Chapter 21
Calibrating Coefficients of Emerged Vegetative Open Channel Flow

Priya Shejule, Jnana Ranjan Khuntia, and Kishanjit Kumar Khatua

Abstract Vegetation is a crucial element of the river system. In open channel hydraulics, vegetation has a significant effect on flow structure; it offers resistance to the flow and responsible for flood level increase by reducing the carrying capacity of the flood. Researchers throughout the globe have analyzed the resistance provided by vegetation with a theoretical and experimental study. Many flow and channel parameters affect the flow resistance. Out of all these parameters, vegetation is an influential one in vegetative channels. It alters the velocity profiles in an open channel, which affects the roughness coefficients. The roughness coefficients in vegetative channels vary with the flow depths and sections. Therefore, due to the complex structure, it is tedious to come up with a flow model based on previous research. Though it is challenging to determine directly from a field exercise, a laboratory study has been carried out in emergent vegetation at Hydraulics Engineering Laboratory, NITR, to explore the vegetation influence. The Shiono Knight Method (SKM) has been applied to calculate the boundary shear stress and depth-averaged velocity distribution in an open channel flow. For this purpose, three calibrating coefficients, namely bed friction (f), dimensionless eddy viscosity (λ), and transverse gradient for secondary flow (Γ), have been incorporated to modify the existing SKM. A mathematical model was formulated to find the calibrating coefficients in the channel and compared with the SKM.

Keywords Open channel flow · Emergent vegetation · Drag coefficient · Bed friction · Eddy viscosity · Secondary flow coefficient · Depth-averaged velocity · SKM

P. Shejule (✉)
Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam 781039, India

J. R. Khuntia
Department of Civil Engineering, St. Martin's Engineering College, Dhulapally, Secunderabad, Telangana 500100, India

P. Shejule · J. R. Khuntia · K. K. Khatua
Department of Civil Engineering, National Institute of Technology, Rourkela, Odisha 769008, India

R. Jha et al. (eds.), *River Hydraulics*, Water Science and Technology Library 110,
https://doi.org/10.1007/978-3-030-81768-8_21

21.1 Introduction

Vegetation offers additional drag forces and hinders the flow capacity of an open channel. Vegetation leads to complex flow structure. It affects the velocity, enlarges the local water level, reduces the flood discharge, and controls the fate of sediments. Vegetation is an essential factor in determining roughness because it affects the flow in a channel. Energy dissipation occurs in a channel due to three factors: (1) bed friction (2) turbulent exchange at the interface responsible for the momentum transfer (3) momentum transfer as a result of mass exchange through subsections (Proust et al. 2009). The most observed influence of vegetation is that it increases the resistance offered to flow and reduces the channel conveyance (Kouwen 1992; Wu et al.1999). Other vegetation characteristics like vegetation species, density, distribution, flexibility, and the submergence degree of vegetation, affect the channel capacity (Abood et al. 2006). The present study is carried out on a straight simple vegetated rectangular channel. Vegetation in wetlands and open channel strongly influences the flow hindrance, (mean) velocity; mass and turbulence exchange (Ghisalberti and Nepf 2005). Flow resistance coefficient mainly depends on flow depth and discharge proven by Jarvela (2002), who carried out a laboratory study.

For a water resources Engineer, wild growth of vegetation is an inconvenience as it reduces the conveyance of a channel. However, vegetation removal is an expensive process, and it affects the ecological integrity of the river system (Karr 1991).

Vegetation in waterways is classified as follows:

I. Vegetation naturally occurring on beds and banks of the river.
II. Artificially planted vegetation.

Velocity in the cross-section varies from section to section due to water surface effects. The velocity distribution in an open channel is three-dimensional and complicated, and it makes the flow modeling difficult (Maghrebi and Givehchi 2009). The hydraulic behavior of flexible submerged vegetation is different from emergent vegetation. Polyethylene plastic strips are used to simulate vegetation (Kouwen et al. 1969). Velocity distribution is considerably impacted by vegetation. When vegetation is introduced in a flowing channel, the vegetation roughness affects the shape of velocity profiles in a stream-wise and vertical direction (Sarma et al. 1983). Khuntia et al. (2016) and Shi et al. (2013) studied the rough bed and vegetation density effect on Manning's coefficient respectively.

