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FLOW CONVEYANCE AND SEDIMENT TRANSPORT CAPACITY IN VEGETATED CHANNELS

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ABSTRACT

This paper reviews the approaches to estimate the roughness of flexible and rigid vegetation under submerged and emergent conditions, and then presents a hydraulic model to compute flow discharge in vegetated channels. The drag effect of vegetation is considered in roughness coefficients in the determination of channel conveyance. The sediment transport capacity in vegetated channels has also been investigated. The bed-load rate is computed using the Wu et al. formula, in which the effective bed shear stress is computed using $\tau_b = \gamma R_s S$, with S being the channel slope, γ the unit weight of water, and R_s the spacing hydraulic radius defined by Barfield et al. The established models have been tested against experimental and field data. The computed flow discharge and bed-load rate agree well with the measured data.

1. INTRODUCTION

Vegetation is an important feature of many rivers, providing habitat for other aquatic organisms and enhancing amenity value for people (Jordanova and James, 2003). Environmental management of rivers requires understanding and predictive capability of these processes, and in particular the influence of vegetation on sediment transport. There is a three-way, mutual feedback relationship among channel hydraulic, sediment transport and vegetation. Vegetation and channel form can determine hydraulic conditions causing flow deceleration and deflection as well as local deposition (Kouwen et al., 1969; Li and Shen, 1973; Shields and Gippel, 1995); vegetation can affect river morphology (Thorne, 1990; Millar, 2002; Brooks and Brierley, 2002; Bennett et al., 2002; Simon and collision, 2002; Montgometry et al., 2003); and hydraulic conditions and vegetation provide aquatic habitat by reduced or highly variable velocity, fine sediment deposition (Wallace and Benke, 1984; Shields and Cooper, 2000).

The drag on vegetation increases overall flow resistance and reduces the shear stress applied to the bed, resulting in reduced capacity for bed-load transport and increased propensity for trapping, deposition, and stabilization of sediment. Experimental researches into the effects of in-channel and

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riparian vegetation on flow resistance and sediment transport have been carried out for many years (e.g. Chow, 1959; Tollner, 1977; Barfield, 1979; Bache and MacAskill, 1984; Tsujimoto and Kitamura, 1995; Jordanova and James, 2003). And also, various approaches have been proposed to model the effects of vegetation on open-channel flow and sediment transport (e.g. Tsujimoto et al. 1993; Schimizu and Tsujimoto, 1994; Darby, 1999; Lopez and Garcia, 2001; Wu and Wang, 2004; Wu et al., 2005). Empirical models have been established in this study to compute flow and bed-load discharges in vegetated channels.

2. FLOW RESISTANCE IN VEGETATED CHANNELS

Vegetation in nature can be either flexible (grass) or rigid (woody species), and either emergent or submerged in low and high flow periods. The effects of these kinds of vegetation roughness on flow need to be determined using different methods, as described below.

2.1 Roughness of Rigid Vegetation

Because the shape of vegetation is highly irregular, it is challenging to represent a vegetation element with simple geometry. As an approximation, a vegetation stem (such as tree trunk) is often conceptualized as a cylinder with a height, h_v, and a representative diameter, *D*. The drag force exerted on a vegetation element is expressed as

$$\vec{F}_d = \frac{1}{2} C_d \rho A_v \left|\overline{U}_v\right| \vec{U}_v \tag{1}$$

where C_d is the drag coefficient, ρ is the water density, $\vec{U}_v$ is the vector of flow velocity acting on the vegetation element, and $\left|\overline{U}_v\right|$ is the magnitude of $\vec{U}_v$. For emergent vegetation, $\vec{U}_v$ is the depth-averaged flow velocity $\vec{U}$. However, for submerged vegetation, $\vec{U}_v$ should be the velocity averaged only over the vegetation layer, as shown in Figure 1. $\vec{U}_v$ can be determined using Stone and Shen's (2002) method as

