark of tide-dominated deltas. Reduced river discharge leads to import of sediment by tides, reducing the water volume within a delta. Our work can help predict long-term delta change and inform engineering and restoration projects to enhance delta resilience.

1. Introduction

River delta morphology results from an intricate balance between fluvial and marine processes (Galloway, 1975; Orton & Reading, 1993). Natural and human-induced changes can upset this balance and induce persistent morphologic adjustments that may lead to inundation and erosion hazards. Predictions of future delta morphology are therefore vital. However, any accurate prediction of delta change requires a firm understanding of delta morphology itself. What makes a delta have the shape it has today? How do tides or waves affect delta shape?

Following recent work that provided a prediction of the shape of wave-dominated deltas (Nienhuis et al., 2015), we here propose a relationship between tides and delta morphology. Although the impact of tides on deltas is multifaceted, their first-order morphologic effect is channel widening (Figure 1; Langbein, 1963; Wright et al., 1973). We hypothesize that if the tidally driven discharge is much larger than the fluvial discharge, the delta is tide-dominated and channels should widen downstream. We provide a simple method to predict the magnitude of deltaic channel widening that we test using a selection of 72 deltas globally. We then apply our method to investigate potential changes in delta morphology due to river discharge changes.

2. Background

River deltas form where fluvial sediment carried by the river settles near the river mouth in a lake, bay, or ocean. Tides exert a strong control on coastal water levels, and tidal waves can propagate upstream and alter the hydrology and sediment transport of deltaic channels (Godin, 1985; Savenije, 2012). The channel morphology of alluvial estuaries and tide-influenced deltas is therefore distinct from nontidal rivers. Grain size tends to decrease landward, as tidal flow weakens, but then increases again upstream into the fluvial portion of the delta (Dalrymple & Choi, 2007). The temporal and spatial scales of these processes vary greatly between different systems, but for large, low-gradient rivers tides can modulate sediment transport as far as 1,000 km upstream (Hoitink & Jay, 2016).

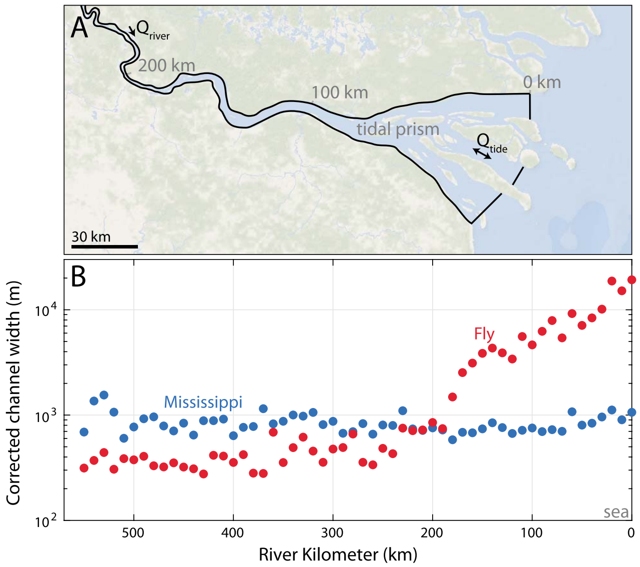

Figure 1. Channel width as an indicator of tidal influence. (a) The Fly Delta with its channel banks outlined. (b) The width (corrected for the number of major distributary channels) of the Mississippi River and the Fly River between the river mouth and 550 km upstream.

By affecting sediment transport, tides can alter delta morphology and stratigraphy. Studies of tide-dominated delta morphology typically approach the topic either from an alluvial estuarine perspective, constrained by the channel width and with only a reduced morphologic flexibility (e.g., Bolla Pittaluga et al., 2015; Sassi et al., 2012; Todeschini et al., 2006), or from a delta geology perspective, typically greatly simplifying tidal processes but allowing tidal channels to self-form and migrate (e.g., Fagherazzi, 2008; Geleynse et al., 2011).

