International Symposium on Water Management and Hydraulic Engineering
Ohrid/Macedonia, 1-5 September 2009

Paper: **A01**

Methods of Roughness Coefficient Determination in Natural Riverbeds

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Abstract. The roughness coefficient determination in natural river beds is based on the analysis of boundary layer development along the canal walls. The structure of the open canal can be very complex and changeable which results in different evaluation methods of determining the roughness coefficient *n*. A considerable number of measured valued for similar surface canal characteristics are analyzed in order to determine the roughness coefficient for the observed natural canal. The paper offers parameters which affect the roughness coefficient variability in beds. The roughness coefficient variability along the flow which depends on water level changes has been additionally described and graphically presented. The paper presents the vertical velocity profiles which are result of the aquatic vegetation. The paper offers review of the most represented methods of roughness coefficient evaluation used in practice, as well as numerous empiric methods based on the grading structure of the slopes and the bottom of the canal as well as methods based on measuring data.

Keywords: Roughness coefficient, boundary layer, evaluation methods, vertical velocity profile

1 Introduction

Determination of the roughness coefficient presents a provocative and a creative task of the contemporary hydraulics of open flows. An initially simple determination of the roughness coefficient *n* becomes a very complex problem because the coefficient has been changing in time and space depending on geometric, geomorphological and hydraulic parameters of water current beds. It is an interdisciplinary task because it includes the knowledge of hydrology, statistical data processing, hydromechanics, hydraulics, geology and mechanics.

All more pronounced appearances of the large watery waves in water currents, to which regulated water currents are no exception, are a consequence of both noted climatic changes and inappropriate water-managing solutions. Although regular conceptions of water-managing solutions have the crucial influence on the efficiency of flood protection system, the inappropriate functioning of sewage systems is also to be found at conceptually well set solutions, but with inappropriate hydraulic dimensioned systems [1]. Most often it is the result of negligence during the design phase when the conditions of bed state were idealized during the exploitation phase. The designed state which was mostly constructed by the design is liable to changes in bed geometry and bottom fall. The plant cover state often significantly varies from the designed conditions [2].

The surface roughness n of natural beds varies along the wetted canal scope. In the drain trench, for example, rocky bottom with concrete slopes for erosion protection can be found. In that case the coefficient n will be different for low waters in respect to larger depths at the flowing. Similar to this, the river bed can have one value of the roughness coefficients n appropriate for its normal flow and another value of the coefficient n for flood periods when the flow also occurs in flood retention areas.

A canal covered in ice often has different values of the roughness coefficient n for the considerably reduced water level [2], [3]. Such a canal is not an “open” canal, although the analysis of such flowing has often been based on equations for flow in open canals. This is acceptable as long as the icy cover is thin enough to make the firm border in the conditions of shear stress resistance. For a more accurate determination of the roughness coefficient the bed can be divided into more subareas. By doing so a separate roughness coefficient n is then determined for each subarea. This kind of calculation is more accurate in relation to methods by using of which the coefficient n is obtained based on the total surface of the bed cross section [2], [4].

2 Roughness Coefficient of Natural River Beds in General

Unlike the constructed canals, the natural river beds (lowland and mountain watercourses, rivers and streams) have irregular shapes of cross sections, changes of the bottom slopes and numerous curves along their flow. The changes of hydraulic parameters along the flow, the presence of shallow waters and hydrodynamic forces which influence the changes along the length and the depth of the flow (Figure 1) are very frequent. The natural regime of river flows can be abruptly changed due to construction of dams, water-storage facilities and other hydropower structures in river beds. Thus the dams provoke the reducing of the flow which sometimes extends also to several dozen of kilometers upstream from the dam [1].

The roughness coefficient of natural beds depends on many factors, the most significant of those being the corresponding basic bed roughness, the irregularity of cross section shapes, the occurrence of gullies in the bed, the wearing away of the alluviums and other. Experience has shown that the roughness coefficient changes not only along the bed [5], [6], but also when the water level changes occur (Figure 2).

This is the reason why the roughness coefficient *n* is usually determined according to hydrometric data of the observed river bed.

