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EFFECTS OF RIPARIAN AND FLOODPLAIN VEGETATION ON RIVER PATTERNS AND FLOW DYNAMICS

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ABSTRACT

Flume experiments and field observations demonstrating the effects of vegetation on river planforms are reported in literature, but numerical studies of these effects at the river scale are lacking. We investigated the effects of vegetation in a 2D morphodynamic model using submodels for flow resistance and colonisation of newly formed deposits. In the vegetated areas, the flow resistance was divided into a resistance exerted by the bed and a resistance exerted by the plants, adopting Baptist's formulation. In this way the model was able to reproduce the decrease in bed shear stress thereby reducing sediment transport capacity, and the increase in hydraulic resistance thereby reducing flow velocities. Colonisation was reproduced by assigning vegetation to the areas that became dry at low water stages. Bank accretion and erosion were reproduced as drying and wetting of the computational cells at the channel margins. The rate of bank erosion was related to the rate of bed degradation at the adjacent wet cells. The model was applied to a hypothetical case with the same characteristics as the Allier River near Moulins, France. The river was allowed to develop its own geometry starting from a straight and uniform channel. Different vegetation densities were found to produce different river planforms. At the highest density the flow concentrated in a single channel and the river formed incipient meanders. Without floodplain vegetation the river showed a clear braided pattern, with the formation of several bars. At low vegetation density the river showed a transition pattern, i.e. a low braiding degree with distinguishable meanders. The braiding degree was also influenced by overbank flows. Since both the river hydraulic regime and floodplain vegetation depend on changes such as climate, river damming and restoration, it is recommended that the impacts on river morphology and vegetation are assessed jointly in an integrated manner.

Key words: River morphology, meandering, braiding, flow through vegetation, colonisation by plants, bank erosion.

1. INTRODUCTION

Riparian vegetation increases the bank resistance against erosion directly by root binding, and indirectly by enhancing local deposition of organic material and fine sediment, which increases the soil cohesion (Tal et al., 2004). Besides, the flow resistance due to vegetation reduces the velocities between and above the plants and concentrates the flow in non-vegetated areas. The lower flow velocities between the plants result in a decrease in bed shear stress, soil erosion and sediment transport (Thorne, 1990; Carollo et al., 2002). The effects of vegetation on river banks and floodplains can be seen at all spatial scales. At the cross-sectional scale, vegetation causes deflection of the main flow towards the centre of the river channel (Tsujimoto, 1999), reduces bank erosion and enhances bank accretion, which results in smaller width-to-depth ratios. At the reach scale, riparian vegetation reduces the braiding degree of the river (e.g. Tal et al., 2004 and Kurabayashi and Shimizu, 2003).

Previous numerical studies on the effects of vegetation on the river pattern reproduce changes at the flume scale. Tsujimoto (1999) showed that floodplain vegetation reduces the channel width-to-depth ratio using a 2D model reproducing a laboratory experiment without bank erosion. Jang and Shimizu (2007) reproduced the morphological behaviour of an experimental channel with and without floodplain vegetation with a 2D model including bank erosion. Without floodplain vegetation the channel developed a braided pattern; with vegetation a meandering planform with a smaller width-to-depth ratio. Channel mobility decreased with increasing vegetation density.

This work aims at reproducing the effects of vegetation at a real river scale by means of a 2D model with a simplified bank erosion formulation, taking into account colonisation by plants of newly formed sediment deposits. The model includes the effects of vegetation on the hydraulic roughness, distinguishing between the flow between the plants and the flow above the plants, as suggested by Baptist (2005). The model does not take into account the effects of vegetation in decreasing the local soil erodibility.

The river chosen as example for the investigation is the Allier River just upstream of Moulins (France), which is at the transition between meandering and braiding. The characteristics of this river were used to construct a hypothetical river, which was allowed to develop its own geometry starting from a straight and uniform channel. Different floodplain vegetation densities were considered.

2. GENERAL SETTING

The Allier River is located in Auvergne (France) and is a main tributary of the Loire. In the study area (last 6 km upstream of the city of Moulins), the river forms three meanders and presents one or more channels (Figure 1).

