PORT SAID ENGINEERING RESEARCH JOURNAL

Faculty of Engineering - Port Said University
Volume 29 No. 2 pp: 16:26

The Influence of Submerged and Floating Vegetation on Manning's Roughness Coefficient: An Experimental Analysis

*Marwa F. Shaheen[1], Gamal M. Abdel-Aal[2], Mohamed Galal Elbagoury[3, *]*

[1] *Civil Engineering Department, Pyramids Higher Institute for Engineering and Technology, Giza, Egypt, email:* Shaheen20007@yahoo.com

[2] *Water and Water Structures Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt, email:* gamal.abdelaal.g1960@gmail.com,

[3] *Water and Water Structures Engineering Department, Faculty of Engineering, Zagazig University, Zagazig, Egypt, email:* dr.eng.mohamedgalal@gmail.com,

**Corresponding author,* *DOI: 10.21608/pserj.2024.331268.1374.*

Received 28-10-2024

Revised 15-12-2024

Accepted 25-12-2024

ABSTRACT

The Manning Equation is widely used in hydraulic engineering to estimate mean velocity and discharge in open channels. This equation is based on various parameters, with the roughness coefficient being the most crucial factor. The nature of the channel is the primary factor in estimating this roughness coefficient. In vegetated channels, several factors affect the roughness coefficient, including water depth, velocity, friction slope, type, height, and density of the vegetation. In this research, an experimental investigation is conducted to analyze the roughness coefficient caused by submerged and floating vegetation. Artificial flexible elements made of perspex are used to simulate submerged vegetation, while foam integrated with aluminum wires is utilized to represent floating vegetation. The roughness coefficient values are estimated for various discharges (25.0, 30.0, 35.0, and 40.0 *l/sec*), flow depths (0.25, 0.30, and 0.35 *m*), and friction slopes in both non-vegetated and vegetated channels with various bed slopes (0.0010, 0.0020, 0.0023, 0.0049, and 0.0062). An analysis of the relationship between the roughness coefficient and the Froude number reveals that this coefficient exhibits a power function relationship with the Froude number. The roughness coefficient increases with higher friction slopes and decreases as the Froude number rises. Additionally, the presence of vegetation significantly increases the roughness coefficient from 0.032 to 0.098 when the submerged ratio is 0.94, the bed slope is 0.0062, and the Froude number is 0.19. The roughness coefficient further escalates with higher submerged ratios. New empirical equations have been developed to estimate the roughness coefficient.

Keywords: Open Channel Flow, Flexible Vegetation, Floating Vegetation, Manning Roughness Coefficient.

1.NOTATION

The following symbols are used in this paper:

A	Cross-sectional area of the flow
B	Channel width
L	Channel length
S	Channel bed slope
S_f	Friction slope
y	Flow depth
z	Distance from the measurement point to the bed
h_{def}	Deflected height of submerged vegetation
h_f	Friction head loss
l	length of water along the course
h_{def}/y	Submerged ratio

R	Hydraulic radius
n	Manning roughness coefficient
u	Streamwise velocity
U	Average flow velocity
Q	Flow discharge
g	gravitational acceleration
F	Froude number
a_x	Longitudinal spacing of submerged vegetation
a_y	Transverse spacing of submerged vegetation
$a_{\bar{x}}$	Longitudinal spacing of floating vegetation
$a_{\bar{y}}$	Transverse spacing of floating vegetation
I_s	Density of submerged vegetation
I_f	Density of floating vegetation
ρ	Density of water

2. INTRODUCTION

Aquatic vegetation in open channels significantly affects flow resistance. This vegetation obstructs the flow in the channel and leads to an increase in flow resistance. As a result, this increase reduces flow capacity, decreases flow velocity, raises water level, and increases energy head losses.

Wu et al. [1] simulated vegetation on watercourses to estimate the difference in the vegetative roughness coefficient with the water depth using a horsehair mattress. It was found that during the unsubmerged condition, the roughness coefficient decreased as water depth increased. At the beginning of submergence, the roughness coefficient increased at shallow water depths; however, as the water level continued to rise, it eventually dropped to an asymptotic constant value. Wilson and Horritt [2], Wilson [3], Rizalihadi et al. [4], Schugerl et al. [5], Hinsberger et al. [6], Orakwe et al. [7], and Chen et al. [8] demonstrated that the Manning coefficient increased as the flow depth decreased under submerged conditions. Moreover, the Manning coefficient tended to approach a constant value when the flow depth exceeded approximately twice the height of the vegetation. Zhang et al. [9] investigated the impact of double-layer vegetation on flow resistance under various submerged conditions. The results indicated that the flow resistance coefficient increased with rising water depth while it decreased with increasing discharge.

Chen et al. [10] indicated that there was a strong relationship between roughness coefficient and Froude number. Gad et al. [11] stated that the roughness coefficient decreased with increasing Froude number and then gradually approached a constant value. Fathi-Moghadam and Drikvandi [12], Yusof et al. [13], and Barinas et al. [14] stated that the roughness coefficient decreased with increasing flow velocity. Muhammad et al. [15] concluded that the flow resistance depended on flow velocity, flow depth, slope, and vegetation height.

In the case of non-submerged flow, Jarvela [16] investigated the flow resistance caused by both stiff and flexible vegetation. Nikora et al. [17], and Meng et al. [18] demonstrated that the type of vegetation affected flow resistance, and the longest grass created a vigorous retarding effect on the flow. Rhee et al. [19] examined three types of Korean native vegetation to evaluate flow resistance under submerged and un-submerged conditions. It was noted that the resistance coefficients were affected by the plant states, whether green or dormant. The dormant plants exhibited lower resistance coefficients than the green plants. Vinatier et al. [20] studied the effect of vegetation types and densities on the roughness coefficient. The roughness was higher in rigid vegetation than in flexible vegetation. Bora and Misra [21] studied the impact of vegetation flexibility on the roughness coefficient. The results showed that the roughness coefficient decreased with an increase in vegetation flexibility. Chembolu et al. [22] investigated the effect of heterogeneous vegetation patches on roughness coefficient. Zhang et al. [23] studied the effect of vegetation lodging angle on the roughness coefficient. It was found that the roughness coefficient decreased gradually with increasing lodging angle. Silva-Araya and Rodríguez-Quiñones [24] examined four grass species from the Caribbean area to evaluate the roughness coefficient, including Bahia, Zoysia, Pangola, and Bermuda grass. Zhang et al. [25] revealed the influence of reed vegetation on the Manning roughness coefficient. It was found that, in the case of submerged vegetation, the roughness was smaller than in the non-submerged case.

