Effect of upstream meanders on bifurcation stability and sediment division in 1D, 2D and 3D models

Maarten Kleinhans
*Universiteit Utrecht, Fac. Geosciences, Dept. Physical Geography, Utrecht, The Netherlands*

Bert Jagers
*WL | Delft Hydraulics, Delft, The Netherlands*

Erik Mosselman & Kees Sloff
*WL | Delft Hydraulics, and Delft Univ. of Technology, Fac. Civil Eng. and Geosc., Delft, The Netherlands*

At river bifurcations, water and sediment are divided over two branches. The dynamics of the division determine the long-term evolution of the downstream branches, which can be studied by 1D models. For such models, a relation describing the sediment division is necessary, but this is poorly understood. We study the division of sediment and the morphodynamics on a time scale of decades by idealised 2D and 3D modelling of bifurcations with upstream meanders and dominantly bed load transport. Initially, migrating alternating bars in the models caused damped quasi-periodic fluctuations in bed levels, water and sediment division until the bars are near equilibrium. Varying the radius of upstream meanders and the slope of one of the downstream channels led to subtle changes in the sediment transport direction and the location of bars and pools. This caused large differences in which branch becomes dominant and in the rate of change in discharge asymmetry. The effects of wider downstream branches or of an overall narrower or wider river are dramatic, again demonstrating the importance of bars. The resulting division of sediment, on the other hand, is similar to the division of flow discharge in all runs after the initial fluctuations have damped out and until the discharge division becomes very asymmetrical. We conclude that bifurcations are extremely sensitive to local conditions affecting the secondary currents and the sediment transport direction, and to the downstream boundary conditions. Although most combinations of parameters lead to the development of an asymmetrical discharge division, some combinations lead to a quasi-stable symmetrical division. Finally we discuss the limitations of the models and the applicability to natural meandering rivers.


1 INTRODUCTION

Bifurcations distribute water, sediment and, indirectly, flooding risks over the downstream river branches. Over a much longer time, fluvial plains and river deltas are built up by avulsing and (temporarily) bifurcating rivers. In order to understand these phenomena, the local water and sediment transport division must be understood. Such understanding can be obtained by combining observations and geological reconstructions with models. However, 2D and 3D models are computationally too expensive for such long-term morphological predictions. A 1D model has to be extended with a ‘nodal point relation’ for dividing the sediment at the bifurcation, which is not well understood.

The objectives are to understand the causes of bifurcation (in)stability in meandering rivers and to predict the division of sediment to aid future 1D modelling. Accurate measurements of bed level evolution and sediment transport rates at meandering river bifurcations are rare for single events and non-existent for periods long enough to cover significant changes in morphology and discharge division. We therefore focus on systematic idealised modelling with 2D and
3D models to study the effect of specific factors such as the radius of a meander bend upstream of the bifurcation, and the slope of the downstream branches. The input parameters of the model are loosely based on the river Rhine in the Netherlands, which had more than 80 bifurcations in the past 8000 years, some of which were destabilised within a few decades after their creation, whereas some others were stable for many centuries (Stouthamer and Berendsen, 2000).

First we compare two state-of-the-art relations for sediment division that are used in 1D models, and whether these result in stable or unstable bifurcations. Next we describe the 2D and 3D model setup. After presenting the main results, a number of extra tests are presented to assess the effect of various channel widths and other parameters. Finally, the shortcomings of the models are discussed as well as the applicability of the results to real meandering rivers, and general conclusions are drawn.

2 RESULTS OF A 1D MODEL
A 1D model of a river with a bifurcation consists of three branches connected by a node. At the node, discharge and sediment supply from the upstream branch (1) is divided over the two downstream branches (2,3). The division of flow discharge $Q_1$ into $Q_2, Q_3$ at the nodal point follows from mass conservation, the condition that the water levels in the three branches are equal at the nodal point and the other specifications. The depth-width-integrated sediment transport $S_1$ is divided as $S_2, S_3$ according to the nodal point relation, in this case by Wang et al. (1995) or Bolla Pittaluga et al. (2003). The Bolla Pittaluga et al. relation divides the sediment based on the bed level differences of the downstream channels, assuming that the influence of this difference extends to the area upstream of the bifurcation and ignoring meander bend effects from upstream. The Wang et al. relation is empirical:

