

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

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Introduction

The presence of vegetation in riverine habitats, together with the alteration of substrate composition during the low streamflow, aquatic and riparian plants interact with sediment and affect morphology of bed channel, besides the additional drag provided by stems and foliage. In the same way, water flows and bed erosion have an impact on the growth and survival of vegetation systems. While the interactions of flood vegetation with river hydrology and morphological dynamics are increasingly known, their modeling and the quantification of their effects are still objects of research. Particularly, it is widely documented in literature that the mutual interactions between the presence of aquatic plants and the morphodynamic evolution of a river reach result in an organized dispersion of vegetation (Johanneski and 2002) within the channel reach (see Figure 1).

Preliminary results

After having applied 2D linear stability analysis and expanded the spatial velocity approximation for the liquid phase (i.e. $\rho \frac{dU}{dt} = \rho \nabla \cdot (\mathbb{T} \nabla U)$), preliminary results show how the model is able to predict the critical conditions for the formation of 2D large scale patterns (i.e. bars) of multiple orders. Vegetation parameters of growth (μ) and decay (ν) were chosen in the range analyzed by Carbonari et al. (2018), whereas diffusion coefficient (κ) took on the values within of drag coefficient. As an example, stability plot for the different orders are reported in Figure 2.

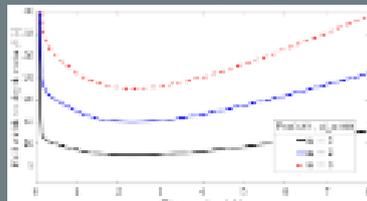
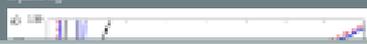


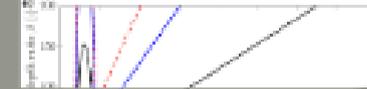
Figure 2. Stability plot of the real part of the eigenvalue (Re(λ)) versus the wavenumber (k) for the most parameters investigated ($\mu = 0.1$, $\nu = 0.1$, $\kappa = 0.1$ to 0.5). In the case, the plots are representative of the complex behavior of the system. The area below the blue curve (see table 1) examples of stability where the system is unstable system.

Then, we considered the presence of vegetation on a level bed ($\beta = 0$) to investigate the critical conditions for the plant already instability. Results are shown in Figure 3, with representative parameter highlighted in legend. Results show that for different coefficients μ , ν plays a significant role in the stability conditions. Particularly, the competition between growth (μ) and decay (ν) in Figure 3 shows that different values of the μ , combination may result in a stability plot which is not simply corrected (also when the streamflow plot in the inset in panel (b)).



Additional results

For the same values of diffusion coefficient as shown in Figure 2, we tested different values of growth and decay coefficients. In particular, Figure 4 shows that stability plot may become not simply corrected by particular values of vegetation pattern order (i.e. in black in 1 in panel (a) of Figure 1). Moreover, the right part of the stability plot may also change for particular combinations of the three vegetation parameters (i.e. panel (b) in Figure 4).



Set of equations and closure relationships

The system of equations reads:

$$\frac{\partial U}{\partial t} = -U \frac{\partial U}{\partial x} - V \frac{\partial U}{\partial y}$$

$$- \frac{1}{Fr_0^2} \left[\frac{\partial U}{\partial x} - \frac{\partial \eta}{\partial x} \right] - \beta \frac{\partial U}{\partial y}$$

$$\frac{\partial V}{\partial t} = -U \frac{\partial V}{\partial x} - V \frac{\partial V}{\partial y}$$

$$- \frac{1}{Fr_0^2} \left[\frac{\partial V}{\partial x} - \frac{\partial \eta}{\partial y} \right] - \beta \frac{\partial V}{\partial y}$$

$$\frac{\partial \eta}{\partial t} = -\nabla \cdot (Y \nabla \eta)$$

Conclusions

Moreover, we performed a stability analysis of 2D shallow water, 2D liquid and vegetation during expansion 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 (growth, diffusion and decay), stability plot may exhibit different behaviors. Being simply corrected or not. Additionally, we found that such analysis may identify the critical conditions of a system organized on level beds, providing the formation of multiple patches (i.e. vegetation pattern order higher than 1). Instead of a linear vegetation (i.e. vegetation pattern order equal to 1). Such results are consistent with studies on river morphodynamic development in the same. The crucial interactions between channel and plant density oscillations will be further investigated.

