SPLITTING NATURE AT ITS SEAMS:
MORPHODYNAMIC STABILITY OF RIVER AND TIDAL BIFURCATIONS

Maarten Kleinhans (1), Kaspar Sonnemans (1), Michele Bolla Pittaluga (2),
Maarten van der Vegt (1), Lisanne Braat (1), Jasper Leuven (1), Stefano Lanzoni (3),
Alessandro Sgarabotto (3), Manuel Bogoni (3), Zheng Bing Wang (4),
Nicoletta Tambroni (2), Giovanni Coco (5) & David Todd (6)

(1) Utrecht University, the Netherlands, E-mail: m.g.kleinhans@uu.nl
(2) University of Genova, Italy, E-mail: michele.bollapittaluga@unige.it
(3) University of Padua, Italy, E-mail: stefano.lanzoni@dicea.unipd.it
(4) Delft University of Technology, Netherlands, E-mail: Z.B.Wang@tudelft.nl
(5) University of Auckland, New Zealand, E-mail: g.coco@auckland.ac.nz
(6) HR Wallingford, England, E-mail: D.Todd@hrwallingford.com

Channel bifurcations split flow and sediment around fluvial and tidal bars in rivers and estuaries and at junctions in river deltas and tidal deltas. Their long-term development depends on the balance between sediment partitioned at the bifurcation and the transport capacity in the bifurcated channels. For unidirectional flow, theory predicts that stability depends on channel width-to-depth ratio and sediment mobility, but this has not been tested under high sediment mobility and in tidal conditions. Here we report on nine unidirectional and bidirectional flow experiments on a sand bed with a splitter plate wherein bed development and flow partitioning were monitored. Results show that fluvial and tidal experiments develop unstable bifurcations for intermediate and high sediment mobility and channel width-to-depth ratio in agreement with theory.

1. INTRODUCTION

Multithread rivers such as the Jamuna and Mekong have networks of channels separated by bars that change with every flood. Likewise, tidal systems such as the Scheldt, Humber and Columbia estuaries and short tidal basins in the Wadden Sea and in Florida, have interacting channels and shoals formed by ebb and flood currents. Main channels are economically important shipping fairways, whilst shoal areas that emerge and submerge daily are ecologically valuable habitats.

Channel bifurcations are critical elements that partition flow and sediment through the channel network, govern bar merging and splitting and are locations where bed steps form in shipping lanes, as in river bifurcations. Stability and equilibrium configurations are mostly unknown for tidal bifurcations except for one recent theory (Jeuken & Wang 2010). In particular, we have a fair understanding of the tidal flow dynamics, but understanding of the morphodynamics, especially related to the sediment division at the bifurcation, is mostly lacking. Here we begin to build on the better but as yet incomplete understanding of river bifurcations.

The stability of river bifurcations has been studied for two decades in fieldwork, experimentation, linear stability theory and numerical modelling (e.g., Wang et al. 1995, Bolla Pittaluga et al. 2003, Kleinhans et al. 2013). A recent theory (Bolla Pittaluga et al. 2015) synthesises many of the earlier results as follows. For the case of a symmetrical bifurcation with a minor water depth perturbation in one of the bifurcates, the nonlinear relation between flow and sediment transport leads to higher transport in the deeper bifurcate, while the upstream sediment division is symmetrical. This tends to cause runaway channel incision in the deeper channel, and more so close to the beginning of sediment motion or high suspension where the nonlinear effects are more important. However, as one channel deepens and the other shallows, a transverse bed slope develops around the bifurcation. This leads to downslope sediment deflection, causing a transverse flux towards the deeper channel. For low aspect ratios, i.e. width-to-depth ratio, the slope effect is sufficient to counteract the incision of the deeper channel, with the result that the bifurcation stabilises. The theory assumes that the slope effect also affects the suspended bed material load for lack of better understanding of the lateral diffusion processes. In brief, bifurcation stability depends mainly on channel aspect ratio and sediment mobility.

As a result, symmetrical bifurcations in bedload-dominated rivers of modest and larger aspect ratios are predicted to be unstable and shift, when perturbed, towards a highly asymmetrical division of discharge and sediment. In the case of suspended sediment-dominated rivers the theory predicts stable bifurcations for intermediate sediment mobility. However, there is very little data for conditions intermediate between low and high mobility rivers.