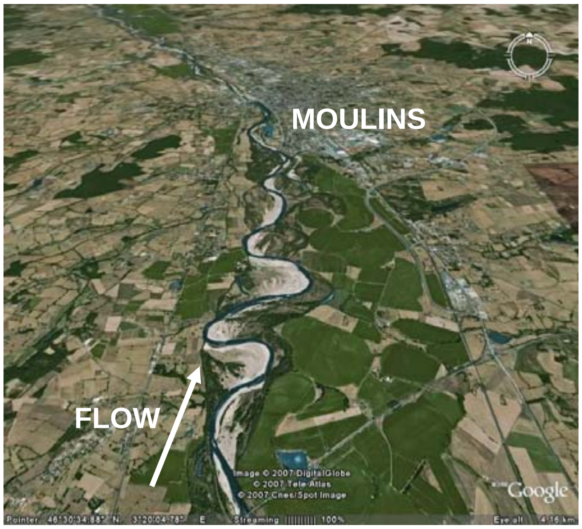

Figure 1 – The Allier River upstream of Moulins (image © Digital Globe Google Earth).

The sediment forming the riverbed is gravel characterised by strong horizontal and vertical variations (sorting and armouring). Discharges vary between 10 and 1400 m^3/s. Bankfull and mean yearly discharges are 300 and 140 m^3/s, respectively; the minimum discharge that is able to move the armour bed layer and produce morphological changes is 200 m^3/s.

In the study area, the river banks are unprotected. Between August 2003 and August 2004 the river bank retreat rates ranged between 10 and 65 m/year, whereas at the other side of the channel the point bars advanced by 30 to 40 m (De Jong, 2005). Moving away from the river, floodplain vegetation varies from pioneer vegetation, herbs and weeds to softwood forest. Table 1 summarises the main river characteristics (Blom, 1997).

Table 1 –Characteristics of the Allier River near Moulins at bankfull conditions.

Main channel width	River corridor width	Valley slope	Mean water depth	Chézy coeff. main channel	D_{50}
65 m	1000 m	0.000833	2 m	50 $m^{1/2}/s$	5 mm

3. METHODOLOGY

The 2D morphological model used for the investigation (Lesser et al., 2004) is based on the continuity and momentum equations for water, coupled to the balance and transport equations for sediment, designed for curved channels. In the equations, the sediment transport direction is corrected to take into account the transverse bed slope and the spiral flow in river bends (Struiksma et al., 1985), whereas the spiral flow itself is reproduced in a parameterised way (Blanckaert et al., 2002). Bank erosion is treated in a simplified way: the model assigns a part of the erosion occurring inside the wet cells that are located at the margin of the water flow to their adjacent dry cells, which then become wet. This "erosion distribution" is weighted by a coefficient having the same value in the entire model domain.

The model simulated the morphological development of a river having the characteristics of the Allier, starting from a straight channel. The sediment was assumed uniform with a diameter equal to the D_{50} (Table 1) and the same sediment characteristics were imposed to the entire model domain. Due to the long-term character of the investigation, the discharge hydrograph was simplified to reproduce a characteristic year, which was repeated for the number of years defining the duration of the investigation period. Two discharge regimes were considered: a varying discharge, derived from the duration curve 1968-1995 (Blom, 1997), ranging between 200 and 800 m^3/s (overbank flow for about one month per year) and a constant discharge of 200 m^3/s (no overbank flow). The modelled area was 1 km wide, including main channel and floodplains, and 6.5 km long. The rectangular grid consisted of 71 cells in cross-sectional direction and 186 cells in longitudinal direction. The size of the grid cells was smaller (10 m) in the central part of the river corridor (Figure 2).

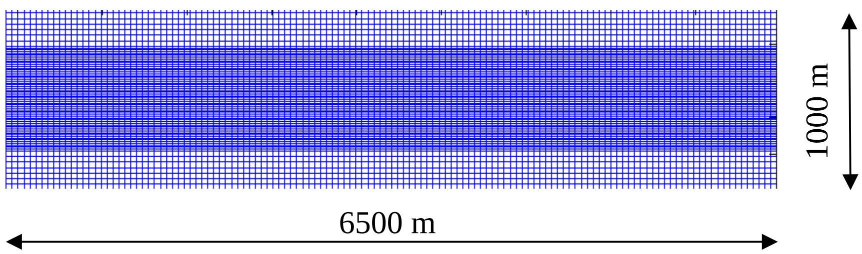

Figure 2 – Computational grid.

