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The effect of flexible vegetation on flow in drainage channels: Estimation of roughness coefficients at the real scale

A. Errico[a,f,*], V. Pasquino[b], M. Maxwald[c], G.B. Chirico[d], L. Solari[e,f], F. Preti[a,f]

[a] GESAAF, University of Florence, Via San Bonaventura 13, 50145 Firenze, Italy
[b] DICEA, Department of Civil, Architectural and Environmental Engineering, Via Claudio, 21-80125 Napoli, Italy
[c] IBLB, Institute of Soil Bioengineering and Landscape Construction, University of Natural Resources and Life Sciences, Vienna, Austria
[d] Department of Agricultural Sciences, University of Naples Federico II, Italy
[e] DICEA, University of Florence, Italy
[f] WaVe, Water and Vegetation Research Unit, University of Florence, Italy

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1. Introduction

Vegetation along rivers and channels is often considered as an unwanted impediment to the flow discharge that needs to be controlled, especially in the urban environment where hydraulic risk can be relevant (Pitlo and Dawson, 1990). During the vegetative season, aquatic and hygrophile vegetation rapidly grows along riverbeds and banks, thanks to the constant availability of water and nutrients. In several lowlands of Italy, Land Reclamation Authorities are responsible for the maintenance of channel networks draining agricultural as well as urban areas. In Northern Tuscany (Italy), the removal of the entire vegetation cover from banks and channel bottom is a common maintenance practice, aiming at maximizing the discharge capacity of natural and artificial drainage networks. In the last thirty years, the increasing attention for the environment raised a conflict between different interests involved in the freshwater management. On the one hand, the presence of vegetation within the flow section can significantly increase the bed roughness reducing the channel conveyance, therefore rising the flood hazard. On the other hand, drainage channels constitute a fundamental habitat within the agricultural and urban environment, which needs to be preserved as important refuge-site for flora and fauna, some of which are endangered species. A fundamental component of these ecosystems is represented by vegetation, which plays a key role in supporting animal life throughout several functions, such as repairing, nesting, shading, feeding and producing biomass that is at the base of most of the food webs. Indeed, the management of these environments requires the quantification of the effects of vegetation on flow, in order to support policy makers in their choices. Among these, the evaluation of flow resistance appears to be crucial in hydro-morphological models for channels and rivers.

Flow resistance at the reach scale is due to different types of aquatic and riparian vegetation that can be found in a river. A recent review on flow resistance estimators, validated with a large experimental dataset in vegetated beds, can be found in Vargas-Luna et al. (2015). From a modelling perspective, flow in vegetated channels has been generally distinguished into emergent and submerged conditions, as the flow field changes considerably when the flow depth exceeds the vegetation height.

In the case of fully-submerged vegetation, such as in the case of aquatic vegetation, flow resistance can be estimated by modelling the average longitudinal flow velocity profile as composed by different layers. In the simplest case, two layers have been considered: a bottom layer with ‘slow’ flow inside the vegetation, and an upper layer or free water layer, above the vegetation. This approach has been adopted by many authors (e.g. Baptist et al., 2007; Luhar and Nepf, 2013; Huai et al., 2014a, 2014b), even for the estimation of flow resistance produced by sediment in case of macro-roughness conditions (Canovaro et al., 2007), and it assumes that flow resistance is given by the sum of two contributions: one due to the vegetation roughness and one related to the bottom roughness. Thus, the overall resistance is smaller than in the case of emergent vegetation. In this circumstance, i.e. for riparian trees, a first schematization is represented by considering the

* Corresponding author at: GESAAF, University of Florence, Via San Bonaventura 13, 50145 Firenze, Italy.
E-mail address: alessandro.errico@unifi.it (A. Errico).

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Fig. 1. Location of the study channel, stretching for 400 m in the Versilia-Massaciuccoli reclamation district, an agricultural area nearby the Regional Park of Migliarino-San Rossore – Massaciuccoli.

vegetation elements as rigid cylinders, with a given spatial density (Petryk and Bosmajian, 1975).

