Nodal bifurcations in gravel-bed multi-thread rivers

Bifurcations nodales des rivières en tresses graveleuses

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RÉSUMÉ

Les fleuves en tresses sont composés d'irrégulières séquences de bifurcations et confluences nodales asymétriques. Ces dernières sont inter-connectées par des canaux qui présentent une haute variabilité en termes de longueur, largeur, profondeur, débits solide et liquide. La géométrie et la partition des flux (i.e. débit liquide et transport solide) de ces bifurcations sont – dans le cas des fleuves graveleux – majoritairement régis par l'instabilité à l'interface solide-liquide et les « forceurs » que sont la courbure de l'axe longitudinal du canal entrant, la différence de longueur des canaux ainsi que leur section. L'analyse mathématique du système discrimine deux cas de partition des flux vers les canaux avals, selon que la largeur du canal entrant rapportée à sa profondeur moyenne (β_0) outrepasse (ou non) une valeur critique β_{cr} : il fournit une solution stable et symétrique pourvu que $\beta_0 < \beta_{cr}$. Dans l'autre cas, la bifurcation trouve trois équilibres : un instable avec répartition symétrique des flux et les deux autres stables et réciproques avec répartition asymétrique des flux. La plupart des bifurcations observées sont asymétriques et présentent deux caractéristiques: un facteur $\delta_W > 1$ multiplie la largeur du canal entrant pour obtenir la somme de celle des canaux sortants, et de même pour un facteur $\delta_S > 1$ comparant la pente du canal entrant à la moyenne de celle des canaux sortants. L'analyse mathématique concorde qualitativement avec ces observations.

ABSTRACT

Braided streams are composed by irregular sequences of asymmetric nodal bifurcations and nodal confluences. The latter connect to each other via channels which present a high variability in their length, water depth, water and sediment discharges, both at high and low regime. The geometry and hydraulics of these bifurcations are governed by the intrinsic instability of the node (free bifurcation) and surrounding « forcings » induced by an asymmetric geometry of the channels (cross section, upstream channel curvature, angle at the node). The mathematical analysis of the system discriminates two cases in which the flux partition towards the downstream branches finds equilibrium, depending on whether the with-to-depth ratio (β_0) of the upstream channel crosses a threshold value β_{cr} : only one balanced equilibrium exists provided that $\beta_0 < \beta_{cr}$. In the other case, the bifurcation finds three equilibria: one unstable balanced and two reciprocal stable unbalanced flux partitions. The majority of observed river bifurcations are asymmetrical and unbalanced and often present the two following characteristics: (1) the width of the upstream channel has to be multiplied by a factor $\delta_W > 1$ to match with the sum of the widths of the downstream branches. (2) The slope of the upstream channel has to increase by a factor $\delta_S > 1$ to meet the average of the downstream channel slopes. The mathematical analysis yields qualitatively similar results.

MOTS CLES

Fluvial bifurcations, braided streams, channel geometry.

Bifurcations fluviales, fleuves en tresses, channel geometry.

1 BACKGROUND

River bifurcations are fundamental nodal elements of the multi-thread types of streams that can be considered as local flow field disturbances. In combination with other disturbances called « forcings » such as the bed topography and curvature of the upstream channel, or the slope advantage and deviation angle of the downstream branches, the nodal bifurcations determine the partition of water and sediment fluxes into the bifurcates, hereby influencing their morphology and activity.

Focusing on the simplest case of the symmetrical and straight bifurcation (i.e. without any forcing) and neglecting bank erosion, such as done by Bolla Pittaluga et al. (2003) - model called “BRT”, the discharge partition ΔQ along the anabranches is determined by the aspect ratio, the Shields stress and the slope at the entering channel (resp. β_a, θ_a and S_a). Depending on whether β_a is below or above a critical value β_{cr}^0, the system finds only one or three equilibrium solutions for the discharge partition. In the former case, the solution is at equilibrium with a balanced configuration: the flux evenly spreads across the bifurcates ($\Delta Q = 0$). In the latter case, the balanced solution becomes unstable and two reciprocal stable equilibria are found: one of the bifurcates dominates while the other carries a limited amount of water and sediment (cf. dotted curves in Fig.1).