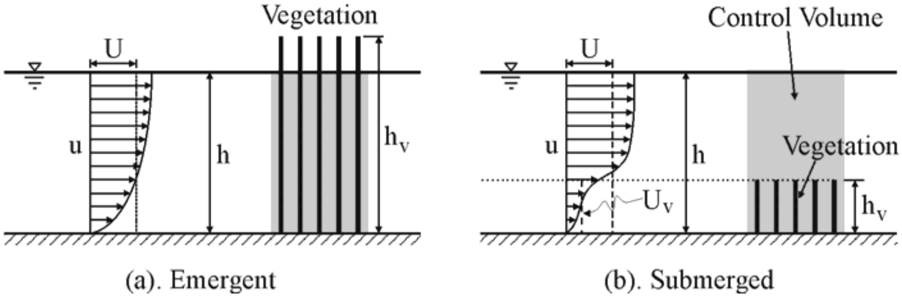
$$U_v = \eta_v U \left(\frac{h_v}{h} \right)^{1/2} \tag{2}$$

where *h* is the flow depth, and η_v is a coefficient of about 1.0.

For a group of rigid vegetation elements, the total resistance, τ, consists of the bed shear stress, τ_b, and the drag force of vegetation, $N_a F_d$:

$$(1 - c_v)\tau = (1 - c_v)\tau_b + N_a F_d \tag{3}$$

where N_a is the vegetation density, which refers to the number of vegetation elements per unit bed area; and c_v is the vegetation volumetric concentration, defined as $c_v = N_a \pi D^2 \min(h_v, h) / 4h$. Note that the factor $1 - c_v$ appears in eq. 3 to account for only the bed area occupied by flow. If the vegetation is relatively sparse, $1 - c_v$ is close to 1 and can be eliminated from eq. 3.



(a). Emergent (b). Submerged

Figure 1 Rigid vegetation in open channels (side view)

Define the total resistance and the bed shear stress as

$$\tau = \frac{\rho g n^2 U^2}{R_s^{1/3}}, \qquad \tau_b = \frac{\rho g n_b^2 U^2}{R_s^{1/3}} \tag{4}$$

where c_f and n are the friction factor and Manning coefficient corresponding to the total roughness, c_{fb} and n_b are the friction factor and Manning coefficient corresponding to the bed roughness, and R_s is the hydraulic radius of the bed with vegetation. The hydraulic radius R_s has been defined differently in the literature. Many models simply set R_s as the flow depth h, while Barfield et al. (1979) considered the effect of vegetation on the flow "eddy size" and suggested the following relation:

$$R_s = \frac{h l_n}{2h + l_n} \tag{5}$$

where l_n is the lateral spacing of vegetation elements. By analogy, for submerged vegetation, one may define R_s as

$$R_s = \frac{h_v l_n}{2h_v + l_n} + h - h_v \tag{6}$$

Note that apparently there might be confusion and inconsistence when one sets R_s as h or determines R_s using eqs. 5 and 6. This is not essential because the Manning roughness coefficient is calibrated based on the chosen definition of R_s and has different values correspondingly. However, cross-referring the Manning roughness coefficients calibrated based on different definitions of R_s should be cautioned.

Substituting eqs. 1, 2, and 4 into eq. 3, one can derive

$$n^2 = n_b^2 + \frac{1}{2g(1 - c_{v0})} C_d N_a A_v \eta_v^2 \frac{h_v}{h} R_s^{1/3} \tag{7}$$

For the channel with densely distributed vegetation, the drag of vegetation becomes the major contributor to the total resistance, and thus the term of n_b in eq. 7 can be eliminated.

Determination of the drag coefficient is the key aspect for eq. 7 to be used in practice. The drag coefficient for a single cylinder is related to the Reynolds number $R_e = U_v D / v$ (White, 1991). Li and Shen (1973) investigated the drag coefficient for a group of cylinders with various set-ups. They identified four factors that need to be considered to determine the drag coefficient: (1) turbulence of flow; (2) nonuniform velocity profile; (3) free surface; and (4) blockage. Lindner (1982) concluded that, in densely vegetated channels, the first two of these factors are of minor importance and can be neglected. He extended the work of Li and Shen (1973), resulting in a method to computer the drag coefficient, C_d, for a single plant group. Based on Lindner's approach and further experiments, Pasche and Rouve (1985) presented a semi-empirical process to determine C_d. Many other investigators, e.g. Klaassen and Zward (1974) and Jarvela (2002), suggested the drag coefficient C_d has values of about 1.5 for most practical cases.