Moreover, we have no idea whether bifurcations in reversing tidal flow are unstable for configurations and conditions similar to those of rivers. Here we consider configurations that are entirely free of topographic forcing on the flow, namely straight channels split into two branches over some length, with one perturbed in depth. Any form of topographic forcing and channel curvature will cause deviations in bifurcation stability (van Veen 1950, Kleinhans et al. 2008) and are disregarded here. Our objective is therefore to experimentally investigate bifurcation stability under a range of sediment mobility and channel aspect ratio in unidirectional flows and reversing tidal flows.

2. METHODS AND MATERIALS

The methodology is to study the development of initially symmetrical, but perturbed bifurcations in the idealised condition of a straight flume with a splitter plate that schematize a central bar without any planimetric, topographic forcing. Creating reversing tidal currents in large morphodynamic experiments is challenging. Here we use the novel Fast Flow Facility at HR Wallingford (UK, http://www.hrwallingford.com/facilities/fast-flow-facility). The flume has a main working channel of length 70.00 m and width (W) 4.00 m and water depths (h) in the range of 0.85 m to 2.00 m. The facility is equipped with two pumps with a combined discharge of up to 4.9 m^3/s.

The initial bathymetry was created on a mock bed by screeding a freely erodible sand bed of length 31.3 m. The well-sorted sand had a median diameter of about 0.2 mm to maximise mobility, suppress dunes in favour of ripples, and avoid cohesion. The length of the centered splitter plate was 16 m. A perturbation, necessary to initiate bifurcation instability, was made by setting a 5 cm sediment hump in one of the channels over a given length and height.

Selected conditions (Table 1) were based on the theory of Bolla Pittaluga et al. (2015). Low mobility was impossible to test because of run time limitations and higher mobility experiments were run as briefly as possible to be able to investigate a larger number of conditions. In addition, there are already experimental data for low mobility unidirectional flows and most tidal systems are suspension-dominated. Tidal flows were run for comparable conditions to test stability. The test duration was assessed on the basis of sediment transport rate estimated by a predictor and the time required to either remove the perturbation on the bed or to assure a measurable growth. The Shields mobility number for unidirectional flow was calculated from measured flow velocity and skin friction, while for the reversing flow was calculated from the peak flow velocities in both directions.

Table 1. Approximate experimental conditions.

exper	**run-time (hr)**	**depth (m)**	**dis-charge (m3/s)**	**(peak) veloc (m/s)**	**target Shields**	**aspect W/h**	**uni-directional / tidal**	**tidal period (s)**	**target bifurcation**
4	13	0.14	0.22	0.39	0.5	29	uni		Unstab
5	35.24	0.50	0.85	0.42	0.5	8	uni		Stable
6	18	0.50	0.85	0.42	0.5	8	tidal	216	Stable
7	18.5	0.14	0.22	0.39	0.5	29	tidal	280	Unstab
8	19.5	0.50	0.85	0.42	0.5	8	tidal	216	Stable
9	2.24	0.25	0.77	0.77	2	16	uni		Unstab
10	18.5	0.50	0.85	0.42	0.5	8	uni		Stable
11	38	0.14	0.22	0.39	0.5	29	tidal	280	Unstab
12	0.9	0.80	2.60	0.81	1.5	5	uni		Stable

The following instruments were used for monitoring purposes (see Data Storage Report, Kleinhans and Sonnemans 2018):

- two line-laser scanning systems for bed elevations in both parallel channels, used to scan the initial bed, the developing bed about halfway through the experiment and the final bed.

- two Nortek Vectrino ADVs for velocity measurements in both parallel channel branches, both upward looking and at an elevation of about 0.1 m above the bed
- six pressure sensors for measuring water levels along the flume
- one Nortek HR Aquadopp acoustic device for discharge measurements related to pump control frequency

The bifurcation development was quantified by data analysis of bed scans and velocity measurements. The spatially-averaged difference in bed level height between the perturbed channel and unperturbed channel quantifies the overall morphological asymmetry. As the bed level data has a high spatial resolution over a reach much longer than the bedform length, this leads to highly accurate averages for the initial, perturbed bed and the two development stages (i.e., halfway and at the end of a run). On the other hand, the velocity measurements were taken at only a few points even though with high time resolution, allowing quantification of the development. Velocity was measured at a fixed elevation, while water depth varied especially in tidal conditions because the pump in the racetrack flume was not centered to equal distance from the splitter plate, which requires correction to depth-averaged velocity in future analyses. The combination was used to interpret the stability of each condition.