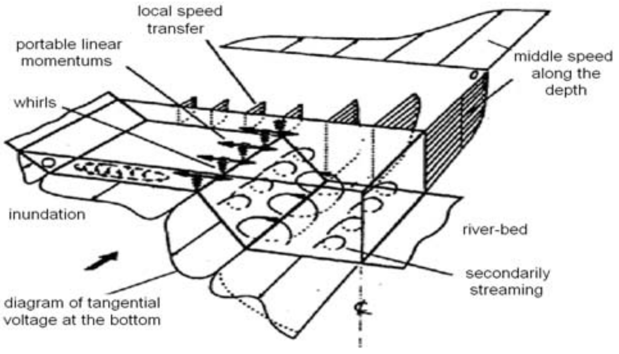


Fig. 1. The conceptual model of flow structure on the borderline between the main canal and inundations, [1]

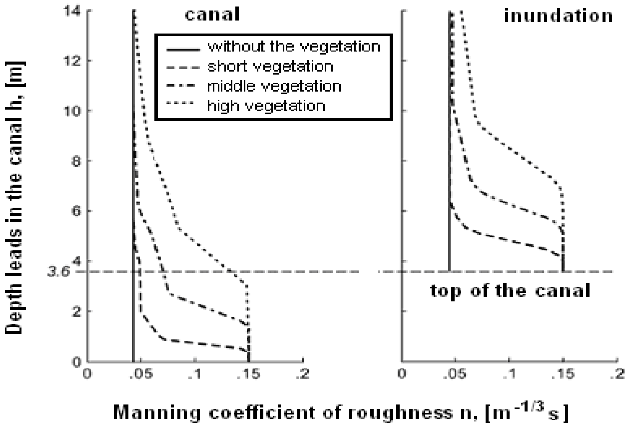


Fig. 2. Change of the roughness coefficient *n* depending on the water level height in the main canal and inundation, [6]

Figure 3 shows the way by which the roughness coefficient *n* can be varied depending on the vegetation at two different locations within the same bed. In case of very tall vegetation on canal walls, the roughness coefficient is approximately constant while in the case of a middle and short vegetation on canal walls prominent roughness coefficient changes occur at the bed walls through time (Figure 3).

The canal roughness and flow conditions are significantly determined by the flood wave velocity (Fisher and Reeve, 1994, Kouwen and Fathi-Moghadam, 2000), [6]. The influence of roughness is more prominent at smaller flood waves in relation to greater flood waves. At numerous water currents the roughness coefficient diminishes with the enlargement of water level, but then sharply increases as soon as the inundations are included in the live section (Fig. 2). Due to lack of hydrometric data which could make the basis for determining the roughness coefficient *n,* the data collected from water currents or beds similar to the analyzed river are often used in practice, [2], [7].

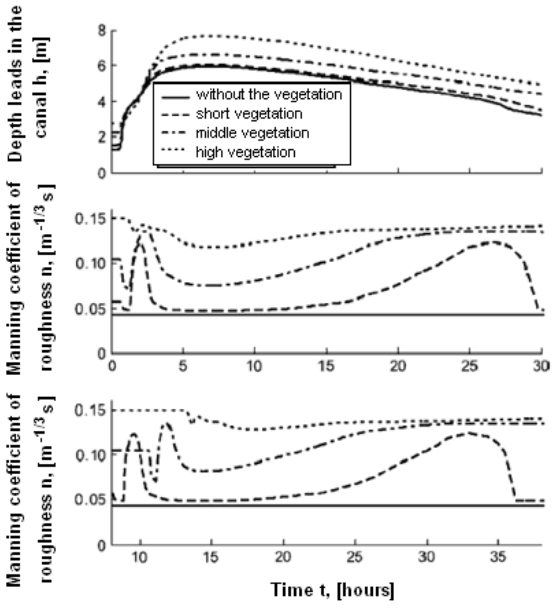


Fig. 3. Roughness coefficient *n* change depending on time at two different locations within the measuring canal, [6]

3 Formation of Boundary Layer in Natural River Beds

In case of a complete roughness development at flowing in the open beds, the vertical velocity profile in the wall area follows the logarithmic law which can be described mathematically in accordance to the Prandtl logarithmic law modified by Nikuradse (1933), [8]. Different methods of velocity profile adjustment through the vegetation for the sunken flowing as the modification Prandtl logarithmic law and calculations of crucial parameters (roughness heights and zero surfaces moving) are presented in Table 1. Single marks in equations characterize: n_{ras} – roughness coefficient for vegetation, (m), R - the hydraulic radius, (m), v_{yP} – velocity inside the vegetation at the determined height y, (m/s), κ_o – the modified Karman constant, the absolute roughness ε, (mm), the integration constant C, while A and B are empiric constants.