$$\frac{S_2}{S_3} = \left(\frac{Q_2}{Q_3}\right)^k \left(\frac{W_2}{W_3}\right)^{1-k}$$  

where $k$ is an empirical power. Wang et al. found from a nonlinear stability (phase-plane) analysis that bifurcations are stable for $k > n/3$ and unstable for $k < n/3$, where $n$ is effective power on flow velocity to calculate the sediment transport. For Engelund and Hansen (1967) $n = 5$; for Meyer-Peter and Mueller (1948) $n > 3$ depending on the ratio of actual to critical shear stress.

An intuitive understanding of the Wang et al. model is offered as follows. Suppose the discharge of a branch decreases. The effect of a large $k$ would be a much larger decrease of the sediment input than the decrease of the sediment transport capacity. Consequently, the bed of the closing branch is scoured to some extent, which increases the flow discharge capacity of this channel. So a large $k$ stabilises the bifurcation.

![Figure 1: Results of 1D model. A. Time-series of discharge for the less steep branch. B. Sediment and discharge division over the downstream branches.](image)

Each branch has a length of 6 km with a step size of 150 m. The model is run for 50 years with a time step of 0.05 year. The flow in the 1D model is based on the Belanger equation (backwater curve) and the Manning-Strickler roughness predictor. The specified model parameters are upstream discharge ($Q = 2500$ m$^3$/s), width ($W_1 = 532$ m, $W_2 = W_3 = W_1/2$), Nikuradse roughness length ($k_s = 0.19$ m), calibrated so that the water depth is about equal to that in the 2D model, initial bed and water surface slope ($i_1 = i_2 = i_3 = 1 \times 10^{-4}$ m/m), and downstream water levels of the two downstream channels which were chosen such that the flow is uniform initially. The morphology is computed from an initial bed, a sediment transport predictor (Meyer-Peter and Mueller (1948) or Engelund and Hansen (1967)) and the Exner sediment conservation law. The grain size
is specified as $D_{50} = 2$ mm.

The 1D model predicts a decrease of discharge through the downstream branch with the smallest slope as expected (Fig. 1). Using the Bolla Pittaluga et al. nodal point relation, the discharge division always becomes very asymmetrical, or, in other words, a dominance of one of the channels. The rate of closure depends on the sediment transport rate, which in the present setting is larger using Engelund and Hansen (1967) than for Meyer-Peter and Mueller (1948). For the Wang et al. nodal point relation the bifurcation is increasingly asymmetrical for $k = 1$ but stable for $k = 2, 3$. The sediment division by the Bolla Pittaluga et al. relation is initially similar to that of Wang et al., with $k \approx 1$ and gradually changes to $k \approx 2$ for increasing asymmetry.

For both the 1D and 2D/3D model cases we study the range of model conditions from initial plane bed and symmetrical discharge division to (nearly) fully developed bar morphology with highly asymmetrical discharge divisions. For numerical reasons and due to model simplifications it is not possible yet to draw conclusions on the final branch closure process if a branch closes fully at all but this will be addressed in the discussion and in ongoing studies.

3 SETUP OF THE 2DH AND 3D MODELS

The Delft3D-FLOW morphodynamic model system was used (version 3.50.05.00BJ03). The parameters for the 2D and 3D models were very similar to that of the 1D model. The flow and morphology are calculated according to Lesser et al. (2004). The roughness formulation is Darcy-Weissbach with $k_s = 0.15$ m. The initial bed was plane and had a slope of $i = 1 \times 10^{-4}$ m/m, except where the slope of one downstream channel was deliberately increased. The downstream water levels were equal (for cases with $i_2 = i_3$) and chosen such that the flow was uniform initially ($\pm 2$ cm). The sediment transport predictor, unless mentioned, is Engelund and Hansen (1967). The bed slope effect on sediment transport is calculated according to Talmon et al. (1995) (see also Struiksmra et al., 1985; Lesser et al., 2004). The spiral flow is schematised in the 2D model according to Struiksmra et al. (1985); Lesser et al. (2004). The time step of the flow was 30 seconds to ensure numerical stability, and an initial period without morphological updating was allowed to stabilise the flow. Assuming that the flow is not appreciably affected by erosion and sedimentation during a time step, the morphological change in each time step can be multiplied by a large factor to predict the morphological evolution. The chosen factor was 100 which gave no significant differences with larger and much smaller factors.

