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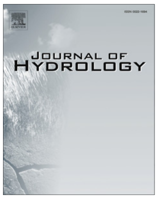

The links between water profile, net deposition and erosion in the design and performance of stiff grass hedges

Sina Akram[a,*], Bofu Yu[b], Hossein Ghadiri[a], Calvin Rose[c], Janet Hussein[c]

[a] Environmental Futures Centre, School of Environment, Griffith University, 170 Kessels Road, Nathan, QLD 4111, Australia
[b] School of Engineering, Griffith University, 170 Kessels Road, Nathan, QLD 4111, Australia
[c] School of Environment, Griffith University, 170 Kessels Road, Nathan, QLD 4111, Australia

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SUMMARY

Strips of dense and stiff grass are commonly used to reduce sediment delivery to aquatic systems. Grass strips cause changes in resistance to the flow, which can lead to a reduction in transport capacity and an increase in sediment deposition. Experiments were carried out in controlled conditions and the profile of water surface was recorded upstream and within narrow and stiff hedges for different slope length and steepness, and for different flow rates. The results showed that water surface profiles in stiff hedges no longer follow the classic M_2 profile and the friction slope can be quite high within the narrow hedges. A model is developed to simulate the water profile upstream and within grass strips. Simulated water surface profiles compare well with observations, and this study re-confirms the non-linear relationship between the Manning's n and Froude number in densely vegetated areas. As water approaches the downstream end of stiff hedges, the reduction in water depth leads to flow acceleration, and an increase in friction slope and stream power, and as a consequence net deposition of sediment is unlikely to occur.

1. Introduction

The rate of sediment and nutrients transport to rivers is affected by interactions between water, soil and land management practices. Vegetated buffer strips are commonly used as an effective method for controlling sediment and nutrient losses to streams. In order to model sediment transport through vegetated buffer strips, simulation of the water profile upslope and within the vegetated area is essential.

Vegetated buffer strips can be divided into two main types. First, there are dense, stiff and erect grass strips often called grass hedges, examples being vetiver or switchgrass species (Blanco-Canqui et al., 2004b; Dabney et al., 1995; Hussein et al., 2007a,b; Meyer et al., 1995). Second, there are more sparse and flexible vegetation types called filter strips, examples being fescue or meadow species (Daniels and Gilliam, 1996; Hook, 2003; Magette et al., 1989; Munoz-Carpena et al., 1999; Robinson et al., 1996). This paper discusses the performance of the first type, which commonly act as barrier strips rather than filter strips in trapping sediments. The term 'barrier strip' implies that most of the sediment retention occurs upstream the grass strip, in the backwater region.

Increased hydraulic roughness and reduced flow velocity within the vegetated zone is the main reason why narrow grass hedges are effective in removing sediment and associate pollutants.

Estimating the drag force in different vegetation types enables designers to precisely predict the flow characteristics. The drag force for the surface flow in a vegetated area can be described as the following equation:

$$F_d = 0.5\, C_D \rho A V^2 \tag{1}$$

where C_D is the drag coefficient of vegetation, ρ is the water density, A is the cross-sectional area of vegetation, and V is the flow velocity through the vegetation.

There have been many studies of estimating the drag coefficient within highly resistive areas (Fischenich and Dudley, 2000; Lee et al., 2004; Nepf, 1999; Righetti, 2008; Stone and Shen, 2002; Tanino and Nepf, 2008). Estimation of the drag coefficient is based on whether or not the vegetation is submerged (Stone and Shen, 2002). Nepf (1999) developed a model supported by laboratory and field experiments, describing the drag, turbulence and

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[*] Corresponding author. Postal address: Mailbox 15, School of Environment (N55), Griffith University, 170 Kessels Road, Nathan, QLD 4111, Australia. Tel.: +61 7 3735 6713; fax: +61 7 3735 7459.
E-mail address: s.akram@griffith.edu.au (S. Akram).

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diffusion of the flow through non-submerged vegetation. There is a significantly positive correlation between the drag coefficient and grass density which refers to the number of stems per unit surface area (Kothyari et al., 2009). Some studies showed that drag coefficient is strongly a function of the Reynolds number (Tanino and Nepf, 2008; Wu et al., 1999). However Ishikawa et al. (2000) used steel cylinders as plant stems in their study and found that the relationship between drag coefficient and the Reynolds number is not significant. Baptist et al. (2007) presented a new approach of using genetic programming for finding water depth-related resistance caused by vegetation.

Some studies used equivalent roughness coefficients in order to simulate the flow within highly resistive strips (FathiMaghadam and Kouwen, 1997; Järvelä, 2004; Kouwen and Fathi-Moghadam, 2000; Noarayanan et al., 2012). Ree and Palmer (1949) developed the empirical *n-VR* method representing Manning's coefficient based on the average flow velocity and hydraulic radius. Kouwen et al. (1981) disputed the validity of the *n-VR* method under certain natural conditions.