The above described framework was improved by Miori et al. (2006) by introducing a regime formula that relates the hydraulic parameters to an equilibrium width, hereby cancelling one degree of freedom of the system. In the present work, we applied this model by considering the regime formula proposed by Ashmore (2001), here modified to make it dimensionally sober. The system then only depends on two parameters (chosen to be β_a and S_a), assigning a value of θ_a to each value of β_a.

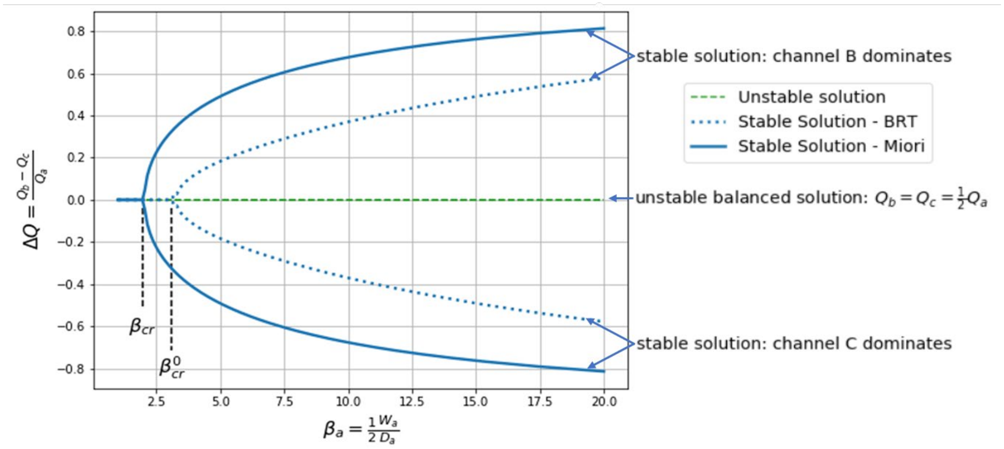

Figure 1: Water discharge partition ΔQ varying along β_a, with d_{50} = 0.02 m and S_a = 0.01

Considering bank erosion in the bifurcates shifts the unbalanced stable solution of the BRT-model towards a more unbalanced, but still stable equilibrium solution (cf. solid curve in Fig.1), making it even less likely for a balanced partition to be stable ($\beta_{cr}^0 \rightarrow \beta_{cr}$).

In summary, the mathematical analysis of the discharge partition at a nodal bifurcation at equilibrium yields highly unbalanced, stable solution. This uneven partition is stabilized by the appearance of an inlet step at the bifurcation node: the erosion and deposit processes create a local transverse slope which directs the sediment towards the deeper channel, ensuring to satisfy its transport capacity. The shallower is the entering channel, the more likely the flow field splits unevenly, which leads to highly unbalanced equilibrium.

2 EQUILIBRIUM WIDTH AND SLOPE OF THE BIFURCATES

Applying the regime formula to the bifurcation branches allows to compare their equilibrium width ($W_{b,c}$ vs W_a), as well as to compute the channel slopes $S_{b,c}$ that comply with this equilibrium. These computations allow the definition of two new parameters: (1) channel enlargement δ_W as the sum of the widths of the bifurcates divided by the width of the upstream channel; (2) the slope variation δ_S as the average of the slopes in the bifurcates divided by the slope in the upstream channel. As illustrated in Fig. 2, the trend of both parameters highly differs, depending on the balanced (unstable) or unbalanced (stable) nature of the solution. In the balanced case, the bifurcation strongly affects the total wetted area and the average slope of the channels. The computation yields factors ranging over [1.47,1.60] for δ_W and [1.16,1.35] for δ_S (cf. Fig. 2).

