International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

Effect of Vegetation on Sediment Transport by Stream Flow

Umesh C. Kothyari[1]
Department of Civil Engineering
Indian Institute of Technology, Roorkee, INDIA
E-mail: umeshfce@iitr.ernet.in

Haruyuki Hashimoto
Department of Civil Engineering
Kyushu University, Fukuoka, 819-0395, JAPAN
E-mail: hasimoto@civil.kyushu-u.ac.jp

Kenjirou Hayashi
Department of Civil and Environmental Engineering
The National Defense Academy, Yokosuka, 239-8686, JAPAN
E-mail: hayashik@nda.ac.jp

ABSTRACT: Several studies are available on resistance to flow due to rigid and flexible submerged and unsubmerged vegetation. Much less numbers of investigations are however available on the topic of sediment transport through vegetated channels. A critical review on this topic is presented herein with field examples. An analytically derived expression is presented for estimation of flow velocity through the vegetated channel flows which is validated by using the laboratory data. A procedure is also outlined for determination of the tractive force or effective shear stress by the flow responsible for sediment transport in vegetated channel flows. Thus derived effective shear stress values are noticed to be strongly correlated with the sediment transport rates observed in a vegetated laboratory channel flow. The topics for future investigations on the subject of vegetated channel flows are also outlined.

INTRODUCTION

Role of riparian vegetation is very important from viewpoint of prevention of floods, ecological and environmental disasters. The environmental management of rivers requires understanding of the interaction between flow, vegetation and sediment. Vegetation that grows in the stream bed and floodplains increases resistance to flow and thus plays an important role to the fate of sediments, acting as a trap as well as reducing the stream's sediment carrying capacity. Recently the topic on influence of vegetation on water, sediments, nutrients and pollutants transport both in the streams and on the flood plains has attracted the attention of several researchers (Jordanova and James, 2003). Vegetation also plays an important role in ecological functions of the river systems (Järvelä, 2002, 2006). Many efforts are therefore being taken up presently world wide for river restoration, re-naturalization and rehabilitation of the watersheds and water courses (Shields *et al.*, 2003). Growing of the vegetation is the foremost step for achieving the objective of river system restoration (Musleh and Cruise, 2006).

It is well known that the knowledge on resistance to the flow by vegetation and sediment transport flows helps in designing effective measures for reducing the shear force applied to bed surface soil particles for control of the soil erosion. Concrete units and stones are commonly used for slope protection of banks of rivers, lakes and coasts. These conventional materials work well to protect the erosion of bank surface caused by currents and waves. But they do not provide environmentally good aesthetics and can cause large scale reflection of waves causing difficulties in sailing of the ships. A good alternative material for solving wave reflection problem and protecting the erosions of coasts and banks is by growing plant like reeds. The aboveground biomass of reed, stalk, has the possibility to decrease the kinetic energy of waves and currents,

[1]Conference speaker

while the underground biomass of it, roots and rhizomes, keep together the soil particles (Bouter, 1991). Figure 1 illustrates the way by which kinetic energy of flow is reduced by the underlying vegetation which helps in reducing sediment and nutrient transport. In the vegetated flows a significant portion of the total fluid force acts on the vegetation and the remaining portion acts on the bed surface. The fluid force acting on bed surface is responsible for detachment and transport of the bed material particles and hence sediment transport. Evaluation of the fluid force acting on vegetation is thus useful in studies related to sediment transport through vegetative surfaces (Li and Shen, 1973).

In this paper a critical review is presented about effects of vegetation on flow resistance and sediment transport in streams. Based on the analysis of data on flow velocity and sediment transport of flows through vegetated open channels presented here, it is revealed that present understanding about mechanism of flow-vegetation-sediment interaction is not adequate.

CRITICAL REVIEW

Little or no information is possibly available presently on influence of submerged and partially submerged flexible stem vegetation (such as shrubs, small trees etc.) on resistance to flow and hence soil erosion and sediment transport. Due to flexibility the vegetation orients itself as per the flood flow (Figure 2) by bending itself in the flow direction.