From an alluvial estuarine perspective, empirical and theoretical studies have found that the cross-sectional area of an estuarine channel with no fluvial discharge scales with the tidal prism (D'Alpaos et al., 2010; Langbein, 1963). This observed scaling explains why estuaries generally widen downstream. Downstream widening has also been observed in estuaries with significant fluvial discharge (Langbein, 1963; Wright et al., 1973), although no straightforward scaling law exists (Sassi et al., 2012). Trends in the width of distributary channels show similarities to trends in tidal prism and channel depth (Kästner et al., 2017; Sassi et al., 2012).

To explain trends in estuarine channel depths, Bolla Pittaluga et al. (2015) used a morphodynamic model of an idealized alluvial estuary. They showed that the equilibrium estuarine channel-bed slope increases with decreasing fluvial discharge, increasing grain size, and increasing fluvial sediment concentration. A steep channel-bed slope limits the estuary length and the tidal prism. Sassi et al. (2012) studied the Mahakam Delta in Indonesia with a hydrodynamic model and found that channel widening occurred when the tidally driven discharge exceeded the fluvial discharge. However, neither of these studies considered the morphologic adjustment of the channel width. We are not aware of any predictive model of delta channel width, even though channel width is one of the primary characteristics of a deltaic system.

From a delta geology perspective, tides are often grouped with the river discharge and waves as the three major morphological controls on deltas (Galloway, 1975). Morphologically, tides tend to widen delta distributary channels and also keep relict fluvial channels open after a fluvial avulsion, resulting in generally more distributary channels than their wave- and river-dominated counterparts.

The Fly Delta (Figure 1a) is considered an end-member tide-dominated delta in the classification of Galloway (1975). However, it is unclear from Galloway's initial analysis why the Fly Delta morphology is considered to be tide-dominated, or how much a delta would have to change to transition from a wave- or river-dominated regime to a tide-dominated regime. Previously used metrics to rate tidal influence include tidal range (Fisher, 1969) and tidal power (Baumgardner, 2015; Harris et al., 2002), but they are not predictive; there is no quantifiable delta attribute associated with a particular magnitude of tidal range or tidal power, and therefore, they cannot be used to predict delta change.

Recently, Nienhuis et al. (2015) cast the transition from river to wave dominance into a sediment flux ratio that predicts the shape of wave-dominated deltas. Here we propose an analogous method to predict the shape of tide-dominated deltas, casting the transition from river to tide dominance on the delta planform into a water discharge ratio that predicts channel widening due to tides. An a priori prediction of the effect of tides on deltas adds an important constraint to generally poorly understood questions about deltaic environments such as long-term future changes in response to the construction of reservoirs, or the interpretation of ancient deltas from the stratigraphic record.

3. Predicting Channel Width

In this study we hypothesize that if the mean annual fluvial discharge (Q_{river}, m^3/s) is much larger than a characteristic tidal discharge amplitude at the river mouth ($\widehat{Q}_{tide}$, m^3/s, where the circumflex denotes amplitude), the channel should not significantly widen downstream (e.g., Mississippi River; Figure 1b). If, on the other hand, $\widehat{Q}_{\text{tide}} \gg Q_{\text{river}}$, tides would shape the fluvial channel into an alluvial estuary, with a characteristic river-mouth width that is much larger than the upstream channel width (e.g., Fly River; Figure 1b) because both tidal and fluvial discharges are expressed in the channel width (Langbein, 1963). We define the tide-dominance ratio T as

$$T = \frac{\widehat{Q}_{\text{tide}}}{Q_{\text{river}}}. \tag{1}$$

A delta is predicted to be tide-dominated if the characteristic tidal discharge amplitude at the river mouth is greater than the fluvial discharge. An end-member tide-dominated delta is an alluvial estuary with negligible fluvial influence ($T = \infty$) but with a self-formed width (i.e., not an underfilled "drowned" river valley). T is strongly related to the Canter-Cremers estuary number, the ratio between fresh and saline water discharge in an estuary (Savenije, 2012).