Carollo et al. [26] analyzed the effect of vegetation concentration on flow resistance under flexible submerged conditions. It was noted that the resistance coefficient depended on the relative submergence and the degree of vegetation inflection at low concentrations. However, at high concentrations, it depended on the shear Reynolds number. Abood et al. [27], Musleh and Cruise [28], Ebrahimi et al. [29], Wu [30], Fathi-Moghadam et al. [31], Xu et al. [32], Xia and Nehal [33], Rizalihadi and Safiana [34], Ye et al. [35], Zhang et al. [36], Rizalihadi [37], Shafaei et al. [38], Cai et al. [39], and Zhang et al. [40] demonstrated that the Manning coefficient increased with increasing vegetation density. Kiss et al. [41] examined the effect of long-term changes in land cover on floodplain roughness. Derakhshan et al. [42] investigated the effect of the distribution of vegetation patches on flow resistance, while the vegetation density remained constant. Derakhshan et al. [43] studied the effect of vertical variation of submerged vegetation density on the roughness coefficient. Nicosia et al. [44] studied the effect of different arrangements of flexible vegetation on the roughness coefficient, including full-vegetated, half-vegetated, non-vegetated, central vegetation cut, and extensive vegetation cut.

Kouwen and Fathi-Moghadam [45] modified an equation to estimate the resistance coefficient based on velocity, flow depth, vegetation density, and vegetation flexibility. James et al. [46] suggested a new equation to estimate the resistance coefficient for simple cylindrical stems in regular arrangements. Green [47] developed an empirical equation to calculate the roughness coefficient based on the blockage factor. Li et al. [48] proposed an equation to estimate the roughness coefficient based on vegetation density for submerged flexible vegetation. Abd-Elmoaty and El-Samman [49] developed an empirical equation to estimate the roughness coefficient using parameters such as weed infestation percentage and slope.

To the authors' knowledge, no studies have been conducted to investigate the combined effect of bed slope and submerged ratio on the roughness coefficient in vegetated channels that contain both submerged and floating vegetation. The major objectives of this research are as follows: (1) to investigate the effect of bed slope on the roughness coefficient, (2) to examine the effect of vegetation on the roughness coefficient, (3) to analyze the effect of submerged ratio on the roughness coefficient in vegetated channels, and (4) to develop an empirical equation to predict the roughness coefficient in both non-vegetated and vegetated channels.

3.DIMENSIONAL ANALYSIS

Several equations are utilized to determine the flow in open channels. The Manning equation serves as a common method for estimating the mean velocity and discharge in open channels, as shown in Equation (1). The Manning roughness coefficient and the friction slope are calculated using Equations (2) and (3), respectively.

$$Q = \frac{1}{n} A R^{2/3} S_f^{1/2} \tag{1}$$

$$n = \frac{1}{U} R^{2/3} S_f^{1/2} \tag{2}$$

$$S_f = \frac{h_f}{l} \tag{3}$$

where Q is the flow discharge, n is the Manning roughness coefficient, A is the cross-sectional area of the flow, R is the hydraulic radius, U is the average flow velocity, S_f is the friction slope, h_f is the friction head loss, and l is the length of water along the course.

Dimensional analysis based on Buckingham's theory is used to develop a functional relationship between the Manning roughness coefficient and the other relevant variables. The roughness coefficient n can be expressed as shown in Equation (4). The density of submerged and floating vegetation are calculated using Equations (5) and (6), respectively.

$$n = f\left(B, h_{def}, y, S, l, I_s, I_f, Q, U, \rho, g\right) \tag{4}$$

$$I_s = \frac{1}{a_x a_y} \tag{5}$$

$$I_f = \frac{1}{a_{\bar{x}} a_{\bar{y}}} \tag{6}$$

where B is the channel width, h_{def} is the deflected height of submerged vegetation, y is the flow depth, S is the channel bed slope, I_s is the density of submerged vegetation, I_f is the density of floating vegetation, ρ is the density of water, g is the gravitational acceleration, a_x is the longitudinal spacing of submerged vegetation, a_y is the transverse spacing of submerged vegetation, $a_{\bar{x}}$ is the longitudinal spacing of floating vegetation, and $a_{\bar{y}}$ is the transverse spacing of floating vegetation.

Applying the Buckingham theory with y, U, and ρ as repeating variables, Equation (7) can be written in dimensionless form as:

$$n = f\left(F, S, S_f, I_s, I_f, \frac{h_{def}}{y}\right) \tag{7}$$

where the F is the Froude number, and h_{def}/y is the submerged ratio.

4.EXPERIMENTAL WORK

The experimental work is conducted in the hydraulic laboratory of the Hydraulic Research Institute in Alqanatir Alkhayria, Egypt. The experiments are carried out using a reinforced concrete flume with a length of 20.0 m, a width of 0.60 m, and a height of 0.65 m. A hydraulic circuit is established by connecting the inlet and outlet of the flume. Gravel filters are installed at the entrances to dissipate excess energy and achieve a uniform flow distribution. A tailgate, fixed at the end of the flume, is used to control the tailwater depth. The schematic drawing of the experimental setup is shown in Figure 1.

The ultrasonic flow meter is installed on the feeding pipe to measure the passing discharge into the flume. Tests are conducted at different discharges of 25.0, 30.0, 35.0, and 40.0 *l/sec*, and at different tailwater depths of 0.25, 0.30, and 0.35 *m*. The channel bed slope is adjusted to values of 0.0010, 0.0020, 0.0023, 0.0049, and 0.0062. The Electromagnetic Current Meter (EMS), manufactured by Delft Hydraulics in Netherlands, is used to measure flow velocity. The velocity is measured in both the longitudinal and transverse directions. In the longitudinal direction, velocities are measured at seven different cross-sections located at distances of 2.50, 5.00, 7.50, 10.00, 12.50, 15.00, and 17.50 *m* from the inlet. In the transverse direction, velocities are measured at five different points, located at distances of 0.10, 0.20, 0.30, 0.40, and 0.50 *m* from the side of the flume for each cross-section. In the vertical direction, velocity is measured at 0.20, 0.60, and 0.80 of the flow depth from the water surface at every point. Additionally, at the centerline of the flume, velocity is measured at further flow depths of 0.90 and 0.95 of flow depth. The flow depths are measured along the channel centerline using a point gauge mounted on a traveling instrument bridge. The average of the mean velocity is used to calculate the Manning roughness coefficient.

To simulate the behavior of naturally submerged vegetation, artificial flexible elements made from perspex are used, as shown in Figure 2 (a). The vegetation height is 0.22 *m*, with a density of 246 *stems*/m^2. The floating vegetation consist of two parts: the floating part is made of foam with a height of 0.03 *m*, and the submerged part is made of aluminum wires, also with a height of 0.03 *m*, as shown in Figure 2 (b). The density of the floating vegetation is 5000 *stems*/m^2. Shaheen et al. [50] studied the effect of the density of submerged and floating vegetation on the Manning roughness coefficient. The submerged vegetation density ranged from 62 to 246 *stems*/m^2, while the floating vegetation density ranged from 1250 to 5000 *stems*/m^2, and the bed slope was 0.0062. It was recommended that, in the case of submerged and floating vegetation with densities of 246 and 5000 *stems*/m^2, respectively, the maximum value of the Manning roughness coefficient was achieved compared to other vegetation densities. Therefore, these values have been used in this study.