3. RESULTS

The main results are that all experimental conditions, including the tidal conditions, behave as predicted by the theory (see in Table 1). Lower aspect ratios and lower mobilities lead to stable bifurcations with disappearing bed perturbation and flow asymmetry. Conversely, higher aspect ratios and higher mobilities lead to unstable bifurcations, with increasing bed elevation in the perturbed channel and increasing flow through the unperturbed channel branch (example in Figure 1,2). The development towards symmetry observed in the stable bifurcation experiments also demonstrates that the flume setup did not lead to significant topographic forcing on the bifurcations.

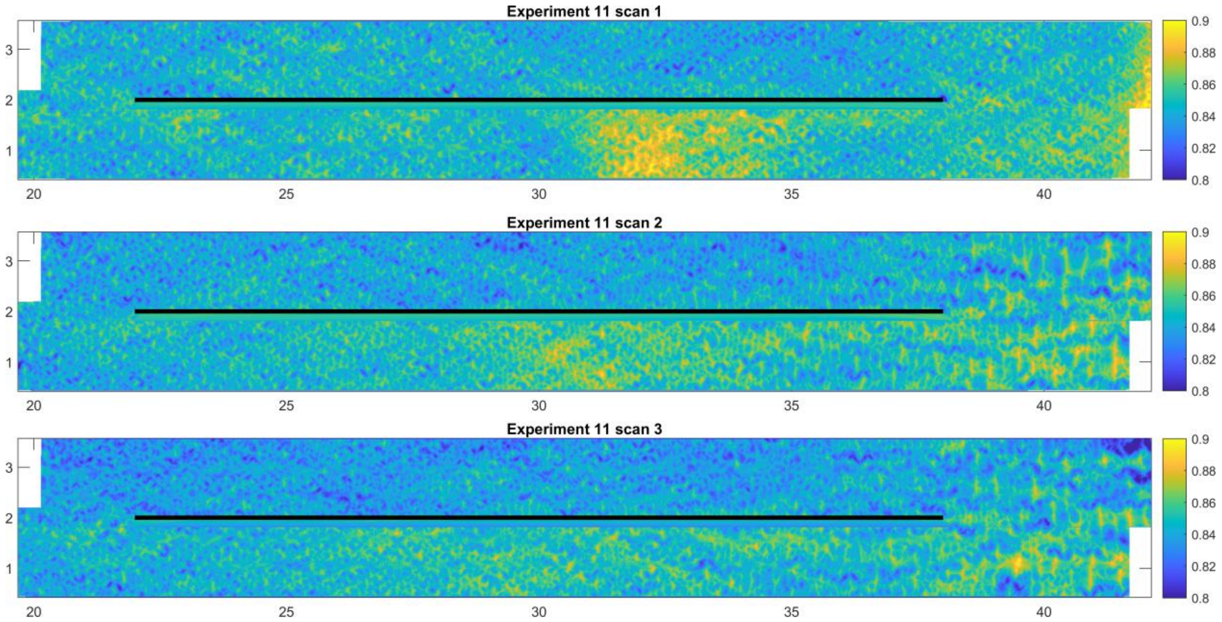

Figure 1. Bed scans of tidal experiment 11 which was interpreted as unstable.
Bottom channel was perturbed; net sediment transport to the left. All dimensions in m.
The splitter plate position is indicated by the bold black line. Microrelief are ripples resolved in the scans.