In the absence of tides ($T = 0$), the discharge upstream of the delta should be roughly equal to the discharge at the river mouth at any given time, resulting in a roughly constant channel width. If $T = \infty$, the discharge at the river mouth is fully controlled by tides, and the cross-sectional area should depend on the tidal prism (D'Alpaos et al., 2010; Stive & Rakhorst, 2008). At $T = 1$, the tidal discharge has the same order of magnitude as the fluvial discharge. There may not be a depth-averaged reversal of the flow at the mouth, but the channel will still experience some widening.

We relate delta morphology to the tide-dominance ratio T via the tidal prism P, defined as Q_{tide} integrated over an ebb tide. Fundamentally, our method is based on sediment transport, where the cross-sectional area of a tidal or fluvial channel is determined by the tidal prism or river discharge such that there is no net erosion or deposition. In the case of both tidal and fluvial discharge, we assume that the widening of the channel compared to the upstream fluvial channel is due to the tidally driven discharge. We quantify this addition by

$$A_m - A_u = kP, \tag{2}$$

where A_m is the cross-sectional area of the river mouth (m^2); A_u is the upstream cross-sectional area of the river (m^2); $k = \omega\left(\sqrt{\Theta_s D_{50}} RC\pi\right)^{-1}$ (m^{-1}), where ω is the tidal angular frequency (s^{-1}); Θ_s is the critical Shields number for sediment motion; D_{50} is the median grain size; R is the submerged specific gravity of sediment; C is a Chézy roughness coefficient; and P is the tidal prism (m^3; D'Alpaos et al., 2010; Gerritsen et al., 1991; Stive & Rakhorst, 2008). The proportionality coefficient k relates the tidal prism to an equilibrium cross-sectional area that will neither erode nor aggrade and is therefore dependent on grain size, Shields stress, and flow roughness (Stive & Rakhorst, 2008).

We assume the that aspect ratio of the channel is independent of T and define $\beta = w/d$, where w is the channel width and d is the channel depth, making $A = w^2/\beta$. Using β, we then relate the river-mouth width w_m (m) and the fluvial channel width w_u (m) to the tidal prism,

$$\left(w_m^2 - w_u^2\right)/\beta = kP. \tag{3}$$

Because the tidal prism is related to channel surface area, we can obtain a closed-form expression of the river-mouth width. Arguably, the simplest relationship between offshore tidal range and the dimensions of an estuary assumes a plan view funnel shape that is roughly trapezoidal in shape (Figure 2a). The tidal prism is the surface area of the tidally influenced reach times the tidal range (Savenije, 2012; Wright et al., 1973). The tidal prism is approximated as

$$P = 2\cdot a\cdot A_e = 2\cdot a\cdot\frac{1}{2}(w_m + w_u)\cdot L, \tag{4}$$

where a is the offshore tidal amplitude (m), A_e is the surface area of the estuary (m^2), and L is a characteristic estuarine length scale (henceforth estuary length) for long-wave propagation in a distributary channel (m). We estimate the estuary length as the upstream channel depth (d_u) divided by the delta channel slope (S), $L = d_u/S$. Alternative estuary length estimates have been published (e.g., Prandle, 2004; van Rijn, 2011), but those studies assume tide dominance and are therefore inappropriate to predict whether or not a delta is tide-dominated.