The grids were curvilinear, and were automatically generated to ensure repeatability. The grids were orthogonalised as much as possible in an automated procedure. The average length of the grid cells was 150 m as in the 1D model. The width of the cells was 28 m for the standard models, 35 m for the wider, and 21 m and 16 m for narrower models. For the 3D models the flow was divided vertically in 10 layers of equal thickness, which was adapted to water depth changes (Lesser et al., 2004).

To split one channel into two, one row of cells had to disappear downstream of the bifurcation for numerical reasons. To ensure that $W_2 + W_3 \geq W_1$, the width of the cells downstream of the bifurcation was increased. The transition to this increased width was done gradually in the five cells upstream of the bifurcation. All three branches had the same lengths and consisted of 40 cells each.

The grids were generated with varying upstream bend radii, where the bend was 17 cells long downstream of a straight stretch. Downstream of the bifurcation a constant bend radius of $R = 20W$ was specified.

Avulsions commonly take place because of a slope advantage of the new flow direction over the old channel. To test the effect of an increased slope in one downstream branch, this slope increase was specified in the initial bed levels and the downstream water levels were again adjusted to ensure initial uniform flow.

New downstream branches often are less wide than the old branches, and usually $W_2 + W_3 \geq W_1$. Also, there is an effect of width-depth ratio on the bar dynamics. Three effects of width were tested: an equal increase or decrease of the width of all branches, an equal increase of the width of the downstream branches, and a change in the width ratio of the downstream branches. These were specified as factors on the cell width.

4 RESULTS

4.1 Bar dynamics

The 3D model initially predicted a rather complex morphological evolution (Fig. 2). In the first few model years alternating bars developed from the plane bed and migrate downstream. After some time, a fixed bar developed in the inner bend upstream of the bifurcation. Meanwhile, a bar and pool migrated side-to-side into the bifurcated branches and become fixed in position as well. Since more water is discharged into the channel with the pool than into the channel with the bar, the balance of the bifurcation was tipped and one channel became dominant. The rate of bar development and migration depended on the bend radius: the sharpest bends had the fastest development of a fixed bar. Bolla Pittaluga et al. (2003) assumed that the influence of bed level difference of the downstream channels extends to the area upstream of the bifurcation, which is confirmed here (Fig. 2, lowest
Figure 2: Classified bed levels at 3, 6, 12 and 25 years minus the initial bed level, illustrating the bar and pool evolution. At $T = 25$ years, the bed elevation difference between the downstream branches becomes so large that the inner-bend bar in the upstream bar is no longer visible due to the larger color interval spacing for larger $T$.

4.2 Effect of bend radius

The 2D and 3D models always predict a development to a stable, highly asymmetrical discharge division. As expected, the outer-bend branch becomes dominant when the downstream conditions in the two branches are equal (Fig. 3A).

Since the effective secondary flow intensity in the 3D model is slightly smaller than in the 2D model, the bars and pools are slightly less pronounced in the 3D model and consequently migrate slightly faster. Unexpectedly, the present 2D runs for gentle bends predict dominant inner-bend branches although the results are similar to the 3D models for sharper bends ($R > 10W$) (Fig. 3A). This unexpected result might be caused by differences in the submodels for bed-slope and spiral flow effects. In addition, an older version of Delft3D (also in 2DH mode) with which much experience and good results were obtained in the past predicts dominant outer-bend branches. The 2D model results for sharp bends will therefore be interpreted with care and the gentle bends will not be used. Preliminary runs with the latest 2D version demonstrated that this numerical problem has already been solved and that the conclusions in this paper are still valid.

Intriguingly, a plot of $S_2/S_3$ against $Q_2/Q_3$ shows a considerable nearly-linear range with $k \approx 1$ (Fig. 3B). This means that the division of sediment transport is fairly similar to that of the flow. Initially the flow and sediment division fluctuates in a damped, quasi-periodic manner. This is caused by the develop-
ment and migration of the bars from an initially plane bed. Once the bars are nearly in equilibrium and the balance is tipped, the flow and sediment are increasingly discharged into one branch.