Dimensionless geometric and hydraulic factors affects the vegetal drag coefficient (Panigrahi and Khatua 2015). The vertical velocity profile was studied for different discharges and different vegetation densities. Understanding the flow resistance and conveyance capacity is required to determine the stage-discharge characteristics of a reservoir. The Shiono and Knight Method (SKM) (1990) is applied in a two-dimensional approach. This method is obtained after the depth-averaging of the Navier–Stokes equation. Here, the momentum equation is simplified. It is used to derive the depth-averaged velocity and distribution of boundary shear stress. For applying SKM, one has to calibrate factors like (f) representing bed shear, (Γ) representing secondary flow, and (λ) denoting the lateral shear. Liu et al. (2013) proved that the prediction of flow velocity and Bed Shear Stress (BSS) are significantly affected by secondary flow, and their ignorance gives inaccurate results. BSS distribution in a channel alters sediment transportation (Yu and Smart 2003).

In the present study, an experiment is performed in a rectangular flume with a rough bed situation at National Institute of Technology, Rourkela, Laboratory.

21.2 Theoretical Background

The SKM helps in finding depth-averaged velocity. This method uses the RANS model, i.e., two-dimensional Reynold's Averaged Navier–Stokes equation. The momentum equation is simplified and blended with the continuity equation to get the lateral variation in mean velocity and boundary shear stress. A secondary flow term is introduced in this method, which helps get accurate velocity and BSS results.

For uniform flow, the stream-wise momentum equation is

$$\frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho g S = \rho\left(U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z}\right) \tag{21.1}$$

where x, y, z are the stream-wise, lateral, and vertical directions, respectively. τyx and τzx are the Reynolds stress on the planes perpendicular to y and z, respectively; ρ is the flow density; g is the acceleration due to gravity; S is the valley slope; U, V, W are the velocity components along the stream-wise, lateral, and vertical directions. Equation (21.1) referred from Liu et al. (2014).

Shiono and Knight (1988) derived the depth-mean-averaged equation by taking the integration of Eq. (21.1) over depth H as follows:

$$\frac{\partial}{\partial y}\left\{H(\rho U V)_d\right\} = \rho g H S_0 + \frac{\partial H \tau_{yx}}{\partial y} - \tau_b\sqrt{\left(1 + \frac{1}{s^2}\right)} \tag{21.2}$$

The depth-averaged transverse shear stress (τ_{yx}) is formulated in the form of a lateral gradient of depth mean velocity as follows:

$$\tau_{yx} = \rho \varepsilon_{yx}\frac{\partial U_d}{\partial y} \tag{21.3}$$

where ε_{yx} is the depth-averaged eddy viscosity. The eddy viscosity has a dimension of $\mathrm{m}^2\ \mathrm{s}^{-1}$. It corresponds to local shear velocity U^* and depth H, by the dimensionless eddy viscosity coefficient, λ, and expressed as

$$\varepsilon_{yx} = \lambda H U^* \tag{21.4}$$

But, the local shear velocity $U^* = \sqrt{\frac{\tau_b}{\rho}}$ is influenced by the free shear-layer-turbulence and the secondary flows. The Darcy–Weisbach friction factor $f = \frac{8\tau_b}{\rho U_d^2}$ is linked to U^* and $U_{d,}$ giving

$$U^* = \sqrt{\frac{1}{8}f}U_d \tag{21.5}$$

The depth-averaged eddy viscosity in (21.1) then given as

$$\varepsilon_{yx} = \lambda H\sqrt{\frac{1}{8}f}U_d \tag{21.6}$$

Substituting (21.5) and (21.3) into (21.2), we get the depth-averaged expression for stream-wise Reynold's Averaged Navier–Stokes equation as follows:

$$\rho g H S_0 - \frac{1}{8}\rho f U_d^2\sqrt{\left(1+\frac{1}{s^2}\right)} + \frac{\partial}{\partial y}\left\{\rho\lambda H^2\sqrt{\frac{1}{8}f}U_d\frac{\partial U_d}{\partial y}\right\} = \frac{\partial}{\partial y}\left\{H(\rho U V)_d\right\} \tag{21.7}$$

H = water depth; S_0 is the bed slope; U_d = depth-averaged stream velocity, f is Darcy–Weisbach friction factor; U, V are the velocity components; S represents the side slope of the channel, and λ = dimensionless eddy viscosity, respectively.

