Advances in Water Resources 93 (2016) 205–222

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Representing plants as rigid cylinders in experiments and models

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ARTICLE INFO

Article history:
Available online 19 October 2015

Keywords:
Vegetation
Rigid cylinders
Morphodynamics
Laboratory experiments
Numerical modeling

ABSTRACT

Simulating the morphological adaptation of water systems often requires including the effects of plants on water and sediment dynamics. Physical and numerical models need representing vegetation in a schematic easily-quantifiable way despite the variety of sizes, shapes and flexibility of real plants. Common approaches represent plants as rigid cylinders, but the ability of these schematizations to reproduce the effects of vegetation on morphodynamic processes has never been analyzed systematically. This work focuses on the consequences of representing plants as rigid cylinders in laboratory tests and numerical simulations. New experiments show that the flow resistance decreases for increasing element Reynolds numbers for both plants and rigid cylinders. Cylinders on river banks can qualitatively reproduce vegetation effects on channel width and bank-related processes. A comparative review of numerical simulations shows that Baptist's method that sums the contribution of bed shear stress and vegetation drag, underestimates bed erosion within sparse vegetation in real rivers and overestimates the mean flow velocity in laboratory experiments. This is due to assuming uniform flow among plants and to an overestimation of the role of the submergence ratio.

1. Introduction

There is increasing awareness of the need to include the effects of vegetation in studies dealing with the morphological response of rivers and estuaries (e.g., [1,2]). Numerical models and laboratory experiments (e.g., [3]) have recently shown that riparian vegetation can reduce river braiding and vegetation growth on point bars has been recognized as one of the major factors governing river meandering (e.g. [4–7]).

Plants increase the local hydraulic roughness, reducing flow velocity and bed-shear stress (e.g., [8,9]) and promoting sedimentation [10,11]. Vegetation cover protects the soil, and root systems increase the soil strength against erosion. In the end, plants act as ecosystem engineers since they create the conditions that favor the survival and establishment of new vegetation [12–15]. The relevance of vegetation processes for the morphological response of rivers and estuaries has resulted in an increased amount of research from several disciplines based on field investigations, laboratory experiments, and numerical models (e.g., [16–23]).

Considering the relevance of vegetation for flow resistance, much research focused on calculating the hydraulic roughness of vegetated beds (e.g., [24–26]), and on the drag imposed by arrays of cylinders under submerged [27,28] and emergent conditions [29–31].

A number of mobile-bed laboratory experiments used alfalfa sprouts to analyze the morphological changes caused by the presence of vegetation [3,32–34], the influence of riparian vegetation on bank erosion [35], and the morphological effects of its spatial distribution [36], among other aspects (e.g., [37,38]). More recently, the use of alfalfa sprouts has been combined with the supply of wooden dowels in order to reproduce the combined effects of living vegetation and floating logs [39]. These works showed important aspects of the effects of vegetation on the morphology of river systems, but provided mere qualitative results due to the difficulty of translating the laboratory results to the real river scale (upscaling).

The study of the flow around isolated cylindrical elements started in the early 1950's (e.g., [40,41]), but it was only 20 years later that arrays of cylinders were considered in laboratory experiments to simulate vegetation (e.g., [42–44]). These studies helped identifying the relevance of the stems density and spatial distribution on flow resistance, flow field and sediment processes. Other studies showed that the representation of plants as rigid cylinders neglects the reconfiguration of plant foliage under flowing water [45,46] which decreases the projected area and drag forces [47–51]. Several research contributions have advanced our understanding of how an array of cylinders

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http://dx.doi.org/10.1016/j.advwatres.2015.10.004
0309-1708/

Notation

a	Projected plant area per unit volume (m^{-1}), $= mD$
B	Channel width (m)
B_e	Equilibrium channel width (m)
C	Chézy coefficient obtained from the measurements ($m^{1/2}/s$)
C_f	Friction coefficient obtained from the measurements (–), $= g/C^2$
C_b	Chézy coefficient of the bare soil for vegetated beds ($m^{1/2}/s$)
C'_b	Chézy coefficient of the bed for submerged plants ($m^{1/2}/s$)
C_D	Mean drag coefficient of the vegetation (–)
C_r	Chézy coefficient for the global resistance of emergent plants ($m^{1/2}/s$)
C'_r	Chézy coefficient for the global resistance of submerged plants ($m^{1/2}/s$)
D	Plants characteristic diameter (m)
g	gravity acceleration (m/s^2)
h	Water depth (m)
h_v	Vegetation height (m)
I	Sorting index (–)
I_S	Channel sinuosity (–)
m	Stems surface density (m^{-2})
Q	Flow discharge (m^3/s)
R_h	Hydraulic radius (m)
Re_D	Element Reynolds number (–)
s_1	Separation between elements in parallel direction to the flow (m)
s_2	Separation between elements in perpendicular direction to the flow (m)
$u(z)$	Vertical velocity profile (m/s)
u	Mean flow velocity (m/s)
u_c	Mean flow velocity in the vegetation layer (m/s)
S_w	Longitudinal water surface slope (–)
ν	Cinematic viscosity of the fluid (m^2/s)
ρ	Mass density of water (kg/m^3)
κ	Von Kármán's constant (–), $= 0.41$
τ_b	Bed shear stress (N/m^2)
τ_v	Shear stress caused by vegetation (N/m^2)

modifies vertical velocity profiles [52–54] and turbulent structures [27,55,56], affecting bed load [57,58] and suspended load [59,60], as well as depositional processes [11,61].

