Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 8 (11): 2118-2123, 2008
ISSN 1812-5654

Effects of Flow and Vegetation States on River Roughness Coefficients

[1]N.G. Ebrahimi, [1]M. Fathi-Moghadam, [1]S.M. Kashefipour, [2]M. Saneie and [3]K. Ebrahimi
[1]School of Water Science Engineering, Shahid Chamran University, Ahvaz, Iran
[2]Soil Conservation and Watershed Management Research Institute,
Ministry of Jehad Keshavarzi, Tehran, Iran
[3]Department of Irrigation and Drainage Engineering, Abureyhan Campus,
University of Tehran, Tehran, Iran

Abstract: Vegetation roughness coefficients are the main parameters used to determine river flow characteristics and are known to depend on the flow condition (depth and velocity) as well as vegetation condition (type and density). Flume experiments were conducted to investigate the variation of roughness coefficients with flow conditions and vegetation density for submerged vegetation in river bed, banks and flood plains. Artificial plastic plants, for a length of 0.2 m, were laid on the floor of a 14 m long and variable slope flume facilitated in the Hydraulics Laboratory of the Soil Conservation and Watershed Management Research Institute, Tehran-Iran for this study. The Manning's n values were estimated for different slopes, discharges, flow depth and vegetation densities. The results reveal that the Manning roughness coefficient (n) increases as vegetation density increases, while it decreases when the flow depth and velocity increase. Significant variation of the Manning's n value with flow and vegetation conditions urges the consideration of the flow and vegetation conditions in estimation of the Manning roughness coefficient (n).

Key words: Vegetated rivers, flexibility, density, Manning's coefficient

INTRODUCTION

Submerged vegetation in river bed and flood plains produce high resistance to flow and have a large impact on water levels in rivers and their upstream lakes, in particular during flood events. For this reason, the estimation of the friction factors is an important aspect of work dealing with conservation of land and hydraulic structures on banks and bay shores and also the calibration and validation of river hydraulic models. In open channel flow the most common friction factors include Darcy-Weisbach friction factor (f) and manning coefficient (n) which can be easily converted to each other through common channel flow equations.

In general, effective factors in estimation of river roughness coefficients include the roughness of channel bed materials, the cross section shape, vegetative type and density, river meandering and obstacles in flow path. Among those, vegetation has significant and dominant effect on estimation of river roughness. For more than a century many empirical and quasi-theoretical equations have been derived for the estimation of rigid and full submerged roughness but little is known about the effect of no rigidity and depth variation in vegetative roughness. For vegetation roughness, the flow resistance equations can be classified in two different categories for flow over short submerged vegetation and flow through tall non-submerged vegetation. Theory of resistance to flow in submerged vegetation is completely different from that in non submerged vegetation. The governing equations for the submerged condition are based on the relative roughness and theory of boundary layer flow above the vegetation, while for non-submerged vegetation, they are based the drag force and flow momentum absorbed by vegetation.

For the submerged vegetation, the quasi-theoretical equations are generally based on the universal Log Law, which limits their implementation to the relative roughness condition, where a well-defined velocity profile extends above the roughness height. This requirement dose not meets the non-submergence condition. In non-submerged vegetation, according to Einstein and Banks (1950), the total resistance due to an array of submerged roughness elements that exhibit primarily profile drag characteristics may be based upon the drag coefficient value for an individual element and the additive property among separate roughness contributions.

For non-submerged vegetation, based on extensive field measurements, the US Department of Agriculture published a list of friction factors for different row crops

---

Corresponding Author: M. Fathi-Moghadam, School of Water Science Engineering, Shahid Chamran University, Ahvaz, Iran and small slope vegetated waterways where the effect of vegetation deformation was negligible (Ree and Crow, 1977). Based on the flood events in rivers and waterways, Arcement and Schneider (1989) also reported the Manning's n values for the flood plains flow. Petryk and Bosmajian (1975) based their analysis of resistance to flow through non-submerged vegetation on the additive property although their analysis did not include deformation of the plants due to a flow. This additive property was found to hold for a set of single and multiple cedar and pine tree models placed with different patterns and densities in a flume (Fathi-Moghadam and Kouwen, 1997; Kouwen and Fathi-Moghadam, 2000). The advantages of the most recent mathematical model for estimation of non-submerged vegetation roughness (developed by Fathi-Moghadam, 2007) over previous equations i.e., by Petryk and Bosmajian (1975) and methods (Arcement and Schneider, 1989) are to account for effects of depth variation and bending of vegetation with flow.