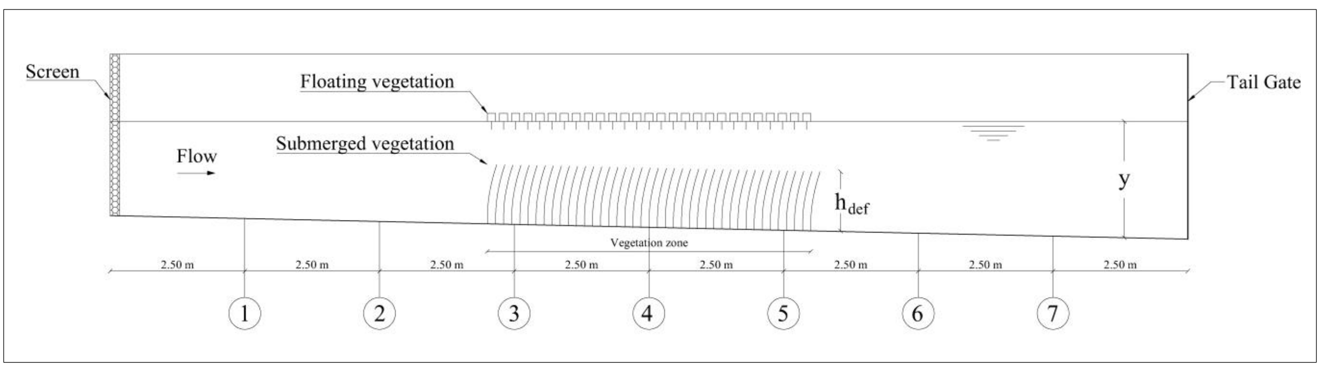

Figure 1: Schematic diagram for the experimental setup (long view, not to scale).

The vegetation region is 6.0 *m* long and is located at a distance of 7.0 *m* from the inlet. Flow characteristics are measured at seven sections, with a distance of 2.50 *m* between each section. Sections 1, 2, 6, and 7 are located outside of the vegetation area. Sections 3 and 4 are located at the edge of the vegetation area. Section 5 is located at the center of the vegetation area. Tests are conducted in both the presence and absence of vegetation.

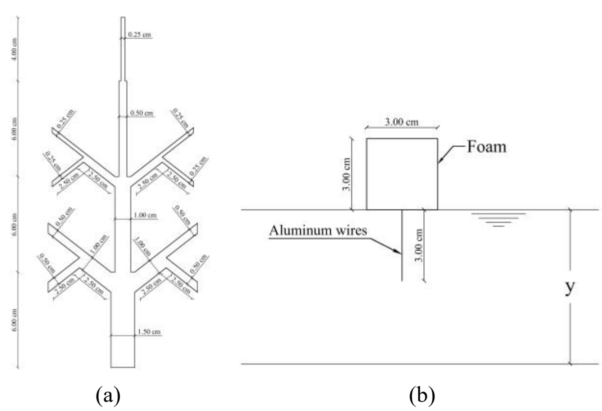

Figure 2: Artificial vegetation; a) submerged vegetation, and b) floating vegetation.

5.RESULTS AND DISCUSSIONS

5.1. The Effect of Bed Slope on the Roughness Coefficient

In non-vegetated scenarios, sixty experimental tests have been conducted to investigate the effect of the bed slope on the roughness coefficient. Five bed slopes are applied: 0.0010, 0.0020, 0.0023, 0.0049, and 0.0062. The velocity has been measured to range from 0.06 *m*/*sec* to 0.46 *m*/*sec*. The Froude number for each run indicates that the flow condition is classified as subcritical flow, with values ranging from 0.075 to 0.218. In each experimental run, the roughness coefficient is calculated using the Manning Equation. A power function is employed to plot the relationship between the calculated roughness coefficient and the Froude number. Figure 3 illustrates the relationship between the roughness coefficient and Froude number for different bed slopes.

It is observed that the roughness coefficient increases with an increase in bed slopes, while it decreases with an increase in the Froude number. Gradually, as the Froude number rises, the roughness coefficient approaches a constant asymptotic value. The roughness coefficient ranges as follows: 0.0210 to 0.0386, 0.0224 to 0.0388, 0.0196 to 0.0386, 0.0239 to 0.0446, and 0.0300 to 0.0585 for slopes of 0.0010, 0.0020, 0.0023, 0.0049, and 0.0062, respectively. Compared to the slope of 0.0010, the roughness coefficient increases by factors of 1.14, 1.25, 1.35, and 1.62 for slopes of 0.0020, 0.0023, 0.0049, and 0.0062, respectively. Consequently, the bed slope is an important factor that influences the roughness coefficient, which ranges from 0.0196 to 0.0585.

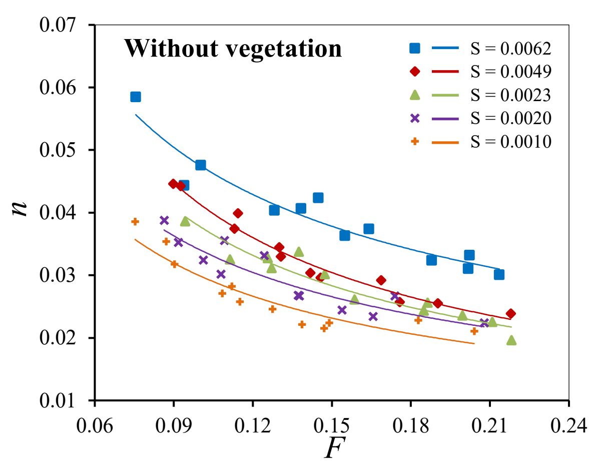

Figure 3: Relationship between *n* and *F* for different bed slopes *S* in a channel without vegetation.

5.2. The Effect of Vegetation on the Roughness Coefficient

In vegetated scenarios, sixty experimental tests have been conducted to investigate the effect of submerged and floating vegetation on the roughness coefficient. Three submerged ratios are applied: 0.69, 0.80, and 0.94. The velocity has been measured to range from 0.07 *m*/*sec* to 0.37 *m*/*sec*. The Froude number for each run indicates that the flow condition is classified as subcritical flow, with values ranging from 0.078 to 0.200. Figure 4 shows the vertical distributions of streamwise velocity for Non-vegetated channels and the upstream section of vegetated channels, with a bed slope of 0.0062, a submerged ratio of 0.94, and a discharge of 40 *l*/*sec*. Where *z* is the distance from the measurement point to the bed, *y* is the water depth, and *u* is the streamwise velocity at that point. The velocity profile in non-vegetated channels exhibits a logarithmic relationship with water depth, a pattern also observed in the upstream section of vegetation. Figures 5, 6, and 7 illustrate the relationship between the roughness coefficient and the Froude number for different bed slopes in both non-vegetated and vegetated channels at submerged ratios of 0.69, 0.80, and 0.94, respectively. The roughness coefficient also shows an increase with an increase in bed slopes and a decrease with an increase in the Froude number, which is consistent with the conclusions of Zhang et al. [40]. In addition, the roughness coefficient increases when vegetation cover is present compared to its absence.

