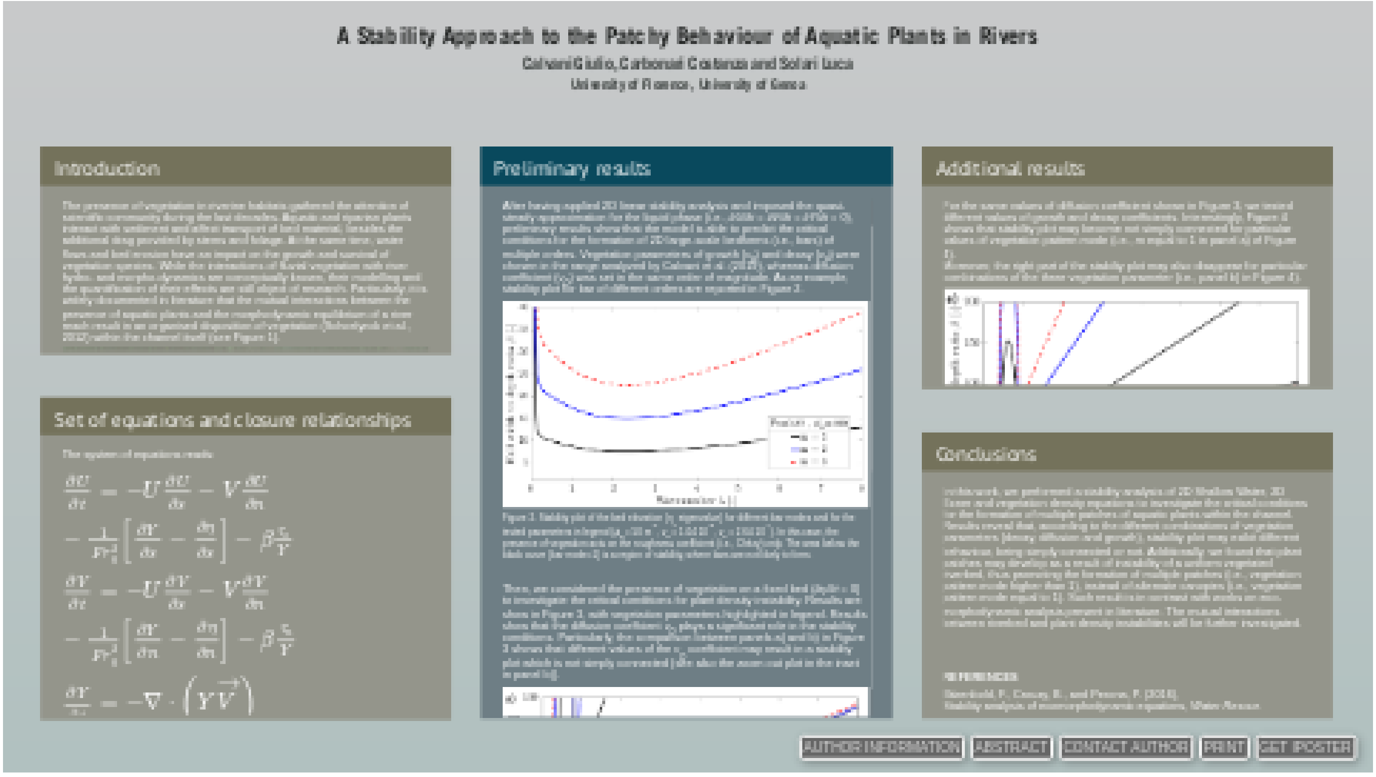
A Stability Approach to the Patchy Behaviour of Aquatic Plants in Rivers



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INTRODUCTION

The presence of vegetation in riverine habitats gathered the attention of scientific community during the last decades. Aquatic and riparian plants interact with sediment and affect transport of bed material, besides the additional drag provided by stems and foliage. At the same time, water flows and bed erosion have an impact on the growth and survival of vegetation species. While the interactions of fluvial vegetation with river hydro- and morpho-dynamics are conceptually known, their modelling and the quantification of their effects are still object of research. Particularly, it is widely documented in literature that the mutual interactions between the presence of aquatic plants and the morphodynamic equilibrium of a river reach result in an organised disposition of vegetation (Schoelynck et al., 2012) within the channel itself (see Figure 1).