The drag coefficient C_d in eq. 1 is based on the apparent velocity U_v. Stone and Shen (2002) suggested that the drag coefficient C_{dm} based on the constricted cross-sectional velocity U_{vm} shown in Figure 2 is more appropriate than C_d. This is because C_{dm} is closer to the drag coefficient for a single cylinder and has less variation for a wide range of values for vegetation density, stem size, and cylinder Reynolds number as compared to C_d. The relationship between C_d and C_{dm} is

$$C_d = C_{dm} \frac{U_{vm}^2}{U_v^2} \tag{8}$$

If the vegetation elements with a diameter of D are distributed uniformly in the lateral direction with a spacing of l_n, $U_v = U_{vm}(1 - D / l_n)$ and eq. 8 can be written as

$$C_d = C_{dm} / (1 - D / l_n)^2 \tag{9}$$

Furthermore, if the vegetation stems are arranged in a staggered pattern with equal spacing in the longitudinal and transverse directions, $U_v = U_{vm}(1 - D\sqrt{N_a})$ and eq. 8 can be written as

$$C_d = C_{dm} \Bigg/ \left(1 - \sqrt{\frac{4 c_v h}{\pi \min(h_v, h)}}\right)^2 \tag{10}$$

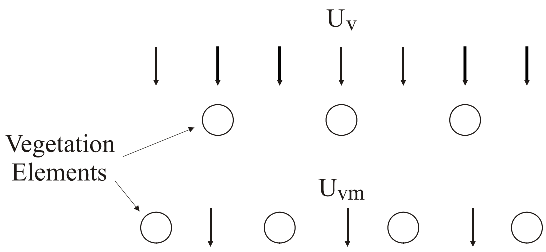


Figure 2 Definitions of U_v and U_{vm} in a matrix of vegetation elements

Thompson and Roberson (1976) presented a method to determine the velocity in the wake behind rigid vegetation:

$$\frac{u_w}{u} = \begin{cases} 0.48\left(s_v/d_v\right)^{0.14} & 4 \le s_v/d_v \le 20 \\ 0.70\left(s_v/d_v\right)^{0.08} & 20 < s_v/d_v \le 100 \end{cases} \tag{11}$$

where u_w is the flow velocity in wake area, u is the approach velocity, s_v is the space between vegetation elements, and d_v is the diameter of vegetation. These equations are based on simulated data obtained from application of a mathematical model developed by Li and Shen (1973). Having obtained the corrected wake velocity using the above equations, Darcy-Weisbach friction factor is estimated using

$$\lambda = \frac{8gRS}{u_w^2} \tag{12}$$

where S is the channel gradient, R is the hydraulic radius of the channel, and g is the acceleration due to gravity.

2.2 Roughness of Flexible Vegetation

Several investigators (Kouwen et al., 1969; Pethick et al., 1990) have shown that resistance to flow in channels with flexible vegetation can be based on a relative roughness approach similar to the widely accepted resistance relationships developed for rigid roughness in pipes and channels. Kouwen and Li (1980) suggested that the Darcy-Weisbach friction factor, λ, can be obtained using a semi-logarithmic resistance equation (the Colebrook-White equation):

$$\frac{1}{\sqrt{\lambda}} = a + b\log\left(R/k\right) \tag{13}$$

where k is the roughness height of vegetation, R is the hydraulic radius of the channel, and a, b are two fitted parameters that are found to be dependent on the relative magnitude of the shear velocity U_* and a critical value U_{*crit}. In a numerical model test, Darby (1999) used the Hey (1979) equation as a general approach to estimate the roughness of vegetation and movable bed:

$$\frac{1}{\sqrt{\lambda}} = 2.03\log\left(\frac{a_s R}{k}\right) \tag{14}$$

where a_s is a dimensionless shape correction factor, determined by $a_s = 11.0\left(R/h_{\max}\right)^{-0.314}$ with $h_{\max}$ being the maximum flow depth in the cross section.