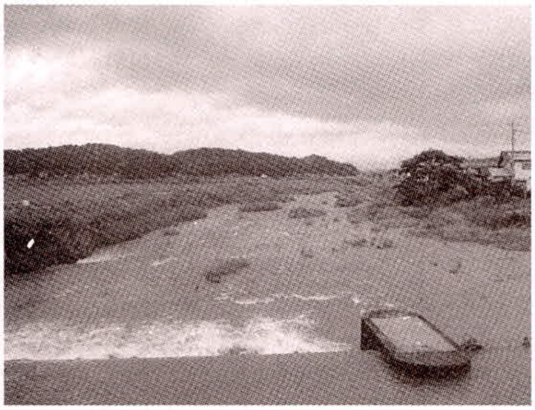

Fig. 1: Retardation of the flow kinetic energy by the submerged vegetation

Adequate studies are also not available on the variation of flow resistance due to group of homogeneous flexible stem plants and mixed flexible stem plants. Effect of variation in plant densities and sizes and stream bed sediment characteristics on the flow resistance needs also be studied. The process of channel scour, deposition and grain sorting under these scenarios also should be modeled be modeled as these scenarios are often encountered in the real life situations (Figure 3).

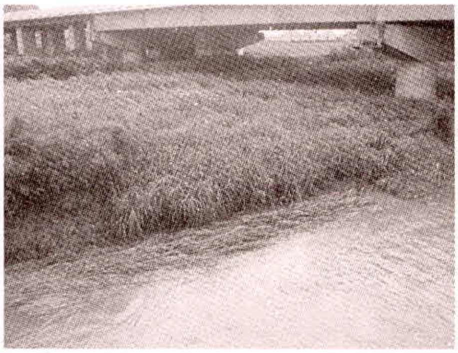

Fig. 2: Bending of vegetation by the flood flow

Fig. 3: Flow of river Sandai, Kagoshima, Japan during flood of 2006

Mathematical models are yet to be developed for estimating the value of roughness coefficient for flow computations in terms of easily measurable characteristics of plants, flow and sediment such as plant stiffness, density, relative height, channel slope, sediment size and gradation so as to simulate the effects of flood flows through the vegetation in the channel beds (Figure 4).

Fig. 4: Deposition of sediment in vegetated channel bed due to receding of the flood flow during 2006 in river Sandai, Kagoshima, Japan

RESISTANCE TO FLOW IN VEGETATED STREAMS

In the studies on modeling of soil-erosion and rainfall-runoff processes, an important consideration that determines velocity, depth and shear stress due to flow in overland flow region, flood plains and channel bed is the effect or influence on resistance to flow by submerged and un-submerged vegetation. The process of runoff generation and soil erosion are greatly affected due to changes in resistance to flow by vegetation in overland flow region, flood plains and channels. However, the resistance to flow is conventionally represented in mathematical models by parameters such as a fixed value of Manning's roughness coefficient (Kothyari *et al.,* 1997). It has been well demonstrated that temporal and spatial patterns of flow accumulation in overland flow areas and the outflow hydrograph from a catchment are extremely sensitive to the variation in Manning's roughness coefficient caused by interaction of vegetation and flow.

Several investigators have studied the effect of flow depth, solid stem vegetation (their density and height), channel slope and degree of submergence on roughness coefficient (Tsihrintzis, 2001, Wu *et al.,* 1999). Thus effect of solid stem plants (trees) on flow resistance and sediment transport is thus relatively well understood.

Several research investigations have also been made in the recent past on influence of vegetation on flow resistance. The effect of submerged and un-submerged rigid and flexible vegetation on flow resistance has been studied amongst others by Kouwen *et al.* (1969), Li and Shen (1973), Kouwen and Unni (1973), Petryk and Bosmajian, (1975), Fathi-Moghadam and Kouwen, (1997), Wu *et al.* (1999), Kouwen and Fathi-Moghadam, (2000), Stephan and Gutknecht, (2002), Stone and Shen, (2002), Carollo *et al.,* (2002), James *et al.* (2004), Järvelä, (2002, 2004, 2005) and others. An updated and detailed review on the topic is available in Baptist (2005) and Järvelä *et al.* (2006). It has been generally assumed that the particle resistance in vegetated flows is negligibly small (Stone and Shen, 2002) and the flow resistance in vegetated flows has been considered in most of the above studies to mainly consist of the vegetation resistance and hence stem or vegetation drag.