Under the same conditions of a vegetated submerged ratio of 0.69, the roughness coefficient increases compared to the non-vegetated slope, increasing by factors of 1.26, 1.30, 1.35, 1.34, and 1.38 for slopes of 0.0010, 0.0020, 0.0023, 0.0049, and 0.0062, respectively. At a submerged ratio of 0.80, the roughness coefficient increases by factors of 2.25, 2.18, 2.22, 2.33, and 2.22 for the same slopes. Similarly, for a submerged ratio of 0.94, the roughness coefficient increases by factors of 3.15, 3.05, 2.97, 2.91, and 2.73 for the same slopes.

The vegetation acts as an obstacle to the flow, which leads to an increase in water level on the upstream side, then decreases within the vegetated zone and gradually returns to the normal depth downstream of the vegetated zone. This observation agreed with previous studies (Pasha and Tanaka, 51; Rashedunnabi and Tanaka, 52; Anjum and Tanaka, 53; Ahmed et al., 54; Eraky et al., 55). The difference in water levels between the upstream and downstream leads to an increase in the friction slope. When the water depth increases, the average flow velocity decreases. According to the Manning equation, the roughness coefficient increases as the friction slope increases and the velocity decreases. Consequently, vegetation leads to an increase in the roughness coefficient, which ranges from 0.0353 to 0.1125. This was similar to the conclusions drawn by Gad et al. [11], which indicated that the roughness coefficient was greater in the case of the grassed canal than in the un-grassed canal.

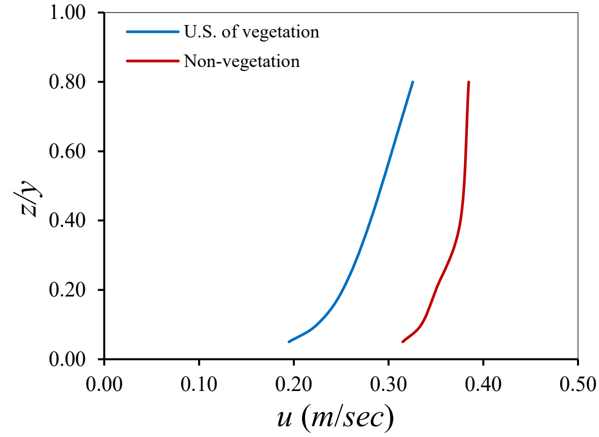

Figure 4: Vertical distribution of streamwise velocity for Non-vegetated channels and the upstream section of vegetated channels, with S = 0.0062, h_{def}/y = 0.94, and Q = 40 *l/sec*.

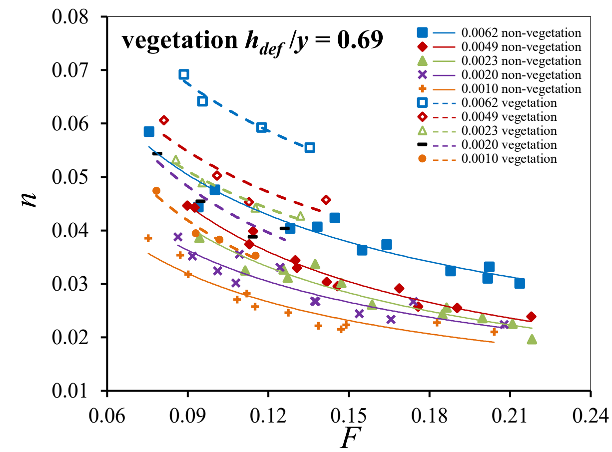

Figure 5: Relationship between n and F for different bed slopes S in Non-vegetated and vegetated channels at h_{def}/y = 0.69.

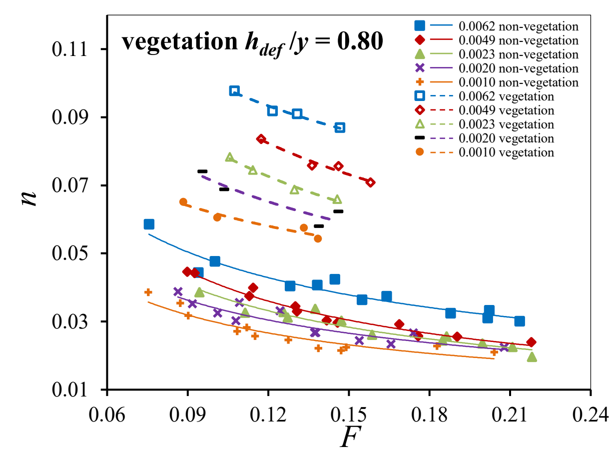

Figure 6: Relationship between n and F for different bed slopes S in Non-vegetated and vegetated channels at h_{def}/y = 0.80.

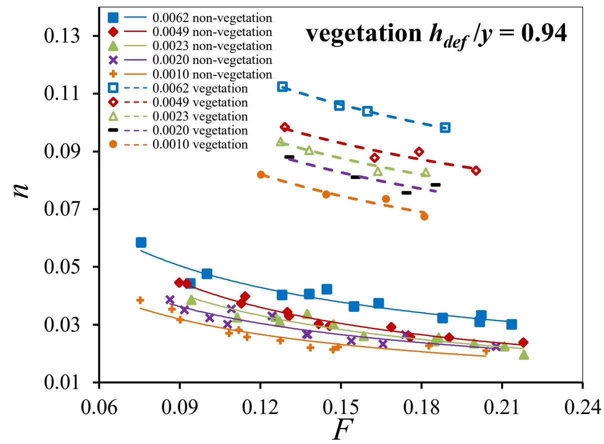

Figure 7: Relationship between n and F for different bed slopes S in Non-vegetated and vegetated channels at h_{def}/y = 0.94.

5.3. The Effect of Submerged Ratio on the Roughness Coefficient

The effect of the submerged ratio on the roughness coefficient has been examined, with the submerged ratio analyzed in a range from 0.69 to 0.94. The degree of submergence is defined as the ratio of the deflected height of submerged vegetation to flow depth. The relationship between the roughness coefficient and the Froude number for different submerged ratios at bed slopes of 0.0010, 0.0020, 0.0023, 0.0049, and 0.0062 is shown in Figures 8, 9, 10, 11, and 12, respectively.