For flexible, submerged vegetation, Kouwen and Li (1980) showed that the roughness height varies as a function of the amount of drag exerted by the flow and the parameter *MEI*:

$$k = 0.14 h_v \left[\frac{(MEI/\tau)^{0.25}}{h_v} \right]^{1.59} \tag{15}$$

where τ is the bed shear stress, and *MEI* is the flexural rigidity. Based on laboratory experiments, Kouwen (1988) and Temple (1987) developed empirical equations to calculate the *MEI* with vegetation height for a variety of growing and dormant grass species as follows:

$$MEI = \begin{cases} 319 h_v^{2.3} & \text{for green, growing grass} \\ 25.4 h_v^{2.26} & \text{for dormant or dead grass} \end{cases} \tag{16}$$

Eq. 17 is only applicable to grasses. For woody vegetation, a method proposed by Kouwen and Fathi (2000) can be used to estimate the friction factor:

$$\lambda = 4.06 \left(\frac{U}{\sqrt{\xi E / \rho}} \right)^{0.46} \frac{h}{h_v} \tag{17}$$

where ξ accounts for all aspects of deformation of the plant as a result of an increasing flow velocity. The parameter ξE is called the "vegetation index", which is obtained from the resonant frequency, mass, and length of a tree and a mathematical model based on works by Niklas and Moon (1988), Fahi and Kouwen (1977), and Fathi (1996) as $\xi E = Nf_1^2 m_s / h_v$, where m_s is the total mass; and Nf_1 is the natural frequency of the tree. Fathi (1996) provided the average vegetation indices ξE for four species of coniferous trees.

3. FLOW CONVEYANCE IN VEGETATED CHANNELS

Assuming uniform flow in a vegetated channel yields

$$Q = K \sqrt{S_0} \tag{18}$$

where Q is the flow discharge, S_0 is the longitudinal channel slope, and K is the channel conveyance. If the entire cross section is covered by nearly uniformly distributed vegetation, the conveyance K can be determined as

$$K = \frac{A^{5/3}}{n P^{2/3}} \tag{19}$$

where A is the flow area and P is the wetted perimeter at the cross section. Both the channel bed friction and vegetation drag are accounted for through the Manning *n*, which is determined by eq. 7, 12, 14 or 17 depending on the vegetation species.

If the cross section is partially covered by vegetation or the vegetation density varies along the cross section, the flow velocity significantly varies in vegetated and non-vegetated zones or even in different vegetated zones. One needs to divide the cross section into a suitable number of subsections, either vegetated or non-vegetated, as shown in Figure 3. The conveyance in each subsection is determined as

$$K_i = \frac{A_i^{5/3}}{n_i P_i^{2/3}} \tag{20}$$

where K_i, A_i, P_i, and n_i are the conveyance, flow area, wetted perimeter, and Manning roughness coefficient of subsection *i*, respectively. The total conveyance *K* can be obtained by summing the conveyances of all subsections as

$$K = \sum_i K_i \tag{21}$$

The drag on vegetation is related to the flow velocity, which in each subsection is determined using the Manning equation as

$$U_i = \frac{K_i \sqrt{S_0}}{A_i} \tag{22}$$

Eqs. 18 and 20-22 are iteratively solved together with a relation for the Manning roughness coefficient, i.e., eq. 7, 12, 14 or 17 depending on the vegetation species.