The above form is the clear and reduced version of the SKM. The right side term $\frac{\partial}{\partial y}\left\{H(\rho U V)_d\right\}$ indicates secondary current (Γ). On the left side, the first term denotes the gravity term in uniform flow, the second term represents Reynold's shear stress, and the last term arises due to the bed shear.

Secondary current (Γ) relies on two factors:

1. The average boundary shear stress represented as (τ_{avg}) and
2, Average boundary shear stress per unit length of the (compound) channel denoted as ($\rho g H S_0$).

The reason is that the secondary current flows significantly affect boundary shear stress distribution and the depth average velocity. k is a factor expressed as the ratio of average boundary shear stress per unit length and average boundary shear stress per unit length of the compound channel. In the case of variable depth, flow depth is taken as average depth all through the domain. So here,k is given by

$$k = \frac{\tau_{avg}}{\rho g H S_0} \tag{21.8}$$

$\mathit{\Gamma}$ changes along with the flow depth; therefore, k is represented as a function of dimensionless hydraulic and geometric parameters. In above equation $\rho g H S_0$ is called as secondary flow factor. Devi and Khatua (2016) gave a simplified formula for τ as follows:

$$\Gamma = \rho g H S_0 (1 - k) \tag{21.9}$$

It is observed that the above equation depends on *(f)* representing bed shear, *($\mathit{\Gamma}$)* representing secondary flow, and *(λ)* representing the lateral shear.

21.3 Model Parameters

For applying the SKM approach, it is necessary to calculate three critical factors such as bed friction (f), non-dimensional eddy viscosity (λ), and transverse gradient for secondary flow ($\mathit{\Gamma}$).

Depth-averaged velocity and boundary shear stress are obtained by experimenting in a laboratory using ADV. The Darcy–Weisbach friction factor is then back computed from the obtained experiment (Tang and Knight 2009).

$$f = \frac{8gn^2}{R^{0.33}} \tag{21.10}$$

where f is the Darcy–Weisbach friction factor, n is the manning's roughness coefficient, g represents acceleration due to gravity, and$R$ represents hydraulic radius.

Dimensionless eddy viscosity is a constant and given by expression as follows:

$$\varepsilon_{yx} = \lambda H U* \tag{21.11}$$

where ε_{yx} is the depth-averaged eddy viscosity; H represents flow depth; U^* denotes shear velocity; and λ represents dimensionless eddy viscosity.

Secondary flow term (Γ)

Secondary flow arises because of velocity fluctuations in a turbulent flow. Shiono and Knight (1988) experimented and commented that depth-averaged velocity fluctuates linearly in the lateral direction. Factor k depends on the geometric and hydraulic parameter given by Eq. (21.8). Thus, secondary flow Γ can be expressed by Eq. (21.9) as

$$\tau = \rho g H S_0 (1 - k)$$

21.4 Experimental Setup

The experiment is conducted in a rectangular flume available at the NIT Rourkela laboratory. Rectangular flume has a length of 12 m; flume width 0.6 m and depth 0.6 m. The rectangular flume has a testing section made up of glass. The walls and bottom of the flume are made of mild steel. The rigid grass is fixed along the channel bed to impart roughness. The longitudinal slope denoted by S_0 was set to 0.0012, i.e., 1.2 cm in 10 m and remained constant all through the experiment. The top view of the experimental channel is given in Fig. 21.1. The cross-section of experimental rectangular channel is shown in Fig. 21.2. Point gauges are fixed to measure the flow depth. The test section is 10 m from upstream, where flow stabilizes and uniform flow is observed. A tailgate is installed downstream to achieve uniform flow conditions (Khuntia et al. 2018, 2019).