For the submerged condition, many experiments have been conducted by the US Department of Agriculture to estimate vegetation roughness in small channels and crop furrows. Result of the research was the construction of a series of n-VR curves to relate manning roughness coefficient (n) to velocity (v) and hydraulic radius (R) for submerged crops (Kouwen, 1992).

The quasi-theoretical equations for submerged roughness have a wide range of application, from small-scale pipe flow to large-scale atmospheric boundary layer flow. For open-channel flow, Keulegan (1938) developed a semi-empirical equation that became the basis for most of the recent studies of river roughness and sediment transport. Stephan and Gutknecht (2002) and Jarvela (2002, 2003) used the log velocity profile of turbulent boundary layer flow to estimate the roughness for flow over vegetation.

The ratio between vegetation drag and bed shear resistance has been directly measured by Fathi-Moghadam and Kouwen (1997) for a variety of the vegetation type and density. The numerical simulations of Lopez and Garcia (1998) show that by increasing the plants density, the intensity of the uncovered bed shear stress is reduced. This corroborates the usual approximation that if the density of the plants is sufficiently high, the global resistance of a water course is determined only by the plants resistance (Temple, 1987). Moreover, the flexibility of the plant exerts a significant influence on the hydraulic resistance, increasing the complexity of the problem. The bending of the plants under the effects of flow let the plants assume a more streamlined configuration; this can lead to a significant reduction of the drag coefficient.

For submerged grass in channels, Kouwen (1992) developed an equation capable of accounting for the flexibility of vegetation in the calculation of relative roughness. This was a requirement for a rational method to estimate the roughness coefficient for flow over submerged vegetation. In a more analytical approach, Nikora *et al*. (2001) investigated turbulent characteristics of the boundary layer flow above the submerged vegetation. The vertical distribution of mean velocity and turbulence stress were measured with laser Doppler anemometry techniques, by means of spatial and time averaging rules (Armanini and Righetti, 1998).

In this study, a dimensional analysis supported by experimental results is used to develop a relationship between roughness conditions (i.e., density and vegetative type) and flow conditions (i.e., velocity and depth of flow) for submerged vegetative zones of rivers and flood plains.

MATERIALS AND METHODS

Formulations: The shear velocity U_* by definition is the fluid velocity at elevation $Z = Z_0 e^k$, where Z_0 is the elevation corresponding the zero velocity, k is the Von Karman constant equal to 0.4 and the zero-plane displacement (Z_0) is neglected as $Z >> Z_0$. Therefore shear velocity is the characteristic velocity for turbulent flows at a given wall shear stress and is defined as Schlichting and Gersten (2000);

$$U_* = \sqrt{\tau_o / \rho} \tag{1}$$

In which τ_o is the bed-shear stress and ρ is the density of fluid (kg m^{-3}). In case of wide and shallow channel the bed shear stress is

$$\tau_o = \rho g y_n s \tag{2}$$

where, y_n is the depth of flow (m) and s is the water surface slope (m m^{-1}) and g is the gravitational acceleration. Inserting Eq. 2 into to Eq. 1, the friction velocity is

$$U_* = (g y_n s)^{1/2} \tag{3}$$

For a wide rectangular channel, Manning's equation is

$$U = n^{-1} y_n^{2/3} s^{1/2} \tag{4}$$

where, U and y_n are in m-k-s units, the Manning's n is not dimensionless. Combining Eq. 3 and 4

$$UU_*^{-1} = n^{-1} y_n^{1/6} g^{-1/2} \qquad (5)$$

where, the n coefficient represents boundary resistance to stream flow. The following form of the momentum equation is referred to as the Darcy-Weisbach equation which was originally developed for use in predicting pipe flow and was later modified to account for flow resistance in natural channels:

$$U = (8 g y_n S)^{1/2} f^{-1/2} \qquad (6)$$

where, f is a dimensionless parameter called Darcy-Weisbach friction factor and is commonly used in head loss calculations. Using the definition of U_*, the Darcy-Weisbach equation can be rewritten as

$$UU_*^{-1} = 8f^{-1/2} \qquad (7)$$

When Eq. 7 is compared to Eq. 5, the following expression is obtained

$$n = y_n^{1/6} f^{1/2} (8g)^{-1/2} \qquad (8)$$

The above equation shows that Manning's roughness coefficient n and Darcy-Weisbach friction factor (f) are consistent and interchangeable, provided that the flow is fully turbulent and hydraulically rough.

Dimensional analysis: Many hydraulics and fluid dynamics problems must be solved by experimentation and grouping the important variables in dimensionless form for analysis. Judgment in selecting variables comes through practice and experience.

There are many forms of dimensional analysis in the literature for estimation of vegetation roughness where flow in a small slope channel is assumed uniform (Ree and Crow, 1977). Since these studies are limited to low flow velocities in shallow irrigation channels, the flexural rigidity parameter for the vegetation was neglected from the analysis. In a study of resistance to flow in submerged grass-lined channels, Kouwen (1992) found this parameter to be important when grass deflects due to stream-flow.

In this study, for submerged vegetation in river be and flood plains, the dominant parameters for the estimation of Darcy-Weisbach friction factor are assumed to be:

$$f_1 = \left(f, y_n, g, \gamma, h, U, \rho, \mu, U_*, l_1, \ldots, l_n\right) = 0 \qquad (9)$$

Where:

f = Darcy-Weisbach friction factor
y_n = Normal flow depth
g = Gravitational acceleration
h = Average canopy height
U = Mean channel stream velocity
ρ = Mass density of water
μ = Fluid viscosity
U_* = Shear velocity
$l_1 \ldots l_n$ = Characteristic lengths defining spacing or density of plants in canopy

The assumptions for Eq. 9 are:

- Soil surface shear is negligible compared to the total drag
- Distribution of plant and stems are randomly uniform in a horizontal plane, but a considerable change of density can exist in the vertical direction. As is it already dimensionless, let (f) be the first dimensionless parameter.

Applying the Buckingham π theory to the rest of the variables by assigning y_n, U and ρ as the repeated variables to represent length, time and mass scales, respectively, all the dimensionless parameters can be grouped in a functional form as:

$$f_2\left(f, \frac{U}{U_*}, \frac{l_1}{y_n}, \frac{l_2}{y_n}, \frac{h}{y_n}, \frac{U^2}{g y_n}, \frac{\rho U g}{\mu}, \frac{\rho U_* g}{\mu}\right) = 0 \qquad (10)$$

It is assumed that all individual uniformly shaped and spaced plants are placed in equal volume boxes in the canopy occupying a horizontal surface area of $a = l_1 l_2$ and a vertical height of h, where l_1 and l_2 are cross and flow-wise lengths occupied by single vegetation roughness element. In this study, density of vegetation is defined as the ratio of horizontal surface area covered by vegetation (A) to the total horizontal area (a), so (A/a) accounts for effect of vegetation density in the calculation of friction factor (f).

The last three dimensionless parameters in Eq. 10 are the well known Froude number (F_r), Reynolds number (R_e) and shear Reynolds number (R_e^*), respectively. Since, flow through dense submerged vegetation is in the fully turbulent zone, the flow is considered to be independent of the Reynolds number (R_e). The resistance to flows in a uniform open channel is independent of the Froude number (F_r) when the flow is stable. On the other hand, most river flows involving vegetation are turbulent and subcritical ($F_r<1$). Since the (R_e^*) can be obtained from (U/U_*) and (R_e), it is dropped from farther analysis. Therefore, the most significant parameters for estimation of the resistance coefficient (f) in Eq. 10 are (U/U_*), y_n/h and vegetation density (A/a). As the Manning' n value is most common roughness coefficient in open channel flow, using Eq. 8, it will be used instead of (f) in farther analyses.