The vegetation drag coefficient has been used as the fitting parameter in most of the studies carried out so far on resistance to flows in vegetated flows. However the occurrence of sediment transport by flows through densely vegetated surfaces has been reported in literature (Tsujimoto, 1999, Specht, 2002, Baptist, 2003, Jordanova and James, 2003, Baptist, 2005) signifying that particles resistance (grain resistance or effective resistance) in vegetated flows is not negligible. Therefore a realistic estimation of resistance to flow through vegetated channels must involve the partitioning of the total resistance to flow into vegetation resistance and the particle resistance. The determination of drag due to vegetation and thus the vegetation resistance in open channel flows therefore should be the main objective of the future research work on this topic. The particle or grain drag, also called effective stress which is responsible for sediment transport is simply the difference between total drag by the flow and the vegetation drag. The laboratory based experimental studies therefore can be carried out for estimation of the fluid forces and hence drag on the simulated vegetation. The fluid forces on both stiff and flexible vegetation that is submerged or unsubmerged can be quantified through laboratory experimentation (Thompson *et al.,* 2003, 2004, Armanini *et al.,* 2005).

VELOCITY OF VEGETATED FLOWS

Consider a steady, uniform, open channel flow with submerged or unsubmerged cylindrical stems of equal length distributed uniformly over the channel bed. For a control volume of unit bed area extending from the bed to the water surface, the momentum balance in the streamwise direction would produce (Stone and Shen, 2002),

$$\tau_t = \rho g h S(1-\lambda h^*) \qquad \ldots (1)$$

where τ_t is the total shear stress due to the flow, ρ is mass density of fluid, g is acceleration due to gravity, λ is area concentration of stems, h is flow depth, S is energy slope, $h^* = l/h$, with l being the vegetation heightfor unsubmerged vegetation $h^* = 1$.

Equation (1) represents the streamwise component of the weight of the water mass. The total resistance to the flow is sum of the vegetal resistance and the grain resistance. The resistance due to the drag around the stems called vegetal resistance, τ_D can be expressed as,

$$\tau_D = \frac{1}{2}\rho C_D N d l V_c^2 \qquad \ldots (2)$$

where C_D is the coefficient of stem drag, N is number of stems per unit plan area of bed and thus $\lambda = N\pi d^2/4$ with d being the stem diameter, V_c is the actual ensemble velocity of the flow. As per Manning's equation the grain resistance τ_b can be expressed as,

$$\tau_b = \rho g n_b^2 R_b^{2/3} V_c^2 \qquad \ldots (3)$$

where n_b is the Manning's roughness coefficient which is mostly estimated for the study of sediment transport by the Manning-Strickler relation namely,

$$n_b = \frac{d_{50}^{1/6}}{24.6} \quad \dots (4)$$

where d_{50} is the median size of the bed material in m. In Eq. (3) R_b is the hydraulic radius with respect to the bed roughness which must be computed by taking care of λ. As explained earlier,

$$\tau_t = \tau_D + \tau_b \quad \dots (5)$$

Making use of Eqs. (1) to (5) and following Stone and Shen (2002) we can write,

$$V_c = \sqrt{\frac{g(1-\lambda h^*)}{gn_b^2 R_b^{-1/3} + \frac{2C_D \lambda l}{\pi d}}}\sqrt{hS} \quad \dots (6)$$

Defining the apparent velocity of the vegetated flow V_l such that V_l =flow discharge/gross sectional area of the flow, the Eq.(6) is expanded into the following relation for V_l,

$$V_l = \left(1 - \sqrt{\frac{4\lambda}{\pi}}\right)\sqrt{\frac{g(1-\lambda h^*)}{gn_b^2 R_b^{-1/3} + \frac{2C_D \lambda l}{\pi d}}}\sqrt{hS} \quad \dots (7)$$

Using C_D = 1.05 (Hashimoto and Park, 2003) and computing n_b using Manning-Strickler relation (Eq. 4), the values of V_l were computed using Eq. (7) for the experimental data of Hashimoto and Park (2003). Equation (7) produced reasonably good estimates of the apparent flow velocities through the vegetated channel beds for most of the data of Hashimoto and Park (2003) as can be seen in Figure 5, where, F_r represents the Froude number for the flow. Figure 5 thus indicates that Eq. (7) can be applicable to mildly sloping as well as steeply sloping vegetated channel flows.

