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Hydraulic resistance of vegetated flows: Contribution of bed shear stress and vegetative drag to total hydraulic resistance

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ABSTRACT: Hydraulic resistance of floodplain flows depends on both drag forces exerted by vegetation elements and bed friction. Until today, the contribution of bed shear stress to total hydraulic resistance has often been neglected in hydraulic flume investigations. This has been justified with the dominance of form drag over surface friction for densely vegetated flows. However, in riparian forests where shrubs and bushes are predominant, vegetation density can be relatively low. Therefore, neglecting bed shear stress contribution can result in a significant underestimation of total flow resistance. The objective of this paper is to investigate the contribution of bed shear stress to the overall flow resistance for vegetated flows. Drag forces acting on up to 10 flexible vegetation elements were measured directly and simultaneously with specifically designed drag force measurement sensors in laboratory experiments. The measurements were carried out for three different vegetation densities, two vegetation patterns, mean flow velocities ranging from 0.1 to 0.7 m/s, and just submerged flow conditions. The hydraulic and drag force data are used to estimate bed shear stress and to assess its contribution to total hydraulic resistance dependent on vegetation density, vegetation pattern and hydraulic conditions. Existing relationships for the hydraulic resistance of vegetated flows are tested and the significance of plant specific parameters such as streamlining is highlighted.

Keywords: Vegetation, Flow resistance, Bed shear stress

1 INTRODUCTION

The ecosystems of riparian zones have high levels of biodiversity and the growing awareness of the ecological importance of these zones has resulted in the objective to maintain the functionality of channel and floodplain ecosystems (e.g. Horn & Richards, 2007). Riparian vegetation is an integral part of these ecosystems covering a wide range of conditions from highly flexible low grass to dense bushes to trees with rigid stems. However, vegetation increases flow resistance, changes backwater profiles, and modifies sediment transport and deposition (Yen, 2002). Hence, vegetation also plays a key role for flood risk assessment and sediment transport studies. Thus, it is indispensable to develop sustainable river management strategies which are in accordance with both flood plain management and ecology. The key to developing such strategies is the identification and assessment of physical processes dominating the complex interaction between water flow and vegetation.

The hydraulic resistance of vegetated channels depends on many factors including vegetation density, volumetric and areal vegetation porosities, seasonality, foliage, plant morphology, patchiness, age, plant mechanical properties, and bed surface friction. In traditional approaches vegetation has been typically reduced to boundary roughness by combining all sources of flow resistance, including vegetation, into a single bulk roughness coefficient. Such bulk coefficients have been used widely in the analysis of practical engineering problems and are typically selected with the help of reference publications (e.g., Chow, 1959; Hicks & Mason, 1999). However, bulk approaches are appropriate for one-dimensional considerations only and a detailed investigation of the influence of the vegetation on flow resistance using this approach is not possible (e.g., James et al. 2004, Wilson et al. 2006).

Based on the superposition principle (e.g., Yen, 2002) it is possible to distinguish between the contribution of surface friction and form drag to total flow resistance. Considering steady uniform flow in a control volume with unit width and equating the driving force (downslope weight component of the water in the volume) with the resisting force of the bed and the vegetation elements yields (e.g., Petryk & Bosmajian, 1975):

$$\rho g h S = \tau_0 ' + \frac{\langle F_D \rangle}{a_x a_y} \tag{1}$$

where ρ = water density, g = gravitational acceleration, h = flow depth, S = slope, $<F_D>$ = spatially averaged plant drag force, τ_0' = bed shear stress, and a_x, a_y = longitudinal and transversal spacing of the vegetation elements, respectively. Note that in Eq.(1) the canopy porosity has been neglected. The vegetative drag acting on a single element is usually defined as

$$F_D = \frac{1}{2} \rho C_D A_p u_c^2 \tag{2}$$

where C_D = drag coefficient, A_p = plant projected area, and u_c = characteristic approach velocity. The use of this formulation is straightforward for simple-shaped rigid objects such as cylinders. However, for complex-shaped natural vegetation C_D and A_p are difficult to determine.

Within a canopy the application of Eq.(2) becomes even more complicated as the approach velocity is not the undisturbed one. Therefore, Armanini et al. (2005) and Kothyari et al. (2009) recommend using the cross-sectionally averaged flow velocity as characteristic velocity u_c while Stone & Shen (2002) recommend using the maximum depth averaged velocity between stems. However, the latter depends on plant arrangement and is difficult to estimate for random plant arrangements.

A further problem is associated with the estimation of the drag coefficient C_D. In many studies, C_D-values have been used which were determined in experiments with single isolated stems (or cylinders) as a function of stem Reynolds number. However, these C_D-values are not appropriate for natural flexible vegetation elements and depend on the definition of plant projected area and approach velocity (e.g., Statzner et al., 2006). Furthermore, the flow structure in a canopy differs substantially from the flow structure around a single isolated element as wake flow and sheltering effects dominate the flow pattern.

Methods for the calculation of the drag coefficient for arrays of cylinders have been developed by, e.g., Li & Shen (1973) and Lindner (1982) and recent studies of Poggi et al. (2004) and Tanino & Nepf (2008) showed that the drag coefficient C_D of rigid rods decreases in canopy flows monotonically with the local stem Reynolds number due to sheltering effects. This finding is in contrast to the classical behavior of an isolated cylinder for which the drag coefficient reaches a plateau for stem Reynolds numbers ≥ 1000. Hence it is questionable if drag coefficients estimated from studies with a single vegetation element can be applied unambiguously in canopy studies. It is also not clear how the drag coefficient can be estimated appropriately for flexible and naturally shaped vegetation elements.

From experiments with single elements it is known that flexible plants bend and adapt to the flow, resulting in a more hydrodynamic shape and a reduction of flow resistance compared to stiff vegetation elements (e.g., Vogel, 1994, Järvelä, 2004; Wilson et al., 2008). This deformation directly affects the C_D-value, plant projected area A_p, and the wake flow structure. Thus, within a canopy, the vegetation elements may bend and deform slightly different and therefore one could expect slightly varying drag forces. This indicates the need for specifically designed experiments in which drag forces exerted by vegetation elements in the canopy are measured directly so that the spatial distribution of drag forces can be investigated. Eq.(1) further shows that such measurements are useful to determine bed shear stress in canopy flows (see also Aberle et al., 2010). Until today, the contribution of bed shear stress to total hydraulic resistance has often been neglected in hydraulic flume investigations. This has been justified with the dominance of form drag over surface friction for densely vegetated flows. However, in riparian forests where shrubs and bushes are predominant, vegetation density can be relatively low.

The main objective of this paper is to investigate the spatial variability of drag forces within a canopy composed of flexible elements. Based on preliminary results from specifically designed experiments, the spatial drag force variability will be discussed with regard to the canopy pattern. The data will also be used to assess bed shear stress contribution to overall resistance and to test approaches found in the literature for estimating flow resistance within canopies.

2 EXPERIMENTAL SETUP

Experiments were carried out in a 32 m long, 0.6 m wide and 0.4 m deep tilting flume in the laboratory of the Leichtweiß-Institute for Hydraulic Engineering and Water Resources, Technische Universität Braunschweig, Germany. In the experiments, the discharge Q was controlled by a valve and measured by an inductive flow meter. Water depth in the flume was adjusted by a tailgate located in a distance of 25 m to the flume inlet. Ten