Under the same bed slope conditions, the roughness coefficient increases with increasing submerged ratios and decreases with an increasing Froude number. For the bed slope of 0.0010, the roughness coefficient increases with increasing submerged ratios compared to the non-vegetated case, with factors of 1.26, 2.25, and 3.15 for submerged ratios of 0.69, 0.80, and 0.94, respectively. At a bed slope of 0.0020, the roughness coefficient increases by factors of 1.30, 2.18, and 3.05 for the same submerged ratios. Similarly, at a bed slope of 0.0023, the roughness coefficient increases by factors of 1.35, 2.22, and 2.97. At a slope of 0.0049, it further increases by factors of 1.34, 2.33, and 2.91. Finally, for a bed slope of 0.0062, the roughness coefficient increases by factors of 1.38, 2.22, and 2.73 for the same submerged ratios. Rizalihadi et al. [4] and Gad et al. [11] indicated that the roughness coefficient increased with increasing vegetation height and gradually approached a constant value at a high Froude number. Huthoff et al. [56] stated that the roughness coefficient decreased with a decreasing submerged ratio and approached a constant value when the submerged ratio was less than 0.20. Hinsberger et al. [6] indicated that the roughness remained constant at a submerged ratio of less than 0.17. Wilson and Horritt [2] found that the roughness coefficient reached a constant value at a submerged ratio of 0.33.

Notably, when the submerged ratio exceeds 0.69, the roughness coefficient increases rapidly with further increases in the submerged ratio. For instance, at a submerged ratio of 0.69, the roughness coefficient increases by a factor ranging from 1.26 to 1.38. At a submerged ratio of 0.80, it increases by a factor ranging from 2.18 to 2.33, which is nearly double. Thus, the submerged ratio plays a vital role in significantly affecting the roughness coefficient.

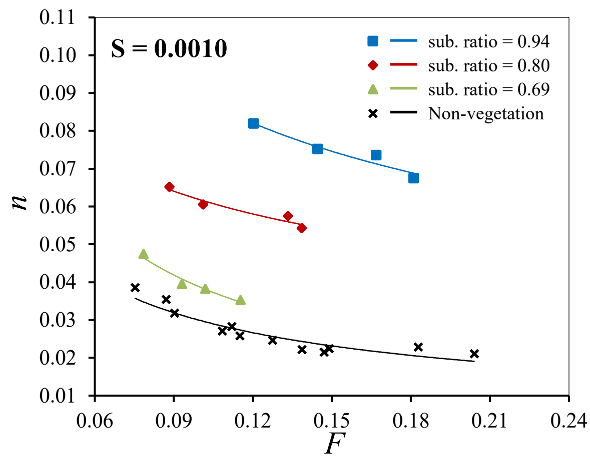

Figure 8: Relationship between *n* and *F* at *S* = 0.0010 for different submerged ratio and Non-vegetated case.

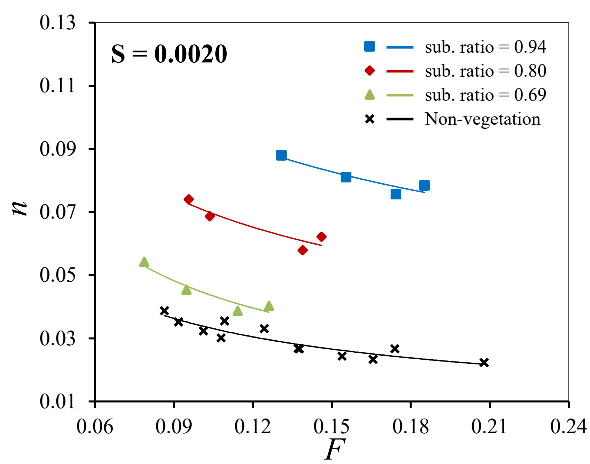

Figure 9: Relationship between *n* and *F* at *S* = 0.0020 for different submerged ratio and Non-vegetated case.

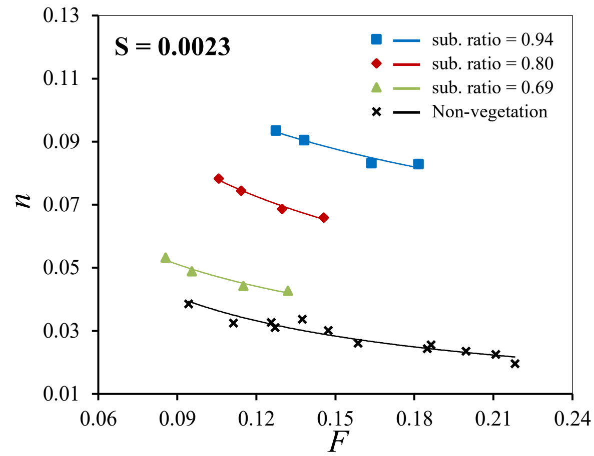

Figure 10: Relationship between *n* and *F* at *S* = 0.0023 for different submerged ratio and Non-vegetated case.

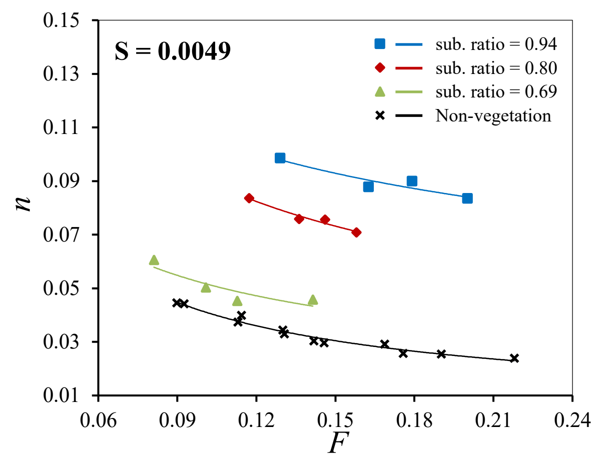

Figure 11: Relationship between *n* and *F* at *S* = 0.0049 for different submerged ratio and Non-vegetated case.

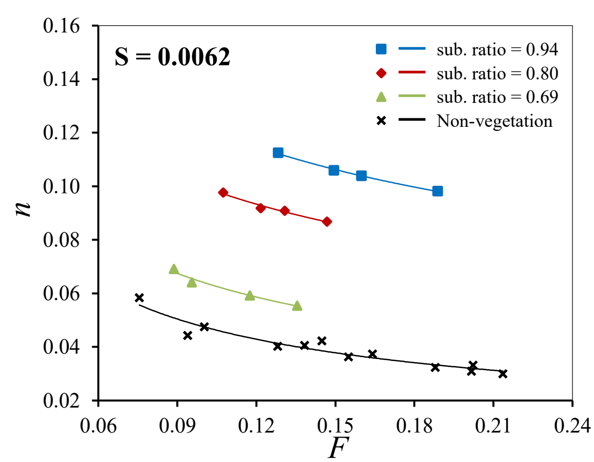

Figure 12: Relationship between *n* and *F* at *S* = 0.0062 for different submerged ratio and Non-vegetated case.