For supplying water into the channel, an overhead tank is built upstream of a flume. The volumetric tank is constructed at the flume downstream to measure discharge at different depths (Shejule 2019) (Fig. 21.2).

A SonTek Micro-Acoustic Doppler Velocimeter (ADV) of 16 MHz is used to measure flow fields. 50 Hz is the maximum sampling rate, and data acquisition time

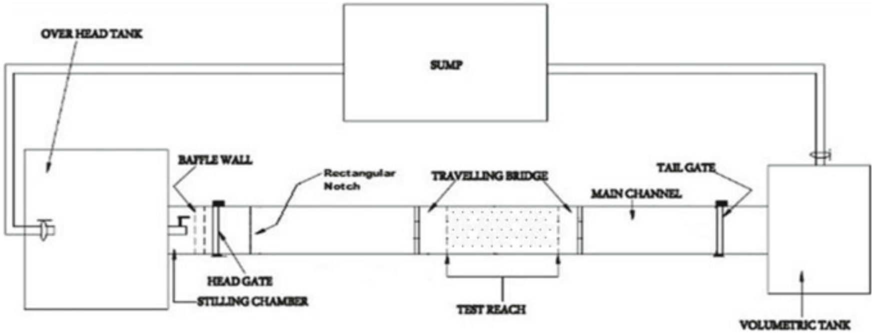

Fig. 21.1 Top view of the experimental flume (channel), hydraulic engineering lab, NIT Rourkela

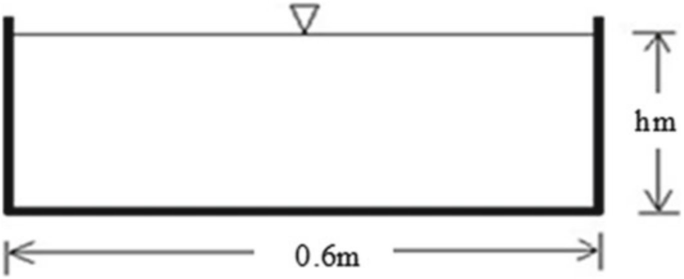

Fig. 21.2 Cross-section of the experimental rectangular channel

Table 21.1 The roughness and geometrical parameters of a channel

Serial no	Description	Parameter
1.1	Channel description	Straight
1.2	Channel section geometry	Rectangular
1.3	base width ‘b’ of channel	0.6 m
1.4	Depth of channel	0.6 m
1.5	Bed slope ‘S_0’	0.0012
1.6	Flume length	12 m
1.7	Test channel length ‘X’	10 m
1.8	Bed surface feature	Rough (Fixed rigid grass)
1.9	Flow condition	Steady flow

is 60 s. ADV sampling volume is placed at a distance of 5 cm below the down probe. 5 cm distance among the probe and sampling volume is considered to minimize flow hindrance. ADV measures the directional velocities U, V, W in x-, y-, z-directions, i.e., along, lateral and vertical to the flume bottom, respectively. Steady flow condition is maintained throughout the experiment. To compute velocities at the boundary along channel periphery, ‘Preston tube’ with outer diameter of 4.77 mm is used. Some important channel attributes are presented in the table below (Table 21.1 and Fig. 21.3).

Fig. 21.3 Photograph of the straight rectangular flume

21.5 Results

The variation of depth-averaged velocity along a lateral-distance of a rectangular straight channel is obtained using Conveyance Estimation System (CES) software. It is based on one-dimensional RANS (Reynold's Averaged Navier–Stokes*)* approach (Figs. 21.4, 21.5, 21.6, and 21.7).

Graphs are plotted to get the variation in calibrating coefficients f, λ, and k against lateral distance (see Figs. 21.8, 21.9, and 21.10).