In case of flexing vegetation with a small relative underwater part, the surface roughness behaves differently when compared to the static roughness [9], [10]. The influence of a pebbly bottom with a small relative underwater part on the velocity profile is not same as for the on the surface covered bottom (Fig. 4).

Table 1. Methods for describing the velocity profile across the vegetation, [8]

Author	Velocity distribution across the vegetation
1. Plate and Quraishi, (1965)	$\frac{\nu}{\nu_*}=\frac{1}{\kappa}\ln\frac{y-h_p}{n_{ras}}$
2. Kouwen and coworkers, (1969)	$\frac{\nu}{\nu_*}=\frac{1}{\kappa}\ln\frac{y}{n_{ras}}+C$
3. Nnaji and Wu, (1973)	$\frac{\nu}{\nu_*}=\frac{1}{\kappa}\ln\frac{R}{n_{ras}}$
4. Haber, (1982)	$\frac{\nu}{\nu_*}=\frac{1}{\kappa}\ln\frac{y}{n_{ras}}+\frac{\nu_{yP}}{\nu_*}$
5. Murota and coworkers, (1984)	Slow sway: $\frac{\nu}{\nu_*}=\frac{1}{\kappa_o}\ln(y-(h_P-h'))+C$ Rapid sway: $\frac{\nu}{\nu_*}=\frac{1}{\kappa_o}\ln y+C$
6. Christensen, (1985)	$\frac{\nu}{\nu_*}=\frac{1}{\kappa}\ln\left(\frac{y-(h_P-\varepsilon/29{,}7)}{\varepsilon}\right)+8{,}5$
7. Temple, (1986)	$\frac{\nu}{\nu_*}=\frac{1}{\kappa}\ln(y-\alpha_{yP})+C$
8. Watanabe and Kondo, (1990)	$\frac{\nu}{\nu_*}=\frac{1}{\kappa}\ln\left(\frac{y-(h_P-h')}{n_{ras}}\right)$
9. El-Hakim and Salama, (1992)	$\frac{v}{v_*}=A+\frac{1}{B}\ln\left(\frac{y}{h_P}\right)$
10. Klopstra and coworkers, (1997)	$\frac{v}{v_*}=\frac{1}{\kappa}\ln\left(\frac{y-(h_P-h')}{n_{ras}}\right)$

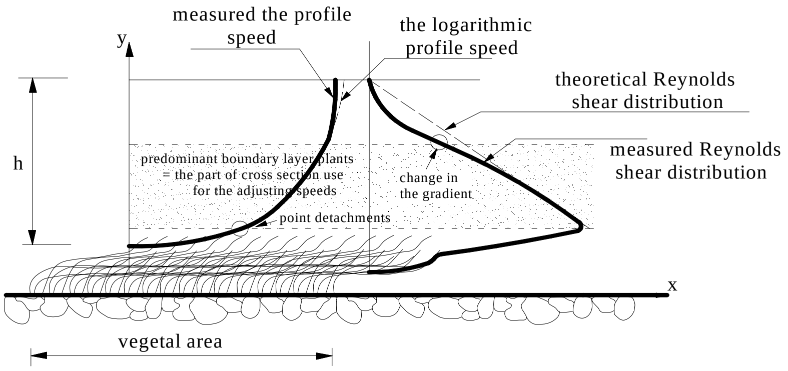


Fig. 4. Presentation of predominant vegetation boundary layer spreading, [8]

4 Methods for Determining Roughness Coefficient in Natural Beds

The surface roughness of the wetted scope of the canal enables the evaluation of the roughness coefficient *n*. If the grain diameters are smaller and more even, the roughness coefficient *n* value is smaller and does not change when the flow depth changes occur. If the material on bed walls is gravel or pebble, the roughness coefficient becomes larger and can significantly vary with the flow depth [10]. When evaluating the coefficient *n* the influence of vegetation in slow and accelerated flow must be also taken into consideration. The relative importance of vegetation for the coefficient *n* can also be observed functioning as the flow depth, density, velocity distribution and the very type of vegetation [11].

