FLOW-VEGETATION-SEDIMENT INTERACTION

ANDREAS DITTRICH[1] and JUHA JÄRVELÄ[2]

[1]Managing Director and Professor, Leichtweiss-Institute for Hydraulic Engineering, Technical University of Braunschweig, Beethovenstrasse 51a, 38106 Braunschweig, Germany
(Tel: +49 531 391 3940, Fax: +49 531 391 8184, e-mail: a.dittrich@tu-bs.de)
[2]Visiting scientist, Leichtweiss-Institute for Hydraulic Engineering, Technical University of Braunschweig, Beethovenstrasse 51a, 38106 Braunschweig, Germany
(Tel: +49 531 391 3946, Fax: +49 531 391 8184, e-mail: juha.jarvela@hut.fi)

Abstract: A good understanding of the interaction between flow, vegetation, and sediment is required for successful river restoration and sustainable flood management. The purpose of this paper is to provide a summary of available methods to determine flow resistance of natural rivers with vegetation, and discuss the influence of vegetation on erosion and sedimentation processes. Recently, significant advances have been made, but the effects of vegetation on flow and sediment dynamics are still not fully understood. Possible solutions to close the gaps in the current knowledge are suggested, with special focus directed to the determination of the interactive width between main channel and vegetated floodplains, the flow resistance of flexible vegetation with and without leaves, and the flow over submerged vegetation with low water depth.

Keywords: hydraulics, flow resistance, vegetation, sediment, rivers, floodplains

1. INTRODUCTION

The extreme floods in the last years in Germany along the rivers Oder (1997), Rhine (1999) and Elbe (2002) have demonstrated in an impressive way the disastrous effects of such events. In many reaches of the rivers flood risk got even higher due to the transportation of enormous amounts of fine sediment during the floods. Depending on topography and vegetation, sediment deposition of a few centimeters up to one meter occurred on the floodplains of these rivers. Figure 1 shows a floodplain at the River Elbe without vegetation and Figure 2 a riparian forest at the River Rhine. As a consequence of the depositions, the discharge capacity of the rivers significantly reduced. After the floods, the growth of vegetation increased due to the nutrients in the deposited sediments. Consequently, flow resistance of the floodplains increased and water stage rose. In other words, the flood events initiated a cyclic process, where fine sediment was filtered out by vegetation, which in turn accelerated the growth of vegetation, and further, the trapping of sediments.

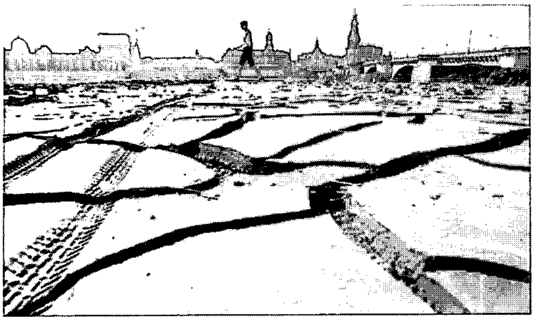

Figure 1. Deposition of fine sediment on the floodplain in the centre of Dresden caused by the flood in 2002 (Foto: Wasser- und Schifffahrtsamt Dresden)

Figure 2. Deposition of fine sediment on the floodplain of the River Rhine close to the city of Breisach after the flood in 1999 (Foto: Dittrich)

In light of the above examples, the flow-vegetation-sediment interaction is of great practical importance and requires fundamental knowledge on the resistance of vegetation and the processes which dominate the flow-vegetation-sediment interaction. Numerous formulas already exist to compute the hydraulic resistance of natural rivers with vegetation, whereas only little information is available on the influence of vegetation on the erosion and sedimentation processes on floodplains. In the following, a summary of the state-of-the-art is given, main deficits are discussed and possible solutions to solve the problems are pointed out. Special emphasis is placed on recent research carried out in the German speaking Europe, as this research is not accessible for most international readers.