Figure 1. Patches of aquatic plants as a result of interactions between flow, sediment and vegetation. Plants in the foreground are bended due to flow drag.

In this work, we investigated the critical conditions for the formation of such organised arrangements in a straight channel of constant width characterised by an erodible bed of uniform sediment with uniform vegetation density. A 2D stability analysis is performed on shallow water equations (SWE) for the water flow, 2D Exner equation for bed elevation dynamics and sediment continuity and an additional equation for vegetation dynamics (Barenbold et al., 2016). As closure relations, we considered the equation proposed by Luhar and Nepf (2013) for vegetation drag in fully submerged conditions and the formula for sediment transport in vegetated conditions proposed by Yang and Nepf (2019). The entire set of equations is reported in the next section.

SET OF EQUATIONS AND CLOSURE RELATIONSHIPS

The system of equations reads:

$$\frac{\partial U}{\partial t} = -U\frac{\partial U}{\partial s} - V\frac{\partial U}{\partial n} - \frac{1}{Fr_0^2}\left[\frac{\partial Y}{\partial s} - \frac{\partial \eta}{\partial s}\right] - \beta\frac{\tau_s}{Y}$$

$$\frac{\partial V}{\partial t} = -U\frac{\partial V}{\partial s} - V\frac{\partial V}{\partial n} - \frac{1}{Fr_0^2}\left[\frac{\partial Y}{\partial n} - \frac{\partial \eta}{\partial n}\right] - \beta\frac{\tau_n}{Y}$$

$$\frac{\partial Y}{\partial t} = -\nabla\cdot\left(Y\overrightarrow{V}\right)$$

$$\frac{\partial \eta}{\partial t} = -\gamma\nabla\cdot\Phi\left\{\cos\delta\,,\ \sin\delta\right\}$$

$$\frac{\partial \phi}{\partial t} = \nu_g\phi\left(1-\phi\right) + \nu_D\nabla^2\phi - \nu_d\phi Y\left|\overrightarrow{V}\right|$$

Closure relationships for shear stress, Chézy coefficient (Luhar and Nepf, 2013), dimensionless sediment transport (Yang and Nepf, 2018) and turbulent kinetic energy are hereafter reported.

$$\left\{\tau_s, \tau_n\right\} = \frac{1}{C^2}\left|\overrightarrow{V}\right|\left\{U, V\right\}$$

$$C = \sqrt{\frac{2}{C_f}}\left(1-\frac{h_v}{Y}\right)^{3/2} + \sqrt{\frac{2}{C_D\phi h_v D_v\beta_v}}\frac{h_v}{Y}$$

$$\Phi = \begin{cases} 2.15e^{-2.06k_t} & k_t \leq 0.95 \\ 0.27k_t^3 & 0.95 < k_t \leq 2.74 \end{cases}$$

$$k_t = gF_r^2\frac{\frac{\left|\overrightarrow{\tau}\right|}{0.19} + \delta_{kt}\left(C_D\frac{128\phi D_v^2\beta_v}{\left(4-\pi\phi D_v^2\beta_v\right)^4}\right)^{2/3}\left|\overrightarrow{V}\right|^2}{\left(\frac{\rho_s}{\rho}-1\right)gd_{50}}$$

PRELIMINARY RESULTS

After having applied 2D linear stability analysis and imposed the quasi-steady approximation for the liquid phase (i.e., $\partial U/\partial t = \partial V/\partial t = \partial Y/\partial t = 0$), preliminary results show that the model is able to predict the critical conditions for the formation of 2D large-scale bedforms (i.e., bars) of multiple orders. Vegetation parameters of growth (v_g) and decay (v_d) were chosen in the range analyzed by Calvani et al. (2019), whereas diffusion coefficient (v_D) was set in the same order of magnitude. As an example, stability plot for bar of different orders are reported in Figure 2.

