<center>HYDROPHYSICAL PROCESSES</center>

Assessing Submerged Vegetation Roughness in Streambed under Clear Water Condition using Physical Modeling[1]

Hosna Shafaei[a], *, Ata Amini[b], **, ***, and Azim Shirdeli[c], ****

[a]Faculty of Agriculture, University of Zanjan, Zanjan, 45371-38791 Iran
[b]Kurdistan Agricultural and Natural Resources Research and Education Center, AREEO, Sanandaj, 66169-36311 Iran
[c]Faculty of Agriculture, University of Zanjan, Zanjan, 45371-38791 Iran
*e-mail: shafaeihosna@gmail.com
**e-mail: ata_amini@yahoo.com
***e-mail: a.amini@areeo.ac.ir
****e-mail: azimshirdeli@yahoo.com

Abstract—Roughness coefficient, also called Manning's coefficient, is one of the most important hydraulic parameters in the rivers. This coefficient, in addition to the flow conditions, depends on streambed characteristics such as type and density of vegetation. In this study, a physical model in a flume with 7 m length, 0.25 m width and 0.25 m height was conducted to evaluate the streambed roughness coefficient and consequently the discharge passing from waterways. Flume bed was filled using uniform sediment with median grain diameter of 1.9 mm, variation coefficient of 1.4 mm and a thickness of 0.4 m. Roughness coefficient variation in the slopes of 0.2, 0.4 ,and 0.6%, discharges of 4, 6, and 8 L/s and vegetation cover densities as 0, 12, 25, and 50% were investigated. To simulate the covering of streambed, vegetation scrub was used in the experiments. The results showed that by increasing the density of vegetation, roughness coefficient increases while with increasing flow velocity, slope and Froude number decreases. By analyzing the data from this study, streambed roughness coefficient was obtained in terms of different variables as applicable relationships for different conditions of flow and streambed. The results of this study with quantifying the effects of various parameters on the roughness coefficient can be used by water engineers.

INTRODUCTION

Study the characteristics of flow in rivers is of interest to researchers. Many hydraulic researchers studied hydraulic behavior of rivers. Establishment of vegetation is a biological method for erosion control [15]. Vegetation growing naturally on the beds of channels or on the riverbanks and reduces energy of water and the flood discharge. Vegetation is a method of inexpensively and natural to control erosion and sedimentation and is important in point of environmental and ecotourism views [8, 13]. River floodplains vegetation typically comprises various combinations of trees, herbs, shrubs, hedges, bushes and grasses [6]. Khublaryan et al. [11] used mathematical model within Higher Aquatic Vegetation to investigate hydraulic roughness of the streambed. They found that the coefficient of hydraulic resistance to flow in the presence of vegetation is strongly affected by the morphometric characteristic of plants: the presence of a single stem or

several stems, the height and diameter of stems, the distance between plants and stem cross-section shape. Gurnell [9] conducted a study to investigate the effect of vegetation on system of the river. He found that the effect of growing vegetation is on all over the river and show sensitivity to the processes of the river. Ciraolo et al. [4] investigated hydraulic resistance of submerged vegetation in the Mediterranean coastal in sandy bed by mathematical models. They used vegetation named *Posidania oceanica* that has thin and flexible leafs. Density of 500 to 1000 branches per square meter was used. This plant is flexible and therefore by increasing the velocity of flow, those remain in direction with flow. Their results showed that the vegetation increases the depth of flow and reduces the velocity, as a result of roughness coefficient increasing. Noor Aliza et al. used physical model to investigate the effect of herbaceous plant cover on the Manning's roughness coefficient [16]. Their results showed that there is a close and linear relationship between the depth, density and arrangement of vegetation. Also Manning's

---

[1] The article is published in the original.