2. FLOW RESISTANCE OF RIVERS WITH VEGETATION

2.1 Compact channels with bank vegetation

The discharge capacity of natural rivers is strongly influenced by bushes and trees on the banks and floodplains. The conveyance can be reduced considerably by such vegetation. In addition to direct vegetation blockage, the flow reduction is due to an intensive macro-turbulent exchange of mass and momentum between the main channel and the vegetated floodplains (Mertens, 1989; DVWK, 1991; Dittrich, 1998; Boelscher et al., 2005). The discharge Q in the main channel can be calculated as:

$$Q = u_m \cdot A = \sqrt{\frac{8}{f}} \cdot \sqrt{g \cdot R \cdot I} \cdot A \qquad (1)$$

with u_m = mean flow velocity, A = cross sectional area, f = Darcy-Weisbach friction factor, g = acceleration due to gravity, R = hydraulic radius, and I = energy slope. The total resistance f of the main channel can be subdivided in sub-resistances f_i resulting from the different boundary conditions at the riverbed and the banks:

$$f \cdot P = \Sigma(f_i \cdot P_i) \qquad (2)$$

with P = wetted perimeter of the cross sectional area A, and P_i = wetted perimeter of the sub-area A_i. In case of compact channels with bank vegetation the cross-sectional area A_H in the main channel is divided into the sub-area A_s (not influenced by vegetation but by roughness of the river bed) and $A_{T,l}$ and $A_{T,r}$ (influenced by vegetation) (Figure 3).

The effect of vegetation in reducing the main channel conveyance is taken into account in the computation by adding a fictive separation line with the resistance f_T or the roughness height k_T at the boundary of the main channel and the banks covered with vegetation. According to Mertens (1989) the friction factor f_T at the separation lines can be determined as:

$$\sqrt{\frac{8}{f_T}} = \frac{u_m}{\sqrt{g \cdot R_T \cdot I}} = 2.5 \cdot \ln\left(\frac{R_T}{k_T}\right) + 6.27 \qquad (3)$$

with R_T = hydraulic radius of the separation line, k_T = equivalent roughness height of the separation line, and u_m = mean flow velocity. The following relationship is recommended for the roughness k_T of the separation line (DVWK, 1991):

$$k_T = c \cdot B_{II,m} + k_{To} \qquad (4)$$

with $k_{To} \cong 1.3 \cdot d_p$, d_p = diameter of the plants, c = coefficient dependent on density and diameter of the plants, and $B_{II,m}$ = interactive width describing the extension of the macro-turbulent eddies. It should be noted that the relationships to determine c are from laboratory experiments where plants were simulated as rigid cylinders.

2.2 Emergent vegetation

In the case of emergent vegetation (e.g. trees and high bushes on floodplains) the total flow resistance f is composed of surface resistance f_s caused by the bed material and form resistance f_{Pf} exerted by the vegetation (e.g. Mertens, 1997). The drag force $F_p (= c_w \cdot \rho \cdot A_P \cdot \frac{u_m^2}{2})$ which acts on a reference area A_P (typically projected areas of plants) and