6.STATISTICAL REGRESSION

In the case of non-vegetated channels, the roughness coefficient is expressed as a function of the Froude number and friction slope, as shown in Equation (8). The results indicate that both the Froude number and the friction slope influence the roughness coefficient. By increasing the Froude number, the roughness coefficient decreases, while an increase in the friction slope leads to an increase in the roughness coefficient. The Froude number is the most significant parameter. Figure 13 illustrates a comparison between the predicted and calculated roughness coefficient for a channel without vegetation, including ±10% error lines. The correlation coefficient R^2 of Equation (8) is calculated to be 0.96, indicating a strong correlation between the variables.

$$n = 0.1\, F^{-0.9} S_f^{0.41} \tag{8}$$

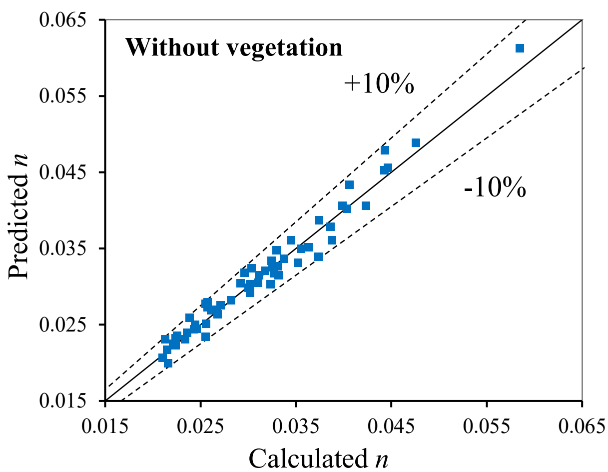

Figure 13: Comparison between predicted and calculated roughness coefficient for a channel without vegetation and ±10% error lines.

In the case of a vegetated channel, a correction factor is included in Equation (8) to account for the effect of the submerged ratio, as shown in Equations (9) and (10). The exponent value of this correction factor depends on the submerged ratio and exhibits a first-degree polynomial relationship with it. As the submerged ratio increases, the roughness coefficient also increases. Additionally, the roughness coefficient shows a high correlation with the Froude number, friction slope, and submerged ratio. Figures 14 and 15 illustrate comparisons between the predicted and calculated roughness coefficients for a vegetated channel at submerged ratio ranges of 0.69 to 0.80 and 0.80 to 0.94, respectively, including ±10% error lines. The correlation coefficients R^2 for Equations (9) and (10) are calculated to be 0.98 and 0.97, respectively. The results indicate a strong agreement between the calculated and predicted roughness coefficient values for all experimental data.

$$n = 0.1\, F^{-0.9} S_f^{0.41} \left(\frac{h_{def}}{y}\right)^{-6.24\left(\frac{h_{def}}{y}\right)+4.02} \qquad 0.80 \geq \frac{h_{def}}{y} \geq 0.69 \tag{9}$$

$$n = 0.1\, F^{-0.9} S_f^{0.41} \left(\frac{h_{def}}{y}\right)^{-38.11\left(\frac{h_{def}}{y}\right)+31.43} \qquad 0.94 \geq \frac{h_{def}}{y} \geq 0.80 \tag{10}$$

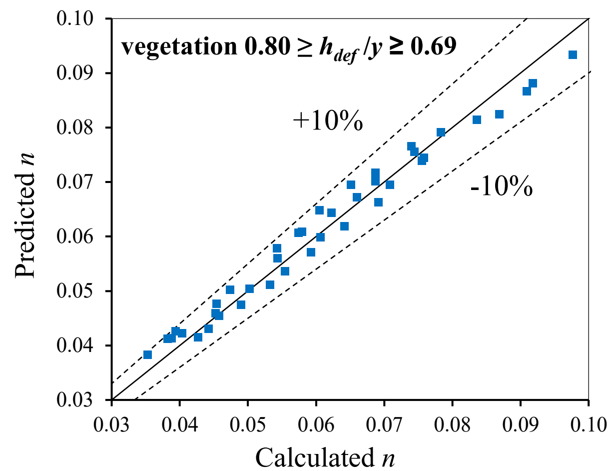

Figure 14: Comparison between predicted and calculated roughness coefficient for vegetated channel at submerged ratio range from 0.69 to 0.80 and ±10% error lines.

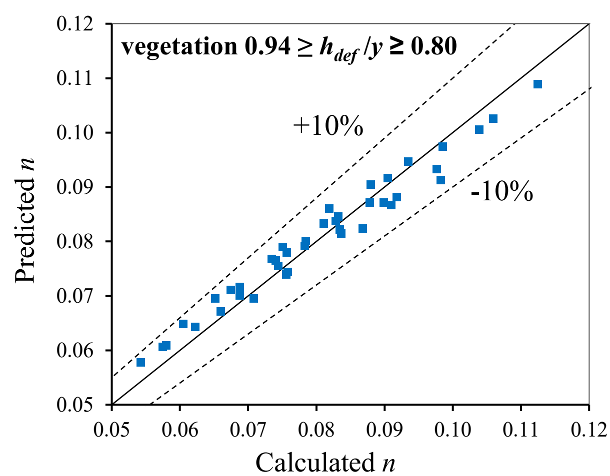

Figure 15: Comparison between predicted and calculated roughness coefficient for vegetated channel at submerged ratio range from 0.80 to 0.94 and ±10% error lines.

7.CONCLUSIONS

This study presents the effect of submerged and floating vegetation on the Manning roughness coefficient in an open channel, with densities of 246 *stems*/*m*² for submerged vegetation and 5000 *stems*/*m*² for floating vegetation. Generally, the following conclusions have been drawn from this research:

1. The roughness coefficient decreases with an increase in the Froude number.
2. Gradually, as the Froude number rises, the roughness coefficient approaches a constant asymptotic value.
3. The roughness coefficient increases rapidly when the submerged ratio exceeds 0.69.
4. New empirical equations have been developed to estimate the roughness coefficient in both non-vegetated and vegetated channels.

8.REFERENCES

[1] Wu, F., Shen, H.W., and Chou, Y. (1999) "Variation of roughness coefficients for unsubmerged and submerged vegetation." *Journal of hydraulic engineering* *125*(9), 934-942 https://doi.org/10.1061/(ASCE)0733-9429(1999)125:9(934).

[2] Wilson, C.A.M.E., Horritt, M.S. (2002) "Measuring the flow resistance of submerged grass." *Hydrological Processes* *16*(13), 2589-2598 https://doi.org/10.1002/hyp.1049.

[3] Wilson, C.A.M.E. (2007) "Flow resistance models for flexible submerged vegetation." *Journal of Hydrology* *342*(3-4), 213-222 https://doi.org/10.1016/j.jhydrol.2007.04.022.

[4] Rizalihadi, M., Shaskia, N., and Asharly, H. (2018) "The effect of ratio between rigid plant height and water depth on the Manning's coefficient in open channel." *IOP Conference Series: Materials Science and Engineering* *352*(1), 012039 https://doi.org/10.1088/1757-899X/352/1/012039.

[5] Schugerl, R., Veliskova, Y., Dulovicova, R., and Socuvka, V. (2021) "Influence of submerged vegetation on the Manning's roughness coefficient for gabčíkovo–topoľníky channel." *Acta Hydrologica Slovaca* *22*(1), 61-69 https://doi.org/10.31577/ahs-2021-0022.01.0007.

