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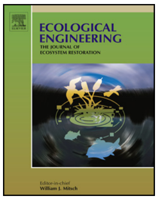

Spatial–structural properties of woody riparian vegetation with a view to reconfiguration under hydrodynamic loading

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ABSTRACT

This paper investigates the structural properties of four common riparian tree species and their reconfiguration under hydrodynamic loading in a towing tank in foliated and defoliated conditions. 3D tree models were generated by digitizing twenty 0.8–3.3 m tall specimens at branch level. Branch diameters and lengths were measured in order to calculate the one-sided stem area and stem volume over the plant height. The novelty of the investigations originated from the characterization of the reconfiguration which was achieved by combining the contracted width, the deflected height, and the underwater projected area in order to determine the porosity at different velocities. The results showed that the basal diameter could be used to predict the entire total one-sided stem area, although this method was not capable of reproducing the observed non-linear vertical distributions. The flow-induced width contraction contributed significantly to the reduction of the rectangular cross-sectional area occupied by the plant. The porosity of the foliated trees increased at the lower velocities, and then decreased at the higher velocities. Overall, detailed spatial–structural analyses of woody vegetation provided valuable information about plant behaviour under load, and thus are helpful for improving the determination of the physically based parameters of complex vegetative elements which is highly relevant for environmental modelling in order to fill the gap of knowledge concerning the hydrodynamic and aerodynamic flow around trees.

1. Introduction

Plants growing within riparian areas are responsible for various ecological, hydraulic–hydrological as well as landscape forming effects. They are a vital element of riverine environments and increase the structural and morphological diversity of the biosphere. They are highly relevant for shadowing effects (Holzapfel et al., 2013) and build an essential source of organic material for the livelihood of aquatic organisms. From a technical point of view, riparian vegetation reinforces riverbanks and retains sediments, however at the same time it can cause erosive processes and increase flow resistance. A sound understanding of the processes and parameters governing vegetated flow is therefore needed (Aberle and Järvelä, 2013, 2015) in order to guarantee both flood risk safety and natural river landscapes.

Hydrodynamic and hydro-ecological studies investigating the flow field of woody riparian vegetation are commonly based on high resolution spatial and temporal flow field data sets. The drag induced bending of the plant structure in flow direction and the drag induced compression were addressed by considering the decrease in projected area and the plant height (Fathi-Maghadam and Kouwen, 1997; Jalonen and Järvelä, 2014; Oplatka, 1998). Conversely, vegetation elements and their spatial properties are generally analyzed on the basis of an integral approach. This approach involves simplifying the complex structure of shrubs and trees which are comprised of heterogeneous plant parts (Västilä and Järvelä, 2014). Attempts to characterize plant area or volume were based on cylinder-analogy with an estimation of stem diameter at a certain height above ground (e.g. DVWK, 1991), photographic image analysis (e.g. Järvelä, 2002), measurement of projected area of the trunk and principal branches (e.g. Armanini et al., 2005; Righetti, 2008), decomposition of entire trees in small increments (Wilson et al., 2006) and the product of effective plant height and effective plant width (Freeman et al., 2000), leaf area index (Järvelä, 2004; Jalonen et al., 2013), and foliage-stem reference area ratio (Västilä et al., 2013). Describing the key hydraulic

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Notation

A_P	frontal projected area of plant [cm^2]
A_{P_tot}	total frontal projected area of plant [cm^2]
A_{PW}	underwater frontal projected area of foliated plant [cm^2]
$A_{PW,0}$	underwater frontal projected area of foliated plant in still water [cm^2]
A_{PWS}	underwater frontal projected area of defoliated plant [cm^2]
$A_{PWS,0}$	underwater frontal projected area of defoliated plant in still water [cm^2]
$A_{PW}/A_{PW,0}$	relative projected area of foliated plant under water [–]
$A_{PWS}/A_{PWS,0}$	relative projected area of defoliated plant under water [–]
A_{RP}	rectangular cross-sectional area occupied by the plant [cm^2]
$A_{RP}/A_{RP,0}$	relative rectangular cross-sectional area occupied by the plant [–]
A_S	one-sided stem area [cm^2]
A_{S_tot}	total one-sided stem area [cm^2]
D_S	diameter of segment [cm]
D_B	basal diameter of plant [cm]
D_m	mean diameter of segment [cm]
$H(z)$	plant height in function of the z-axis [cm]
$H_{\_tot}$	total plant height in still air [cm]
H_d	deflected height of foliated specimen [cm]
$H_{d,0}$	deflected height of foliated specimen in still water [cm]
$H_{d,S}$	deflected height of defoliated specimen [cm]
$H_{dS,0}$	deflected height of defoliated specimen in still water [cm]
$H_d/H_{d,0}$	relative deflected plant height at foliated condition [–]
$H_{dS}/H_{dS,0}$	relative deflected plant height at defoliated condition [–]
L_S	length of stem segment [cm]
u	towing velocity [m/s]
V_S	stem volume [cm^3]
V_{S_tot}	total stem volume [cm^3]
W_c	contracted width of the foliated specimen [cm]
W_{cS}	contracted width of the foliated specimen [cm]
$W_c/W_{c,0}$	relative contracted width of the foliated specimen [–]
$W_{cS}/W_{cS,0}$	relative contracted width of the defoliated specimen [–]
ε_{PW}	porosity of the foliated plant [–]
ε_{PWS}	porosity of the defoliated plant [–]

