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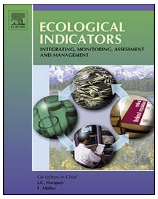

Drag coefficient estimation using flume experiments in shallow non-uniform water flow within emergent vegetation during rainfall

Wei-Jie Wang[a], Wen-Xin Huai[a,*], Sally Thompson[b], Wen-Qi Peng[c,d], Gabriel G. Katul[e,f]

[a] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, Hubei 430072, China
[b] Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA 94720, USA
[c] Department of Water Environment, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[d] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[e] Nicholas School of the Environment, Duke University, Durham, NC 27708, USA
[f] Department of Civil and Environmental Engineering, Duke University, Durham, NC 27708, USA

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ABSTRACT

Vegetation persistence on low-gradient slopes in dryland regions is presumed to be supported by lateral flow of water originating from bare sites with low permeability soil. The hydrodynamics of these flows, which occur during and immediately following intense rainfall events, are challenging to describe with classical approximations to the Saint-Venant equations (SVE). Flume experiments with varying rod density and applied water along the vegetated section are conducted to explore common approximations used to close the SVE when predicting water depth. Guided by these experiments, expressions are then derived that describe the simultaneous effects of spatially uniform vegetation density and rainfall intensity on the drag coefficient (C_d) linking the friction slope to the local kinetic energy head for steady non-uniform flow on a flat surfaces. Spatial variations in C_d through the vegetated patch either exhibit monotonic declines during rain or a non-monotonic 'hump' shape without rain with increasing longitudinal distance into the vegetated section. These spatial variations arise due to the indirect effect of rainfall on the dynamic component of the mean pressure gradient driving flow.

1. Introduction

Water subsidies originating from crusted bare soil and supplied to vegetated sites in arid and semi-arid regions during and immediately after intense rainfall events have well-established ecohydrological significance (Assouline et al., 2015; Bromley et al., 1997; Foti and Ramírez, 2013; Kefi et al., 2008; Klausmeier, 1999; Kletter et al., 2009; Konings et al., 2005; Paschalis et al., 2016; Rietkerk et al., 2002; Thompson et al., 2011, 2008; Valentin and d'Herbès, 1999). These subsidies are particularly significant on low-gradient slopes supporting overland flow, where free water surface gradients instead of ground slopes are responsible for water movement (Rietkerk et al., 2002; Thompson et al., 2011). The hydrodynamics describing these shallow flows constrains the quantity and spatial distribution of water infiltrating into the vegetation root zone. During and immediately after rainfall events, the water level H within the emergent vegetation remains sufficiently shallow that the bulk features of the flow can be reasonably described by the Saint-Venant equation (SVE) (de Saint-Venant, 1871) as described elsewhere (Chen et al., 2013; Thompson et al., 2011).

The application of the SVE to these shallow flows is complicated by multiple factors. Classical simplifications to the SVE such as the kinematic or diffusive wave approximations (French, 1985; Woolhiser and Liggett, 1967), although successfully used to represent overland flow in other contexts, are not applicable here. The kinematic wave approximation fails on low slope gradients, and the diffusive wave approximation cannot be readily applied if advective acceleration (or deceleration) is large. New approximations to the SVE are needed when such non-uniform flows occur within emerging vegetation covering regions with a low slope gradient (Lawrence, 2000). The situation becomes more complicated when such flows are disturbed by rain-action incident on the water surface. The aim here is to advance toward appropriate closure schemes for frictional losses to be used in conjunction with SVE for vegetated surfaces on flat terrain during rainfall events. Controlled experiments on the behavior of non-uniform flow occurring within vegetated canopies and disturbed by extreme rain are a logical starting point for such inquiry. There have been only a limited number of such experiments to date, compared to the wealth of experiments already conducted on uniform-steady flow within submerged or emergent vegetation (Green, 2005; Huai et al., 2009; Huthoff et al., 2007;

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* Corresponding author.
E-mail address: wxhuai@whu.edu.cn (W.-X. Huai).

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James et al., 2004; Järvelä, 2002; Kim et al., 2012; Konings et al., 2012; Kothyari et al., 2009; Liu et al., 2003; Nepf, 2012; Poggi et al., 2004).

When designing such experiments, it is necessary to arrive at some compromises between boundary conditions on the flow and spatial scales that can be resolved by the experiment. During and immediately after an intense storm, the boundary conditions on the SVE must include the rainfall intensity, infiltration rate, vegetation morphology, land surface slope and micro-topography. A complete description of the closure problem to the SVE requires characterizing the effects of large variations across all these factors and their interactions, a task that lies well beyond the scope of a single study or experiment. Consequently, the flume experiments described here address a subset of these factors deemed scientifically uncertain but necessary to the hydrodynamics describing water subsidy. Here, we focus on the interplay between vegetation density and rainfall intensity. Even within this restricted experimental scope, describing all aspects of the hydrodynamics remains a daunting task. Idealized conditions are first considered – steady, non-uniform flow within uniform vegetation, covering a flat slope and subjected to uniform, but intense rainfall. These conditions are selected because they allow the isolation of the direct effect of steady rainfall and its disturbances of the water surface on frictional losses across different vegetation densities. The goal of the laboratory experiments is to provide benchmark data against which conventional models (also analyzed here) and new approximations (proposed here) to frictional losses during extreme rainfall events can be compared when used in conjunction with SVE.