Experimental setup: All experimental data were collected using the newly constructed facilities in the Hydraulics Laboratory at Soil Conservation and Watershed Management Research Institute, Iran. Tests were conducted in a rectangular 0.6×0.6 m cross section flume, 14 m long. Five meters of the flume bed in its middle section was covered with uniform sand 9 mm in diameter. Two meters of the bed in this section was covered by artificial plastic vegetation 8 cm long. They were assumed to model the shrubs and hedges which are widely grown in river banks and flood plains. Experiments were carried out in three vegetation densities of 100, 50 and 28%. The 100% defines a density where artificial vegetation models neatly lay down in flume bed, edge by edge, so sand covering flume bed can not be seen from the flume top. The rest of densities were determined by scanning the pictures taken from the flume top and measuring the vegetated to whole of picture areas. Tests conducted for four discharges of 10, 20, 30 and 40 L sec^{-1} and five slopes of 0.002, 0.004, 0.006, 0.008 and 0.010 were applied to the flume to get the desired flow depth above the artificial vegetation. Flow depth and average velocity above the simulated vegetation were recorded in three sections along the vegetation rig. A Nixon probe micro-propeller was used to measure flow velocity. A sharp V notch weir down stream of the flume was used to control the flow rate.

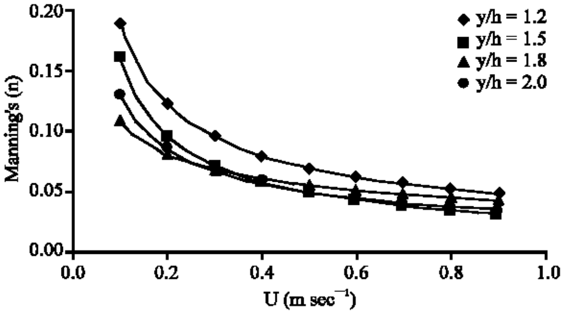

Fig. 1: Variation of the Manning's n-value with average flow velocity (vegetation density 100%)

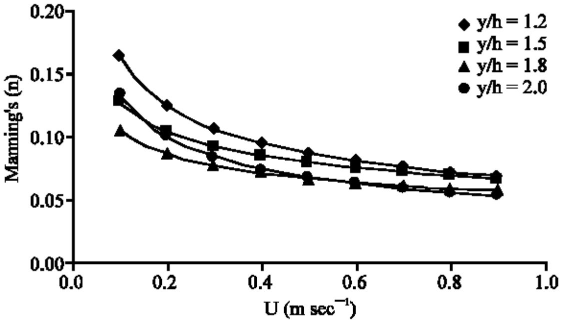

Fig. 2: Variation of the Manning's n-value with average flow velocity (vegetation density 50%)

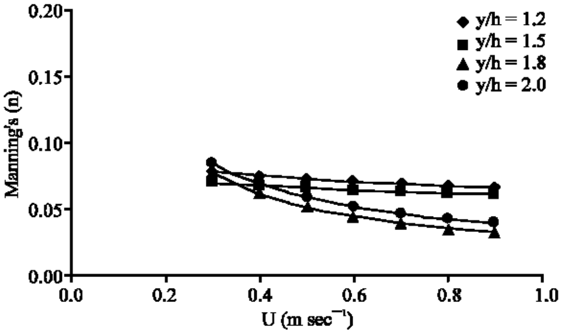

Fig. 3: Variation of the Manning's n-value with average flow velocity (vegetation density 28%)

RESULTS AND DISCUSSION

In rivers and flood plains, flow and vegetation conditions affect the vegetation roughness significantly. Assuming the artificial vegetation models behave dynamically the same as real vegetation (i.e., have same flexibility and structure), only their density along with flow condition (flow depth and velocity) is considered here to affect the roughness coefficients. According to the flow analysis for dimensionless parameters in Eq. 10, the most important dimensionless parameters affecting submerged vegetation roughness coefficient (Manning's n value) are (U/U_*), depth of submergence (y_n/h) and vegetation density (A/a). Using Eq. 4, the n-values were calculated for the vegetation models tested in flume. Figure 1-3 show variation of correlated n-value with average channel velocity for same flow depth and vegetation density. The Fig. 1-3 reveal a decrease of n-value with increase of flow velocity as a result of streamlining of vegetation and prone of roughness elements as was pointed out before by Kouwen (1992) and Fathi-Moghadam and Kouwen (1997). A similar harmonic in decrease of the n-values with increase of flow depth was observed for all vegetation densities. This was due to a decrease of the relative roughness height h/y_n that is a basic principal of the quasi-theoretical equations for turbulent boundary roughness. Higher vegetation densities of Fig. 1 and 2 exhibit higher n-values than the