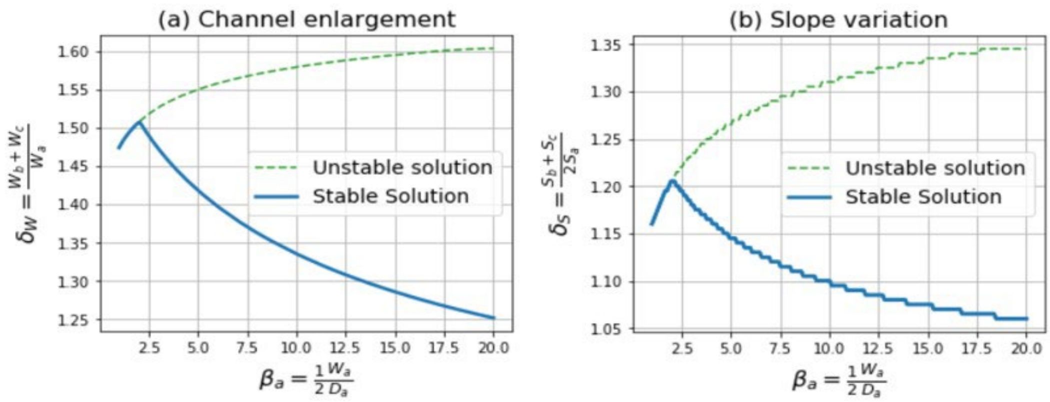

Figure 2: (a) Channel enlargement and (b) Slope variation as function of the upstream aspect ratio.

However, when the discharge parts unevenly (domination of one bifurcate over the other), both δ_W and δ_S assume significantly lower values (ranges are [1.51,1.25] for δ_W and [1.21,1.06] for δ_S), i.e. the total wetted area and the averaged channel slope are less affected by the local disturbance induced by the bifurcation. This manifests another stabilizing effect for the unbalanced flow partition. As the flow field splits, the partition seeks the equilibrium related to the lower disturbance of the morphology of the upstream channel. Along its increasing aspect ratio, the disturbing effect of the bifurcation diminishes.

3 OBSERVATIONS

In a first attempt to verify this hypothesis, the planimetric shape of 50 bifurcations in the special case of channel loops (taken from satellite imagery) is compared with mathematical predictions.

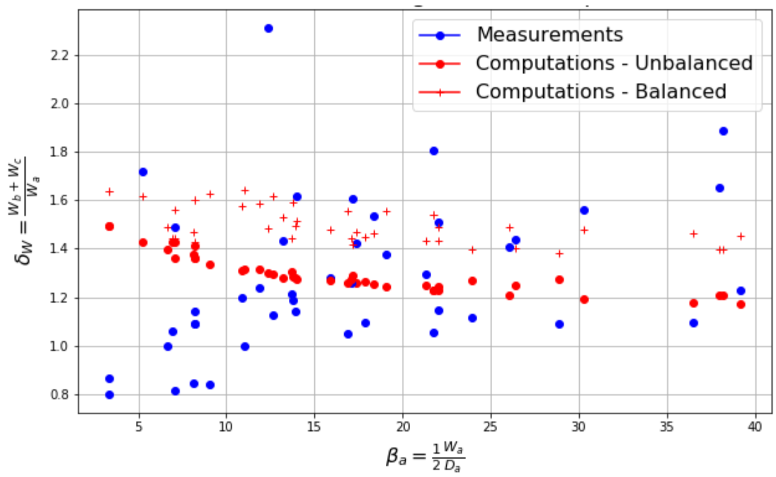

Figure 3: (a) Computed channel enlargement over observed values, (b) Comparison over the aspect ratio

The theory prescribes a channel enlargement δ_W ranging from ca. 1.2 to 1.5, whilst observed values range from 0.8 to 2.3, with 10% of the observations showing a channel narrowing (i.e. $\delta_W < 1$).

The main problem causing the lack of consistency between observations and computations resides in the formulation of the regime formula, which should be calibrated at each data point.

Moreover, with this restricted dataset, the observations sustain the results of the theory qualitatively by showing a vast majority of channel enlargement. An expansion of the dataset to braiding and anastomosing cases as well as including their topography will enable a more profound verification.

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