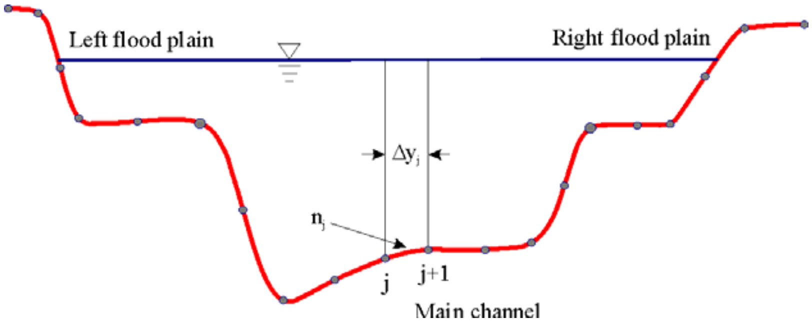


Figure 3 Sketch of a cross section

4. SEDIMENT TRANSPORT CAPACITY WITH VEGETATION EFFECT

Dozens of formulas have been proposed to determine the total and fractional discharges of sediment with uniform and nonuniform sizes in non-vegetated channels. General introductions on this topic can be found in Simons and Senturk (1992) and Yang (1995). Sediment transport in vegetated channels might be different from that in common channels. Okabe et al. (1997), Jordanova and James (2003), and Wu et al. (2005) found that bed-load transport is mainly related to the bed shear rather than the drag force exerted on vegetation elements. If the effective bed shear is used, some existing empirical formulas developed for bed-load transport in common channels can be extended to vegetated channels. Jordanova and James (2003) experimentally investigated the bed-load transport in a flume covered with uniformly distributed vegetation. They used the method of Li and

Shen (1973) to determine the effective bed shear, and proposed a simple empirical formula. Okabe et al. (1997) used the k-ε turbulence model to compute the effective bed shear stress, and found that the Ashida-Michiue (1972) formula can be used to determine the bed-load transport rate in vegetated channels. Wu et al. (2005) used the approach of Barfield et al. (1979) to determine the effective bed shear stress:

$$\tau_b = \gamma R_s S \tag{23}$$

and then applied the formula of Wu et al. (2000) to compute bed load in vegetated zones:

$$\phi_{bi} = 0.0053\left[\left(\frac{n_b'}{n_b}\right)^{3/2}\frac{\tau_b}{\tau_{ci}} - 1\right]^{2.2} \tag{24}$$

where ϕ_b is the non-dimensional bed-load transport rate $\phi_{bi} = q_{bi}/[p_{bi}\sqrt{(\gamma_s/\gamma - 1)gd_i^3}\,]$, q_{bi} is the transport rate of the ith size class of bed load per unit channel width, τ_b is the effective bed shear stress determined using eq. 23, τ_{ci} is the critical shear stress, n_b' is the Manning coefficient corresponding to the grain roughness with $n_b' = d_{50}^{1/6}/20$, and n_b is the Manning coefficient of channel bed.

5. MODEL EVALUATION

5.1 Roughness of Emergent Rigid Vegetation in Laboratory Experiments

Flow in an open channel partially covered by vegetation was experimentally investigated by Tsujimoto and Kitamura (1995). A group of cylinders with a constant diameter was set on the bed at an equal spacing along one side wall of the flume. Quasi-uniform flow with the depth smaller than the vegetation height was studied. The experiments were conducted in two flumes. One was 12 m long and 0.4 m wide (flume-a), and another was 12 m long and 0.5 m wide (flume-b). The experimental conditions are summarized in Table 1, in which B_s = width of vegetation zone, i_b = longitudinal bed slope, h_0 = mean water depth, U_{ave} = bulk velocity, U_k = velocity at the interface between vegetation and non-vegetation zones (depth-averaged), C_f = resistance coefficient of main course, and $\Omega = C_D D h_0/(2s^2)$. The properties of model vegetation are shown in Table 2.

Three methods are used to calculate the roughness of emergent rigid vegetation here. The first method determines the Manning roughness coefficient using eq. 7 with the values of drag coefficient C_d suggested by Tsujimoto and Kitamura (1995): $C_d = 2gs^2/(K_s^2 D)$. The second method determines the Manning roughness coefficient using eq. 7 and the drag coefficient C_d using Stone and Shen's (2002) method, eq. 8. The third method is Thompson and Roberson's (1976) method, which uses eq. 11 to calculate the wake velocity and then eq. 12 to determine the friction factor. The three methods are named as TK, SS, and TR for convenience. Figure 4 shows the comparison of measured and calculated flow discharges. All methods give good agreements between prediction and measurement. The average relative error is 5.3, 4.6, and 5.1% for the three methods, respectively.