[6] Hinsberger, R., Biehler, A., and Yörük, A. (2022) "Influence of Water Depth and Slope on Roughness—Experiments and Roughness Approach for Rain-on-Grid Modeling." *water* *14*(24), 4017 https://doi.org/10.3390/w14244017.

[7] Orakwe, L.C., Ogbu, K.N., Ubah, J.I., Nwachukwu, C.P., Akamonye, R.C., and Okoro, U.P. (2022) "Determination of Hydraulic Roughness Coefficients of Some Vegetated Species in Awka, Nigeria." *ASM Science Journal* *17* https://doi.org/10.32802/asmscj.2022.1008.

[8] Chen, Z., Zhou, J., and Chen, Q. (2023) "Research and Application of the Calculation Method of River Roughness Coefficient with Vegetation." *water* *15*(14), 2638 https://doi.org/10.3390/w15142638.

[9] Zhang, S., Li, G., He, X., Liu, Y., and Wang, Z. (2019) "Water flow resistance characteristics of double-layer vegetation in different submerged states." *Water Supply* *19*(8), 2435-2442 https://doi.org/10.2166/ws.2019.125.

[10] Chen, Y., Kao, S., Lin, J., and Yang, H. (2009) "Retardance coefficient of vegetated channels estimated by the Froude number." *Ecological Engineering* *35*(7), 1027-1035 https://doi.org/10.1016/j.ecoleng.2009.03.002.

[11] Gad, M., sobeih, M.F., Rashwan, I.M.H., and Helal, E. (2020) "Hydraulic features of flow through grassed canal." *Innovative Infrastructure Solutions 5* 1-14 https://doi.org/10.1007/s41062-020-00308-9.

[12] Fathi-Moghadam, M., Drikvandi, K. (2012) "Manning roughness coefficient for rivers and flood plains with non-submerged vegetation." *International Journal of Hydraulic Engineering* *1*(1), 1-4 https://doi.org/10.5923/j.ijhe.20120101.01.

[13] Yusof, K.W., Muhammad, M.M., Mustafa, M.R.U., Zakaria, N.A., and Gahani, A.A. (2017) "Analysis of Manning's and drag coefficients for flexible submerged vegetation." *IOP Conference Series: Materials Science and Engineering 216*(1), 012046 https://doi.org/10.1088/1757-899X/216/1/012046.

[14] Barinas, G., Good, S.P., and Tullos, D. (2024) "Continental scale assessment of variation in floodplain roughness with vegetation and flow characteristics." *Geophysical Research Letters 51*(1), e2023GL105588 https://doi.org/10.1029/2023GL105588.

[15] Muhammad, M.M., Yusof, K.W., Mustafa, M.R.U., Zakaria, N.A., and Ab Ghani, A. (2018) "Prediction models for flow resistance in flexible vegetated channels." *International journal of river basin management* *16*(4), 427-437 https://doi.org/10.1080/15715124.2018.1437740.

[16] Jarvela, J. (2004) "Determination of flow resistance caused by non-submerged woody vegetation." *International journal of river basin management* *2*(1), 61-70 https://doi.org/10.1080/15715124.2004.9635222.

[17] Nikora, V., Larned, S., Nikora, N., Debnath, K., Cooper, G., and Reid, M. (2008) "Hydraulic resistance due to aquatic vegetation in small streams: field study." *Journal of hydraulic engineering* *134*(9), 1326-1332 https://doi.org/10.1061/(ASCE)0733-9429(2008)134:9(1326).

[18] Meng, X., Zhou, Y., Sun, Z., Ding, K., and Chong, L. (2021) "Hydraulic characteristics of emerged rigid and submerged flexible vegetations in the riparian zone." *water* *13*(8), 1057 https://doi.org/10.3390/w13081057.

[19] Rhee, D.S., Woo, H., Kwon, B.A., and Ahn, H.K. (2008) "Hydraulic resistance of some selected vegetation in open channel flows." *River research and applications* *24*(5), 673-687 https://doi.org/10.1002/rra.1143.

[20] Vinatier, F., Bailly, J.S., and Belaud, G. (2017) "From 3D grassy vegetation point cloud to hydraulic resistance: Application to close-range estimation of Manning coefficients for intermittent open channels." *Ecohydrology* *10*(8), e1885 https://doi.org/10.1002/eco.1885.

[21] Bora, P., Misra, U.K. (2018) "An experimental study on effect of flexibility of vegetation on resistance to flow." *International Research Journal of Engineering and Technology (IRJET) 5*(2),

[22] Chembolu, V., Kakati, R., and Dutta, S. (2019) "A laboratory study of flow characteristics in natural heterogeneous vegetation patches under submerged conditions." *Advances in Water Resources 133* 103418 https://doi.org/10.1016/j.advwatres.2019.103418.

[23] Zhang, S., Liu, Y., Wang, Z., Li, G., Chen, S., and Liu, M. (2020) "Effects of slope and flow depth on the roughness coefficient of lodged vegetation." *Environmental Earth Sciences 79* 1-12 https://doi.org/10.1007/s12665-020-8893-9.

[24] Silva-Araya, W., Rodríguez-Quiñones, E. (2023) "Vegetative Flow Resistance for Erosion Control Using Grass Species from the Caribbean Region." *Sustainability* *15*(8), 6580 https://doi.org/10.3390/su15086580.

[25] Zhang, J., Cheng, L., Zhang, B., Yuan, M., Jia, S., Miao, D., and Huang, C. (2024) "Investigation of the Influence of Reed Vegetation on the Hydraulic Characteristics of the Huai River Inflow Channel." *water* *16*(11), 1540 https://doi.org/10.3390/w16111540.

[26] Carollo, F.G., Ferro, V., and Termini, D. (2005) "Flow resistance law in channels with flexible submerged vegetation." *Journal of hydraulic engineering* *131*(7), 554-564 https://doi.org/10.1061/(ASCE)0733-9429(2005)131:7(554).

[27] Abood, M.M., Yusuf, B., Mohammed, T.A., and Ghazali, A.H. (2006) "Manning roughness coefficient for grass-lined channel." *Journal of Science and Technology 13*(4), 317-330

[28] Musleh, F.A., Cruise, J.F. (2006) "Functional relationships of resistance in wide flood plains with rigid unsubmerged vegetation." *Journal of hydraulic engineering* *132*(2), 163-171 https://doi.org/10.1061/(ASCE)0733-9429(2006)132:2(163).

[29] Ebrahimi, N.G., Fathi-Moghadam, M., Kashefipour, S.M., Saneie, M., and Ebrahimi, K. (2008) "Effects of flow and vegetation states on river roughness coefficients." *Journal of Applied Sciences 8*(11), 2118-2123 https://doi.org/10.3923/jas.2008.2118.2123.

[30] Wu, F.S. (2008) "Characteristics of flow resistance in open channels with non-submerged rigid vegetation." *Journal of Hydrodynamics, Ser. B 20*(2), 239-245 https://doi.org/10.1016/S1001-6058(08)60052-9.