It is however to be mentioned that one needs to determine the value of C_D for computing the apparent average velocity of flow through vegetated channels using the relationship of the type expressed by Eq. (7). The C_D value for the cylindrical stems placed in a group is largely different from the C_D value of an isolated cylindrical stem (Stone and Shen, 2002). Sufficient information is however not available presently on this topic. Therefore further studies are being made currently by the authors on variation of the C_D values of cylindrical stems placed with different patterns in groups.

SEDIMENT TRANSPORT BY VEGETATED FLOWS

Studies relating to the interaction of vegetation and sediment transport are only a few. Tollner *et al.* (1982) determined through laboratory experiments steady-state transport capacities for vegetal filters. The vegetal filter consisted of metal rods mounted in a regular and staggered pattern. Only emergent situations were investigated. From a "spacing hydraulic radius" bed shear was predicted and used in the Einstein and Graf sediment transport equation

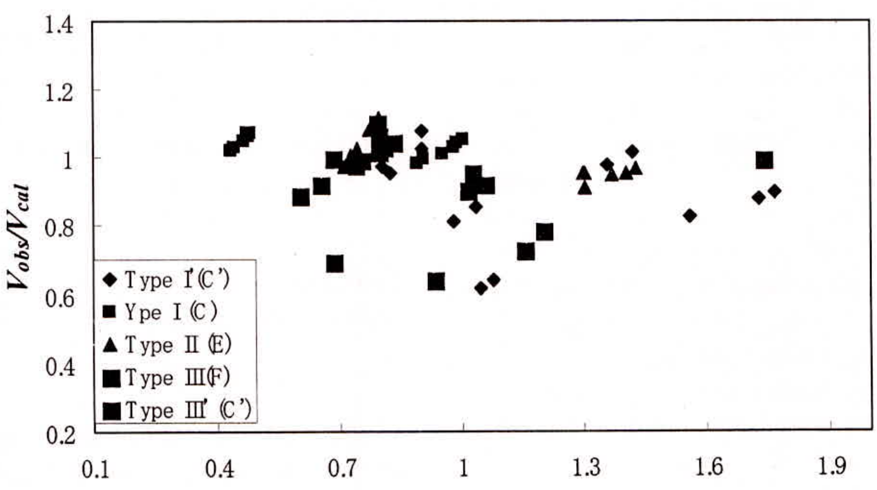

Fig. 5: Comparison of observed and computed values of apparent flow velocity through vegetated channel bed for the data of Hashimoto and Park (2003)

which was calibrated with results from the vegetative filter. Tollner *et al.*, also derived a prediction equation for sediment transport by natural grass. Nakagawa *et al.* (1992) investigated sediment transport in a vegetated channel for submerged conditions through laboratory experiments. Experimental results from flume experiments were compared to results from a numerical analysis based on a turbulence model. Nakagawa *et al.* conducted experiments with rigid bars of different diameters, placed in a systematic pattern. Velocity distribution, turbulence intensity and Reynolds stresses were observed. The suspended sediment concentration distribution was studied and related to the corresponding hydraulic parameters.

Okabe *et al.* (1997) studied the bed-load transport rate on moveable beds covered with vegetation. Two different kinds of artificial, flexible plant models were used in laboratory experiments. Velocity profiles for different discharges were measured. The measured sediment transport rates were compared with the transport rates from bed-load transport formula of Ashida-Michiue. The study of Okabe *et al.*, deals with comparably thin sand beds and short submerged vegetation.

James *et al.* (2001) conducted experiments on bed-load transport through an emerged reed bed. The fixed rigid rods were used for simulating the vegetation. The sedimentation processes and resulting bed slopes were investigated. A further study of James *et al.* (2002) presented similar experiments with steel rods as vegetation and continuous sediment feeding of quartz sand. The experiments were conducted in two scenarios. In first scenario the sediment feeding rates were varied by keeping the flow discharge as constant, while in the second scenario flow discharge was varied and the feeding rate of sediment was kept constant. An evaluation of the equilibrium transport conditions showed increasing bed slopes with increasing bed load transport rates. The sediment transport rate increased with the discharge only up to a certain limit. The transport mostly occurred in the form of bed load.