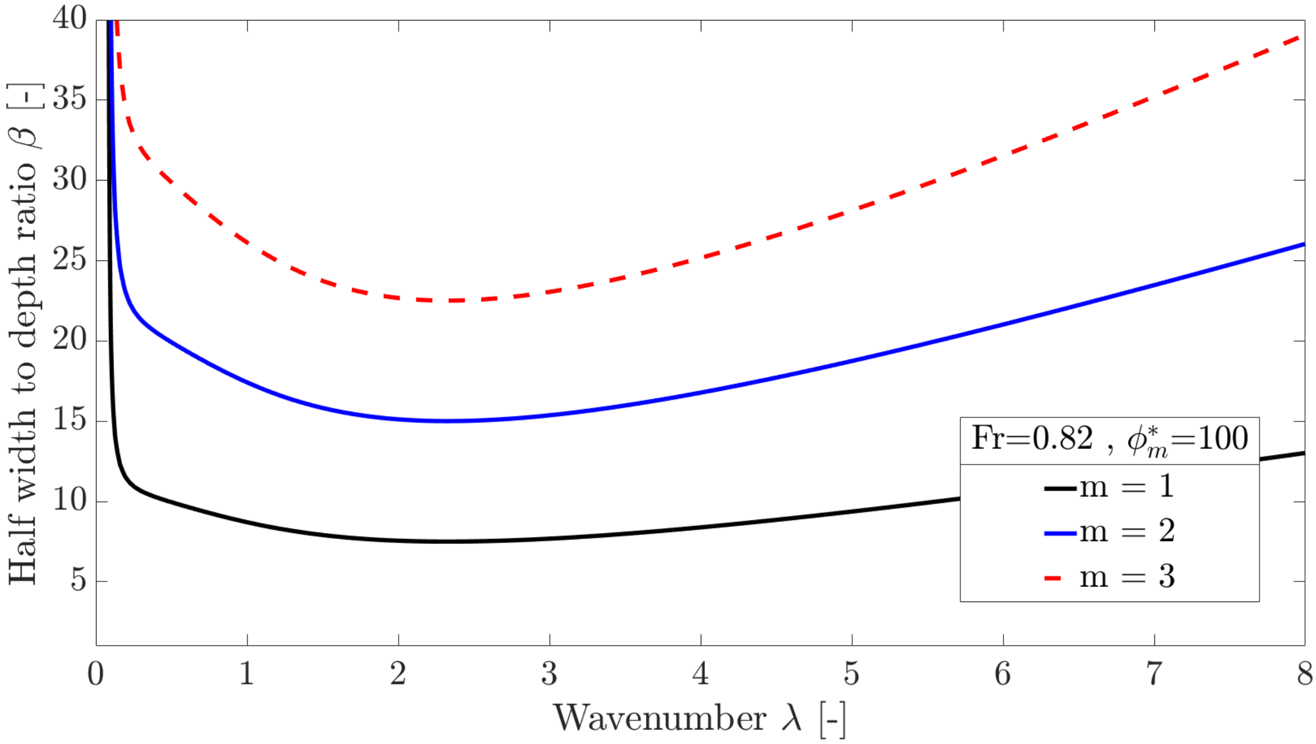

Figure 2. Stability plot of the bed elevation (η_1 eigenvalue) for different bar modes and for the tested parameters in legend (ϕ_m= 50 m^{-2}, v_d = 1.04 10^{-8}, v_g = 2.64 10^{-7}). In this case, the presence of vegeation acts on the roughness coefficient (i.e., Chézy) only. The area below the black curve (bar mode=1) is a region of stability, where bars are not likely to form.