In the final stages ($Q_2/Q_3 > 10$) the decline in sediment transport starts to outweigh the decrease in discharge, thereby apparently increasing $k$ from a value below to a value above the stability threshold. The discharge in the closing branch then stabilises at a small but non-zero value in all cases.

4.3 Effect of asymmetric downstream slopes
The effect of the upstream bend on the choice which branch becomes dominant can be counteracted by increasing the slope of the inner-bend branch (Fig. 4A). For a slope increase of 30% the inner-bend branch always dominates. For a slope increase of only 10% ($i_3 = 1.1 \times 10^{-4}$ as in the 1D model) the inner-bend branch dominates for gentle bends whereas the outer-bend branch dominates for sharper bends. The nodal point relation remains similar to that in other runs (Fig. 4B). In other words, a larger slope (0-20%) in one branch can be counteracted by upstream meander bend flow depending on the position of the steeper branch along the meander. Thus, there exist combinations of bend radius and downstream slopes for which the bifurcation remains quasi-balanced for a longer time. Such meander effects are not yet included in the existing nodal point relations for 1D models.

4.4 Effect of different channel widths
The effect of an equal increase or decrease of the width of all branches is dramatic (Fig. 5A). For narrower channels, all with $R = 10W$, the main flow switches from the inner-bend branch to the outer-bend branch in 3D runs. The 2D runs give very similar results. Additional 2D runs show that a sharp bend ($R = 4W$) switches the flow for even less narrow channels. This indicates that there also exist combinations of bend radius and channel width for which the bifurcations are quasi-stable, e.g. for $R = 4W$ and $W \approx 400$ m.

An equal increase of the width of the downstream branches only, on the other hand, has only a limited effect on the bifurcation stability (Fig. 5B). The closure of the inner-bend branch is slower for increasing downstream widths.

The effect of a change in the width ratio of the downstream branches is limited (Fig. 5B). If either the inner-bend or outer-bend branch is made narrower, the discharge division eventually approaches that of the symmetrical case. Clearly, an increase of the width of the closing channel does not increase the duration to attain the highly asymmetrical division.

Again, all the runs wherein the widths were varied gave similar nodal point relations with $k \approx 1$ as the

4.5 Sensitivity analysis with the 2D model
The effect of the length of the upstream bend was assessed by increasing this length to 5250 m; almost the whole upstream model domain. The bar pattern changed and the phase of increasing asymmetry took more time. The nodal point relation remained unaffected.

Additional runs with the Van Rijn (1984a,b) sediment transport predictor also gave very similar results for the nodal point relation. In the 2D runs with gentle bends only the outer-bend branches became dominant, contrary to the similar 2D runs with the Engelund and Hansen (1967) predictor. In all these model runs the nodal point relation remained unaf-
Figure 5: Time-series of discharge for the inner-bend branch. A. Effect of changing the overall channel width. Results with sharper bends are shown for the 2D model. B. Effect of changing the channel width ($W_2 + W_3$, $W_2/W_3$) downstream of the bifurcation.

Some model runs in which the downstream water level was varied with discharge ('QH-relation') showed that the outer-bend branch became dominant more slowly compared to runs with a constant downstream boundary, but with the same dependence on upstream bend radius. Runs with a constant Chézy roughness length gave similar results. In all these model runs the nodal point relation remained again unaffected, although the effect of these parameters must be investigated in more detail.

5 DISCUSSION

5.1 Limitations of the modelling

Which branch closes off is dramatically sensitive to the model setup. Different setups cause subtle differences in the sediment transport vector field, which decide which branch closes and the rate of closure. Small errors in the numerical scheme, in bed slope effects and in sediment transport predictors therefore have large effects on the outcome at bifurcations, even if the effects on the morphology in single channels are not that sensitive.

Some runs with the 2D model indicate that the results are sensitive to small perturbations of the grid at the bifurcation in cases where both downstream channels tend to be equally dominant initially (for certain combinations of bend radii and downstream slopes). Therefore, they are probably also sensitive to the precise schematisation of the bifurcation. In a curvilinear grid the bifurcation has to be a bluff, whereas in reality it is often a sharp-pointed bar. Further work is planned with a different type of bifurcation with a thin wall in the middle of a simple bend. It is perhaps better to model bifurcations with an unstructured grid, but this option is not yet available in Delft3D.