The effects of vegetation on the hydraulic roughness were obtained by applying *Baptist*'s method (*Baptist*, 2005; *Baptist et al*., 2005). This method separates the bed shear stress (soil) from the shear stress of vegetation and distinguishes between fully submerged and partly submerged vegetation. Plants are schematised as thin, vertical cylinders with given density. The method assumes that the flow velocity through vegetation is uniform over the vertical, which is valid only for high vegetation density. With this formulation, the model was able to reproduce the decrease in bed shear stress that reduces sediment transport and the increase in hydraulic resistance that reduces flow velocities in the vegetated areas.

In the investigation, the floodplain was assumed to be uniformly covered by 0.2 m high grass, in the form of cylinders (stems) having a diameter of 0.015 m. Two densities were considered: 100 and 4.5 stems/m^2. The highest density value is typical for grassland, whereas the low density value takes into account the situation of the Allier River, in which the point bars are mostly covered by low-density pioneer vegetation. A value of 1 was adopted for the drag coefficient.

The model also included the colonisation of new deposits by plants during low flows, which was done by assigning vegetation having the same density as on the floodplains to the areas that became dry at a discharge of 200 m^3/s.

4. RESULTS

Due to the limitations caused by long computational times the simulation period had to be restricted to approximately 10 years. Since the morphological time scale of the River Allier in the study area was estimated using the formula indicated by de Vries (1975) at 150 years, the simulations could reproduce only incipient large-scale river morphological changes. Nevertheless, clear morphological differences appeared between the cases with and without vegetation and between the two vegetation densities. Figure 3 shows the river morphology obtained with variable discharge after 10 years in the three cases: without floodplain vegetation, with high-density vegetation and with low-density vegetation. Figure 4 shows the development of cross-section 176 (location indicated in Fig. 3) without floodplain vegetation. Figure 5 shows the bed shear stress in the two cases with high-density vegetation and without vegetation.

After 10 years, without floodplain vegetation the river configuration was clearly braided with the formation of several bars in the cross-section (Fig. 3B). The braiding degree drastically reduced with low-density floodplain vegetation (pioneer vegetation), yielding a channel at the transition between meandering and braiding. In this case, clear meanders are detectable but at certain locations the flow splits forming more than one channel (Fig. 3C). Finally, the presence of grass on the floodplains was sufficient to impose an incipient meandering character to the river (Fig. 3D).

It should be noticed that only the effects of vegetation on floodplain roughness and sediment transport rates were accounted for in the model. The coefficient weighing the bank erosion rate was the same in all cases and the effects of vegetation on the soil erodibility were not taken into account. The higher roughness caused by the presence of plants increased the flow concentration and the bed shear stresses in the main channel (Fig. 5), which resulted in lower width-to-depth ratios and reduced number of bars. This result agrees with previous investigations (e.g. Tsujimoto, 1999; Tal et al., 2004; Kurabayashi and Shimizu, 2003; Jang and Shimizu, 2007). On the floodplains, vegetation reduced the bed shear stresses (Fig. 5) and the sediment transport capacity.

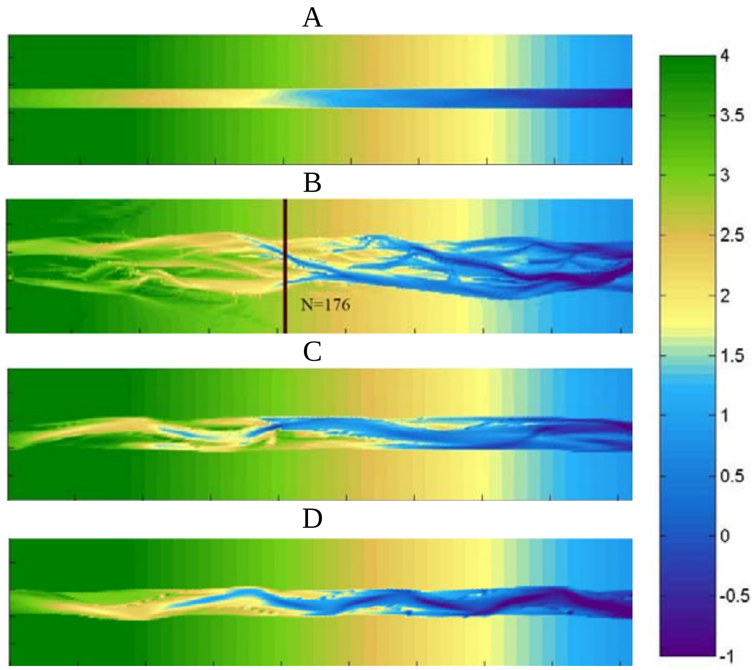

Figure 3 – Initial channel configuration (A) and river morphology after 10 years without floodplain vegetation (B), with low density floodplain vegetation (C) and with high density floodplain vegetation (D). Variable discharge, including overbank flows. Colour bar: bed level in m above reference level.