Table 1 Experiment conditions

Run	Flume	B_s (cm)	i_b ($\times 10^{-3}$)	H_0 (cm)	U_{ave} (cm/s)	U_k (cm/s)	C_f ($\times 10^{-3}$)	Ω
A1	a	12	1.7	4.57	32.0	20.1	3.8	0.05
B1	a	12	1.7	4.28	27.6	16.3	4.0	0.12
B2	a	12	1.7	3.22	23.7	14.1	4.5	0.09
B3	a	12	2.7	4.15	35.1	18.5	3.6	0.11
B4	a	6	1.6	4.23	33.9	14.4	3.5	0.11
C1	a	12	1.7	4.38	22.0	10.5	5.2	0.30
D1	b	25	1.5	3.65	20.3	13.5	3.1	0.18
D2	b	25	2.5	3.82	24.2	16.1	4.2	0.19
D3	b	25	3.9	3.87	27.8	16.8	3.4	0.19

Table 2 Properties of model vegetation

Model Series	Veg. Material	Diameter D (cm)	Height (cm)	Spacing s (cm)	No. of Cylinders at one point	K_s (cm/s)
A	Bamboo	0.15	4.6	2.8	1	295
B	Bamboo	0.15	4.6	2.0	1	234
C	Vinyl chloride	0.02	5.0	1.0	4	120
D	6-6 nylon	0.10	4.1	1.0	1	137
E	Bamboo	0.25	10.0	2.0	1	172

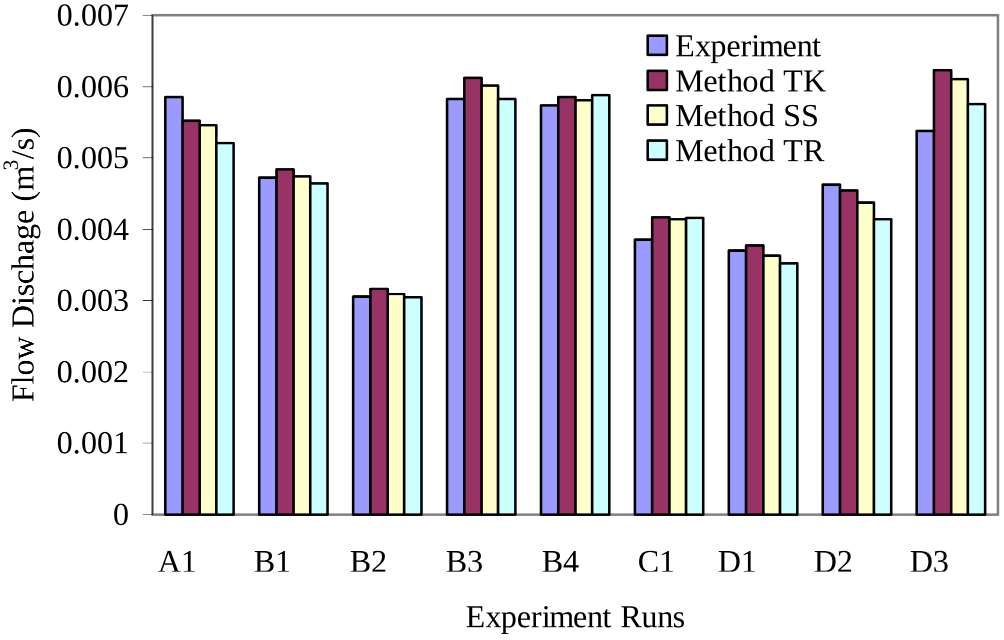


Figure 4 Comparison of measured and calculated flow discharges (m^3/s)

5.2 Roughness of Flexible Vegetation in Natural Rivers

Field data measured in the River Severn at Montford, U.K. and the Era River at Capannoli, Italy (Darby, 1999) are used to evaluate the model of flexible vegetation roughness. Accurate cross-sectional and channel gradient data were obtained at each site using standard surveying techniques. Sediment data were obtained by direct sampling of the bed material. Riparian vegetation characteristics were also recorded during on-site surveys. The characteristics of the two sites are summarized in Table 3.