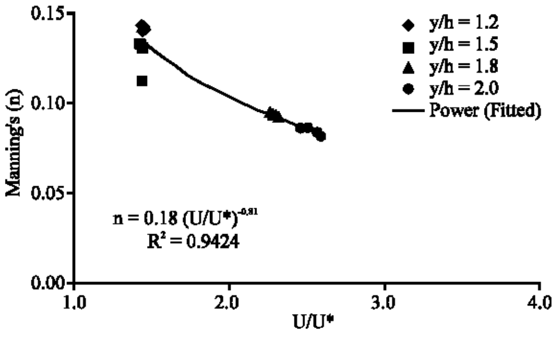

Fig. 4: Variation of the Manning's n-value with (U/U*) (vegetation density 100%)

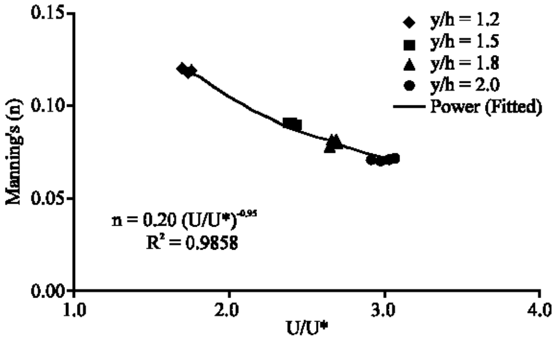

Fig. 5: Variation of the Manning's n-value with (U/U*) (vegetation density 50%)

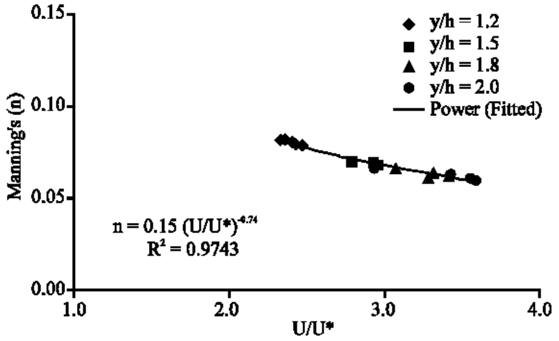

Fig. 6: Variation of the Manning's n-value with average flow velocity (vegetation density 28%)

lower vegetation density of Fig. 3. In all figures, lower velocities produce higher n-value due to less streamlining of vegetation. The effect of relative depth of submergence (y/h) is also greater at lower velocities. Figure 1 shows that larger vegetation density reflects a higher effect of flexibility and streamlining of vegetation. Moreover, contribution of high uncertainties in the lower density tests in Fig. 3 did not allow for the estimation of a valid n-value for low flow velocities.

In order to reduce the effect of flow depth variation in Eq. 4, the calculated n-value is correlated with (U/U_*) based on Eq. 5. The results are shown in Fig. 4-6 for the vegetation densities of 100, 50 and 28%. Since, U* is highly dependant on U, the range of variation of U/U* is very limited in the figures for every depth of submergence (y/h). This allowed three relationships to be correlated for vegetation densities of 100, 50 and 28% in Fig. 4-6. Comparison of the figures proves that a linear additive property is not granted for the vegetation density in the submerged condition as was revealed for non-submerged state in Fathi-Moghadam and Kouwen (1997). Reduction of n-value with increase of relative depth of submergence (y/h) is another dilemma in development of a general equation for estimation of n-value for any vegetation density and flow depth. Since U* covers effects of flow depth and vegetation density, it is used in this study for classification of three correlated equations in Fig. 4-6 as follow;

- Equation in Fig. 4 for high density and low submergence where U/U* = 1-2
- Equation in Fig. 5 for moderate density and submergence where U/U* = 2-3
- Equation in Fig. 6 for low density and high submergence where U/U* = 3-4

The 3rd equation of Fig. 6 involves more uncertainties than other two equations as result of significant roughness effect of bare bed spots and penetration of turbulent eddies into vegetation layer.