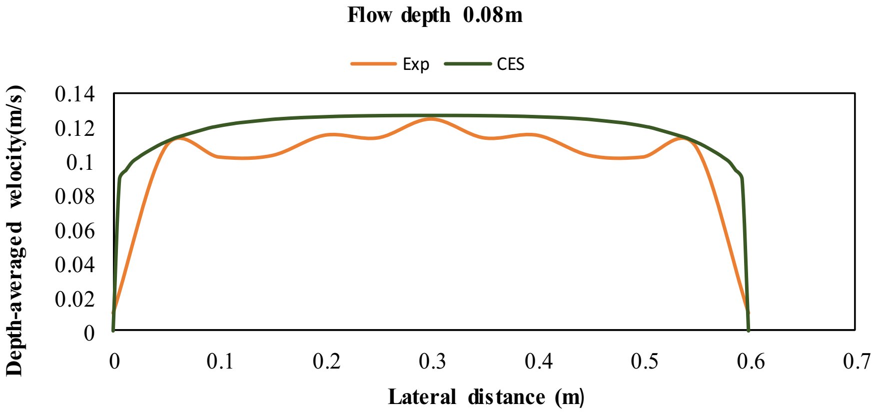

Fig. 21.4 Depth-averaged velocity variation in a rectangular channel for flow depth 0.08 m

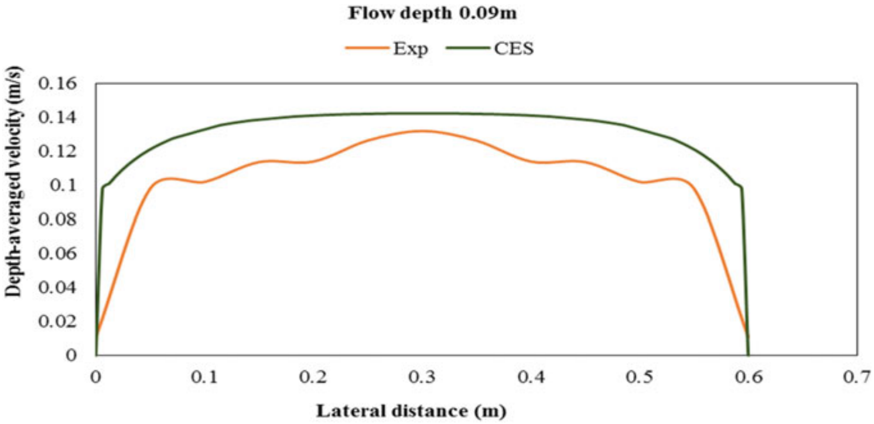

Fig. 21.5 Depth-averaged velocity variation in a rectangular channel for flow depth 0.09 m

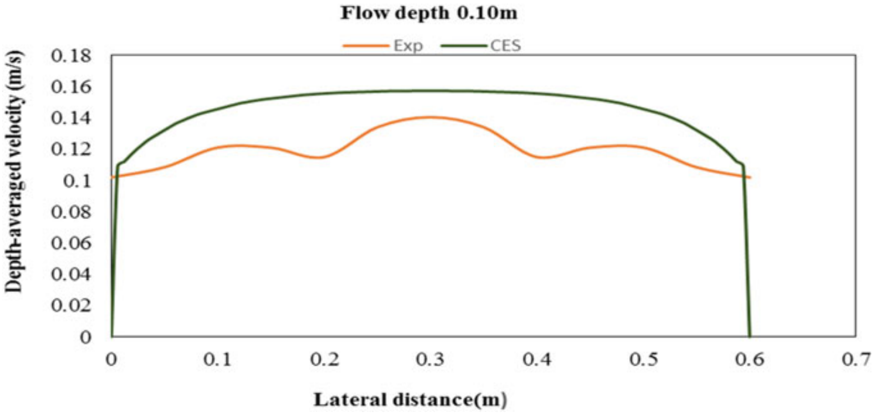

Fig. 21.6 Depth-averaged velocity variation in a rectangular channel for flow depth 0.10 m