More recently Hashimoto and Park (2003) made two kinds of experiments for study of sediment transport by vegetated flows. In one, the sediment transport rates within the model tree areas were examined and in the other effect of the model tress on sediment runoff and deposition were examined. In the later experiments cylinders representing vegetation were installed in multiple rows on the downstream part of the whole channel bed. In case of larger density of cylinder arrangement, sediment deposition occurred in the upstream reach of the model tree area, while, in the case of smaller density, sediment deposition occurred in the downstream reach of the model tree area. The sediment runoff from the model tree area decreased as the bed coverage of the model trees increased.

In the former experiments the sediment transport was measured on the whole channel bed with the multiple rows of cylinders representing vegetation installed uniformly on the channel bed. The sediment transport rates were found to be strongly related to the effective shear stress (grain shear stress). The grain or effective shear stress computed by Eq. (3) is plotted with the sediment transport rates observed by Hashimoto and Park (2003) in Figure 6. A strong relationship between the sediment transport rate and thus computed τ_b is indeed noticed in Figure 6.

In Figure 6 τ_{b*} is the non-dimensional effective (grain) shear stress and $Qs*$ is the non-dimensional sediment transport rate. These variables were defined as,

$$\tau_{b*} = \frac{\tau_b}{\Delta\gamma_s d} \quad \ldots (8)$$

$$\text{with } \Delta\gamma_s = \gamma_s - \gamma_f \quad \ldots (9)$$

$$\text{and } Q_{s*} = \frac{Q_s}{sgd^3} \quad \ldots (10)$$

In above d is the grain size, γ_s and γ_f denote the specific weight of sediment and fluid respectively and Q_s is the sediment transport rate. There is still a lack of knowledge first on determination of the grain shear stress in vegetated flows and secondly on sediment transport in submerged, flexible vegetation in combination. More efforts are therefore suggested for the study of the described situations.

FURTHER RESEARCH NEEDS ON VEGETATED FLOWS

The biomechanical characteristics of the vegetation too have a significant influence on resistance to flow and the same has not been studied as yet. The vegetation is not able to regain its original shape after the receding of the flood in case the bending caused by the flow had exceeded the critical stage of bending. The characteristics of critical stages of the vegetation bending being function of bio-engineering characteristics of the plants has also not been investigated so far. The deformation of plant shape and deflection of its stem and leaves by the flow would significantly alter the resistance to flow in a different way. Whereas there are a number of studies available on effect of the role of

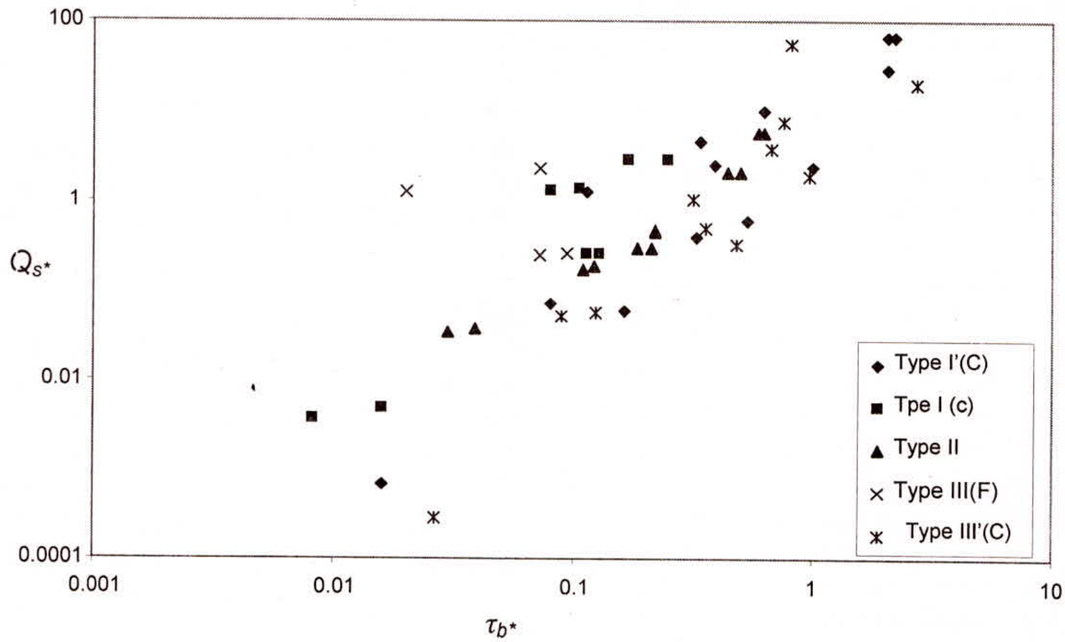

Fig. 6: Relationship between non dimensional sediment transport rate and non dimensional grain shear stress for the data of Hashimoto and Park (2003)

flexible stem riparian plants in the variation of flow resistance, their effect on soil erosion and sediment transport as well as sediment grain sorting in overland flow areas, flood plains and channel beds is yet to be investigated.