roughness coefficient increases with increasing vegetation density. Fengfeng et al. investigated the effect of density and flexibility of vegetation on open channel roughness coefficient [7]. They showed that density of vegetation is the most important parameters influencing on the roughness coefficient. However flexibility of branches has not a significant impact on roughness coefficient. Soltani Fard et al. [17] investigated the effect of vegetation on roughness coefficient in Karun River, Iran. Their results showed that vegetation increases roughness coefficient and by increasing the ratio of hydraulic radius to the median size of particle, (R/d_{50}), roughness coefficient declined. Nehal et al. [14] investigated the effect of submerged vegetation on the flow regime using experimental study. They reported that the vegetation cover is an important factor on flow condition and increases the resistance and the water level. The vegetation also changes the profile of flow velocity in a way that the flow velocity profile is non-logarithmic distribution function. The same results were presented by Xia and Nehal [18]. They experimentally investigated the effect of vegetation on flow and Manning coefficient and found that there was a significant influence of vegetation on hydraulic features and the relative depth ratio of water depth, h, to stem height, hs, was a key determinant of those influences. Furthermore, by increasing Froude number (Fr), the roughness coefficient decreases in a vegetated channel. In another study roughness coefficient in rivers with vegetation was evaluated by Yoshida [19]. He estimated roughness coefficient of streambed using quasi-Newton model and stated that vegetation cover is a factor to reduce capacity of flooding and has a major role on river management. Therefore, he investigated the main natural vegetation effects on streambed resistance and estimated resistance of vegetation on the flow according to drag force per unit mass of fluid. The parameters considered in his study were including density of vegetation, drag value coefficient, streambed morphology and flexibility of stem. The results from Yoshida [19] revealed that the main factors influencing estimation of roughness coefficient are the roughness of the streambed (the characteristics of streambed, cross-section irregularity), arrangement of vegetation, the forms of branches and leaves of trees, the path (straight or spiral), obstacles in the flow path, the time and seasons [5]. The effects of these parameters are generally considered as the roughness coefficient in open channel hydraulics [13]. By conducting experiments under controlled conditions the roughness coefficient values are recommended for real conditions in situ in terms of various vegetation and hydraulic parameters. Vegetation strongly affects river and water management. Therefore, it is necessary to investigate vegetation conditions to explain the corresponding flow resistance to predict and control flood flows and erosion in rivers and embankments. In these study effects of flow rate, streambed slope, the Froude number and density of vegetation on roughness coefficient were investigated and relationships for its calculation using Manning's equation were presented.

MATERIALS AND METHODS

In this study the effect of various variables on the variation of streambed roughness was simulated using a physical model. To conduct experiments a tilting flume with a length of 7 m, width of 0.25 m and depth of 0.25 m located in the Soil Conservation and Watershed Management Research Institute (SCWMRI), Tehran, Iran was used. Water was supplied to the flume from the laboratory head tank in a closed system by an electro-pump. In order to remove the entering turbulent flow into the site of experiment, a network of obstacles such as filters and brick lattice screens were used so that the velocity distribution perpendicular to flow was relatively uniform on test area. The longitudinal and transverse distributions of velocity were recorded using a micro Moline. Walls and bed of flume were built from Plexiglas and the bed of flume was filled with uniform sediment with a thickness of 0.04 m, median diameter $d_{50} = 1.9$ mm and standard deviation σ = 1.4 mm. To achieve a flat streambed, prior to each experiment, a laboratory pointgage and an firm plate were mounted at a constant height on the flume walls to control the smooth surface of the bed.

Conditions of experiments were set so that during the experiments sediment of the bed flume was stable and clear-water conditions were established [2, 10]. To determine sediment entrainment, critical shear velocity (u_{*c}) and critical velocity (V_c) were calculated using the procedure proposed by Melville and Coleman [12] for uniform and non-uniform sediment as follow:

$$\frac{V_c}{u_{*c}} = 5.75\log\left[5.53\frac{y}{d_{50}}\right], \tag{1}$$

$$u_{*c} = 0.00115 + 0.0125d_{50}^{1.4}, \tag{2}$$

where y is flow depth (m), V_c is critical velocity (m/s) and is u_{*c} critical shear velocity (m/s). Average critical velocity was calculated as $V_c = 0.21$ m/s and the critical shear velocity in the status of uncover streambed was obtained as $u_{*c} = 0.001$ m/s while this amount was 0.015 m/s in the presence of vegetation cover. To control the velocity and flow depth, a regulating slice gate set at the end of the flume was used. Variables of the flow with different discharges in each series of experiments were adjusted so that the sediment entrainment was prevented. The flume was supported by a center pin and mechanically connected screw jacks at a distance of 4.5 m from the beginning of flume through a cable and fixed gear that allowed the flume slope to be varied. In the experiments for simulating vegetation cover in the flume, the flexible artificial shrub was used. This shrub was at the height of 0.07 m and was placed on plastic plates with dimensions of 0.25 ×
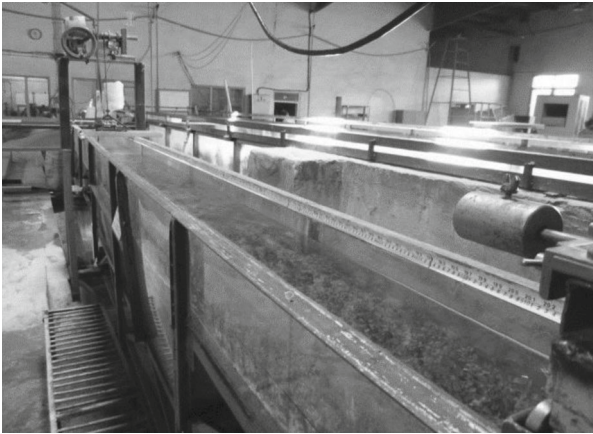
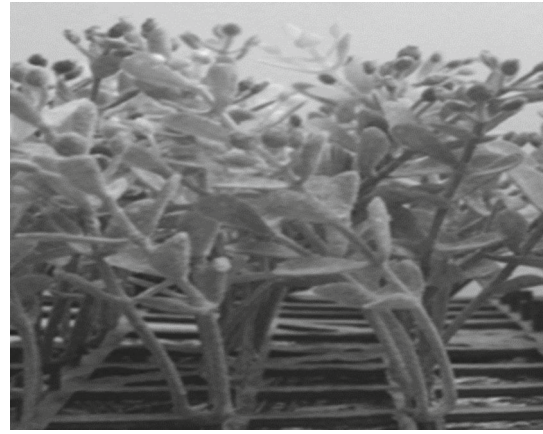**Fig. 1.** Laboratory flume (view of upstream).

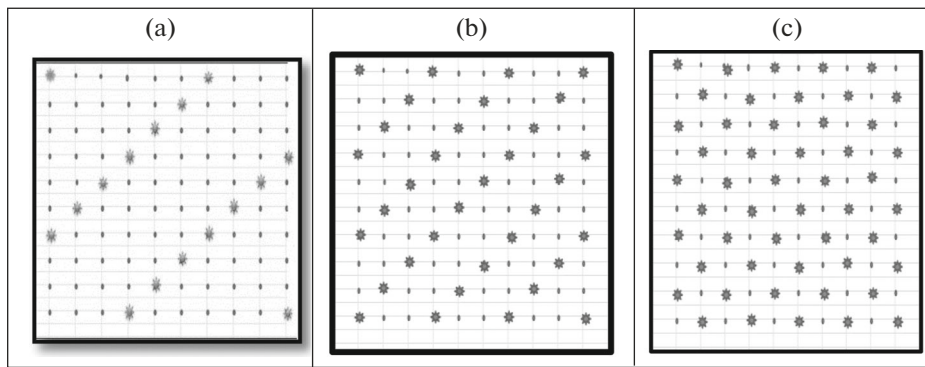
Fig. 2. Artificial vegetation.

Fig. 3. The arrangements of different densities of vegetation cover: (a) 12%, (b) 25%, and (c) 50%.

0.25 m. The plates were connected to thin rods with diameter of 16 mm to keep plates inside sediment layer. These thin rods absorb drag force produced by the vegetation cover. Figure 1 shows the laboratory flume used in this research.