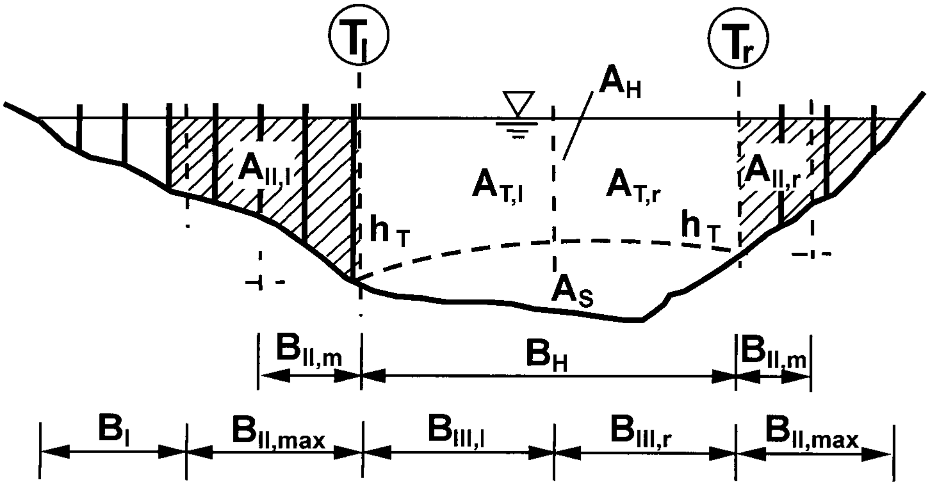

Figure 3. Cross-sectional division according to Mertens (1989) with $B_{II,m}, B_{III}, B_{II,\max}$ = interactive widths, B_H = width of the main channel, B_l = width of the floodplain not influenced by macro turbulence, h_T = water depths at the fictive separation lines T_l and T_r.

causes the form resistance can be applied to the bed area and superimposed with the surface resistance to determine the overall resistance f as:

$$f = f_s + f_{Pf} \tag{5}$$

To determine f_s an analogue assumption can be made as in Eq. (3). However, R_T has to be replaced by the hydraulic radius R_s associated with the bed and k_T by the equivalent sand roughness of the bed material. To determine the resistance factor f_{Pf} of vegetation the formulas of Petryk and Bosmajian (1975) and Lindner (1982) can be used, resulting in:

$$f_{Pf} = 4 \cdot c_w \cdot \frac{A_P}{a_x \cdot a_y} \tag{6}$$

with $A_P = d_P \cdot h_P$ = projected area of the plant, h_P = water depth at the plant, a_x, a_y = distances between the plants in longitudinal and lateral directions, c_w = drag coefficient of individual plants varying between 0.6 and 2.4. A value of $c_w = 1.5$ is recommended by DVWK (1991) and Järvelä (2004) for practical applications. Eq. (6) results from laboratory experiments with rigid plants. Therefore, this equation has only limited applicability when bending of vegetation is significant. In addition to flexibility, the effects of leaves are another factor that cannot be neglected. Järvelä (2004) showed that the resistance of willows increased by a factor of 3 to 7 in the leafy situation compared to leafless case. The following formula is recommended by Järvelä (2004) to estimate the resistance f_{Pf} of emergent leafy vegetation:

$$f_{Pf} = 4 \cdot C_{d\chi} \cdot LAI \cdot \left(\frac{u_m}{u_\chi} \right)^{\chi} \cdot \frac{h}{H} \tag{7}$$

with $C_{d\chi}$ = species-specific drag coefficient, LAI = leaf area index (one-sided area of foliage per unit area of ground), χ = vegetation parameter, u_χ = the lowest velocity used in determining χ, h = water depth, and H = plant height. The vegetation parameter χ accounts for the effects of plant deformation (flexibility and shape) in a flow, and is unique for a particular species. LAI takes into account the effect of the density of vegetation. Eq. (7) can be used to estimate the friction factor for flow inside leafy woody vegetation on floodplains and wetlands, where $\frac{h}{H} \le 1$ and $u_m \ge u_\chi$. Values of χ and $C_{d\chi}$ are presented for different plant species in Table 1.

Table 1. Values of $C_{d\chi}$ and χ for different species of woody vegetation. Data on the corresponding u_χ and LAI are shown for reference (Järvelä, 2004).