CONCLUSIONS

A critical review is presented herein on effects of vegetation on flow resistance and sediment transport in streams. It is revealed that present understanding about mechanism of flow-vegetation-sediment interaction is still not sufficient to establish the theory for sediment transport through vegetated channel or floodplains. Whereas the resistance to flow due to flexible and solid stems is well investigated, studies with regard to effects of bio-engineering characteristics of the plants on flow resistance are not yet made. The studies made so far on sediment transport by vegetated flows are only a few. An attempt is made in the present study to analytically derive the expressions are presented herein for flow velocity and sediment transport of the vegetated channel flows. Laboratory data were used for validation of the derived relationships which suggested the need for more investigations. The topics of interest for future research are therefore outlined.

ACKNOWLEDGEMENTS

The first author worked at the Kyushu University Fukuoka, Japan for this research as invited fellow of the Japan Society for Promotion of Science (JSPS). Support received from the JSPS by him is sincerely acknowledged.

REFERENCES

Armanini, A., Righetti, M. and Grisenti P. (2005). "Direct measurement of vegetation resistance in prototype scale". *Journal of Hydr. Res.*, IAHR. 43(5), 481–487.

Baptist, M.J. (2003). "A flume experiment on sediment transport with flexible, submerged vegetation". *Proc. Int. workshop on riparian forest vegetated channels: hydraulic, morphological and ecological aspects*. Trento, Italy.

Baptist, M.J. (2005). "Modelling floodplain biogeomorphology". *PhD Thesis*, Dept. of Civil Engineering, Technical University of Delft, Delft, The Netherlands.

Bouter, E.E. (1991). "Wave damping by reed - an investigation in environmentally friendly bank protection". *P.I.A.N.C. – A.I.P.C.N., Bulletin* 1991, No 75, 56–63 (in Japanese).

Carollo, F. G., Ferro, V. and Termini, D. (2002). "Flow velocity measurements in vegetated channels". *J. of Hydr. Engrg.*, ASCE. 128(7), 664–673.

Fathi-Moghadam, M. and Kouwen, N. (1997). "Nonrigid, nonsubmerged, vegetative roughness on floodplains". *J. Hydr. Engrg.*, ASCE. 123(1): 51–57.

Hashimoto, H. and Park K. (2003). "Sediment transport and deposition in steep open channels with multiple rows of cylinders". *Prpc. Int. Conf. on Debris Flow Hazards - Mitigation, Mechanics, Prediction and Assessment*, Millpress, Rotterdam, 1291–1301.

James, C.S., Birkhead, A.L., Jordanova, A.A., Kotschy, K.A., Nicolson, C.R. and Makoa, M.J. (2001). "Interaction of reeds, hydraulics and river morphology". *Water Research Commission Report*, No. 856/1/01, 371 pp.

James, C.S., Jordanova, A.A. and Nicolson, C.R. (2002). "Flume experiments and modelling of flow-sediment-vegetation interactions", *Proc. IAHS International Symposium on the Structure, Function and Management Implications of Fluvial Sedimentary Systems*. Sept., Alice Springs, Australia.

James, C.S., Birkhead, A.L., Jordanova, A.A. and O'Sullivan, J.J. (2004). "Flow resistance of emergent vegetation". *J. of Hydr. Res.*, IAHR. 42(4), 390–398.

Järvelä, J. (2002). "Flow resistance of flexible and stiff vegetation: a flume study with natural plants". *J. of Hydrol,* 269(1–2): 44–54.

Järvelä, J. (2004). "Determination of flow resistance caused by non-submerged woody vegetation". *Int. J. of River Basin Management,* IAHR. 2(1): 61–70.

Järvelä, J. (2005). "Effect of flow submerged flexible vegetation on flow structure and resistance". *J. of Hydrol.* 307(1–4): 233–241.