The canal irregularity additionally influences the roughness coefficient changes by changing the cross section of the canal and the wetted scope along the longitudinal axes. In natural river beds the consequences of irregularity occur due to elimination process or rinsing of the canal material. Gradual changes have an insignificant influence on the coefficient *n*, while an unexpected change can result in high coefficient *n* values [4], [7]. Existence of obstructions in the canal (the felling of high and low trees, landslides in the flow, appearance of large trunks and stumps at the bottom of the canal) significantly influence the change of roughness coefficient values. The disturbance level of such obstacles depends on their number and size. While the distortions of the canal of large radii with frequent changes in the flow direction give a relatively small resistance, the strong meanders with curves of a smaller radius will significantly influence the growth of the roughness coefficient *n.* Distortions having large radii influence the formation of the main current and sedimentation in specific parts of the bed [8].

In numerous open canals the value of the roughness coefficient *n* diminishes with the growth of the flow. This is a result of the irregularity which has the crucial influence on the roughness coefficient value at lower water levels. The coefficient *n* value can be increased by the flow increase if the slopes of natural river beds are rough, that is, grassy and covered in bushes. On inundations, the coefficient *n* value varies with the depth of the submerging.

Considering the above mentioned remarks and possible factors which influence the roughness coefficient *n* changes, several methods for determining the roughness coefficient value can be discussed at a considerable level of certainty.

4.1 Storage Methods (SCS Method)

The storage method (Soil Conservation Service method) which is used for roughness coefficient *n* evaluation includes the division of base values for an uniform, straight and regulated bed situated in the original material and then modifies this value with the correction factor determined by the critical observation. SCS method proposes usage of turbulences in the flowing as a measure or indicators of the retardation degree [4]. These factors encourage the larger degree of turbulence which results in the increase of the roughness coefficient *n*.

4.2 Ven Te Chow Method

Ven Te Chow method (1959) is used for the coefficient roughness *n* evaluation in open canals and natural beds. It using table values for the roughness coefficients obtained from measuring the specific canals/beds, [2]. The table quotes the minimal, normal and maximum rates of the roughness coefficient *n* for every single type of open canals. The table values of the roughness coefficient *n* can be found in every book which deals determination of roughness coefficient in natural beds.

4.3 The Photographic Method of Roughness Coefficient Evaluation

Geometry of beds together with hydraulic parameters which specify the bed flow can be used for calculation the surface resistance coefficient [7]. The American geologic society (AGU) uses in its own work the program which enables the hydro technicians to evaluate the resistance coefficient at flowing through the canal with the estimated accuracy of up to ±15 % under different flow conditions. The method provides photos showing all the necessary kinematic and geometric characteristics of the observed bed part (Figure 5).

Calculated Manning roughness coefficient: n=0,038 $m^{-1/3}s$ (Q=17,202 m^3/s)
Date of watery wave: 22nd February 2006
Date of shootings: 23rd February 2006
Depth of flow in the main bed: 2,63 m
Depth of flow in inundations: 0,0 m
Description of the main bed and inundations: strongly expressed erosions on the right bed shore; scattered appearance of gullies, short vegetation of 5 cm in diameter, climbing grass.

Fig. 5. Application of photographic method in the canal Butoniga, Istrian Peninsula, (Post 05+700 km)

Based on the provided photos the following parameters can be characterized:

- position (the place) at which flood line in the bed ca be noticed;
- the peak flow in the canal which was measured by the specific hidrometric wing;
- the marks of high water levels which can be used for determining the surface profile at peak flows;
- the peak flow which is limited in relation to the shores of the canal.

The roughness coefficient is estimated based on measured flows, shapes of water surfaces and characteristics which are observed on more than two transversal sections within the bed [5].

4.4 Empirical Methods and Formulas for Roughness Coefficient Determination

Today there are numerous empiric methods in the world which are used for the roughness coefficient *n* determination. One from them which was suggested by Strickler (1923) determines the roughness coefficient based on the following reference [3]:

$$n=0{,}047 \cdot d^{1/6} \tag{1}$$

The mark *d* presents the grain diameter (in millimetres) of a uniform sandy slope revetment and the canal bottom. Simons and Senturk (1976), [3] state that due to experimental calculations used by Stickler; the Eq. (2) can not be applied on flows with the movable bottom. Henderson (1966) claims that Strickler's experiments were based on water currents with pebbly bottom and also that the value *d* represents the mean value of the bottom material. The equation for the evaluation of the roughness coefficient *n* provided by Henderson (1966) can be written in the following way [3]:

$$n=0{,}034 \cdot d^{1/6} \tag{2}$$

Raudkivi (1976) came to the modified calculation of Strickler equation and offered the following formula for the evaluation of roughness coefficient *n* calculation:

$$n=0{,}042 \cdot d^{1/6} \tag{3}$$

where the value *d* is measured in (m). The Eq. (4) can be widened as following:

$$n = 0{,}013 \cdot d_{65}^{1/6} \tag{4}$$

where d_{65} presents the grain diameter of the bottom material (in millimeters) taken as 65% of material share. Raudkivi additionally quotes that the equations (3) and (4) can be used for the choosing the roughness height in the fixed ground at hydraulic models.

The later research of Garde and Raju (1978) establish that the Strickler analysis of data was based on different streams in Switzerland which have bottoms of rough material and no waves [3]. According to the research of the two quoted authors the roughness coefficients is determined based on the following formula:

$$n = 0{,}039 \cdot d_{50}^{1/6} \tag{5}$$

where d_{50} represents the grain diameter of the bottom material taken as 50% of weight material. Subramanya (1982) gives a more complete equation for the roughness coefficient evaluation [3] which is the following:

$$n = 0{,}047 \cdot d_{50}^{1/6} \tag{6}$$

Petryk and Bosmajian (1975) developed the method for analyzing the vegetation density when determining the roughness coefficient for very thin layers on inundations [2], [5]. By favoring the forces in the longitudinal direction which can be reached and by substituting the Manning formula the following equation for the evaluating the roughness coefficient was obtained:

$$n = n_o\sqrt{1+\left(\frac{C_*\sum A_i}{2gAL}\right)\left(\frac{1}{n_o}\right)^2 R^{\frac{4}{3}}} \tag{7}$$

where n_o is Manning border coefficient of roughness, including the influence of vegetation, ($m^{-1/3}s$), C_* the real coefficient of friction for the vegetation in the flow direction, ΣA_i the total frontal vegetation surface which interrupts the flow in (m^2), g gravity constant in (m/s^2), A cross section of the bed in (m^2), L length of the canal which was reached in the calculation in (m), and R the hydraulic radius in (m).

Limerinos (1970) gives the empiric formula for determining the roughness coefficient based on the calculation of the hydraulic radius R and grain diameter size d_{84} which corresponds the 84% of weight material share in the bed (the values range from 1.5 to 250 mm) [4], [7]. The formula was obtained based on measurements on 11 water currents with changeable structure of bed materials, those ranging from tiny gravel to middle size stone pebbles:

$$n = \frac{0{,}8204 \cdot R^{\frac{1}{6}}}{1{,}16 + 2{,}0 \cdot \log\left(\frac{R}{d_{84}}\right)} \tag{8}$$

Burkham and Dawdy (1976) proved that Limerinos formulation for the evaluation of the roughness coefficient can be used for the upper flow regime in streams with sandy roughness [3]. In Strickler formulas for evaluating the roughness coefficient of stiff beds [2], the absolute height of surface roughness ε is correlated with d_{50} percent of bed sediment:

$$n = C \cdot \varepsilon^{\frac{1}{6}} \tag{9}$$

Chezy coefficient C has in the process the following values C=0,034 for riprap revetment at $\varepsilon = d_{90}$, C=0,038 for the flow capacity of canal riprap at $\varepsilon = d_{90}$, respectively C=0,034 for the natural sediment at $\varepsilon = d_{50}$.

Apart from the above mentioned methods for evaluating the roughness coefficient in complex beds, there are some methods in practice which are relatively close to the former. The General Los Angeles method [10] and Colbatch method [11], [3], [4] must be undoubtedly mentioned in this context:

$$\bar{n} = \frac{(A_1 n_1 + A_2 n_2 + A_3 n_3 + \ldots + A_N n_N)}{A} \tag{10}$$

$$\bar{n} = \frac{(A_1 n_1^{1,5} + A_2 n_2^{1,5} + A_3 n_3^{1,5} + \ldots + A_N n_N^{1,5})^{\frac{2}{3}}}{A^{\frac{2}{3}}} \tag{11}$$

where: $A_1 \ldots A_N$ present the partial surfaces of live canal sections in (m^2), and A is the total surface of cross section in (m^2).