Then, we considered the presence of vegetation on a fixed bed ($\partial \eta/\partial t = 0$) to investigate the critical conditions for plant density instability. Results are show in Figure 3, with vegetation parameters highlighted in legend. Results show that the diffusion coeffcient v_D plays a significant role in the stability conditions. Particularly, the comparison between panels a) and b) in Figure 3 shows that different values of the v_D coefficient may result in a stability plot which is not simply connected (see also the zoom out plot in the inset in panel b)).

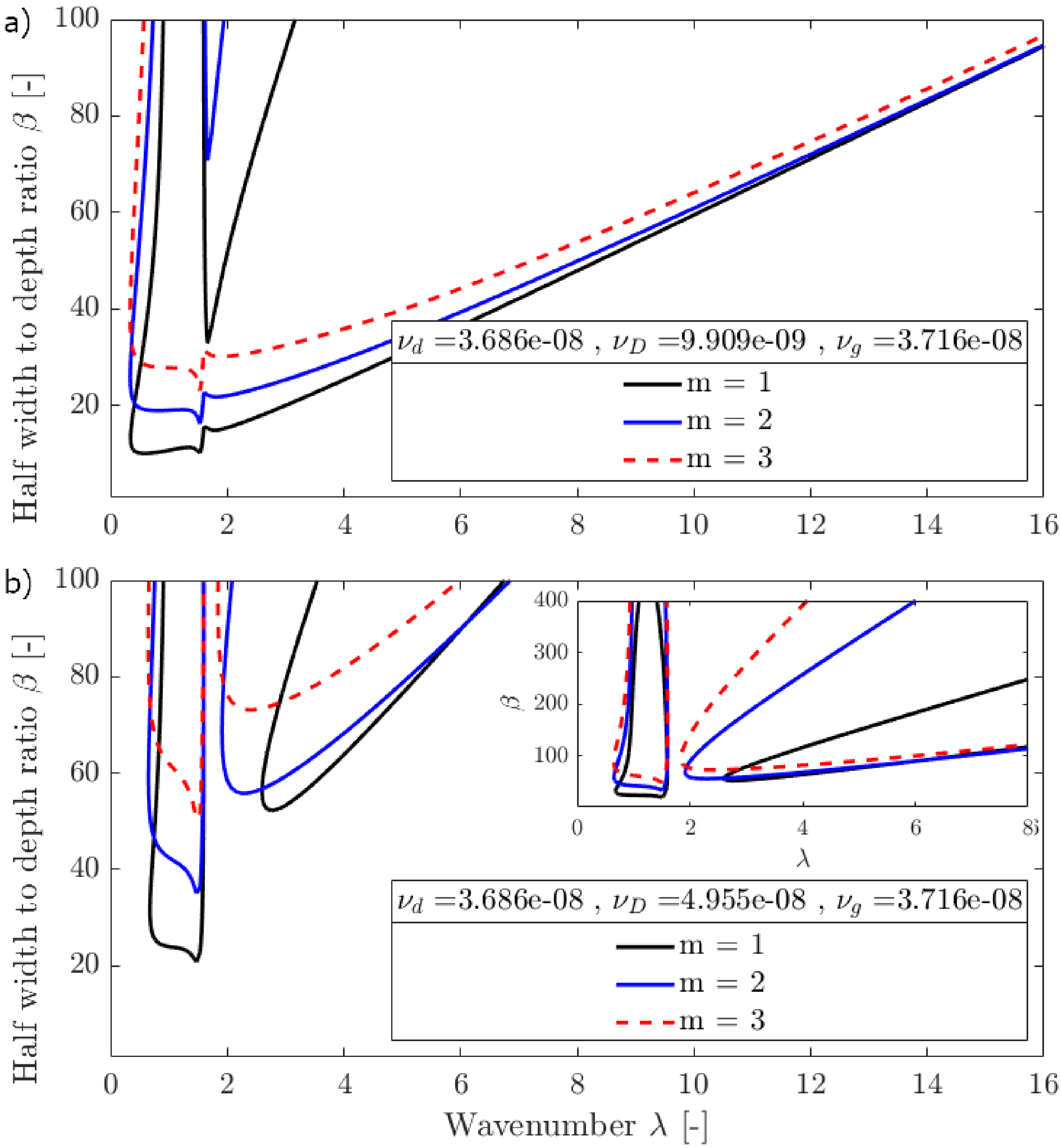

Figure 3. Stability plot for the vegetation density (ϕ) for different vegetation pattern modes and tested parameters in legend (Fr=1.43, C = 28.6, ϕ_m= 50 stem m^{-2}). v_d and v_g are equal in both the panels. v_D is 5 times higher in panel b). Inset panel is a zoom out along the Y-axis to highlight the not-simply connection of marginal curves.

ADDITIONAL RESULTS

For the same values of diffusion coefficient shown in Figure 3, we tested different values of growth and decay coefficients. Interestingly, Figure 4 shows that stability plot may become not simply connected for particular values of vegetation pattern mode (i.e., *m* equal to 1 in panel a) of Figure 4).
Moreover, the right part of the stabilty plot may also disappear for particular combinations of the three vegetation parameter (i.e., panel b) in Figure 4).