CONCLUSIONS

There is a substantial decrease of n-value with flow depth and velocity as a result of streamlining of vegetation and reduction of relative roughness in rivers beds, banks and flood plains. Since the river flow capacity is directly proportional to the n-value, the large variations of n-value with flow and vegetation conditions disqualify application of the previous methods with employ a constant *n*-value for every flow and vegetation condition. The previously reported n-values represent the roughness for an average flow and vegetation condition. However, this is not the case for most flood events where the n-value plays a major role in estimation of water level. While more data is required for development of a general equation for estimation of Manning's n-value for different flow and vegetation conditions, three equations for three ranges (U/U*) are developed for estimation of the n-value for a variety of vegetation densities and rates of submergence. Finally, a linear increase of n-value with vegetation density (additive property) or with flow depth was not confirmed for submergence condition.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Shahid Chamran University, Ahvaz, Iran and the Soil Conservation and Watershed Management Research Institute, Tehran, Iran for financial support and facilitation of the experiments.

REFERENCES

Arcement, G.J. Jr. and V.R. Schneider, 1989. Guide for selection Manning's roughness coefficients for natural channels and flood plains. Water-Resource Paper 2339, U.S. Geological Survey, Washington, DC.

Armanini, A. and M. Righetti, 1998. Flow resistance in composite vegetated channels. Proceedings of ICHE 98 Advances in Hydro-Science and Engineering Conference, Cottbus (D), Sept. 1998.

Einstein, H.A. and R.B. Banks, 1950. Fluid resistance of composite roughness. Trans. Am. Geophys. Union, 31 (4): 603-610.

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

Fathi-Moghadam, M., 2007. Characteristics and mechanics of tall vegetation for resistance to flow. Afr. J. Biotechnol., 6 (4): 475-480.

Jarvela, J., 2002. Flow resistance of flexible and stiff vegetation: A flume study with natural plants. J. Hydrol., 296 (1-2): 44-54.

Jarvela, J., 2003. Influence of vegetation on flow structure in flood plains and wetlands. In: Proceeding of the 3rd IAHR Symposium on River, Coastal and Estuarine Morphodynamics (RCEM 2003), Madrid, IAHR., pp: 845-856.

Keulegan, G.H., 1938. Laws of turbulent flow in open channels. J. Res. Natl. Bureau Standards, 21 (6): 707-741.

Kouwen, N., 1992. Modern approach to design of grassed channels. J. Irrig. Drainage Eng. ASCE., 118 (5): 733-743.

Kouwen, N. and M. Fathi-Moghadam, 2000. Friction factors for coniferous trees along rivers. J. Hydraulic Eng. ASCE., 126 (10): 732-740.

Lopez, F. and M. Garcia, 1998. Open-channel flow through simulated vegetation: Suspended sediment transport modeling. Water Resour. Res., 34 (9): 2341-2352.

Nikora, V., D. Goring, I. McEwan and G. Griffiths, 2001. Spatially averaged open-channel flow over rough bed. J. Hydr. Eng. ASCE., 127 (2): 123-133.

Petryk, S. and G. Bosmajian, 1975. Analysis of flow through vegetation. J. Hydr. Div. ASCE., 101 (7): 871-884.

Ree, W.O. and F.R. Crow, 1977. Friction factor for vegetated waterways of small slope. USDA., Agriculture Research Service, ARS-S-151.

Schlichting, H. and K. Gersten, 2000. Boundary Layer Theory. 8th Edn. Springer-Verlag, Berlin, pp: 799.

Stephan, U. and D. Gutknecht, 2002. Hydraulic resistance of submerged flexible vegetation. J. Hydrol., 1 (2): 27-43.

Temple, D.M., 1987. Closure of velocity distribution coefficients for grass lined channels. J. Hydraul. Div. ASCE., 113 (9): 1224-1226.