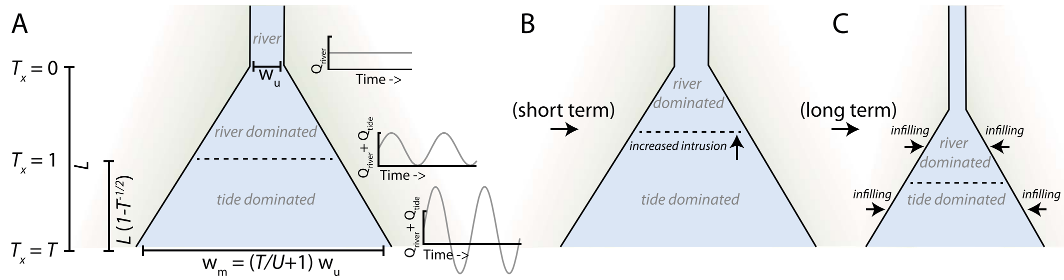

Figure 2. Schematic tide-dominated delta ($T > 1$) with (a) the estuary length (L), the along-channel tide-dominance ratio (T_x), the predicted channel width, and schematized discharge time series. (b) Hydrologic (short-term) response to a river discharge decrease. (c) Morphologic (long-term) response to a river discharge decrease.

Combining (3) and (4), we obtain a simple prediction of the river-mouth width,

$$w_m = \beta \cdot k \cdot a \cdot L + w_u, \tag{5}$$

and a prediction of the tidally driven discharge amplitude $\widehat{Q}_{\text{tide}}$ in the case of a single dominant tidal constituent,

$$\widehat{Q}_{\text{tide}} = \frac{1}{2}\omega \cdot P = \frac{1}{2}\omega\, ka^2L^2\beta. \tag{6}$$

Equation (5) can also be cast into a simple relation for the channel-width ratio,

$$\frac{w_m}{w_u} = \frac{k \cdot a}{S} + 1, \tag{7}$$

that can be rewritten to highlight its dependence on the tide-dominance ratio T,

$$\frac{w_m}{w_u} = \frac{T}{U} + 1, \tag{8}$$

where U quantifies the strength of the tidal flow relative to the fluvial flow,

$$U = \frac{\frac{1}{2}\omega \cdot a}{S \cdot u_{\text{river}}}. \tag{9}$$

The product $½\omega \cdot a/S$ is a characteristic velocity scale for the tidal motion (Wei et al., 2016), and u_{river} is the fluvial flow velocity, defined as $Q_{\text{river}} \cdot \beta / w_u^2$ (m/s). U therefore is a nondimensional velocity scale.

For tide-dominated deltas, where T exceeds unity, we can extend our theory spatially from the mouth into the estuary. Along the channel, Q_{river} remains the same but $\widehat{Q}_{\text{tide}}$ will be progressively reduced (Figure 2a). Within our highly idealized estuary, the tidally affected reach extends from the mouth (where $T_x = T$) up to the distance L (where $T_x = 0$). We predict that tidal intrusion and flow reversal occur up to a distance $L\,(1 - T^{-½})$ from the river mouth, at which $T_x = 1$ (Figure 2a). Note that this prediction is sensitive to the geometry of the estuary, which in reality deviates from our assumed trapezoidal shape.

4. Testing the Prediction

Key to our formulation of the tide-dominance ratio is that it provides a prediction of the river-mouth width that we can test in the real world and apply to predict delta change. We tested our prediction on 72 deltas distributed globally, 44 of which obtained from Syvitski and Saito (2007) that were supplemented with 28 additional, mostly smaller, deltas (see Table S1). Coastal morphology ranges from small wave-dominated strandplains (e.g., Waipaoa River, NZ) to alluvial estuaries (e.g., Thames River, UK) to river-dominated deltas (e.g., Mississippi River, USA).