[31] Fathi-Moghadam, M., Kashefipour, M., Ebrahimi, N., and Emamgholizadeh, S. (2011) "Physical and numerical modeling of submerged vegetation roughness in rivers and flood plains." *Journal of Hydrologic Engineering 16*(11), 858-864 https://doi.org/10.1061/(ASCE)HE.1943-5584.0000381.

[32] Xu, W.G., Zhang, H.Y., Wang, Z.Y., and Huang, W.P. (2012) "A study of Manning coefficient related with vegetation density along the vegetated channel." *Applied Mechanics and Materials 212* 744-747 https://doi.org/10.4028/www.scientific.net/AMM.212-213.744.

[33] Xia, J., Nehal, L. (2013) "Hydraulic features of flow through emergent bending aquatic vegetation in the riparian zone." *water* (5), 2080-2093 https://doi.org/10.3390/w5042080.

[34] Rizalihadi, M., Safiana, D. (2015) "The presence of jeringau (Acorus calamus) as flexible vegetation type in the channel against flow resistance." *Procedia Engineering 125* 250-256 https://doi.org/10.1016/j.proeng.2015.11.036.

[35] Ye, C., Liu, X., and Wang, X. (2015) "Effects of roughness elements distribution on overland flow resistance." *Journal of Mountain Science 12*(5), 1145-1156 https://doi.org/10.1007/s11629-014-3391-8.

[36] Zhang, K., Wang, Z., Wang, G., Sun, X., and Cui, N. (2017) "Overland-flow resistance characteristics of nonsubmerged vegetation." *Journal of Irrigation and Drainage Engineering 143*(8), 04017021 https://doi.org/10.1061/(ASCE)IR.1943-4774.0001196.

[37] Rizalihadi, M. (2019) "The effect of density and height of vegetation in open channel on the Manning's coefficient." *MATEC web of conferences 258* 01002 https://doi.org/10.1051/matecconf/201925801002.

[38] Shafaei, H., Amini, A., and Shirdeli, A. (2019) "Assessing submerged vegetation roughness in streambed under clear water condition using physical modeling." *Water Resources 46*(3), 377-383 https://doi.org/10.1134/S0097807819030084.

[39] Cai, Z., Wang, J., Yang, Y., and Zhang, R. (2021) "Influence of vegetation coverage on hydraulic characteristics of overland flow." *water 13*(8), 1055 https://doi.org/10.3390/w13081055.

[40] Zhang, J., Zhang, S., Chen, S., Liu, M., Xu, X., Zhou, J., Wang, W., Ma, L., and Wang, C. (2021) "Overland flow resistance law under sparse stem

vegetation coverage." *water 13*(12), 1657 https://doi.org/10.3390/w13121657.
[41] Kiss, T., Nagy, J., Fehervary, I., and Vaszko, C. (2019) "(Mis) management of floodplain vegetation: The effect of invasive species on vegetation roughness and flood levels." *Science of the Total Environment 686* 931-945 https://doi.org/10.1016/j.scitotenv.2019.06.006.
[42] Derakhshan, S., Afzalimehr, H., and Singh, V.P. (2021) "Effect of vegetation patch distribution on the flow resistance." *International Journal of Hydraulic Engineering 10* 19-25 https://doi.org/10.5923/j.ijhe.20211001.03.
[43] Derakhshan, S., Dodangeh, E., Afzalimehr, H., Nazari-Sharabian, M., Raeisifar, H., and Karakouzian, M. (2022) "Effect of Vertical Variation of Submerged Vegetation Density on the Flow Resistance." *Hydrology 9*(11), 191 https://doi.org/10.3390/hydrology9110191.
[44] Nicosia, A., Carollo, F.G., Palmeri, V., and Ferro, V. (2023) "Flow resistance of flexible vegetation in real-scale drainage channels." *Hydrological Processes 37*(5), e14883 https://doi.org/10.1002/hyp.14883.
[45] Kouwen, N., Fathi-Moghadam, M. (2000) "Friction factors for coniferous trees along rivers." *Journal of hydraulic engineering 126*(10), 732-740 https://doi.org/10.1061/(ASCE)0733-9429(2000)126:10(732).
[46] James, C.S., Birkhead, A.L., Jordanova, A.A., and Osullivan, J.J. (2004) "Flow resistance of emergent vegetation." *Journal of Hydraulic Research 42*(4), 390-398 https://doi.org/10.1080/00221686.2004.9641206.
[47] Green, J.C. (2006) "Effect of macrophyte spatial variability on channel resistance." *Advances in Water Resources 29*(3), 426-438 https://doi.org/10.1016/j.advwatres.2005.05.010.
[48] Li, Y., Wang, Y., Anim, D.O., Tang, C., Du, W., Ni, L., Yu, Z., and Acharya, K. (2014) "Flow characteristics in different densities of submerged flexible vegetation from an open-channel flume study of artificial plants." *Geomorphology 204* 314-324 https://doi.org/10.1016/j.geomorph.2013.08.015.
[49] Abd-Elmoaty, M.S., El-Samman, T.A. (2020) "Manning roughness coefficient in vegetated open channels." *Water Science 34*(1), 121-128 https://doi.org/10.1080/11104929.2020.1794706.
[50] Shaheen, M.F., Abdel-Aal, G.M., Ahmed, A.A., and Ali, A.M. (2014) "Studying of flow characteristics in channels invested by aquatic weeds." *Zagazig University*
[51] Pasha, G.A., Tanaka, N. (2017) "Undular hydraulic jump formation and energy loss in a flow through emergent vegetation of varying thickness and density." *Ocean Engineering 141* 308-325 https://doi.org/10.1016/j.oceaneng.2017.06.049.
[52] Rashedunnabi, A.H.M., Tanaka, N. (2018) "Physical modelling of tsunami energy reduction through vertically two layered rigid vegetation." *Proceedings of the 12th ISE, Tokyo, Japan* 19-24
[53] Anjum, N., Tanaka, N. (2020) "Experimental study on flow analysis and energy loss around discontinued vertically layered vegetation." *Environmental fluid mechanics 20*(4), 791-817 https://doi.org/10.1007/s10652-019-09723-8.
[54] Ahmed, A., Valyrakis, M., Ghumman, A., Pasha, G.A., and Farooq, R. (2021) "Experimental investigation of flood energy reduction through vegetation at various angles." *River research and applications 37*(4), 644-655 https://doi.org/10.1002/rra.3777.
[55] Eraky, O.M., Eltoukhy, M.A.R., Abdelmoaty, M.S., and Farouk, E. (2023) "Heading up and head losses estimation due to rigid bank vegetation." *Engineering Research Journal (Shoubra) 52*(1), 64-72
[56] Huthoff, F., Augustijn, D.C.M., and Hulscher, S.J.M.H. (2007) "Analytical solution of the depth-averaged flow velocity in case of submerged rigid cylindrical vegetation." *Water Resources Research 43*(6), https://doi.org/10.1029/2006WR005625.