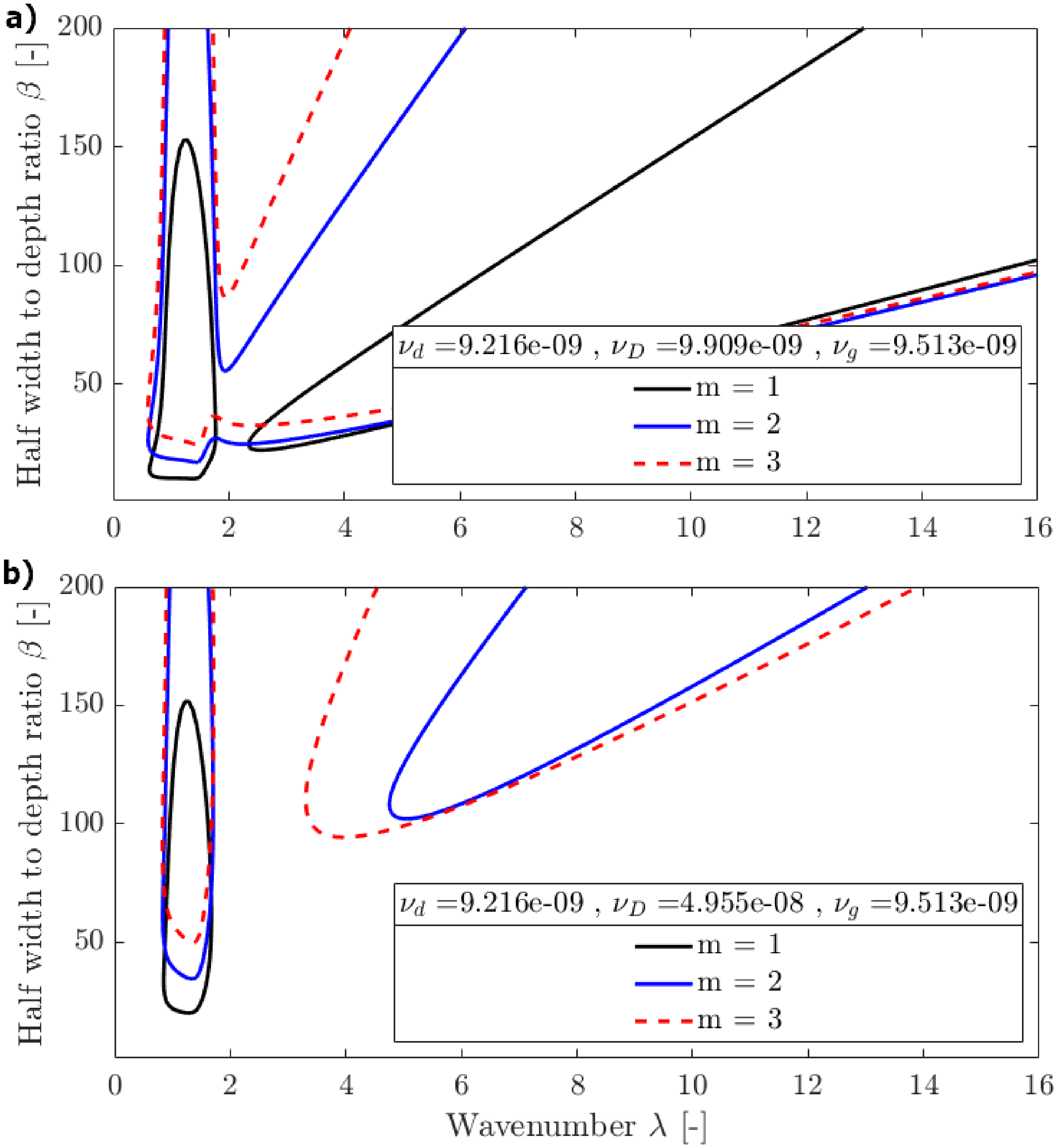

Figure 4. Stability plot of vegetation patterns. Marginal curves for different modes and parameters (Fr=1.43, C = 28.6, ϕ_m= 50 stem m^{-2}) are shown. Different combinations may result in not simply connected plots (see black curve in panel a)) or disappearence of the second region (see panel b)).

As a final remark, we found that marginal curves for patterns of aquatic vegetation may exist, for particular combinations of the vegetation parameters, even when pattern mode is higher than 1, which is contrast to the findings of Bärenbold et al. (2016). Such result is consistent to the existence of multiple patches of vegetation along the channel (see Figure 1) and the cross section (Schoelynck et al., 2012).

CONCLUSIONS

In this work, we performed a stability analysis of 2D Shallow Water, 2D Exner and vegetation density equations to investigate the critical conditions for the formation of multiple patches of aquatic plants within the channel. Results reveal that, according to the different combinations of vegetation parameters (decay, diffusion and growth), stability plot may exibit different behaviour, being simply connected or not. Additionally, we found that plant patches may develop as a result of instability of a uniform vegetated riverbed, thus promoting the formation of multiple patches (i.e., vegetation pattern mode higher than 1), instead of alternate canopies (i.e., vegetation pattern mode equal to 1). Such result is in contrast with works on eco-morphodynamic analysis present in literature. The mutual interactions between riverbed and plant density instabilities will be further investigated.

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AUTHOR INFORMATION