Species	$C_{d\chi}$	χ	u_χ (m/s)	LAI
Cedar	0.56	-0.55	0.1	1.42
Spruce	0.57	-0.39	0.1	1.31
White Pine	0.69	-0.50	0.1	1.14
Austrian Pine	0.45	-0.38	0.1	1.61
Willow	0.43	-0.57	0.1	3.2

2.3 Submerged vegetation

A common approach to determine flow resistance is by using mean cross-sectional velocity u_m and shear velocity u_* to determine the resistance factor f as:

$$\frac{u_m}{u_*} = \sqrt{\frac{8}{f}} \tag{8}$$

By integration of the velocity distribution over the cross-sectional area the mean velocity u_m in Eq. 8 is obtained. Stephan and Gutknecht (2002) and Järvelä (2005) modified the log law and derived an equation for the velocity profile above submerged vegetation

$$\frac{u}{u_*} = 2.5 \cdot \ln \frac{z - h_{P,m}}{h_{P,m}} + 8.5 \tag{9}$$

where u = velocity in height z, z = vertical coordinate, and $h_{P,m}$ = mean deflected plant height (Figure 4).

Eq. 9 is the result of experiments where the discharge through the vegetation was negligible and the water depth was much higher than the thickness of the vegetation layer. In the case of low water depths, the velocity distribution does not follow the classical Prandtl/Nikuradse log law and Eq. 9 is not valid anymore.

2.4 Interaction of flow-vegetation-sediment

In contrast to the calculation of flow resistance in rivers with vegetation, the determination of the flow-sediment interaction in presence of vegetation is very complex and so far not well understood. Successful numerical analyses were carried out by Lopez and Garcia (1997) and Choi and Kang (2004) to simulate the transportation of fine sediment through emergent vegetation on the basis of experimental data from Tollner et al. (1982). More recently a few experiments with sediment transported through submerged vegetation and its numerical simulation were conducted by Baptist (2005). However, in all experiments an idealized situation of the complex interaction was investigated that is far away from being generalized for practical purposes. In a recent project initiated by Dittrich and Florineth (Boelscher et al., 2005) field as well as laboratory experiments were carried out to investigate the erosion and sedimentation behavior of sediment on floodplains covered with vegetation. A preliminary analysis of the field data showed a significant difference in the sedimentation behavior between the grassland and willow areas. The sedimentation rate was two to three times

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higher in the area covered with willows as in the grass meadows. In the laboratory experiments, a

