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Effect of tides on stability of bifurcations in river deltas

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ABSTRACT: In river channel networks, the sediment transport division determines the morphodynamic development of bifurcations. In sand-bed systems, avulsion often occurs, meaning asymmetric division of sediment transport until one branch closes off. In contrast, it has been claimed that bifurcations in tidal deltas tend to be stable such that both downstream channels keep conveying a major portion of the water. In this study, we investigate the effect of tides on stability of river bifurcations. A schematized bifurcation was built in a 1D morphodynamic model, with one upstream channel that splits into two downstream channels. The system is driven by river discharge upstream and symmetrical tidal water level variation from downstream channels. The model was validated against Delft3D in 2DH mode and yielded similar morphological evolution in much shorter time. Subsequently, the 1D model was used to study the morphological stability of bifurcations for a wide range of Shields values, width-to-depth ratios and relative role of tidal forcing over river forcing. We found that tides increase the range Shields stress and width-to-depth ratios for which for a stable bifurcation can be found for increasing tidal dominance. This is because the tide-induced changes of water depth and flow velocity cause a time dependent stability condition. The duration and growth rate of the bed level asymmetry during each condition determine the stability of the bifurcation. Due to the tides the bifurcation is going through periods of stable and unstable conditions, but tidally averaged the bifurcation is stable for a wider range of Shields numbers and width-to-depth ratios. This explains why avulsions are rarely observed in tide-influenced deltas.

1 INTRODUCTION

Unstable bifurcations are often observed in river systems, meaning that one downstream branch of a bifurcation is shallowing while the other enlarges and deepens. Several studies have been conducted to understand this process, pioneered by Wang et al. (1995) for gravel bed rivers and Slingerland & Smith (1998) for sand bed rivers. Bolla Pittaluga et al. (2003) expanded the work of Wang et al. (1995) by introducing a physical based sediment division at bifurcation, which determines the stability of bifurcations in gravel beds. They showed that the stability of bifurcation depends on the Shields number at the bifurcation and the width-to-depth ratio of the upstream channel. Bolla Pittaluga et al. (2015) extended the work of Bolla Pittaluga et al. (2003) to sand and gravel bed rivers. Their linear analysis suggested that unstable bifurcations occur for systems with either constant high or low Shields stress at the bifurcation, while only a limited range of intermediate Shields stresses may result in stable bifurcations.

In tidal systems, bifurcations were claimed to be stable for a wider range of conditions (Hoitink et al., 2017). However, it is not a simple hypothesis to test. The stability theory proposed for river bifurcations cannot directly be applied to tide-influenced bifurcations because tides cause a changing flow magnitude and even direction at the bifurcation, which changes the role of one of the bifurcated downstream branches into an upstream channel, or changes the bifurcation into a confluence. In this contribution, we extended the 1D-models of river-

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bifurcations to tide-influenced systems by allowing for changing flow magnitude and direction at the bifurcation. We investigated the stability of bifurcations for systems that have a mixed tidal and fluvial forcing.

2 METHODS

A schematized bifurcation was built in a one-dimensional (1D) morphodynamic model, with one upstream channel that splits into two downstream channels. The system is forced by river discharge upstream and tidal water level variation from downstream channels. In this study, we defined a straight channel and prescribed a gentle channel slope that is typical for deltaic sand-bed rivers ($3x10^{-5}$ m/m). The upstream channel length is 80 km while the downstream channels are 3 km. This length is sufficient to let the river discharge dampen the tides smoothly.

The hydrodynamics along each channel was computed from the principles of mass and momentum balance using Saint-Venant equations. To compute the sediment transport along the channel, the sediment transport equations by van Rijn (1984a) and van Rijn (1984b) were used. Meanwhile, to compute the sediment distribution at the bifurcation, the nodal point relationship, partitioning the sediment, of Bolla Pittaluga et al. (2015) was extended to allow for changing flow direction condition in tidal deltas. Finally, the morphological change of the bed was calculated using sediment conservation, known as the Exner equation.

We verified the 1D model results with a fully numerical model Delft3D by comparing the hydro-morphodynamic from 1D model against the depth-averaged version of Delft3D (2DH) in short term duration (20 days) and long term duration (200 years). This comparison was conducted to show that the 1D model can produce similar results with well-established model. The short term simulation was conducted to compare hydrodynamic and sediment transport produced by both models using various differences of tidal conditions, channel configurations and river discharges. Meanwhile, the long term simulation was conducted to compare the morphological development results from both models. Since long term simulation is computationally expensive for the 2DH model, we took a few combinations from the short term simulations to ensure that the 1D model is not only valid to simulate hydrodynamic and sediment transport but also the morphological development.