Järvelä, J., Aberle, J., Dittrich, A., Rauch, H.P. and Schnauder, I. (2006). Flow-vegetation-sediment interaction. *River Flow 2006*, Taylor and Francis group, London, 2017–2026.

Jordanova, A.A. and James, C.S. (2003). "Experimental study of bed load transport through emergent vegetation". *J. Hydr. Engrg.,* ASCE. 129(6): 474–478.

Kothyari, U.C., Tiwari, A.K. and Ranvir, Singh, (1997). "Estimation of temporal variation of sediment yield from small catchments through the kinematic method". *J. of Hydrol.* 203, 39–57.

Kouwen, N., Unny, T.E. and Hill, H.M. (1969). "Flow retardance in vegetated channels", *J. of the Irrig. and Drainage Div.*, ASCE. 95(IR2), 329–342.

Kouwen, N. and Unny, T.E. (1973). "Flexible roughness in open channels", *J. of the Hydr. Div.*, ASCE. 99(HY5), 713–728.

Kouwen, N. and Fathi-Moghadam, M. (2000). "Friction factors for coniferous trees along rivers". *J. Hydr. Engrg.,* ASCE, 126(10), 732–740.

Li, R.M. and Shen, H.W. (1973). "Effect of tall vegetations on flow and sediment". *J. of the Hydr. Div.*, ASCE, 99(HY6), 1085–1103.

Musleh, F.A. and Cruise, J.F. (2006). "Functional relationships of resistance in wide flood plains with rigid unsubmerged vegetation". *J. of Hydr. Engrg.*, ASCE, 132(2), 163–171.

Okabe, T., Yuuki, T. and Kojima, M. (1997). "Bed-load rate on movable beds covered by vegetation". *Proc. 27th IAHR- Congress*. San-Francisco.

Nakagawa, H., Tsujimoto, T. and Shimizu, Y. (1992). "Sediment transport in vegetated bed channel". *Proc. 5th Int. Symp. on River Sedimentation*. Karlsruhe.

Petryck, S. and Bosmajian III, G. (1975). "Analysis of flow through vegetation". *J. of the Hydr. Div.*, ASCE.101(HY7), 871–884.

Shields, F.D. Jr., Copeland, R.R., Klingeman, P.C., Doyle, M.W and Simon, A. (2003). "Design for stream restoration", *J. of Hydr. Engrg.*, ASCE. 129(8), 575–584.

Specht, F.-J. (2002). "Einflusch von Gerinnebreite und Uferbewuchs auf die hydraulisch sedimentologischen". *Verh¨altnisse naturnaher Flieschgew¨asser.* PhD thesis, Technische Universit¨at Braunschweig, Germany.

Stephan, U. and Gutknecht, D. (2002). "Hydraulic resistance of submerged flexible vegetation". *J. of Hydrol*, 269(1–2), 27–43.

Stone, B.M. and Shen, H.T. (2002). "Hydraulic resistance of flow in channels with cylindrical roughness". J. of Hydr. Engrg., ASCE. 128(5), 500–506.

Thompson, A.M., Wilson, B.N. and Hustrulid, T. (2003). "Instrumentation to measure drag on idealized vegetal elements in overland flow". *Transactions of the ASAE*, 46(2), 295–302.

Thompson, A.M., Wilson, B.N. and Hansen, B.J. (2004). "Shear stress partitioning for idealized vegetated surfaces". *Transactions of the ASAE*, 47(3), 701–709.

Tollner, E.W., Barfield, B.J. and Hayes, J.C. (1982). "Sedimentology of erect vegetal Filters". *J. of the Hydr. Div.*, ASCE. 108(HY12), 1518–1531.

Tsujimoto, T. (1999). "Fluvial processes in streams with vegetation". *J. Hydr. Res.* IAHR, 37(6): 789–803.

Tsihrintzis, V.A. (2001). "Discussion on 'variation of roughness coefficient for un-submerged and submerged vegetation". *J. of Hydr. Engrg.,* ASCE, 127(3), 241–942.

Wu, F.C., Shen H.W. and Chou Y.J. (1999). "Variation of roughness coefficient for un-submerged and submerged vegetation". *J. of Hydr. Engrg.*, ASCE, 125(9), 934–942.