Density of vegetation (*D*) was defined as the number of branches of vegetation (*N*) per unit area (*A*) and calculated using Eq. (1) as:

$$D = A_V / A, \qquad (3)$$

where A_V is area of vegetation and A is total area (m^2). In the experiments densities were as zero (no cover), 12, 25, and 50%. The vegetation was placed in the flume with the length of 3 m in line with the flow direction. An example of artificial vegetation with density of 50% is shown in Fig. 2. The schematic arrangement of vegetation in the flume was also shown in Fig. 3. In Fig. 3 the location of the branches of artificial vegetation is presented as points.

At this study the experiments were performed with three discharges as 4, 6 and 8 L/s. The flow discharge was set by reading water depth on triangle spillway at the end of the flume. 36 experiments were conducted. Velocity of flow was measured by using electromag-netic velocity meter, OSK (14077) that records velocity in two dimensions. The flow velocity was recorded in five sections at intervals of 0.5 m, started 0.5 m upper and ended 0.5 m lower than vegetation area. To obtain average flow velocity (*V*) Eq. (4) was used:

$$V = \sqrt{(V_x^2 + V_y^2)}, \qquad (4)$$

where V_x is velocity perpendicular to flow and V_y is velocity parallel with the flow (m/s). Depth of flow was measured by using a point gauge with an accuracy of 0.1 mm. Point gauge placed on a wheel that was moveable along and across the flume. Flow depth through the flume, 0.5 m before and after the vegetation area was measured. Such experimental set up and conditions were used in all experiments.

Dimensional Analysis

The roughness of the streambed and waterways is indicated as the Manning's roughness coefficient, *n*. This coefficient is function of streambed friction characteristics that was expressed as follows [5]:

$$n = f\left(\rho, g, u, u_*, D_{50}, l, y, S, H, D\right), \qquad (5)$$

Table 1. Data of measurement in this study

D, %	Q, L/s	S	u/u*	Fr	n
50	4	0.002	5.0	0.150	0.041
50	4	0.004	5.95	0.172	0.034
50	4	0.006	7.36	0.183	0.028
50	6	0.002	5.98	0.172	0.035
50	6	0.004	7.31	0.193	0.028
50	6	0.006	8.84	0.200	0.023
50	8	0.002	7.01	0.195	0.03
50	8	0.004	9.31	0.216	0.022
50	8	0.006	9.71	0.234	0.021
25	4	0.002	5.10	0.154	0.042
25	4	0.004	2.22	0.175	0.031
25	4	0.006	9.87	0.197	0.025
25	6	0.002	7.44	0.178	0.029
25	6	0.004	7.15	0.202	0.019
25	6	0.006	9.24	0.220	0.022
25	8	0.002	6.70	0.149	0.025
25	8	0.004	8.37	0.213	0.025
25	8	0.006	10.12	0.233	0.021
12	4	0.002	4.780	0.165	0.043
12	4	0.004	6.151	0.187	0.034
12	4	0.006	7.846	0.196	0.027
12	6	0.002	7.22	0.174	0.028
12	6	0.004	14.38	0.205	0.025
12	6	0.006	9.165	0.218	0.022
12	8	0.002	7.247	0.202	0.029
12	8	0.004	7.066	0.216	0.029
12	8	0.006	9.418	0.233	0.022
0	4	0.002	4.37	0.174	0.024
0	4	0.004	4.97	0.213	0.021
0	4	0.006	6.53	0.254	0.021
0	6	0.002	3.97	0.204	0.023
0	6	0.004	4.88	0.261	0.018
0	6	0.006	5.21	0.269	0.018
0	8	0.002	3.93	0.236	0.012
0	8	0.004	4.41	0.269	0.014
0	8	0.006	4.71	0.286	0.022