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ABSTRACT

The presence of vegetation in riverine habitats gathered the attention of scientific community during the last decades. Aquatic and riparian plants interact with sediment and affect transport of bed material, besides the additional drag provided by stems and foliage. At the same time, water flows and bed erosion have an impact on the growth and survival of vegetation species. While the interactions of fluvial vegetation with river hydro- and morpho-dynamics are conceptually known, their modelling and the quantification of their effects are still object of research. Particularly, it is widely documented in literature that the mutual interactions between the presence of aquatic plants and the morphodynamic equilibrium of a river reach result in an organised disposition (patches of different size and geometry) of vegetation within the channel itself.

In this work, we investigated the critical conditions for the formation of such organised arrangements in a straight channel of constant width characterised by an erodible bed of uniform sediment with uniform vegetation density. A 2D stability analysis was performed on shallow water equations (SWE) for the water flow, 2D Exner equation for bed elevation dynamics and sediment continuity and an additional equation for vegetation dynamics. Closure relations for drag and sediment transport in vegetated conditions were involved, as well. Results reveal the particular conditions of dimensionless parameters leading either to the suppression of vegetation or to the survival of aquatic plants. In the latter, the analysis suggests that multiple patches (order higher than 1) of vegetation may exist as aa result of instability, which is contrast to the findings prenset in literature.