properties of plants, geometry and flexibility, with species-specific parameters is more sophisticated than the rigid cylinder analogy commonly used in hydraulic engineering practice (Aberle and Järvelä, 2013). Furthermore Aberle and Järvelä (2013) underline the need to elaborate on objective and accurate methods for the characterization of natural vegetation.

Natural riparian plants are increasingly being used instead of artificial plants in laboratory experiments to investigate the resistance and turbulence characteristics of vegetated flows (e.g. Armanini et al., 2005; Jalonen and Järvelä, 2014; Järvelä, 2004; Righetti, 2008; Sukhodolova and Sukhodolov, 2012; Västilä et al., 2013; Whittaker et al., 2013; Wilson et al., 2006). To achieve a better understanding of the influence of natural woody riparian vegetation on flow, it is essential to record and analyze plant data at the same level of detail as hydraulic measurements. An accurate 3D geometrical model of plants enables an extraction of spatial–structural and topological plant parameters, which characterize the plant specimens at different levels of detail (Barthelemy and Caraglio, 2007). As a result, the generated plant model and hydraulic model can be interrelated and form the basis for a holistic approach for considering plant flow interactions. Therefore, a better description and determination of the plant architecture is required for hydro-environmental modelling applications. Furthermore, analyses of species-specific tree growth relationships are essential in order to generalize individual results on species and growth basis.

From a fluid mechanics point of view, trees and bushes are highly complex porous media which consists of stems, branches, stalks and leafs or needles, each of them forming a boundary layer in wind flow, consequently the application of principles of classical bluff body aerodynamics is limited (Gromke and Ruck, 2008). Up until now little attention has been paid to the lateral contraction (Oplatka, 1998) or to the porosity (Gosselin and de Langre, 2011; Righetti, 2008; Schnauder et al., 2007; Zinke, 2010) of riparian plants at full scale under hydrodynamic loading.

The purpose of this study is to explore physically based parameters for an improved characterization of riparian trees in hydro-environmental modelling applications. The specific objectives of this paper are (1) to analyze the woody plant structure of four different riparian species, (2) to correlate the structural plant parameters with the streamlining of the plant specimens in terms of contracted width, deflected height and projected area and (3) to quantify the change in plant porosity at different stages of hydrodynamic loading in foliated and defoliated conditions. The investigations comprise of measurements of 20 selected specimens of four common riparian species. The experiments were conducted parallel to a towing tank study, focusing on the drag of the trees (Jalonen and Järvelä, 2014).

2. Methods

2.1. Plant specimens and description of their structure

Investigations were performed at the hydraulic laboratory of the Department of Civil and Environmental Engineering, Aalto University, Finland. 20 plant specimens were harvested in a nearby wetland area. The species investigated were Black Alder (*Alnus glutinosa* (L.) Gaertn.), Silver Birch (*Betula pendula* Roth), White Birch (*Betula pubescens* Ehrh.) and Goat Willow (*Salix caprea* L.). The specimens were selected in such a way that they strongly differed in terms of morphology and height (80–330 cm), for a wide range of natural variability to be covered.

In the present paper, the description of the plant architecture (topology and geometry) follows the rules of the Multi-scale Tree Graph (MTG) formalism (Godin and Caraglio, 1998). The plant is described in terms of axes and segments. The stem is defined as the 1st order axis. Each branch directly connected to the 1st order axis is defined as a 2nd order axes, each branch directly connected to the 2nd order axes is defined as 3rd order axes, and so on (see Fig. 1). A segment is defined as a portion of a woody part without branching between two measurement points (Sinoquet and Rivet, 1997). As a comparison, the Strahler ordering scheme used by e.g. Antonarakis et al. (2009), Järvelä (2004) and Wilson et al. (2006) for the purpose of characterizing trees in relation to hydraulic drag assign the lowest order number to the outmost branches, increasing the number order towards the main stem. The order numbers are summed up at the joins of the branches with equal order. The Strahler ordering scheme contains information on topology but not on the geometry of the tree segments.