where H is height of vegetation cover (m), ρ is density of fluid (kg/m^3), g is acceleration of gravity (m/s^2), L is length of channel (m), y is depth of flow (m) and S is slope of the streambed. Among these parameters, height of vegetation, average flow velocity and fluid density, as geometrical, flow and fluid parameters respectively, are of most interest to the researchers [9]. To decrease the large number of effective parameters and to conclude the experiments process, technique of dimensional analysis was used to obtain dimensionless parameters. In this method, according to Buckingham method for dimensionless variables effective on roughness coefficient, three parameters of length, mass and time were selected as repetitive variables. The final calculation was derived as follow:

$$n = f\left(D, S, \mathrm{Fr}, \frac{u}{u*} \right). \qquad (6)$$

For calculating of the observed Manning's coefficient the most common empirical equation of flow in open channels, Manning's equation, was used [1, 3] as follow:

$$Q = \frac{1}{n} A R^{\left(\frac{2}{3}\right)} S^{\left(\frac{1}{2}\right)}. \qquad (7)$$

In this relationship, R is the hydraulic radius (m) and A is the cross section (m^2). The observed values of n by using the corresponding discharge, the streambed slope, cross-section with respect to the fixed width of 0.25 m and flow depth substituted in Manning equation was obtained.

Calculated Manning's coefficient estimated by SPSS software. The SPSS is one of the most well-known packages of programs for statistical analysis and data management. In this software the roughness coefficient as a function of effective parameters in each experiments was set and to each parameters a power (a, b, c, d, ...) was devoted. The allocated powers were sorted in a separate row and the value of 1 was used as default power for each parameter. A try and error process was followed to close the observed and estimated roughness coefficient. To evaluate accuracy of the model and calculating the errors, the statistics test of the Mean Error Relative (MER) and Root Mean Square Error (RMSE) were used. These measures are derived using Eqs. (8) and (9), respectively.

$$\mathrm{MER} = \frac{\sum_{i}^{n} \frac{|O - C|}{O}}{n}, \qquad (8)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i}^{n} \left(C_i^2 - o_i^2 \right)^2}{n}}, \qquad (9)$$

where C and O represent calculated and observed data respectively, $i = 1, 2, 3, ...$ and n is number of data.

RESULTS AND DISCUSSION

The data derived from experiments with various variables are shown in Table 1. In Table 1 density of vegetation in percent, discharge (L/s), bed slope, the average velocity to shear velocity, Froude number and Manning's roughness coefficient are included.
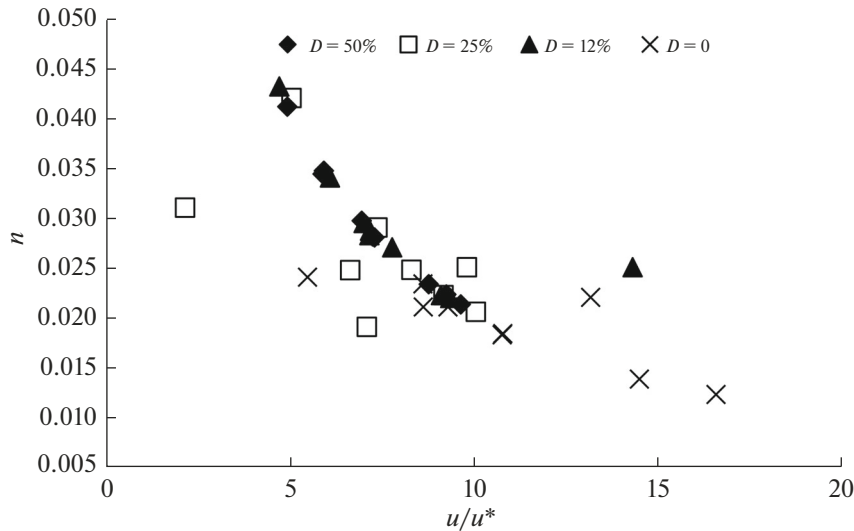
Fig. 4. Variation of roughness coefficient with ratio average velocity to shear velocity.
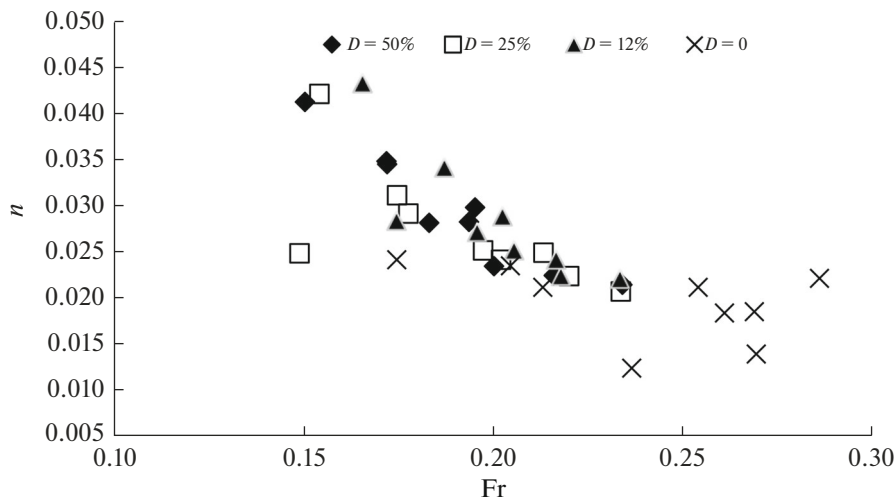