To analyze the effect of tides, two sets of simulations, one fluvial and one with fluvial-tidal influence, were performed. In each case, a series of simulations was conducted for a range of width-to-depth ratios of the upstream channel and the Shields stress. The variation of Shields stress was conducted by varying the sediment grain size for each simulation in the range of sand and gravel (0.1-3 mm). Meanwhile the variation width-to-depth ratio was conducted by varying the width of the channel in each simulation while the initial channel depth was 10 meters. For the fluvial-tidal case, a semidiurnal tidal component (S_2) was imposed from the downstream end of the downstream channels.

The stability analysis was conducted numerically by perturbing the initially symmetric bifurcation by slightly deepening one downstream channel and shallowing the other one of the bifurcates. The initial growth or decay rate of this depth asymmetry was determined from the first year of simulations. A positive value of the depth asymmetry growth rate indicates an unstable bifurcation and a negative value a stable one.

3 RESULTS

Figure 1 shows the stability diagram for the cases modeled. In the case without tidal forcing (Figure 1a; $U_{tide}/U_0=0$), stable conditions are only found for intermediate Shields stress values and small width-to-depth ratios. Moreover, the range of possible stable conditions decreases with the increase of width-to-depth ratio and it is concluded that the river-dominated system is unstable for typical conditions found in nature. The results are similar to those of Bolla Pittaluga et al. (2015, figure 3), except that the range for which stable bifurcations exist has diminished considerably due to presence of the lower bed level gradient (Iwantoro et al., 2019).

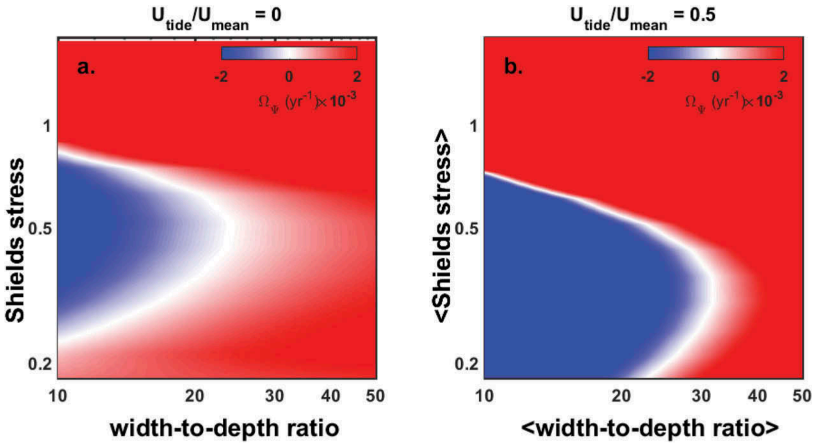

Figure 1. Stability diagram for a. The set of simulations without tidal forcing indicated by zero value of the ratio of tidal flow amplitude over mean flow at bifurcation point in upstream channel (U¬tide/U¬0) and b.with tidal forcing (U¬tide/U¬0 =0.5). < > indicates the tide-averaged value of Shields stress and width-to-depth ratio. The color indicate the asymmetry growth rate, Ω_Ψ (yr^{-1}). Red color indicates the conditions with positive growth rate (unstable bifurcation) and blue color indicatesthe condition with negative growth rate (stable bifurcation).