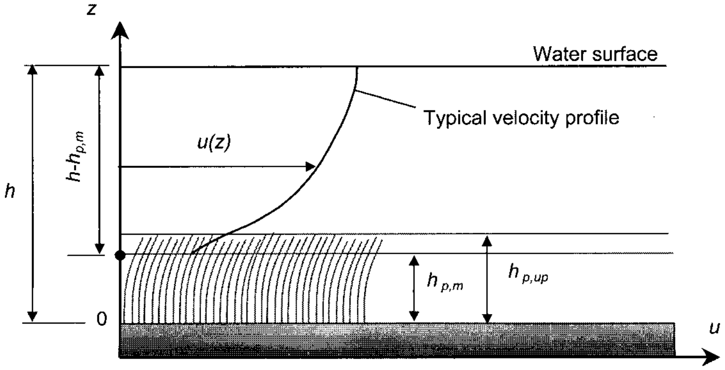

Figure 4. Definition sketch of the used parameters

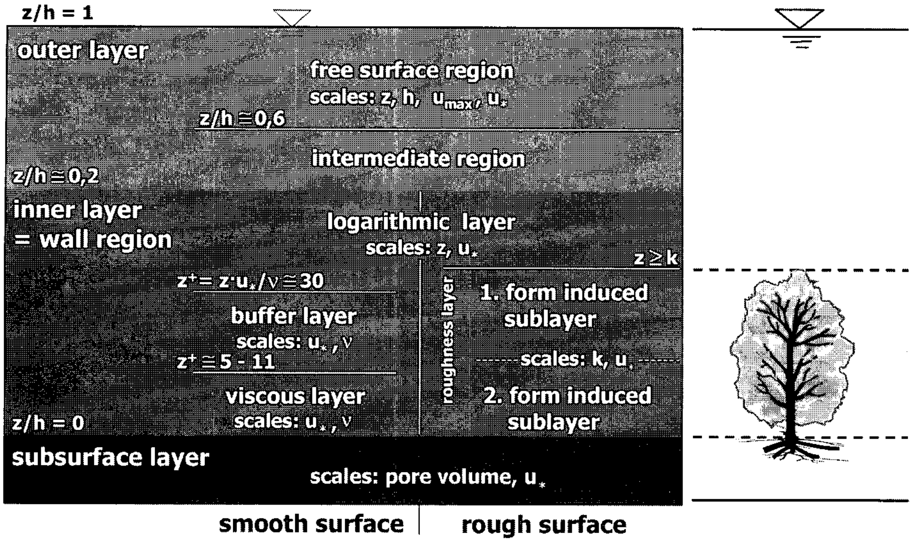

Figure 5. Subdivision of the vertical velocity profile over smooth and rough surfaces into different layers

distinct bar of fine sediment deposited on the floodplain at the interactive zone (dominated by macro eddies) between the main channel and the floodplain. However, a systematic quantification of the deposited sediment bars was not possible because of limitations in the experimental facilities.

3. DEFICITS AND POSSIBLE SOLUTIONS

The computation of the roughness height k_T of the separation line requires the estimation of the interactive width $B_{II,m}$ (Eq. 4). However, only empirical relationships and no physically based formulas exist to determine $B_{II,m}$. To solve the problem, velocity measurements at high resolution close to the separation line are necessary, and the data should be analyzed on the basis of the double averaged Navier-Stokes equations (DAM). A direct coupling of the turbulent flow field and the roughness density is possible with these equations. Wilson and Shaw (1977) investigated the turbulent flow field caused by wind over vegetation, and double averaging was carried out in planes parallel to the surface of vegetation. The same procedure is recommended in the case of water flow through emergent and over submerged vegetation (Sections 2.2 and 2.3) and with planes parallel to the separation lines in the cases of bank vegetation (Section 2.1). A further improvement of the methodology was done by Nikora et al. (2001) and Koll (2002), with experimental data measured over artificial and natural roughness elements at different densities. In numerous laboratory experiments with flow through emergent vegetation and bank vegetation, the plants were simulated in almost all cases with rigid cylinders (Eqs. 3 to 6). Thus, experiments should be carried out to determine flow resistance of flexible vegetation with and without leaves under laboratory as well as field conditions. An improvement of the existing formulas should be possible on the basis of the relationship proposed by Järvelä (2004) (Eq. 7). As Eq. 9 results from the assumption of a classical logarithmic velocity distribution over submerged vegetation, its application is limited to high relative submergences. An improvement of the relationship should be possible by applying the DAM methodology on the turbulent flow field and by subdividing the vertical velocity profile in different layers (see Figure 5 as well as Koll, 2002 and Nikora et al., 2002).

4. CONCLUSION

The key to the development of sustainable river management practices is the proper identification and assessment of physical processes, which dominate the complex interaction between water flow, vegetation, and sediment fluxes. Although the role of vegetation in governing critical flow processes has been widely acknowledged, a physically based numerical understanding of the hydraulic, mechanical, and biological controls remains incomplete. Evidently, further research is required to solve the complex hydraulic-sedimentological interaction problem. Theoretically sound, physically based approaches should provide a better understanding of the variation of flow resistance. For this purpose, the characterization of vegetation and sediments should be based on clearly defined and measurable variables. In particular, a significant research task is to improve the knowledge of the relationship between vegetation characteristics and the turbulent flow field. Herein, a promising direction is the DAM approach, which eliminates the problem of spatial heterogeneity of the flow by spatially averaging the conventional time-averaged hydrodynamic variables and equations.

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Managing Director and Professor, Leichtweiss-Institute for Hydraulic Engineering, Technical University of Braunschweig, Beethovenstrasse 51a, 38106 Braunschweig, Germany
(E-mail: a.dittrich@tu-bs.de)

Visiting scientist, Leichtweiss-Institute for Hydraulic Engineering, Technical University of Braunschweig, Beethovenstrasse 51a, 38106 Braunschweig, Germany
(E-mail: juha.jarvela@hut.fi)