The roughness coefficient *n* value of the main bed and inundations can also be determined by Force sum method. This method has been suggested by Pavlovski, Muhlhofer, Einstein and Banks [2], and is the following:

$$\bar{n} = \frac{\sqrt{O_1 n_1^2 + O_2 n_2^2 + O_3 n_3^2 + \ldots + O_N n_N^2}}{O^{\frac{1}{2}}} \tag{12}$$

where O_i is the wetted scope when dividing surfaces in groups in (m), n_N the roughness coefficient *n* when dividing surfaces in groups in ($m^{-1/3}s$), and *O* the total wetted scope of cross section in (m).

4.5 Methods of Roughness Coefficient Evaluation Based on Measurement Data

Besides empiric formulas for determining the roughness coefficient *n* which were stated in the previous item, there are approximate formulas in practice which enable a swift and reliable estimation of roughness coefficient *n*. The final forms of these formulas are obtained by solving the basic kinematic characteristics and measuring the geometric characteristics of the natural bed [12].

The first way of roughness coefficient *n* determination requires determination of the mean value if power line decrease $\bar{I}_E$, in order to positively determine the average total loss ΔH on the defined bed section ΔL based on this value. It must be stated that the Chezy coefficient *C* is calculated based on Manning formula and that the Manning roughness coefficient for two characteristic cross sections *i* and *i-1* is accepted to be approximately the same ($n_1 \cong n_2 \cong n$):

$$\bar{I}_E = \frac{\Delta H}{\Delta L} = \frac{\bar{I}_E \cdot \Delta L}{\Delta L} = \frac{I_{E,i} + I_{E,i-1}}{2} \Rightarrow n = 2^{1/2} \cdot \frac{(R_i \cdot R_{i-1})^{2/3}}{(v_i R_{i-1}^{4/3} + v_{i-1} R_i^{4/3})^{1/2}} \cdot \bar{I}_E^{1/2} \tag{13}$$

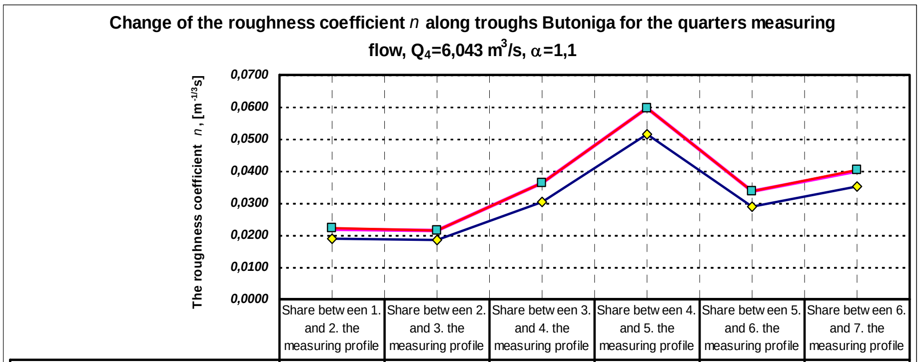
where: R_i, R_{i-1} represents hydraulic radii on *i* and *i-1* cross section in (m), while v_i, v_{i-1} are mean flow velocities on *i* and *i-1* cross section in (mps). The other way for roughly estimating the roughness coefficient *n* focuses on determining of mean velocity $\bar{v}$ and mean hydraulic radius $\bar{R}$ on the interrogated bed section *ΔL*:

$$I_E = \frac{\Delta H}{\Delta L} = \frac{n^2 \bar{v}^2}{\bar{R}^{4/3}} = \frac{n^2 \left(\frac{v_i + v_{i-1}}{2} \right)^2}{\left(\frac{R_i + R_{i-1}}{2} \right)^{4/3}} \Rightarrow n = 2^{1/3} \cdot \frac{(R_i + R_{i-1})^{2/3}}{v_i + v_{i-1}} \cdot I_E^{1/2} \tag{14}$$

The third way of determining the roughness coefficients *n* is based on calculation the roughness coefficients n_1 and n_2 on specific profiles, where by moderating these values the required roughness coefficient *n* value of the required observed section *ΔL* is obtained:

$$n=\frac{n_i+n_{i-1}}{2}=\frac{\left(\frac{R_i{}^{2/3}}{v_i}\cdot I_E^{1/2}\right)+\left(\frac{R_{i-1}{}^{2/3}}{v_{i-1}}\cdot I_E^{1/2}\right)}{2} \tag{15}$$

For identical geometric and kinematic parameters of the interrogated bed sections, the roughness coefficients *n* differ considerably when the first and the second way of determination are applied, while in the third case they almost coincide with the second way of determination (Fig. 6).