Fig. 5. Variations roughness coefficient with Froude number.

The data presented in Table 1 shows that the roughness coefficient decreases with increasing the ratio of average velocity to shear velocity, slope and discharge. However with increasing the vegetation density, the roughness increases. These results are consistent with those reported by Khublaryan et al. [11]. In without vegetation condition the roughness coefficient in discharge of 8, 6 and 4 L/s was varied from 0.026–0.036, 0.024–0.034 and 0.021–0.03, respectively. These values were much lower than that for vegetation condition due to less resistance of the streambed.

Sensitivity Analysis

In order to determine the dependence of roughness coefficient to different variables, sensitivity analysis was performed using recorded data. Examples of the results of the analysis are presented in Figs. 4, 5. Figure 4 shows roughness coefficients versus average velocity to shear velocity in different conditions.

Figure 4 shows that by increasing u/u^* the value of n was decreased. This decrease was decline by increasing vegetation density. The greatest variations were in non-vegetation condition and as expected, Manning's coefficient increased by increasing vegetation. In fact, Manning's coefficient variation in the presence of vegetation is more than non-vegetation condition. The greatest roughness coefficient was recorded in 50% density as 0.043 which corresponds to the lowest streambed slope equal to 0.002. Moreover, the experimental data derived in this study was used to determine the variations of Manning's roughness coeffi-
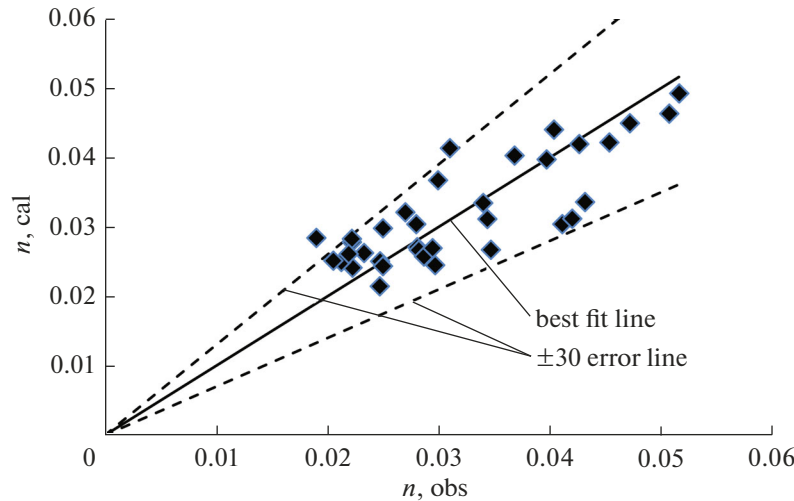
Fig. 6. Comparison between roughness coefficient observed and calculated.

cient with the Fr number and the results are shown in Fig. 5.