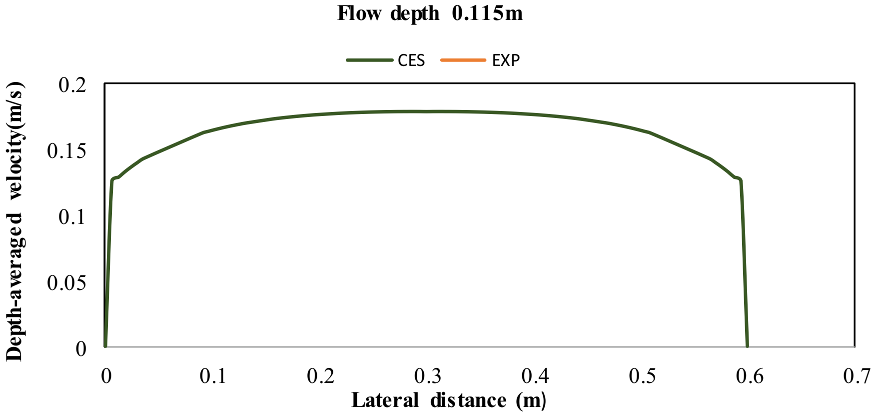

Fig. 21.7 Depth-averaged velocity variation in a rectangular channel for flow depth 0.115 m

21.6 Conclusions

1. Experiment on emergent vegetative open channel flow has been performed to find calibrating coefficients used in the RANS equation. These coefficients are helpful to measure the depth average velocity distribution.
2. The friction factor is found to be of uniform value in a lateral direction of the channel. The friction factor value is higher for low depth of flow and lower for high depth of flow.
3. Secondary flow coefficients show an abrupt change for low flow depth in the lateral direction due to vegetation. For high flow depth, it is observed to be of uniform value.