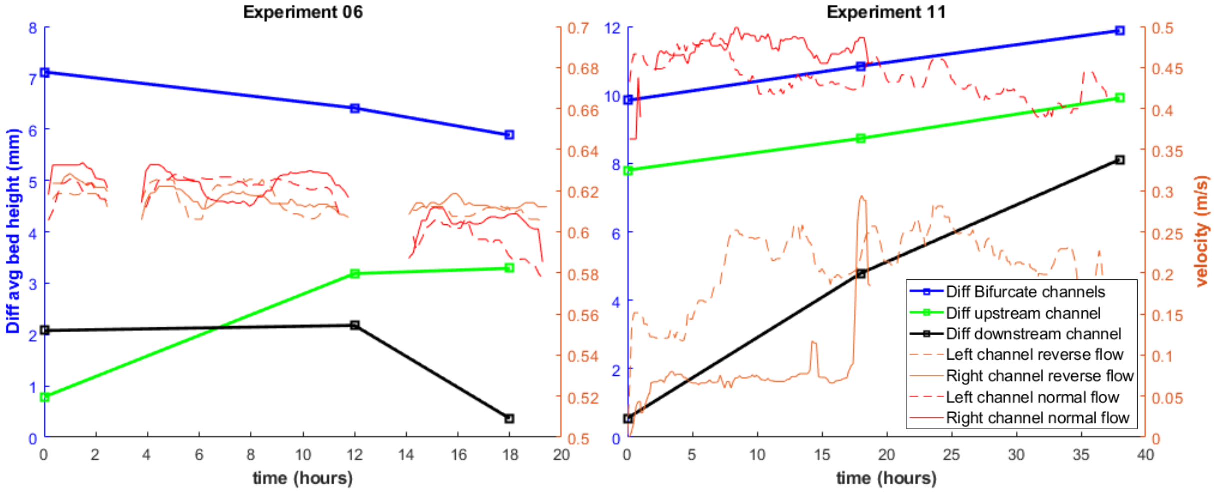

Figure 2. Timeseries of two tidal experiments with intermediate Shields number and low (left) and high (right) channel aspect ratio. Bold lines show bed level difference between perturbed and unperturbed sides averaged upstream of the splitter plate (green), downstream (black) and in the split section (blue). Detailed timeseries are median-filtered flow velocities for left (orange lines) and right (red lines) channel branches (showing gaps in the data). Difference in water depths explains difference in velocity measured at fixed elevation.

The bed scans (see, e.g., Fig. 1) required some interpretation as the morphological development is the result of superimposed development of the perturbation, the bedforms, and, for the highest mobility, the development of a bed wave intiated on the gentle bed ramp. However, the development of stable bifurcations in which the perturbation disappeared and the channels became symmetrical within the measurement accuracy (examples in Fig. 2) showed that topographic forcings were avoided despite the race track setup of the recirculating flume.

