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Flow resistance models for flexible submerged vegetation

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Summary This paper investigates the variation of hydraulic roughness parameters with flow depth for submerged flexible vegetation. In an experimental study flexible grass canopies are used to examine the impact of stem height, grass type and degree of submergence on the flow resistance properties. Results reveal that Manning's *n* roughness coefficient increases with decreasing flow depth reaching an asymptotic constant at lower levels of vegetation submergence. Data suggest that the value of the constant is dependent on the vegetation height and the vegetation properties. Currently the *n-UR* method underpredicts the Manning's *n* and the data from this study extends the USDA method for lower bed slopes and for smaller *UR* values. The vegetal drag-Reynolds number model is extended for submerged flexible grass linings of differing heights and types. Similar values of the vegetative characteristic number *k* are evaluated as from previous studies yet for contrasting vegetation types. The vegetal drag coefficient value was found to be strongly correlated to the vegetation height, and follows a power law relationship. The exponent value was found to be independent of the vegetation characteristics.

Introduction

Vegetation is an effective means of mitigating channel erosion in highway drainage channels, irrigation channels and river bank revetments. Buffer zones are used in both lowland and highland lying river systems to reduce both fertilizer runoff on agricultural land and the impact of acidification in areas of forestation. While grass swales are widely employed to encourage ground infiltration and reduce run off in urban areas. In these cases inputs into the neighbouring surface waters are improved by the vegetation acting as a physical barrier and as a means of controlling pollutants. In fens, bogs and wetland areas vegetation influences both the infiltration rates and the magnitude of overland flows. Yet currently the degree in which vegetation inhibits the area mean velocity in a vegetated system has not yet been determined.

Some of the earliest experimental work on flexible grass-lined channels in their submerged condition was conducted by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) at Spartanburg, SC and

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Nomenclature

a, b, c, d, e, k	regression coefficients
C_D	drag coefficient
C'_D	vegetal drag coefficient (m^{-1})
E	modulus of elasticity (Nm^{-2})
G	gravitational acceleration (ms^{-2})
h	undisturbed vegetation height (m)
$h_{deflected}$	deflected height (m)
I	moment of inertia (kg m^2)
M	stem density (m^{-2})
N	Manning's n roughness coefficient ($m^{-1/3}s$)
R	hydraulic radius (m)
Re	Reynolds number where $h_{deflected}$ is used as the characteristic length
S	bed gradient or energy gradient
U	area mean velocity (ms^{-1})
u_*	shear velocity (ms^{-1})
Y	flow depth (m)
Z	bed elevation relative to datum (m)
ρ	density of water (kg m^{-3})
α	for emergent vegetation is equal to unity, for submerged vegetation equal to $y/h_{deflected}$
λ	area fraction per unit length (m^{-1})
ω, ψ, ξ	regression coefficients

Stillwater, OK. The results of this work together with those from Ree (1949) led to the development of the 'Handbook of Channel Design for Soil and Water Conservation' (USDA, 1947) and the associated '*n-UR* method'. This approach is based on the premise that for a particular vegetation type there is a unique relationship between the Manning's n roughness coefficient and the product of the mean area velocity (U) and hydraulic radius (R), regardless of the relative values of U and R. The spatial location on the *n-UR* graph and retardance class is dependent on grass type, grass height and quality of the 'stand'. Few studies include a quantitative measure of the stem density and Kirby et al. (2005) include such information in their study which examines lower degrees of grass submergence. Chen and Cotton (1988) have shown the impact of grass height on the retardance class for Bermuda grass. This study highlights the importance of the vegetation thickness and height on the hydraulic resistance.

Kouwen and Unny (1973) proposed that for a flexible boundary lining the roughness coefficient is primarily a function of the relative roughness and parameterised the degree of bending to the boundary shear in terms of plant physical properties such as stem density (M), modulus of elasticity (E) and second moment of area:

$$\frac{h_{deflected}}{h} = \frac{3.57}{h}\left(\frac{\mathrm{MEI}}{\rho u_*^2}\right)^{1/4} - 0.286 \quad (1)$$

The flexural rigidity of an individual grass blade is difficult to determine and highly variable; variations in modulus of elasticity of up to 100% can occur between samples. Furthermore Kouwen (1988) observed that there was a large degree of variability in the MEI value depending on whether the grass was dormant or in growth. In a flexible canopy, the stems directly behind other stems are shielded from the full force of the flow and hence a densely packed group of blades will have different bending properties compared to a single blade, hence correlating deflected height as a function of bending stiffness may be inappropriate.

Following on from an approach based on a roughness coefficient as a function of the velocity or flow regime, Wu et al. (1999) developed a flow resistance model based on the relationship between the vegetal drag coefficient C'_D and Reynolds number. Through multiple linear regression they attempted to elucidate hydraulic resistance by examining the relationship between parameters which influence the vegetal drag coefficient and Reynolds number relationship. The vegetal drag coefficient was based on the assumption that the gravitational force was equated to the drag of the vegetation, and that the bed skin friction was negligible. The vegetal drag coefficient was defined as:

$$C'_D = \alpha\frac{2gS}{U^2} = \lambda C_D \quad (2)$$

where for emergent vegetation α is equal to unity and for submerged vegetation α is equal to the ratio y/h where h is the vegetation thickness. C_D is the drag coefficient and λ is defined by:

$$\lambda = \frac{A_p}{AL} \quad (3)$$

λ is the ratio of the projected plant area to the total flow area per unit length. Therefore the vegetal drag coefficient has units of m^{-1} and should be more appropriately named a parameter rather than a coefficient. While this may be seen as a drawback it allows the projected area of the vegetation to be lumped together with the drag coefficient. Furthermore, the projected area of the vegetation or vegetation porosity is not often specified in studies on vegetation linings (see for example Ree and Palmer, 1949; Chen, 1976; Wu et al., 1999) and it is difficult to determine. Hence the vegetal drag parameter allows us to combine two unknowns and form comparison between data sets collected over half a century ago. In the study by Wu et al. (1999) a rubberised horsehair mattress was used to simulate dense, porous vegetation and due to its rigidity its thickness remained unchanged with increasing flow action. Therefore the flow depth was used as the characteristic length in the Reynolds number formula for the emergent condition, and vegetation height or 'thickness' h was used for the submerged condition. They conducted a comprehensive experimental study examining the variation in Manning's n roughness coefficient and the vegetal drag coefficient for both emergent and submerged vegetation conditions. The experiments focussed on vegetation thickness and energy slope as experimental variables.