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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:

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

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

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

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

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

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.

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

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

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

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

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.

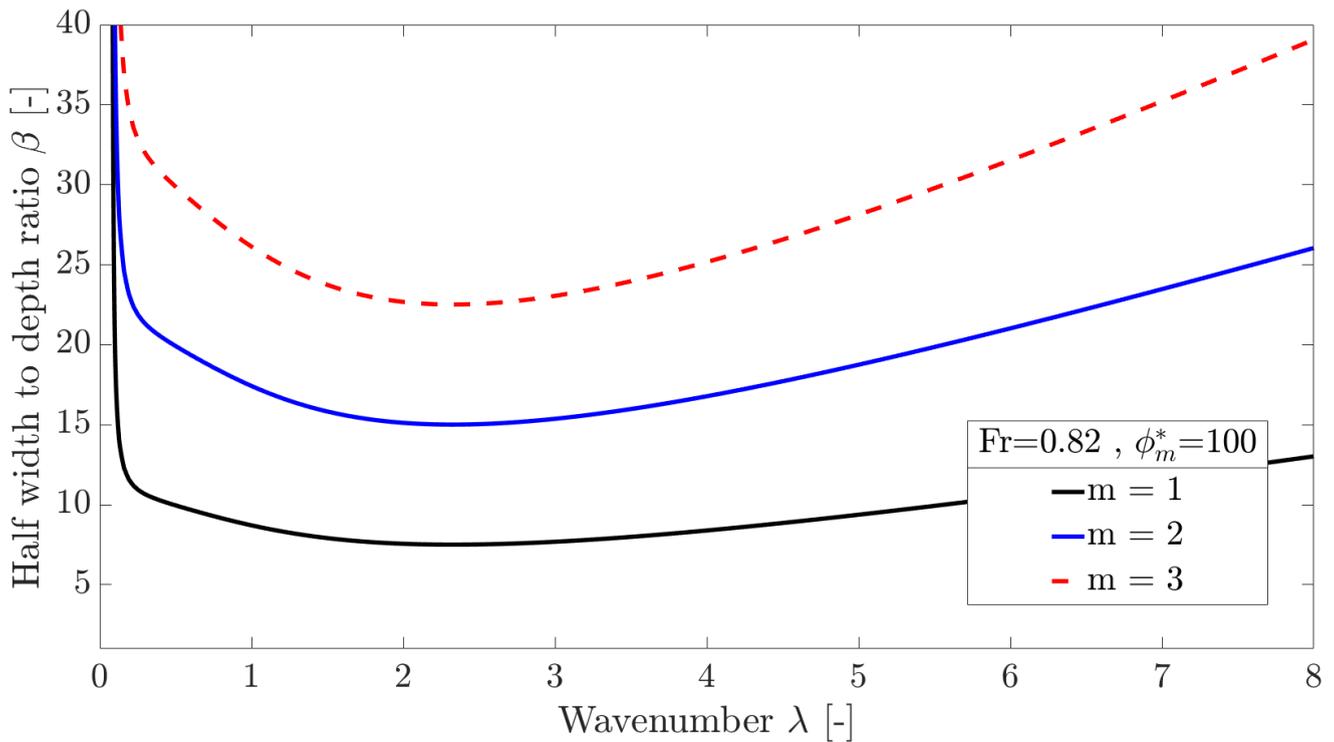


Figure 2. Stability plot of the bed elevation (η_I eigenvalue) for different bar modes and for the tested parameters in legend ($\phi_m = 50 \text{ m}^{-2}$, $v_d = 1.04 \cdot 10^{-8}$, $v_g = 2.64 \cdot 10^{-7}$). In this case, the presence of vegetation acts on the roughness coefficient (i.e., Chézy) 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 shown in Figure 3, with vegetation parameters highlighted in legend. Results show that the diffusion coefficient 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)).