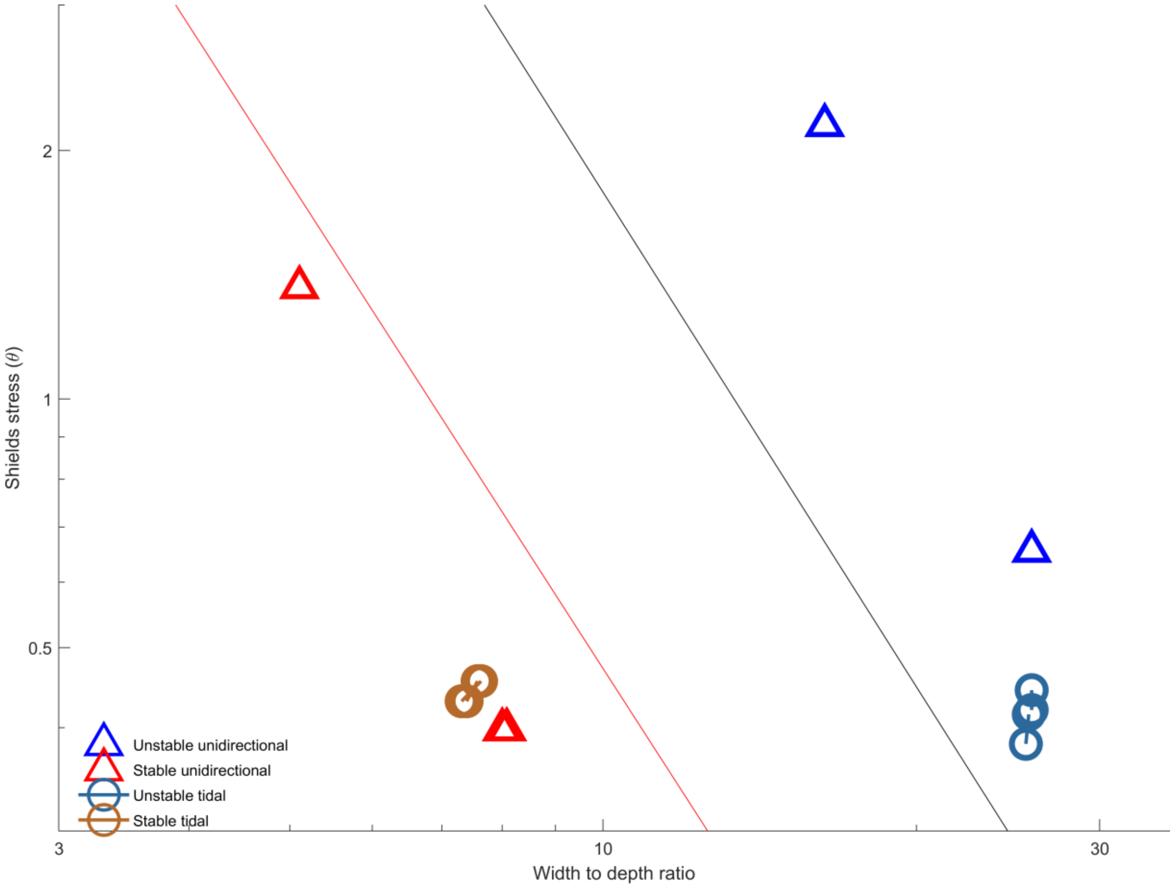

Figure 3. Summary of all experiments plotted in the bifurcation stability space for suspension-dominated conditions (Bolla Pittaluga et al. 2015), where the range between the two lines represent the uncertainty in the transition from stable to unstable bifurcations due to model parameter choices. Connected double symbols show tidal experiments with slight difference between peak ebb and flood conditions.

All experiments plot in agreement with the theory in the channel aspect ratio and sediment mobility parameter space. The agreement is found for both intermediate mobility and high mobility in the fluvial setup, and for the tidal setup under intermediate mobility conditions. The theory thus appears to hold for intermediate and high sediment mobility conditions as well as for tidal conditions. Furthermore, as many channels in nature have aspect ratios far above 10, theory and data suggest that the majority of bifurcations in nature are unstable.

Because of the limited amount of time available for the tests no runs in the transition zone between stable and unstable bifurcations. Therefore, we cannot draw conclusions about the predicted sensitivity of the transverse bed slope effect over a certain length in the undivided channel, which requires further experiments. Overall, the agreement of the experiments with the theoretical predictions suggests that the physical framework of the theory is sufficient to explain general bifurcation stability in idealised conditions, notably the lack of topographic forcing.

4. CONCLUSIONS

We conclude that, in the absence of topographic forcing, channel bifurcations in fluvial and tidal systems are unstable in relatively wide and shallow channels and intermediate to high mobility.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654110, HYDRALAB+. We gratefully acknowledge technical and organisational support by HR Wallingford staff. MK, LN and JL were supported by a Vici grant by the Netherlands Organisation for Scientific Research (NWO, grant TTW 016.140.316 to MK).

REFERENCES

Bolla Pittaluga, M., Repetto, R. and Tubino, M. (2003). Channel bifurcation in braided rivers: Equilibrium configurations and stability, Water Resour. Res., 39(3), 1046, doi:10.1029/2001WR001112.

Bolla Pittaluga, M., Coco, G. and Kleinhans, M.G. (2015). A unified framework for stability of channel bifurcations in gravel and sand fluvial systems, Geophys. Res. Lett., 42, 7521–7536, doi:10.1002/2015GL065175.

Jeuken, M.C.J.L., Wang, Z.B., (2010). Impact of dredging and dumping on the stability of ebb–flood channel systems. Coast. Eng. http://dx.doi.org/10.1016/j.coastaleng.2009.12.004.

Kleinhans, M.G., Jagers, H.R.A., Mosselman, E. and Sloff, C.J. (2008). Bifurcation dynamics and avulsion duration in meandering rivers by one-dimensional and three-dimensional models, Water Resour. Res., 44, W085454, doi:10.1029/2007WR005912.

Kleinhans, M.G., Ferguson, R.I., Lane, S.N., and Hardy, R.J. (2013). Splitting rivers at their seams: Bifurcations and avulsion, Earth Surf. Processes Landforms, 38, 47–61, doi:10.1002/esp.3268.

Kleinhans, M.G. and Sonnemans, K. (2018). Data Storage Report; Splitting nature at its seams: morphodynamic stability of river and tidal bifurcations. Hydralab+, http://dx.doi.org/10.5281/zenodo.1456622.

van Veen, J. (1950). Ebb and flood channel systems in the Netherlands tidal waters, J. Roy. Dutch Geographical Soc., 67, 303–325.

Wang, Z.B., Fokkink, R.J., De Vries, M. and Langerak, A. (1995). Stability of river bifurcations in 1D morphodynamics models, J. Hydraul. Res., 33(6), 739–750.