We measured the river channel width upstream (w_u) of its distributary network (if present) where it assumes a roughly constant width (e.g., ~250 km for the Fly River; Figure 1b). We also measured the river-mouth width (w_m), which we define as the most downstream location where the width still increases gradually and the banks are self-formed (Figures 1 and S1). For deltas with multiple distributary channels, the sum of the

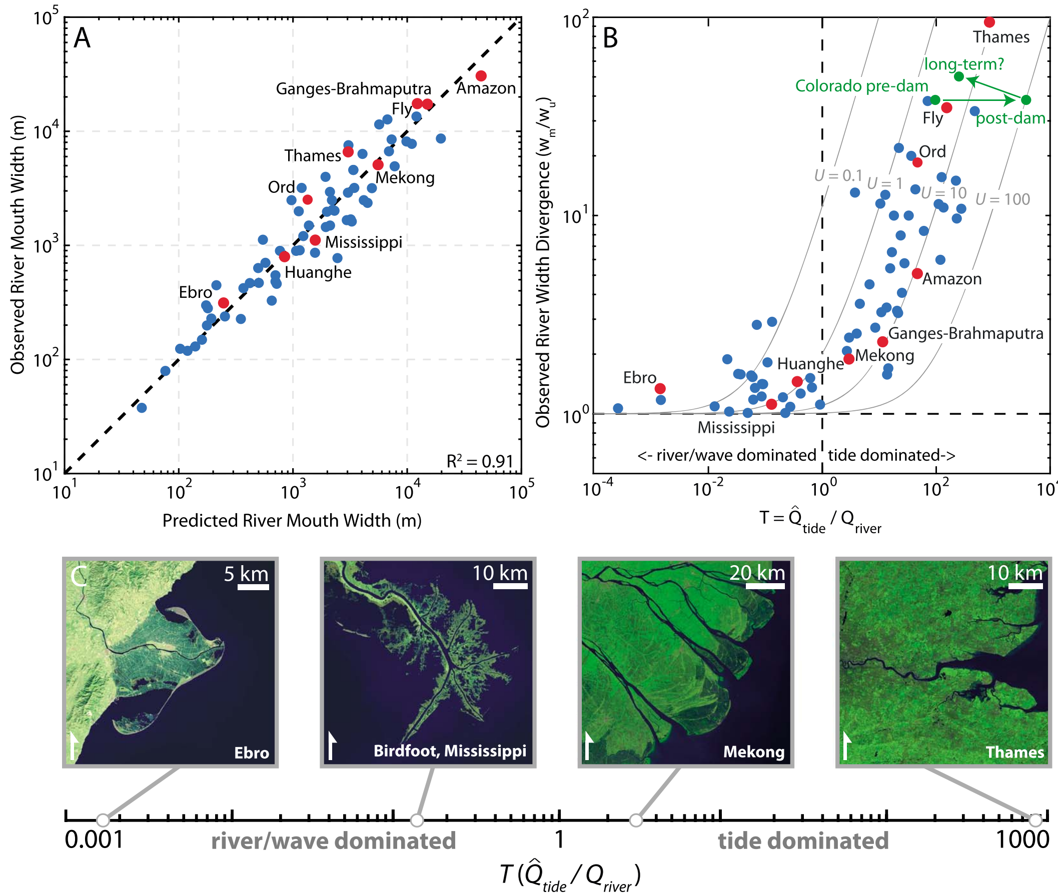

Figure 3. Tests of the new tide-dominance ratio showing (a) the predicted river-mouth width (equation (5)) compared to the observed river-mouth width corrected for bifurcations. (b) The observed river-mouth width divergence compared to the predicted tide-dominance ratio T. The trend lines follow the predicted channel width divergence for a specific value of U (equation (8)). The green arrows indicate the predicted trajectory of the Colorado Delta in response to a decrease in river discharge. (c) The tide-dominance ratio T calculated for a selection of well-known deltas.

channel-mouth widths is greater than the upstream channel width even without tides, simply because channel widths tend to scale with discharge to about one half power (Langbein, 1963). In order to focus on the effect of tides on channel width divergence, we estimated the single distributary channel width as the sum of all distributary channel widths multiplied by $n^{-0.5}$, such that $w_m = n^{-\frac{1}{2}}\sum_{i=1}^{n} w_i$, where n is the number of distributary channels. We estimated the upstream channel depth d_u following hydraulic geometry rules based on the mean annual discharge (Mikhailov, 1970).