Figure 5 shows that with increasing Fr number the amount of n was decreased. This decrease was decline as the vegetation density was increased so that the variation reached its minimum value in non-vegetation condition. Meanwhile, as expected, by increasing vegetation density the Manning's coefficient increases. More analysis showed that in conditions of non-vegetation by increasing discharge, roughness coefficient increased. However in comparison of vegetation, due to flow resistance, the trend was slighter. In case of water depth, variation of Manning's roughness coefficient in the presence of vegetation cover is higher and increases by increasing water depth. In condition of vegetation sensitivity analysis indicated that the most effective parameters were streamed slope with MER = 0.16, correlation coefficient as $R = 0.85$ and RMSE = 0.00003 and density of vegetation with MER = 0.18 and correlation coefficient as $R = 0.78$.

The Proposed Model

Sensitivity analysis for the data derived in this research exposed the effects of streamed slope, Froude number, vegetation cover and the ratio of average velocity to shear velocity on roughness coefficient. It was found that these effects are different in the status of with and without vegetation. Considering the data presented in Table 1 the SPSS software was used to detect and quantify the effect of each variable using multivariate regression for dimensionless parameters. The relations for roughness coefficients with and without vegetation were obtained as Eqs. (10) and (11) respectively as follows:

$$n = 0.006\mathrm{Fr}^{-0.234}\left(\frac{u}{u^*}\right)^{-1.52} S^{-0.717} D^{0.035}, \quad (10)$$

$$n = 0.0013\mathrm{Fr}^{-2.10}\left(\frac{u}{u^*}\right)^{-1.89} S^{-1.02}. \quad (11)$$

Equation (10) shows that by increasing the Froude number, the slope of the streambed and the ratio of average velocity to shear velocity, the roughness coefficient reduces. Indeed, the vegetation acts as a barrier and increases flow depth and flow resistance and consequently decreases the flow energy. Besides, roughness coefficient directly related to the vegetation density and by increasing the density of vegetation, roughness coefficient increases. As presented in Eq. (10), the most effective parameter was the ratio of average velocity to shear velocity. This result was consistence with result obtained by other researchers [5, 12, 14]. In case of non-vegetated streambed, the results showed that the streambed slope, the ratio of average flow velocity to shear velocity and Froude number changes the roughness coefficient inversely so that by increasing each of these parameters roughness coefficient decreases (Eq. (11)). The most effective parameter in Eq. (11) was Froude number. Figure 6 shows comparison between observed and calculated roughness coefficients for different conditions of experimental data.

The correlation coefficient R, MER, and RMSE were determined as 0.83, 0.2 and 0.0007 respectively. These values and the obvious comparison with the best fit and ±30% error lines presented in Fig. 6 indicated the significant accuracy of the obtained equations.

CONCLUSIONS

In this study the effect of various parameters on the Manning's roughness coefficient was investigated using experiments conducted in a laboratory flume. The results showed that vegetation density was the most effective variable on roughness coefficient. In term of vegetated streambed, density parameter caused reduction of the effects of other variables such as the Froude number, velocity and slope. Vegetation increases the flow depth and decreases flow velocity which these can lead to a significant rise of roughness coefficient. By increasing the flow velocity, the resistance against the flow was reduced and vegetation cover was lead to flow direction resulting reduction of roughness coefficient. While in status of non-vegetated streambed, slope, velocity and Froude number were with the most obvious effects on reducing the roughness coefficient. In addition, relations for Manning's roughness coefficient as a function of the streambed slope, the ratio of average velocity to shear velocity, the Froude number and vegetation density were presented. The obtained relations can be employed by hydraulic and river engineers for an accurate estimation of discharge through naturally vegetated and non-vegetated waterways.

ACKNOWLEDGMENTS

REFERENCES

1. Amini, A., Arya, A., Eghbalzadeh, A., and Javan, M., Peak flood estimation under overtopping and piping conditions at Vahdat Dam, Kurdistan, Iran, *Arabian J. Geosci.*, 2017. doi 10.1007/s12517-017-2854-y

2. Amini, A., Melville, B.W., Thamer, M.A., and Ghazali, H., Clearwater local scour around pile groups-shallow water, *J. Hydraul. Eng.*, 2012, vol. 138, no. 2, pp. 177–185.