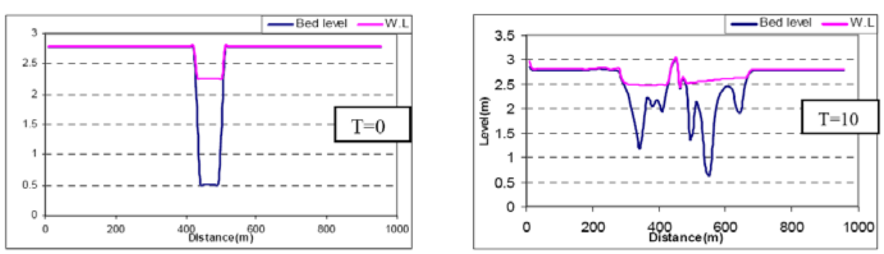

Figure 4 – Initial and final configuration of cross-section N = 176 without vegetation. Purple line: bed level. Pink line: water level (at dry places the model assumes that the water level coincides with the bed level).

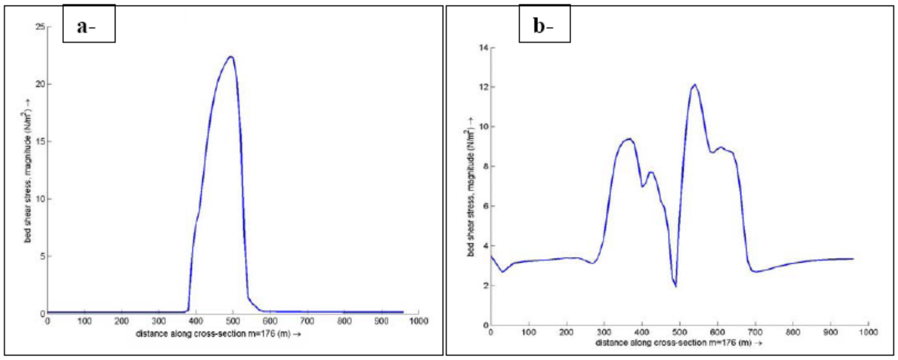

Figure 5 – Bed shear stress at peak discharge (800 m^3/s) at cross-section N = 176 after 10 years, with vegetation (a) and without vegetation (b).

A braided river configuration was obtained also with a constant discharge of 200 m^3/s (lower than bankfull, but sufficient to produce morphological changes), as shown in Figure 6, but in this case the braiding degree was lower than when overbank flows occurred (Fig. 3B).

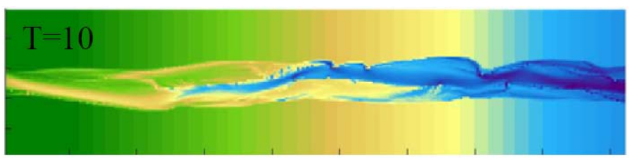

Figure 6 – River morphology after 10 years: no floodplain vegetation, constant discharge (colours as in Figure 3).

5. CONCLUSIONS

We numerically investigated the effects of floodplain vegetation on river planform characteristics at the scale of real rivers, using submodels for bank erosion and colonisation by plants of newly formed sediment deposits. The study shows that floodplain vegetation (grass) is able to transform a braided channel into a meandering one also at the scale of real rivers. The presence of pioneer vegetation (low density grass) is sufficient to lower the braiding degree, producing a channel at the transition between meandering and braiding, as the real River Allier. The investigation included only the effects of vegetation on the hydraulic roughness. Including also the effects of vegetation in reducing the soil erodibility would further increase the detected trend. A braided pattern can result from discharges lower than bankfull, whereas overbank flows were found to enhance the braiding degree.

As a conclusion, floodplain vegetation should be taken into account to assess the long-term morphological changes of river systems. River damming and restoration works, as well as climate changes, by altering hydrology and floodplain vegetation, on the long term alter the river pattern.

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