Table 3 Characteristics of field sites (Darby, 1999)

Parameter	Severn River	Era River
50-year flood discharge (m^3/s)	392	475
5-year flood discharge (m^3/s)	243	193
Bankfull discharge (m^3/s)	165	60
Left floodplain width (m)	68	3
Right floodplain width (m)	27	5
Bankfull main-channel width (m)	34	29
Bankfull main-channel depth (m)	6	3.9
Width-to-depth ratio of main channel	5.7	7.4
Floodplain-to-channel width ratio	2.8	0.3
Channel gradient S	1.94×10^{-4}	1.12×10^{-3}
Bed-material particle size (mm)	88	47
Vegetation characteristics:	5-cm-high green grass rowing over entire floodplain.	Approximately 2/3 of floodplain is covered by woody vegetation while1.5m high grasses and reeds cover remaining Floodplain and banks.

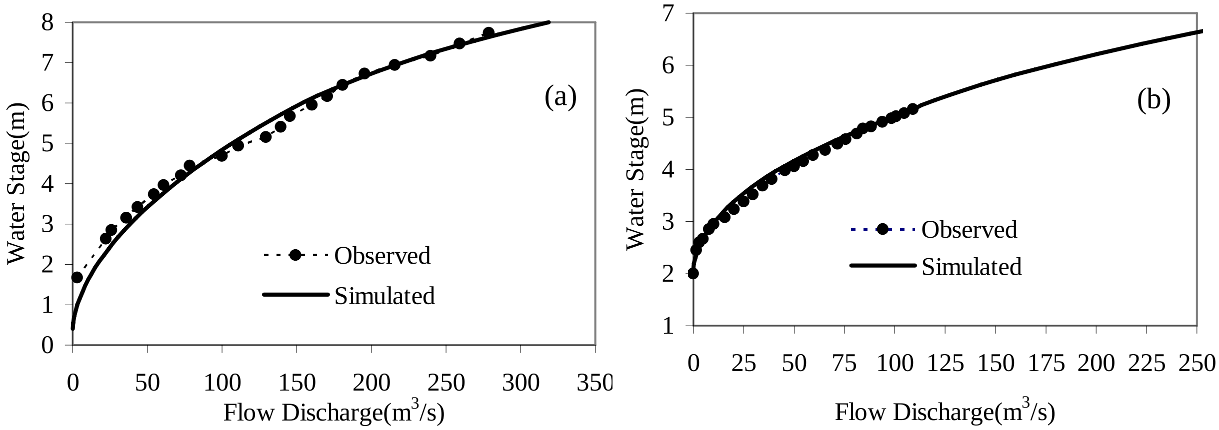


Figure 5 Comparison of calculated and gauged stage-discharge curves in (a) Severn River and (b) Era River

In these two cases, the grass and reed are treated as flexible vegetation, whose roughness is determined using Eqs. 14-16. The woody vegetation is treated as rigid and its roughness is calculated using eq. 7. The roughness of bed materials is determined using van Rijn's (1984) method modified by Darby (1999). Figure 5 shows the comparisons of calculated and gauged stage-discharge curves at two field sites. For the River Severn at Montford, the predicted discharges are larger than the measured ones for water stages of < 4.0 m, which is well below bankfull stage, while the predicted discharges agree well with the measured data above this elevation. For the Era River at Capannoli, the model predicts discharge generally well. The average relative errors between predicted and measured flow discharges are 20.1% for the Severn River case and 12.8% for the Era River case. The major errors come from low discharge stages.

5.3 Sediment Transport in Vegetated Flumes

The sediment transport capacity with vegetation effect is evaluated by two sets of experiments, in which rigid vegetation species are considered. The vegetation roughness is calculated by eq. 7, and the transport capacity of bed load is determined by eq. 24. The effective bed shear stress τ_b is computed by using eq. 23. First, the flow discharge and bed-load transport rate in vegetated channels computed using this approach are compared with measured data presented by Jordanova and James (2003). In the experiments, emergent vegetation was simulated by cylindrical metal rods arranged in a staggered pattern, and the median grain size of the sediment was 0.45 mm. Figure 6 shows very good agreement between observed and predicted flow discharges and bed-load transport rates. The average relative errors between prediction and measurement are 6.6% for flow discharge and 13.6% for sediment rate.