The models suggest that the bifurcations stabilise in a highly asymmetrical condition. However, the final closure process of one of the branches cannot be understood from the present model runs and has to be studied in more detail. It is possible that several assumptions and numerical aspects affect the value of $k$ in the highly asymmetrical stages. Notably, we assume a constant roughness length and constant downstream water levels, and convert cells to permanently dry cells for water depths $<0.1$ m.

5.2 Implications

The value of $k \approx 1$ for the nearly-linear range in the nodal point relation of Wang et al. is a robust outcome of all given model setups. It means that the division of sediment is close to that of the flow discharge. The implication is that bifurcations are always unstable, or become highly asymmetrical, in partial agreement with Wang et al. (1995). For rivers with parameters similar to the modelled ones, the time scale of reaching the highly asymmetrical condition is of the order of decades to perhaps a few hundreds of years. This is a surprising result, because a number of bifurcations in similar rivers (Red River, Volga) are known to be stable in a more symmetrical condition on much longer time scales of observation, although other bifurcations, such as the historical Rhine bifurcation, were notoriously unstable. In addition, some data sets suggest larger values of $k$.

Preliminary results of runs with much longer downstream branches suggest that the location of the downstream constant water level (or, the distance from the bifurcation to the lake or sea) is important. For branch lengths approaching the backwater length (which can be estimated as $h/3i$), the discharge distribution becomes asymmetrical much more slowly. Moreover, they stabilise at more symmetrical discharge distributions when they are located at a long distance from the downstream boundary, or have a downstream wa-
The reality is more complex than the model in some, perhaps crucial, points. The discharge is highly variable, affecting the bar development at the bifurcation. The timing of a large discharge peak may tip the balance in the opposite direction.

The models were loosely based on the River Rhine in the Netherlands, and became stably asymmetrical, which can be interpreted as closure, while persistent bifurcations are related to quasi-equilibria that result from a proper combination of upstream bend radius, channel widths or downstream slopes. Model runs will be done in the future with schematised discharge waves, changing grids, initial bars, other roughness formulations, downstream water levels that depend on discharge and erodible banks to assess their effects on the nodal point relation. Moreover, historical maps and the soil auger archive of the Rhine delta at Utrecht University will be studied (see, e.g., Stouthamer and Berendsen, 2000), as well as satellite images of the Ganges-Brahmaputra delta (see, e.g., Klaassen and Van Zanten, 1989) to test various hypotheses based on the model outcomes.

6 CONCLUSIONS
Based on more than 100 idealised 2D and 3D morphodynamic models we conclude that bifurcations always attain a highly asymmetrical division of discharge and sediment, except for a few specific combinations of parameters that give quasi-stable symmetrical divisions for a much longer period. The division of sediment at the bifurcations is similar to the division of flow discharge during the phase of increasing asymmetry in all models. This is the case for both bed-load and suspended-load transport-dominated conditions.

The models were loosely based on the River Rhine in the Netherlands, and became stably asymmetrical.
in periods of the order of a decade to perhaps a few centuries for special quasi-balanced cases. The rate of change of symmetry and the choice which branch becomes dominant is extremely sensitive to a number of competitive factors:

1. a slope advantage of one downstream branch increases the discharge through this channel,
2. a bend upstream of the bifurcation can counteract downstream slope advantages of 0-20% for decreasing bend radii,
3. the width of all channels strongly determines the bar pattern and dynamics, which may cause the flow to switch to the other downstream branch compared to cases with other widths,
4. the results are sensitive to the submodels for bed slope effects and sediment transport.

The subordinate branch was never entirely closed in the model runs, but this is perhaps an effect of model assumptions and numerical aspects. The closure process has to be studied further.

ACKNOWLEDGEMENTS
MGK is supported by the Netherlands Earth and Life sciences Foundation (ALW) with financial aid from the Netherlands Organisation for Scientific Research (grant ALW-VENI-863.04.016). Mohamed Yossef is thanked for discussion.

REFERENCES