Another key feature is related to the flexibility of vegetation and its feedback with flow hydrodynamics. In the case of flexible vegetation, such as for aquatic vegetation, stem reconfiguration due to its flexibility is a crucial aspect as it can reduce the roughness and therefore significantly influence flow velocity, compared to rigid vegetation. For instance, Luhar and Nepf (2013) showed, through the interpretation of laboratory experiments, that vegetation reconfiguration can almost double flow velocity compared with the case when vegetation remains undeflected and upright in flow. Moreover, they showed that this occurs especially when the vegetation elements assume a prone position lying on the bed. Dijkstra and Uittenbogaard (2010) developed a fully mechanistic model for predicting flow velocity and plant configuration of very flexible aquatic vegetation; the model was validated by means of laboratory experiments with flexible plastic strips. A similar, though simplified, approach was later proposed by other authors (Huai et al., 2014a, 2014b, Pasquino et al., 2018) who predicted stem configuration using the cantilever beams theory for large-deflections. Luhar and Nepf (2013), by means of mechanistic and empirical considerations, noted that flow resistance due to vegetation is determined primarily by the blockage factor, at the channel reach scale.

In the case of flexible leafy bushes and soft-wood trees, the emergent and just-submerged flow conditions (i.e. flow through the vegetation layer), are the most important conditions for the evaluation of flow resistance. In this context, a pioneer study was carried out by Freeman et al. (2000), who conducted a comprehensive experimental campaign on a large-scale flume with the aim of quantifying the vegetation-induced roughness for different broadleaf deciduous species. The study showed how the contribution of leaves to drag production cannot be neglected, as shown also by later studies (Aberle and Järvelä, 2013). For instance, in the case of black poplars, Västilä et al. (2011) showed that leaves contributed to almost 90% to the total flow drag. Järvelä (2004), followed by Wilson et al. (2008) and Jalonen et al. (2013), applied Leaf Area Index (LAI) in flow resistance formulations as a parameter describing the effect of foliage. LAI is defined as the ratio of total one-sided leave area to the downward projected area of the canopy and it is often considered as the parameter for canopy density (Jalonen et al., 2013). LAI can be determined by remote sensing or field measurements or values from the literature. However, these models were typically validated with laboratory experiments, where vegetation was reproduced with artificial elements in flumes. Therefore, their applicability to field conditions is subjected to large uncertainties.

Phragmites australis (Cav.) Trin. ex Steud. (also referred to as common reed) is a plant species which is spread almost all over the world. It was recognized as invasive species in US and Canada, while it is endemic in wetlands and lowlands of Europe and Asia. Thanks to its abundance and diffusion in aquatic environments, this species has been object of a relevant number of studies, also concerning its hydraulic effect. Investigations on the hydrodynamic behavior of common reed were conducted in open channel flow by, among others, Rhee et al. (2008), Sandercock and Hooke, (2010), Leonard et al. (2002), Akgul et al. (2013), Meijer and Van Velzen (1998). However, most of the experimental research was conducted in flumes, whereas real scale studies are missing. As observed by Nikora (2010a,b), measurements at the organism scales still represent great challenges and thus data related to these scales remain very limited.

The main motivation of this study was to bring additional knowledge on the flow dynamics in channel vegetated by common reed. The experimental campaign was designed to provide useful hints for managing this vegetation in drainage networks, as it represents a very common issue worldwide (Clevering and Lissner, 1999; Guo et al., 2013). Given the present knowledge about the flow-vegetation interactions, this work aims at experimentally assessing the impact of spontaneous reed on flow, both in terms of resistance and velocity distribution, by means of open-field hydraulic experiments at the real scale of an existing drainage channel. To our knowledge, the study of reed-induced flow alteration was never studied before with such a full-scale experiment conducted on a real channel. The experiments were planned in a drainage channel of Versilia reclamation area, Tuscany (Italy), in July 2016, after a first test in 2015 (Errico et al., 2015). Vegetation and flow parameters were measured under controlled hydraulic conditions under different vegetation scenarios. The impact of the different vegetation scenarios on the hydraulic resistance is analyzed and discussed.

2. Materials and methods

2.1. Study area

The experimental campaign was conducted along a channel stretching in a lowland managed by the Land Reclamation Authority of