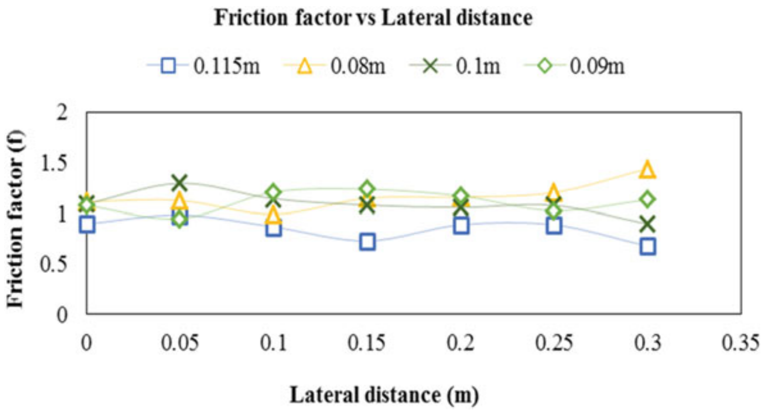

Fig. 21.8 Variation of friction factor against lateral distance

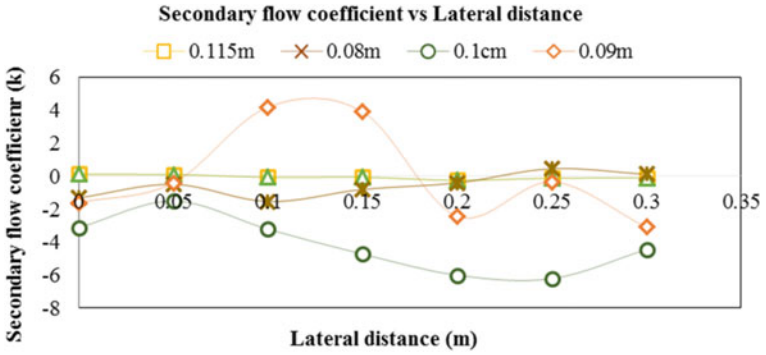

Fig. 21.9 Variation of Secondary flow against lateral distance

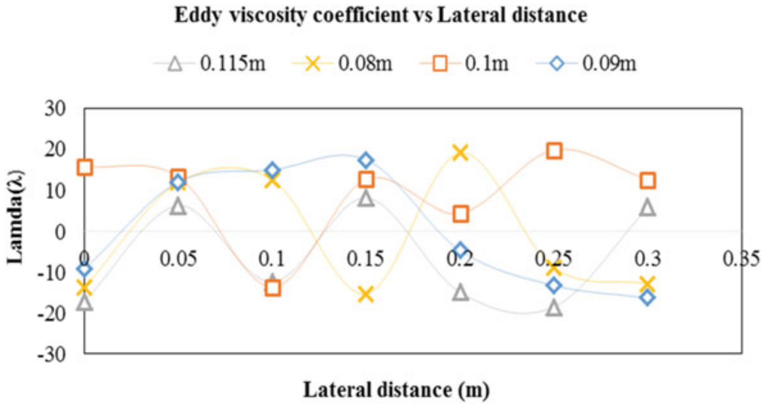

Fig. 21.10 Variation of eddy viscosity against lateral distance

4. Similar to the secondary coefficient, an abrupt change in eddy viscosity is observed for low flow depth.
5. The depth-averaged velocity results obtained using the RANS equation and from the CES software are compared. CES is found to overpredict depth-averaged velocity because of improper accounting of calibrating coefficients. The modeling of calibrating coefficients needs to be done.

References

Abood MM, Yusuf B, Mohammed TA, Ghazali AH (2006) Manning roughness coefficient for grass-lined channel. J Sci Technol 13(4):317–330

Devi K, Khatua KK (2016) Prediction of depth averaged velocity and boundary shear distribution of a compound channel based on the mixing layer theory. Flow Meas Instrum 50:147–157

Ghisalberti M, Nepf H (2005) Mass transport in vegetated shear flows. Environ Fluid Mech 5(6):527–551

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

Karr JR (1991) Biological integrity: a long-neglected aspect of water resource management. Ecol Appl 1(1):66–84

Khuntia JR, Devi K, Khatua KK (2016) Variation of local friction factor in an open channel flow. Indian J Sci Technol 9(46):1–6

Khuntia JR, Devi K, Khatua KK (2018) Prediction of depth-averaged velocity in an open channel flow. Appl Water Sci 8(6):172

Khuntia JR, Devi K, Khatua KK (2019) Turbulence characteristics in a rough open channel under unsteady flow conditions. ISH J Hydraul Eng, 1–12. https://doi.org/10.1080/09715010.2019.1658549

Kouwen N (1992) Modern approach to design of grassed channels. J Irrig Drain Eng 118(5):733–743

Kouwen N, Unny TE, Hill HM (1969) Flow retardance in vegetated channels. J Irrig Drain Div 95(2):329–344

Liu C, Luo X, Liu X, Yang K (2013) Modelling depth-averaged velocity and bed shear stress in compound channels with emergent and submerged vegetation. Adv Water Resour 60:148–159

Liu C, Wright N, Liu X, Yang K (2014) An analytical model for lateral depth-averaged velocity distributions along a meander in curved compound channels. Adv Water Resour 74:26–43

Maghrebi MF, Givehchi M (2009) Estimation of depth-averaged velocity and boundary shear stress in a triangular open channel. J. Water Wastewater 2:71–80

Panigrahi K, Khatua KK (2015) Prediction of velocity distribution in straight channel with rigid vegetation. Aquatic Procedia 4:819–825

Proust S, Bousmar D, Riviere N, Paquier A, Zech Y (2009) Non-uniform flow in compound channel: A 1-D method for assessing water level and discharge distribution. Water Resour Res 45(12)

Sarma KV, Lakshminarayana P, Rao NL (1983) Velocity distribution in smooth rectangular open channels. J Hydraul Eng 109(2):270–289

Shejule PA (2019) Calibrating coefficients of emerged vegetative open channel flow. MTech thesis, National Institute of Technology, Rourkela

Shi JZ, Li YH, Hughes JM, Zhao M (2013) Hydrological characteristics of vegetated river flows: a laboratory flume study. Hydrol Sci J 58(5):1047–1058

Shiono K, Knight DW (1988) Two-dimensional analytical solution for a compound channel. In: Proceedings of 3rd international symposium on refined flow modelling and turbulence measurements, pp 503–510. (July 1988)

Tang X, Knight DW (2009) Analytical models for velocity distributions in open channel flows. J Hydraul Res 47(4):418–428

Wu FC, Shen HW, Chou YJ (1999) Variation of roughness coefficients for unsubmerged and submerged vegetation. J Hydraul Eng 125(9):934–942

Yu G, Smart G (2003) Aspect ratio to maximize sediment transport in rigid bank channels. J Hydraul Eng 129(12):927–935