3. Akgiray, Ö., Explicit solutions of the Manning's equation for partially filled circular pipes, *Canad. J. Civil Eng.*, 2005, vol. 32, pp. 490–492.

4. Ciraolo, G., Ferreri, G., and Loggia, G., Flow resistance of Posidonia Oceanic in shallow water, *J. Hydraul. Res.*, 2006, vol. 44, no. 2, pp. 189–202.

5. Ebrahimi, N.G., Fathi-Moghadam, M., Kashefipour, M., Saneie, M., and Ebrahimi, K., Effect of flow and vegetation states on river roughness coefficients, *J. Appl. Sci.*, 2008, vol. 8, no. 11, pp. 2118–2123.

6. Fu-Chun, W., Hsieh, W.S., and Yi-Ju, C., Variation of roughness coefficients for unsubmerged, *J. Hydraul. Eng.*, 1999, vol. 125, no. 9, pp. 934–942.

7. Fengfeng, G., Lin, M., Dingman, Q., Li, J., Lingshuang, K., and Yuanyang, W., Study on roughness coefficient for unsubmerged reed in the Changjiang Estuary, *Acta Oceanol. Sin.*, 2011, vol. 30, no. 5, pp. 108–113.

8. Gholami, V. and Khaleghi, M.R., The impact of vegetation on the bank erosion (Case study: the Haraz River), *Soil Water Res.*, 2013, vol. 8, pp. 158–164.

9. Gurnell, A., Plants as river system engineers, *Earth Surface Processes and Landforms (ESPL)*, 2013, vol. 39, pp. 4–25.

10. Hosseini, R and Amini, A., Scour depth estimation methods around pile groups, *KSCE J. Civil Eng.*, 2015, vol. 19, no. 7, pp. 2144–2156.

11. Khublaryan, M.G., Frolov, A.P., and Zyryanov, V.N., Modeling water flow in the presence of higher vegetation, *Water Resour.*, 2004, vol. 31, no. 6, pp. 668–674.

12. Melville, B.W. and Coleman, S., Bridge scour, Water Resources Publications, LLC, Colorado, 2000.

13. Mohammadi, S. and Kashefipour, S.M., Numerical modeling of flow in riverine basins using an improved dynamic roughness coefficient, *Water Resour.*, 2014, vol. 41, no. 4, pp. 412–420.

14. Nehal, L., Hamimed, A., and Khaldi, A., Experimental study on the impact of emergent vegetation on flow, *17th Int. Water Technol. Conf.*, IWTC17, 5–7 November 2013, Istanbul, Turkey.

15. Nezo, I. and Naot, D., Partly vegetated open channels, new experimental evidence, *IAHR Conf. Graz*, 1999.

16. NoorAliza, B.A., Dwi, T., Zarina, M.A., Nur, S.L., and Asyraff, B.S.M., Laboratory study on effects of vegetation on the open channel hydraulic roughness (Pennisetum Purpureum and Ipomoea Aquatica), *Int. Conf. Water Resou. (ICWR 2009)*, Langkawi, Kedah, Malaysia, 2009.

17. Soltani Fard, R., Heidarnejad, M., and Zohrabi, N., Study factors influencing the hydraulic roughness coefficient of the Karun river, Iran, *In. J. Farm. Allied Sci. (IJFAS)*, 2013, vol. 2, no. 22, pp. 976–981.

18. Xia, J. and Nehal, L., Hydraulic features of flow through emergent bending aquatic vegetation in the riparian zone, *Water*, 2013, vol. 5, pp. 2080–2093.

19. Yoshida, K., Inverse estimation of distributed roughness coefficients in vegetated flooded river, *J. Hydraul. Res.*, 2014, vol. 52, no. 6, pp. 811–823.