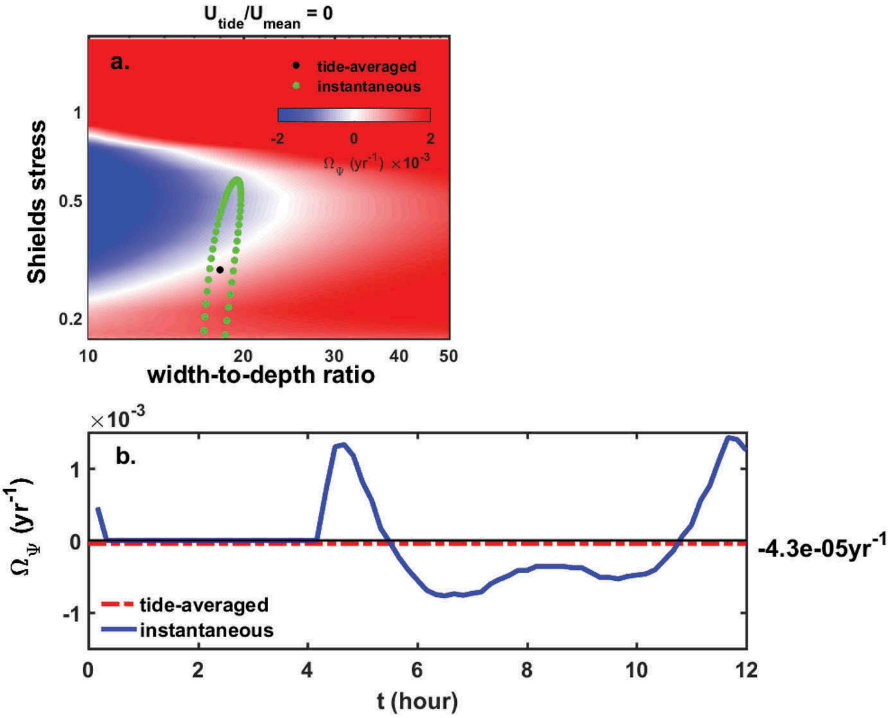

Figure 2. a. Stability diagram for river overlaid by the observed tidal averaged (black dot) and instantaneous Shields stress and width-to-depth ratio condtion for one tidal cycle (green dots). b. The time series of instantaneous asymmetry growth rate (blue solid line) and its tide-averaged value (red dashed line).

For the second case (Figure 1b), a tidal forcing was prescribed. Therefore, at the bifurcation the ratio U_{tide}/U_0 is 0.5. In other words, the flow magnitude changes in time but not the flow direction. Therefore, the flow is still always in downstream direction. This small tidal influence has expanded the range of stable conditions considerably towards larger width-to-depth ratios and smaller Shields numbers. To understand the effects of tides we compare the results of the tidal case to river-only simulations. Due to tides the width-to-depth ratio and Shields number change continuously because water levels and flow velocity become time-dependent. If one takes a simplified view, the tide can be considered to be a continuous series of river flows with different water depth and discharge. Each condition will have a corresponding growth rate of the asymmetry for the river only case, either being negative or positive. As a result, due to tides the growth rate of the asymmetry becomes a function of time and the actual growth on the long-term is the tidally averaged value. We tested this for one model setting that was unstable in the river only case, but stable when U_{tide}/U_0 is 0.5. The results show that due to tides the system is periodically shifting from unstable to stable conditions (Figure 2). The tidally averaged value of the asymmetry growth rate of a series of changing river stages turned out to be negative (Figure 2b). Therefore, though only a small tidal forcing was prescribed, the stable condition regime expanded. According to this result, we can argue that a larger tidal influence results in a larger regime with stable bifurcations and a decreased tendency of river avulsion. This mechanism might explain the presence stable bifurcations observed in tide-influenced deltas, such as in Mahakam delta, Berau River Delta and Mekong delta.

4 DISCUSSION

From the findings, the instability of bifurcations induced by the river settings and sediment properties can be opposed by the presence of tides depending on the relative influence of tides over the river discharge. The presence of tides will cause the extension of stable bifurcations condition in the intermediate Shields stress as shown by Bolla Pittaluga et al. (2015). Furthermore, in the river networks, meandering upstream channel and gradient advantage of one downstream channels induces avulsion (Kleinhans et al, 2008). In tidal systems, the avulsion due to these settings can be balanced by tides keeping both channel to convey the water flow.

Some limitations of the implemented model may be improved for future studies. In nature, tide-influenced rivers typically have widening channel downstream. The effect of this widening channel may also affect the stability of bifurcations since this setting increase the tidal flow upstream. Furthermore, besides river bed, channel banks also evolve to adjust the flow conditions. In river systems, including this effect increases the possibility of unstable bifurcations (Kleinhans et al., 2011). Including evolving channel banks in tide-influenced bifurcations may also increase the stable conditions because by allowing channel bank evolution the diverging channel width will occur and enhance the influence of tidal flow upstream.

5 CONCLUSIONS

A modelling study has been conducted to investigate the effect of tides on the morphological stability of bifurcation. In river dominated systems a limited range of conditions leads to stable bifurcations. The presence of tides increases this range and opposes the asymmetric evolution typically observed in non-tidal sand-bed river bifurcations.

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