	Share between 1. and 2. the measuring profile	Share between 2. and 3. the measuring profile	Share between 3. and 4. the measuring profile	Share between 4. and 5. the measuring profile	Share between 5. and 6. the measuring profile	Share between 6. and 7. the measuring profile
—◇— The roughness coefficient n on the given share (1. way calculates)	0,0190	0,0185	0,0305	0,0515	0,0290	0,0351
—— The roughness coefficient n on the given share (2. way calculates)	0,0220	0,0215	0,0362	0,0598	0,0337	0,0399
—□— The roughness coefficient n on the given share (3. way calculates)	0,0221	0,0216	0,0362	0,0597	0,0337	0,0402

Fig. 6. Change of roughness coefficient *n* on the interrogated section of Butoniga bed (Istrian Peninsula) in three characteristic cases of roughness coefficient determination, [12]

5 Conclusions

In everyday practice of designing the expertness in roughness coefficient *n,* that is, the knowledge of a real range of changes of its values for specific types of canal development and level of its maintenance during the calendar year is of outmost significance. The roughness coefficient *n* for different bed and revetment types is usually chosen from the literature. The descriptions, based on such choices, usually provide the designer a large possibility of subjective concluding. In the world literature the roughness coefficient of different revetments is well described and defined, whereas its determination depends on many parameters which can change within the short or the longer period of exploitation, especially for earth beds and inundations. These changes of bed state happen due to the change of water level in the bed, when the full range of hydraulic parameters changes due to change of bed geometry through time (the instability of embankment slope) and change of bed vegetation thickness.

The contemporary model approaches to the problem solving from the domain of open canal hydraulics whose usage at planning the water-managing solutions ensures better or more rational dimensioning of particular regulation structures and beds, emphasizes the need of a more reliable defining of bed roughness to even larger extent. In this sense it is necessary to conduct field research of particular hydraulic characteristics, as well as their analysis. Apart from the intentionally conducted field research and analyses, the interpretation must be also based on the whole row of other information and data primarily tied to the bed maintenance regime, the observed appearances of large waters as well as to the previously conducted hydrometric measurements.

Reference

1. Jovanović, M.B.: Regulation river, Faculty Of Civil Engineering Belgrade, Belgrade, 2002.
2. Chow, V.T.: Open channel hydraulics, Mc Graw-Hill, (1983)
3. French, R.H.: Open channel hydraulics, Mc Graw-Hill, (1986)
4. Anonym, Methods forward pass Predicting n Values forward pass Manning Equation, (1994)
5. Gurnell, M., Midgley, P.: Aquatic weed growth and flow resistance: influence on the relationship between discharge and stage over a 25 year river gauging station record, Hydrological Processes 8, (1994) 63-73
6. Anderson, G., Rutherfurd, I.D., Western, A.W.: An analysis of the influence of riparian vegetation on the propagation of flood waves, Environmental Modeling and Software 21, (2006) 1290-1296
7. Barnes, H.H.: Roughness characteristics of natural channels, US Geological Survey Water Supply Paper 1849., US Government Printing Office, Washington, (1967)
8. Stephan, U., Gutknecht, D.: Hydraulic resistance of submerged flexible vegetation, Journal of Hydrology 269, (2002) 27-43
9. Helmiö, T.: Flow resistance due this lateral momentum transfer in partially vegetated rivers, Water Resources R&D 40 (5), (2004)
10. Murota, T., Fukuhara, M., Sato: Turbulence structure in vegetated open channel flows, Journal of Hydro science and Hydraulic Engineering 2 (1), (1984) 47-61
11. Kouwen, N.: Effect of riparian vegetation on flow resistance and flood potential discussion, Journal of Hydraulic Engineering ASCE 126 (12), (2004) p. 954
12. Žic, E.: The roughness coefficient analysis on the example of Butoniga river bed in Istria, master's thesis in the making, Rijeka (2008)