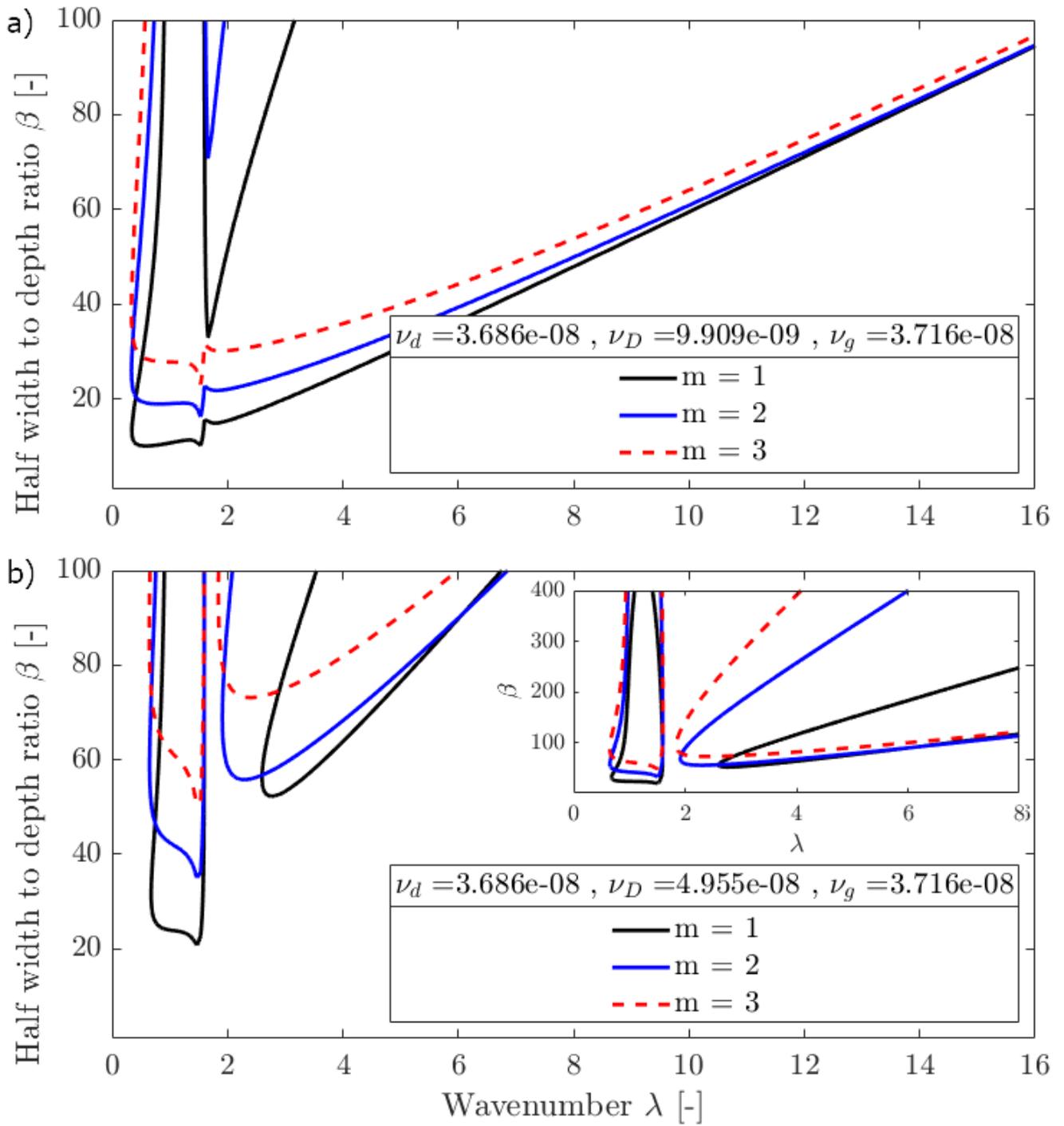


Figure 3. Stability plot for the vegetation density (ϕ) for different vegetation pattern modes and tested parameters in legend ($F_r=1.43$, $C=28.6$, $\phi_m=50$ stem m^{-2}). ν_d and ν_g are equal in both the panels. ν_D is 5 times higher in panel b). Inset panel is a zoom out along the Y-axis to highlight 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 stability plot may also disappear for particular combinations of the three vegetation parameter (i.e., panel b) in Figure 4).