We retrieved tidal and predam fluvial characteristics from data published by Syvitski and Saito (2007) supplemented by WBMSed (Cohen et al., 2013) and TOPEX (Egbert & Erofeeva, 2002). Delta channel slopes were measured using SRTM data (Farr et al., 2007; see Text S1 and Figure S2 for details). We used an aspect ratio $\beta = 100$, a Shields number of 0.2, a grain size of 100 μm, a Chézy roughness coefficient of 55, and a submerged specific gravity for sediment of 1.65. These numbers are representative for coastal environments (Stive & Rakhorst, 2008).

We find that our simple river-mouth width estimate is a remarkably good approximation of the observed river-mouth width (Figure 3a). The data show no systematic bias, not even for widths that diverge more than 2 orders of magnitude from the upstream width. Translating our prediction into the ratio T, we find that it provides a first-order estimate of the delta morphology (Figure 3). For $T < 1$, deltas are expected to be river or wave-dominated and the river-mouth width tends toward the upstream width, but there is some predicted widening even for $T < 1$ if $\widehat{Q}_{tide} > 0$. For $T > 1$, the delta is predicted to be tide-dominated, and we observe that the widths diverge. The amount of channel width divergence for a given tide-dominance

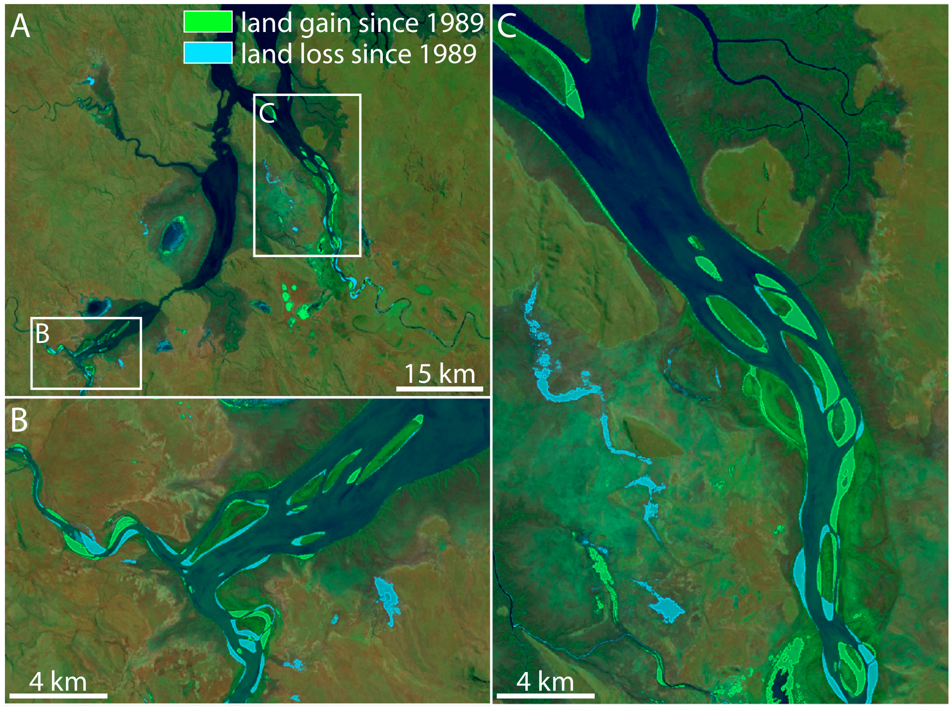

Figure 4. Land area change in the alluvial estuaries of the Ord River between 1989 and 2016. (a**)** Overview of the lowermost reach of the west and east arms of the Ord River, highlighting the difference between the **(b)** relatively stable undammed west arm and (c) infilling of the dammed east arm. Data from aquamonitor.deltares.nl (Donchyts et al., 2016). See also Wolanski et al. (2001).

ratio T also depends on the ratio of the characteristic tidal flow velocity and the river flow velocity, U, although this varies significantly less than T among the different deltas.