The synthetic vegetation selected here are slender and rigid cylinders broadly resembling the morphology of common perennial desert grasses (e.g., *Hilaria rigida* in California, *Stipagrostis sabulicola* in Namibia, and *Triodia* and *Plectrachne* genuses in Australia). The infiltration contrasts between crusted bare soil patches and permeable vegetated sites, along with the processes of crust formation that can be significantly affected by rainfall, is not explicitly considered. Accommodating a wide range of infiltration contrasts and accounting for rainfall-crust formation interaction is too difficult to experimentally control. Rather than treating these features explicitly, the experiment accommodates their effects by maintaining the type of non-uniformity describing the free water surface shape resulting from the infiltration contrast between crusted soil and vegetation (Rietkerk et al., 2002). A drop-structure is positioned immediately after the vegetated section to ensure that the free water surface directed from the upstream section toward the drop is classified as gradually varied on mild slopes or 'M-type' (French, 1985) as anticipated in such problems (Rietkerk et al., 2002). Such a configuration ensures that the spatially variable free water surface gradient is the main driver for water flow at all locations within the emergent vegetated section. The experiments here feature wide ranging vegetation density (sparse to dense) and *extremal* rainfall intensities, set to unfold the spatial patterns in the drag coefficient (C_d) linking the frictional slope to the kinetic energy head in the SVE during rainfall. The rainfall intensity adopted in the experiment is purposely set to be extreme (4000–8000 mm h^{-1}) – approximately an order of magnitude greater than the highest recorded hourly rainfall rates in the U.S. (Kilauea Plantation, Kauai, Hawaii, January 24, 1956 of approximately 300 mm h^{-1}). While unrealistic in a field setting, we deliberately adopted these extreme rates for the flume experiments for pragmatic reasons – (i) to enable a sufficiently deep water level and ensuing depth non-uniformity that can be accurately resolved through water surface profile imaging while maintaining a sufficiently shallow flow suitable to an SVE approximation. This minimum depth (and its spatial variation) requirement precludes the study of sheet-flow, which may occur in several instances when lateral water is initially created or at some later time as water levels are receding following the passage of the storm. For reference, typical water levels associated with such overland flow can be on the order of 1 cm (Thompson et al., 2011). (ii) Any adjustments to C_d originating from surface water disturbances by rainfall are likely to be amplified in the extreme cases chosen here. The flume experiments are not intended to exactly replicate a particular hydrological situation or ecosystem configuration but they do provide data on the interplay between mechanisms described by the SVE that are likely to be responsible for causing spatial variability in C_d.

After exploring failures of conventional approaches to modeling water level H using the SVE for the flume experiments here, an operational model linking C_d to vegetated patch properties, rainfall intensity, and water level is proposed. The model mainly summarizes the outcome of the flumes experiments by revealing the key mechanisms responsible for the spatial patterns in $C_d(x)$ in the presence or absence of rain within the confines of the SVE. When spatially averaging these outcomes along the vegetated patch length, the resulting bulk C_d values can also be compared to published data for steady-uniform flow within emergent vegetation.

2. Theory

The flow configuration considered here addresses steady flow within a rectangular flume section of width B and bed slope $S_0 \approx 0$ covered with a cylindrical rod canopy. The rods have diameter D and height h_v, are spaced at an average center-to-center distance of ΔS, and extend over a "vegetated reach" defined by a length L_{veg}. At all spatial locations and flow conditions, $h_v > H$ is maintained. The canopy density is described in terms of the volume fraction occupied by the vegetation, $\phi_{veg} = \pi D^2/(4\Delta S^2)$ (Nepf, 2012). Due to the presence of rods, the width available for the flow within the vegetated section is narrower than B. The effective flow width B_e is derived as follows: The total bed area per unit length along the streamwise direction is B. In this area, flowing water occupies an area of $B(1-\phi_{veg})$ resulting in an effective flow width $B_e = B(1-\phi_{veg})$. Similarly, the effective surface area on which rainfall can intercept freely flowing water is given by $A_e = B_e L_{veg}$. The volumetric steady flow rate occurring within the vegetated section in the absence of rainfall is designated by Q_0. When spatially uniform rainfall with rate P is applied over the entire vegetated area A_e, the steady flow rate must increase by some increment $Q_r = PB_e L_{veg}$ above Q_0. At a longitudinal distance $x \in [0, L_{veg}]$ with $x = 0$ set at the starting point (inlet) of the flow into the vegetation zone, the steady flow rate Q_x is given by:

$$Q_x = Q_0 + (PB_e)x = Q_0 + \left(\frac{Q_r}{L_{\text{veg}}}\right)x. \tag{1}$$

In addition to changing the mass balance over the vegetated section, the presence of rainfall and vegetation alters the drag coefficient C_d and frictional energy losses, the main focus here. In the absence of any infiltration I, the steady state mean continuity equation and SVE can be expressed as (Thompson et al., 2011; Chen and Liu, 2001)

$$\frac{\partial q_x}{\partial x} = P, \tag{2}$$

$$\frac{\partial}{\partial x}\left(\frac{q_x^2}{H} + \frac{gH^2}{2}\right) + gH(S_f - S_0) = 0, \tag{3}$$

where $q_x = U\,H$, and U is the area-averaged velocity, g is gravitational acceleration, S_f is the friction slope. Upon combining Eqs. (2) and (3), P can be made to appear explicitly in the conservation of momentum (or SVE) resulting in

$$U\frac{\partial U}{\partial x} + g\frac{\partial H}{\partial x} = g(S_0 - S_f) - \frac{PU}{H}, \tag{4}$$

where the term ($P\,U/H$) arises from finite steady rain when connecting the mean continuity to the momentum balances. If I is treated as a constant in space set to the infiltration capacity, then P can be readily replaced by $P' = P - I$ without any additional modifications due to finite infiltration. The presence of vegetation introduces an additional drag C_d beyond any side and bed-slope friction (both are negligible