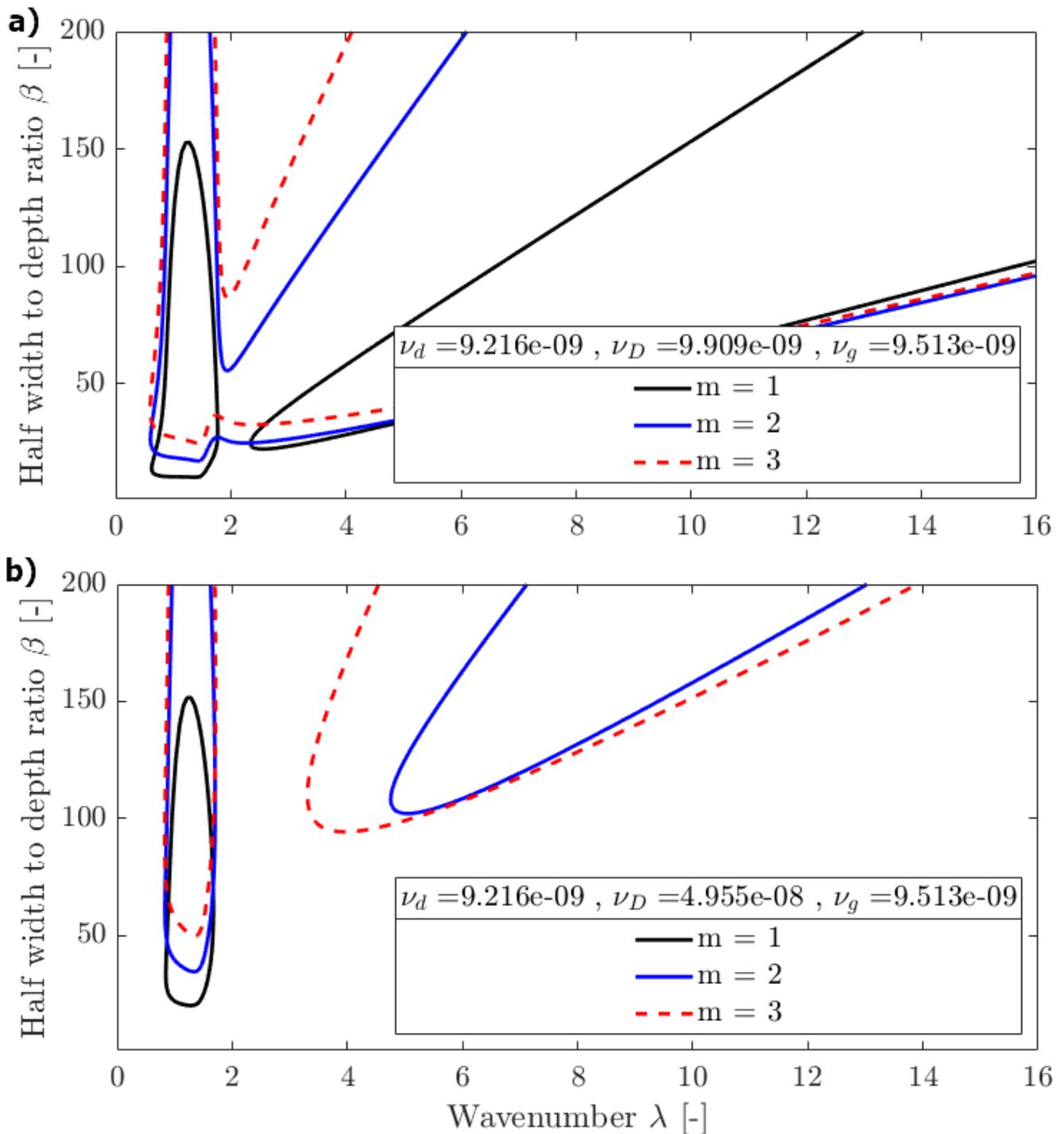


Figure 4. Stability plot of vegetation patterns. Marginal curves for different modes and parameters ($Fr=1.43$, $C=28.6$, $\phi_m=50$ stem m^{-2}) are shown. Different combinations may result in not simply connected plots (see black curve in panel a) or disappearance of the second region (see panel b).

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 exhibit 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

1

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 a result of instability, which is contrast to the findings present in literature.