5. Application to Changing Deltas

Climate change and human impacts such as the construction of reservoirs as well as direct water withdrawal are expected to significantly decrease the river discharge feeding many of the world's deltas, especially densely populated deltas (Haddeland et al., 2014). By coupling river discharge and upstream channel dimensions to delta morphology, the theory presented herein can be applied to investigate potential future changes to modern deltas.

For example, the tide-dominated Colorado Delta in Mexico has lost more than 95% of its fluvial discharge in the last 100 years (Carriquiry & Sánchez, 1999). On short timescales (years) delta morphology (channel width) remains unchanged such that a 95% decrease in fluvial discharge results in a 27-fold increase in the tide-dominance ratio T. Without any changes in w_m and w_u, the increase in the tide-dominance ratio will lead to a landward extension of tidal dominance (Savenije, 2012; Figure 2b, first green arrow of Figure 3b).

Over longer timescales (decades to centuries) delta morphology will adjust, and analyses such as the one presented here can help to estimate potential changes. Assuming discharge will remain negligible in the Colorado River, the upstream channel depth and width will decrease to a new equilibrium that can be estimated using well-established hydraulic geometry relationships (Mikhailov, 1970). We estimate that the upstream adjustment of the Colorado will trigger estuary infilling that leads to a sevenfold decrease in the tidal prism, and an ~2 km narrowing of the river mouth due to deposition (Figure 3b). Estuary infilling can also result from land reclamation and the loss of coastal wetlands. A lower tidal prism and tidal discharge $\widehat{Q}_{\text{tide}}$ will cause siltation and a subsequent decrease in channel area (Dai et al., 2016; Figure 2c).

Even for modest changes in mean annual river discharge, dam construction can have major implications for tide-influenced deltas because of the attenuation of fluvial floods. In a natural setting, tide-dominated deltas export sediment out of the estuary under high river discharge conditions and import sediment under low flow conditions (Hoitink et al., 2017). Decreasing flood discharge therefore leads to increasing periods of tidally driven sediment import and estuary infilling, such as observed in the Ord River in Australia (Wolanski et al., 2001; Figure 4). The recent developments near the mouth of the East Arm of the Ord River illustrate that these adjustments can take place within a lifetime. Whereas the neighboring West Arm estuary with little human interference has witnessed no large-scale adjustments, the estuary of the East Arm experienced a 50% reduction of the channel surface area within 30 years after dam construction, due to the suppression of large floods (Wolanski et al., 2001; Figure 4). This rapid response is likely due to the fact that the tidal range in the Ord can reach 8 m during low flows, when sediment import into the delta is largest. With smaller tides, morphologic adjustment to altered discharge regimes may take longer.

Other changes to deltas, such as an increase in mean discharge, will in the short term lead to increased flooding and a seaward movement of the point of flow reversal (lower T; Savenije, 2012). Over longer timescales, a discharge increase will lead to bank erosion to restore morphologic equilibrium. However, there could be hysteresis in the width adjustment to increasing and decreasing fluvial discharge such that a more sophisticated model would be necessary.

6. Discussion and Conclusions

We present and test a simple predictive theory of tidal influence on delta morphology and delta change. Our two metrics use equilibrium relationships to connect channel widening to the ratio of tidal to fluvial discharge, which for tide-dominated deltas is greater than one (Figure 3b). In general, the expressions obtained for the river-mouth width and the tidal discharge capture the well-known forcing factors controlling delta morphology (Galloway, 1975). For small tidal amplitudes, the river-mouth width tends toward the upstream width (equation (7)). For increasing tidal amplitude there is an increased tidal prism and tidal discharge. Higher fluvial discharge results in less channel divergence and reduced tidal intrusion for a similar tidal amplitude.