Rigid cylinders have been used in laboratory experiments also to analyze the flow-vegetation interaction in vegetated patches and on floodplains. Regarding vegetated floodplains, a considerable amount of experimental work has been carried out to study the effects of vegetation on overbank flow [62], shear-stresses at cross-sectional interfaces [63], hydraulic conveyance [64], stream-bank erosion [65], near-bank turbulence [66], turbulent coherent structures [67,68], and flow field alterations [69]. A few studies have considered wake structures and flow field alterations on finite vegetation patches in channels with fixed beds [70–72] and even fewer studies have considered bed level changes around vegetation patches [73].

From the available modeling approaches that have been proposed to describe plants in a schematic easily-quantifiable way, the most common one represents vegetation as a set of rigid cylinders with given height, diameter, stem distribution and density (a review can be found in Vargas-Luna et al. [74]). However, linking the settings of rigid cylinders to real vegetation is an important unsolved issue. In nature it is possible to find plants that can be well represented by cylindrical rigid stems (Fig. 1a), but in most cases it is simply impossible to represent the variability of their geometrical and physical characteristics by this basic approach (Fig. 1b). Plant flexibility is considered only by a few models (e.g., [75]), but these models are not suitable for practical applications, which reinforces the common practice of using simpler approaches.

Experiments with rigid cylinders have the advantage of using the approach adopted by a number of numerical models (e.g., [24,25,76,77]). This allows using the numerical models to interpret the laboratory results for real systems, since upscaling is a known problem for all experiments dealing with vegetation and sediment. However, it is still unclear whether numerical models based on the rigid cylinder representation of vegetation provide realistic results at the scale of real rivers and estuaries.

This work explores the implications of representing plants as rigid cylinders by means of new laboratory experiments and by reviewing the results of published model simulations. The first set of experiments, carried out in a straight flume with glass walls (Flume No. 1), studies the correspondence between the effects of real and artificial vegetation and those of rigid cylinders on water flows. This aspect is addressed by comparing the hydraulic roughness of channel beds covered either with plants or with rigid cylinders under the same flow regimes. The second set of experiments analyzes the evolution of a channel with erodible bed and banks (Flume No. 2) to explore the feasibility of using rigid cylinders to simulate the effects of floodplain vegetation on the channel width formation. A third set of experiments, carried out in a similar, but larger, flume (Flume No. 3), explores the feasibility of using rigid cylinders to simulate vegetated bank dynamics.

The work is complemented by a thorough review of the results obtained by two-dimensional (2D) morphodynamic models adopting Baptist's method to evaluate the consequences of using a rigid-cylinder schematization for the simulation of the morphological developments of real rivers. To substantiate the analysis of model results, the predictive capacity of the method developed by Baptist [25] in estimating water depth and mean flow velocity is assessed by comparing the results to the data obtained from the first set of experiments.

This paper represents a first step in assessing the effects of representing real vegetation with rigid cylinders in laboratory experiments and numerical models. The results allow identifying the limitations of the approach and provide some preliminary guidelines on its application.

2. Theoretical background: Baptist's method

The flow resistance estimator for vegetated beds considered in this study was developed by Baptist in 2005 [25]. It is based on a rigid-cylinder representation of vegetation and can be considered as representative of the models adopting this approach. Baptist's method [25] predicts the total flow resistance of a river bed covered by vegetation, which forms the base for water depth predictions. Sediment transport and bed level changes predictions, instead, are derived by considering the bed shear stress, which is reduced by the presence of vegetation, resulting in more realistic bed level changes in the vegetated areas [78]. The method is implemented in the open-source Delft3D software (www.deltares.nl), computing the morphological changes of rivers, estuaries and coasts in two and three dimensions. Delft3D was used in the simulations reviewed in Section 5. Baptist's method performance was analyzed and compared to the performance of a number of other models [74], where it proved to be one of the most complete vegetation models, since it is valid for both submerged and emergent plants, and it is the most accurate one with respect to predictions of laboratory data.

Baptist described plants as sets of rigid cylinders with a characteristic diameter, D, height, h_v, and stem surface density, m, defined as the number of stems, N, per bed surface area (Fig. 2). The basic