While many studies considered vegetation stems as rigid cylinders (Murphy et al., 2007; Nepf, 1999; Rose et al., 2002; Tanino and Nepf, 2008), Kouwen (1988) examined the effects of deflection and flexibility in determining vegetation roughness. FathiMaghadam and Kouwen (1997), Kouwen and Fathi-Moghadam (2000) developed a relationship between roughness components (i.e., density and rigidity) and flow components (i.e., velocity and depth) for floodplains and trees under non-submerged flow conditions. They proposed magnitudes for roughness coefficient for flexible vegetations as a function of flow depth. Diaz (2005) developed a new method of estimating Manning coefficient using the Froude number for small depths and steep conditions. He applied different flow rates to the grass bed, measured normal water depth, and calculated flow characteristics for every event. Finally, an equation in the form of $n = a\,Fr^{-b}$ was derived where n is Manning's coefficient, Fr is the Froude number and a and b are empirical constants.

Momentum theory (Eq. (2)) is commonly used to find flow characteristics within vegetated strips. Fig. 1 shows a uniform steady non-submerged flow within a vegetated area. Water flow through this segment of dense vegetation is controlled by the three forces of water weight, static pressure, and drag (Eq. (2)).

$$WS_0 + Fp_2 - Fp_1 - F_d = \rho q(V_2 - V_1) \tag{2}$$

where W is the weight component, S_0 is the bed slope, F_p is the static pressure force, F_d is the drag force, ρ is the water density, q is the surface water flow rate per unit width, and V is the flow velocity.

As most erosion and deposition models in vegetated area use Manning's equation which is based on the bed friction law, we intend to modify the equivalent Manning's roughness coefficient within densely grassed zones. However the following equations show the relationship between equivalent Manning's n and drag coefficient, therefore results obtained from this study can readily be used to estimate the drag coefficient if needed.

Considering Fig. 1 the bed shear stress can be calculated from the following equation:

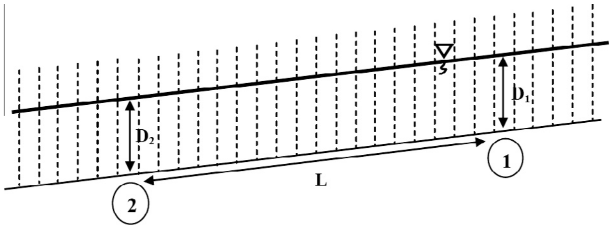

Fig. 1. Uniform steady non-submerged flow within a vegetated area.

$$\tau_0 = \frac{F_d}{L\,b} \tag{3}$$

where L is the distance between the two points, and b is the channel width. Combining Eqs. (1) and (3) leads to:

$$\tau_0 = \frac{0.5\,C_d\,A\,\rho V^2}{L\,b}$$

On the other hand for steady and uniform flows (Fig. 1) and using the bed friction law, Eq. (2) can be written as:

$$W\,S_0 = F_d$$

$$\rho\,g\,b\,L\,D\,S_0 = \tau_0\,b\,L$$

where g is the acceleration due to gravity, and D is the flow depth. Therefore:

$$\tau_0 = \rho\,g\,D\,S_0$$

Also by definition

$$\tau_0 = \rho\,V_*^2$$

where V_* is shear velocity. The Darcy-Weisbach friction factor is defined as:

$$f = 8\left(\frac{V_*}{V}\right)2$$

$$f = 4\,C_d\left(\frac{A}{Lb}\right)$$

And from fluid mechanics textbooks:

$$n = \sqrt{f\left(\frac{D^{1/3}}{8g}\right)}$$

therefore:

$$n = 2\sqrt{C_d\left(\frac{A}{L\,b}\right)\left(\frac{D^{1/3}}{8g}\right)} \tag{4}$$

The above equation (Eq. (4)) shows the relationship between the equivalent Manning's n and the drag coefficient in a vegetated strip for uniform steady flows.

The previously mentioned studies were focused on predicting only the normal depth within the grass strips for different flow rates. As barrier strips are usually narrow, normal depth of flow will not persist for long within the hedge, and it is important to correctly simulate the decay curve in order to predict their effects on sediment transport and settling. Consequently the goal of this paper is to scrutinize the roughness coefficient variations for fixed flow rates in the decay curve within the grass strips.

Manning's equation is commonly used to predict water depth and velocity in vegetated strips. To obtain accurate predictions, appropriate Manning's coefficients have to be applied. Although using Manning equation is a prevalent method of water profile simulation within the highly resistive strip, it has the following limitations:

- The main assumption of Manning's equation is that resistance is caused by friction between the water flow and the surface over which it flows, but in the case of vegetated strips, resistance is dominated by the stems and leaves of the plant rather than soil bed.
- Also according to Manning's equation, the Manning coefficient is dependent on water depth, vegetation density, velocity and slope, therefore its value is not constant throughout the grass hedge.