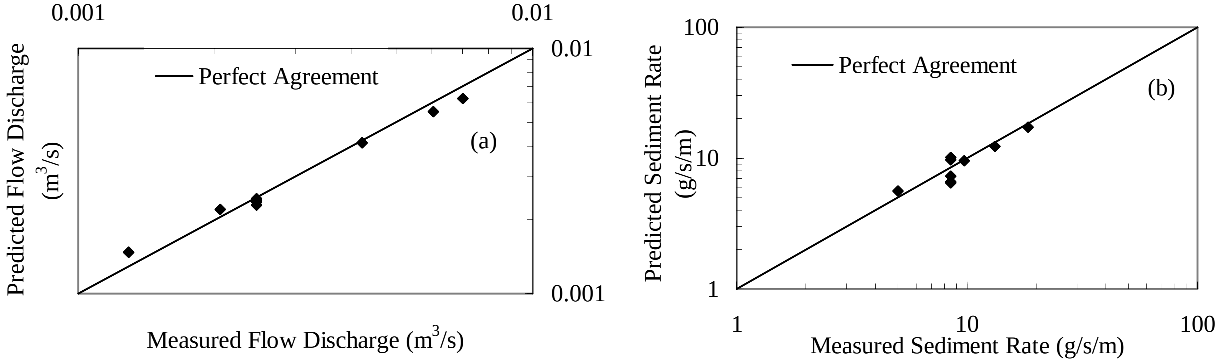


Figure 6 Comparison of calculated and measured flow discharges and bed-load transport rates

Another set of experiments chosen to test the sediment transport capacity is the experiment series A of bed-load rate on movable beds covered by vegetation performed by Okabe et al. (1997) in a 0.4 m wide and 12 m long rectangular flume. The cylindrical and curved plant models were made of silicone tubes with an external diameter of 1 mm. The grain size was 0.6 mm. Figure 7 shows the comparison of measured and predicted bed-load rates. The average relative error between prediction and measurement is 50.9%.

6. CONCLUSIONS

In this study, first the approaches to estimate the roughness of flexible and rigid vegetation under submerged and emergent conditions have been reviewed, and then a hydraulic model has been established to compute flow discharge in vegetated channels. The drag effect of vegetation is considered in the Manning roughness coefficient in the determination of channel conveyance. This model has been tested against Tsujimoto and Kitamura's (1995) experiments and two sets of natural river data. The computed flow discharges and stage-discharge rating curves agree well with the measured data.

The sediment transport capacity in vegetated channels has also been investigated in this study. The bed-load discharge is computed using the Wu et al. (2000) formula, in which the bed shear stress is computed using $\tau_b = \gamma R_s S$, with S being the channel slope, γ the unit weight of water, and R_s the spacing hydraulic radius defined by Barfield et al. (1979). This method has been verified using the measurement data of Jordanova and James (2003) and Okabe et al. (1997). The predictions and measurements are in generally good agreement.

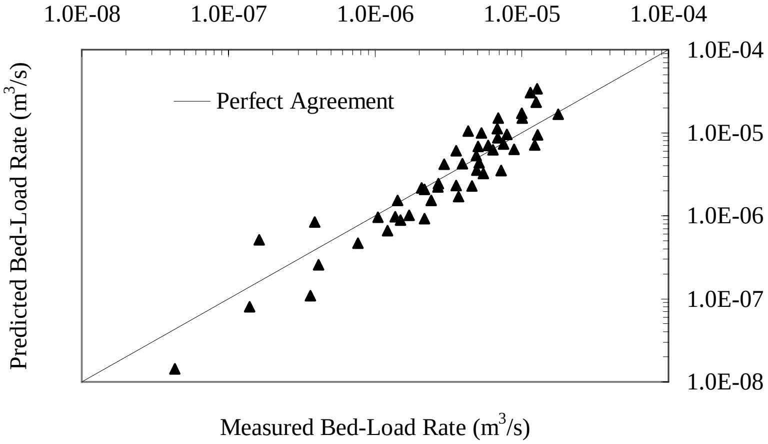


Figure 7 Comparison of measured and predicted bed-load transport rates

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