Journal of Arid Environments 114 (2015) 1–7

Contents lists available at ScienceDirect

Journal of Arid Environments

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

Hydraulic roughness due to submerged, emergent and flexible natural vegetation in a semiarid alluvial channel

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ARTICLE INFO

Article history:
Received 19 May 2012
Received in revised form
12 October 2014
Accepted 24 October 2014
Available online

Keywords:
Ipomoea pes-caprae
Vegetal resistance force
Drag
Hydraulic resistance
Submergence
Turbulent mixing

ABSTRACT

In the semiarid area of Brazil, vegetation in natural streams generates hydraulic resistance and becomes critically important in the design of soil conservation practices. However, most researchers have studied vegetation roughness under laboratory conditions. The present work has been studied under the rare phenomenon of flow conditions and roughness due to Beach Morning Glory (*Ipomoea pes-caprae*) in field conditions of submerged and emergent flexible vegetation on the Jacu River, an intermittent stream in the semiarid region of Brazil. The hydraulic roughness of the Jacu River was characterized by the vegetal drag coefficient (CD′) of 5.93 m^{-1} under submerged condition and 2.702 m^{-1} underemergent condition, which is sensitive to the amount of turbulence, especially when *I. pes-caprae* is submerged. Two zones of the velocity profile were witnessed under submerged and emergent conditions: a shear zone and a fast free flow zone. In the shear zone turbulent mixing and a linear increase in velocity were observed at a submergence ratio between 0.6 and 1, followed by the velocity-defect law. The fast free flow zone occurred on the top of vegetation where there was a decreasing shear dispersion and the velocity followed the logarithmic law for a submergence ratio greater than unity.

1. Introduction

Despite its sparse distribution, vegetation exerts a significant influence on hillslope runoff and sediment transport in arid regions. Natural river channels and adjacent wetlands serve vital ecological functions in fluvial landscapes (Newson, 1992; Ward et al., 2001). Vegetation comprises a diverse and heterogeneous array of herbs, shrubs and trees, that influence sediment transport, nutrient distribution and pollutant concentration (Nepf and Vivoni, 2000). Therefore, vegetation is a controlling factor in the balance between hydrodynamic flow, sediment transport and geomorphology of fluvial systems (Tsujimoto, 1999). The effect of vegetation on flow is significant and complicates hydrological processes (Stone and Shen, 2002).

One area of research that, until recently, has been largely overlooked is the influence of channel vegetation on the mixing characteristics of flow, which is also important to evaluate the spread of nutrients and pollutants through channel treatment facilities that feature vegetation (Shucksmith et al., 2010). In order to asses this eco-engineering ability and enhance the success of restoration and protection attempts, more insight is needed into the interaction between vegetation, currents, waves, sediment transport and water quality (Dijkstra and Uittenbogaard, 2010).

In arid environments, channels are the main conduits of water movement and sediment transport, and the most common channel shapes in arid and semiarid regions are braided, simple and straight, flat-bottom and broad and shallow (Tooth, 2000). Understanding of the natural resources in arid and semiarid regions requires a study of fluvial channels. Surface water in arid regions varies from fully concentrated (channeled) to partly concentrated flow; however, concentrated runoff is dominant in arid environments (Graf, 1988; Tooth, 2000).

Evaluating the vegetation-induced resistance is a necessary precursor to modeling flow on flood plains and hillslopes, and in

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http://dx.doi.org/10.1016/j.jaridenv.2014.10.012
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Symbols list

a	total projected plant area per unit volume ($m^2\ m^{-3}$);
$C_{D'}$	vegetal drag coefficient (m^{-1});
d	stem diameter (m);
D	leaf diameter (m);
F_{Drag}	vegetation resistance force ($N\ m^{-3}$);
Fr	Froude number (dimensionless);
g	gravitational acceleration ($m\ s^{-2}$);
h	flow depth (m);
y	vegetation thickness (m);
K_0	constant (dimensionless);
Ks	equivalent sand roughness for a particular roughness element *k*;
Kx	longitudinal mixing coefficient (m^2/s);
n	Manning's roughness coefficient;
Q	water discharge ($m^3\ s^{-1}$);
Re	Reynolds number (dimensionless);
Re_{plant}	plant Reynolds number based on the spacing between stems (dimensionless);
R_h	hydraulic radius (m);
i	incline of the channel bottom ($m\ m^{-1}$);
s	stem spacing (m);
T	water temperature (°C);
u_*	shear stress velocity ($m\ s^{-1}$);
V	mean flow velocity ($m\ s^{-1}$);
v	kinematic viscosity of water ($m^2\ s^{-1}$);
α	relation between flow depth and vegetation thickness ($m\ m^{-1}$); or submerged ratio (dimensionless);
ρ	density of water ($kg\ m^{-3}$).

irrigated lands, channels and wetlands. The resistance exerted by vegetation on flow varies with the form and dimensions of plants and their rigidity, plant population per unit area, spatial (usually heterogeneous) distribution of vegetation, and the degree of submergence. Other factors that influence the resistance include the Reynolds number, slope of the channel bottom, upstream and downstream limits, channel morphology and meteorological conditions (Lee et al., 2004).