Aside from future changes to deltas, our new analysis can support paleoenvironmental reconstructions by relating a paleo-tidal range and channel width to delta morphology. Although we present our analysis in terms of the river-mouth width, it can be applied anywhere along the length of an estuary to provide a simple indication of along-estuary tidal discharge in poorly constrained environments (Figure 2). Such longitudinal applications can also support paleoenvironmental reconstructions based on bed form orientations, ichnofacies, and paleo-slopes from the stratigraphic record (Dalrymple & Choi, 2007).

Additionally, even though channel width divergence is only one aspect of delta morphology, other delta properties such as the number of distributary channels may covary with the tide-dominance ratio proposed here. For example, cast in terms of channel width, we find that the morphologic transition from tide to river dominance is smooth. There is no tipping point in delta morphology around $T = 1$, in contrast with wave dominance, which is morphologically straightforward to distinguish from river- and tide-dominated delta morphology (Nienhuis et al., 2015). Additionally, whereas wave dominance is mostly associated with smaller deltas (Nienhuis et al., 2015), strongly tide-influenced morphologies appear even in the world's largest deltas, such as the Amazon, Yangtze, and Mekong. A relationship between delta size and tide dominance is likely to occur because the low channel slope that characterizes large rivers leads to a larger tidal prism.

Finally, the metrics proposed here can help to scale laboratory deltas. We speculate that laboratory deltas develop toward wave or river dominance even for high tidal "power" (e.g., Baumgardner, 2015) because of their steep slopes. Tidal power scales with slope to the -1 power (Baumgardner, 2015), whereas our estimate of tidal discharge scales with slope to the -2 power.

This simple theory for tidal effects on deltas depends on parameters such as β, S, and k whose estimation can be inexact. We anticipate uncertainties in channel width predictions of at least a factor of two. Because of these uncertainties we choose a simple formulation for the tidal prism, which assumes a constant tidal amplitude, no significant intertidal area, and a trapezoidal width convergence along the estuary. More complex formulations for the tidal prism exist (e.g., Savenije, 2012), but their application would prohibit an intuitive analytical solution, which is one of the advantages of our theory. We also neglect potential leakage of tidal and fluvial discharge through nonchannelized parts of the delta, which can be significant but for which no general theory exists (Day et al., 2008; Hiatt & Passalacqua, 2015).

Additionally, we stress that while our theory should only be applied to self-formed (alluvial) river mouths and not to drowned/under-filled valleys, these two coastal morphologies can sometimes be difficult to tell apart. For example, model calculations and the existence of two pre-Holocene interdistributary islands suggest the possibility that the Fly Delta is a drowned valley with a channel width inherited from the last sea level low-stand (Dietrich et al., 1999). However, many of the other interdistributary islands in this delta are alluvial (Dietrich et al., 1999), such that the fundamental assumption underlying hydraulic geometry is still met. Regardless of whether or not our theory works for a particular delta, it can serve as a valuable initial hypothesis on the processes shaping its gross morphology.

In conclusion, the tide-dominance ratio T and tidal flow ratio U provide a first-order estimate of delta morphology that can be applied globally and can unite modern deltas with ancient systems and experimental studies. This simple analysis can also be used to test more complex numerical models of river deltas. Predictions of steady state delta shape are a necessary first step toward predicting morphologic change and show that altered river discharge regimes can have far-reaching and long-lasting consequences for tidal intrusion and river delta morphology. In particular, the global-scale decrease of river discharge will likely result in increased tidal intrusion and an enhanced sediment import into deltas, with significant implications for coastal environments and navigability of the world's deltas.

Acknowledgments
All data collected for this study are available in Table S1. We gratefully acknowledge constructive reviews of Paola Passalacqua, Brad Murray, and two anonymous reviewers.

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