In a laboratory study of an open channel with resistance exerted on the flow by cylindrical structures, Stone and Shen (2002) showed that flow resistance varies with the depth of flow as well as concentration, length and diameter of stems. Chen and Cotton (1988) demonstrated the effect of vegetation height on delayed runoff using Bermuda grass (Cynodon dactylon). Only a few studies have included a quantitative measure of stem density; however, Kirby et al. (2005) considered stem density and examined the associated decrease in vegetation submersion.

Velocity profile and turbulence in submerged flow were investigated by Shucksmith et al. (2010) considering an analogy with the mixing layer model developed by Raupach et al. (1996), in which there are three distinct zones. The first zone has a slow moving zone through vegetation, nominated wake zone. The second zone is a shear zone created by the structure of vegetation, which is analogous to a turbulent mixing layer, and the third zone is a faster free-flow zone over the top in emergent conditions, with velocity profile that can be described by a logarithm law.

Righetti and Armanini (2002) have shown that the flexibility of plants also exerts a significant influence on the hydraulic resistance, increasing the flow complexity. Flow-induced curvature allows flexible plants to assume a more aerodynamic configuration, which can lead to a significant reduction in the drag (Kouwen and Fathi-Moghadam, 2000). The average inclined height describes the roughness of plants and can be used as a proxy to describe the characteristics of plants and flow (Stephan and Gutknecht, 2002).

Conventional resistance equations (such as those by Manning, Chézy and Darcy-Weisbach) are inappropriate for flow with vegetation, where resistance is caused primarily by drag on the stem along the depth of flow instead of shear stress at the bottom of the channel (James et al., 2004).

As described by Wilson (2007), Wu et al. (1999) calculated the roughness coefficient as a function of flow velocity or regime and developed a model of flow resistance based on the relationship between the plant drag coefficient (CD′) and the Reynolds number (Re). The hydraulic resistance was determined using multiple linear regression analysis to examine the relationship between the parameters that influence the plant drag coefficient and their relationship with the Reynolds number.

The objective of this study was to investigate the behavior of roughness caused by vegetation along the profile of flow depth and to determine the velocity of flow under both conditions, submerged and emergent *Ipomoea pes-caprae* vegetation in a natural (alluvial) channel in a semiarid area in Brazil.

2. Vegetal resistance

Extending the discussion of vegetal resistance force (Kao et al., 1977; Maheshwari, 1992), Lee et al. (2004) experimentally investigated flow through a vertical segment with plants in multiple spatial arrangements and found the total vegetal resistance force as.

$$F_{Drag} = \frac{CDa\rho v^2}{2} \tag{1}$$

where F_{Drag} is the vegetal resistance force ($N\ m^{-3}$), a is the total projected plant area per unit volume ($m^2\ m^{-3}$) given the diameter of leaves, ρ is the density of water ($kg\ m^{-3}$), CD is the plant drag coefficient (non-dimensional) and when multiplied by a (the total projected plant area per unit volume in $m^2\ m^{-3}$) it becomes (m^{-1}), and V is the mean flow velocity through plants ($m\ s^{-1}$).

Applying Buckingham's π-theorem of dimensional analysis, Lee et al. (2004) found the vegetal resistance force (F_{Drag}) as

$$F_{Drag} = K_0\left(\frac{\rho v^2}{S}\right)\left(Re_{plant}\right)^{a_1}\left(\frac{y}{S}\right)^{a_2}\left(\frac{d}{S}\right)^{a_3} \tag{2}$$

where K_0 is a constant, Re_{plant} is the Reynolds number based on the spacing between stems, S is the spacing between stems (m), d is the stem diameter (m), y is the plant height or plant thickness (m), and a_1, a_2 and a_3 are coefficients.

The plant drag coefficient can be expressed by assuming that (1) the gravitational force is equal to the drag of vegetation and (2) the friction at the bottom of the channel is insignificant in the presence of vegetation (Wu et al., 1999):

$$CD' = \alpha\frac{2gi}{v^2} \tag{3}$$

where CD′ is the plant drag coefficient (m^{-1}), g is the acceleration due to gravity ($m\ s^{-2}$), i is the incline due to the channel bottom ($m\ m^{-1}$), V is the mean flow velocity, and ($\alpha = h/y$) is the