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INFLUENCE OF SUBMERGED VEGETATION ON THE MANNING´S ROUGHNESS COEFFICIENT FOR GABČÍKOVO – TOPOĽNÍKY CHANNEL

Radoslav Schügerl*, Yvetta Velísková, Renáta Dulovičová, Valentín Sočuvka

The aim of this study was to investigate the variation of flow conditions along the Gabčíkovo – Topoľníky channel (Žitný Island) on the base of Manning´s roughness coefficient value. This coefficient is not easy to determine and its value is varying constantly during the growing season, especially in a lowland stream with aquatic vegetation occurrence. Vegetation impedes the water flow and may increase flood risks. Thus, determining the effect of aquatic vegetation on flow conditions in streams is very important for estimation of hydrodynamics in natural streams. Measurements performed during growing season at the Gabčíkovo – Topoľníky channel stream were used for an evaluation of vegetation impact on flow conditions. The variations of roughness coefficients of Gabčíkovo – Topoľníky channel are presented in Manning's equation, and the results reveal that the *n* value increases with the decreasing of flow depth. Manning's coefficient value found in this study is in the range of 0.020 to 0.079. The outcomes of this study can be concluded that the variation of Manning's coefficient value is influenced by the cross-section profile characteristic, flow depth, slope of channel, and especially quantity of submerged vegetations in the channel.

KEY WORDS: Manning´s roughness coefficient, flow conditions, submerged vegetation, River Surveyor

Introduction

The channel roughness is affected by a lot of factors which are difficult to translate into a single value. More authors (Green, 2006; Nikora et al., 2008) stated that aquatic macrophytes are often the dominant factor influencing flow conditions within the channels they occupy. Furthermore, it is more difficult to determine the Manning coefficient for vegetated streams than for open channel flow (Green, 2005). Also Vereecken et al. (2006) showed that seasonal variations in the aquatic vegetation have an important influence on the flow resistance. It is possible to estimate the value, but the deviation from reality may be large.

The flow regime in channels or in surface water at lowland territories during the growing season is often very strongly influenced by the occurrence of aquatic vegetation. From a hydrodynamic point of view, water plants alter the size and distribution of flow velocities at a large rate; they increase the stream bed roughness and decrease the discharge capacity of a stream. As the progress of water plants runs, the coefficient of roughness value is changed. In general, this parameter determines the extent of flow resistence and impacts the flow capacity of channels or watercourses. For correct design or computation of flow in an open channel, it is necessary to evaluate the flow resistance to a stream, which is typically represented by a roughness parameter, such as Manning's (Carollo et al., 2002; Cassan et al., 2015). Its determination is not easy for natural streams, because the characteristics of channels and the factors that affect channel capacity can vary greatly; furthermore, the combinations of these factors are numerous. Therefore, the selection of roughness for natural and constructed channels is often based on field judgment and personal skill, which are acquired mainly through experience (De Doncker et al., 2009; Velísková et al., 2017).

The aim of this contribution is to demonstrate, on the basis of results from experimental field measurements on the Gabčíkovo – Topoľníky channel (Žitný Island – Slovakia), how the sprouting of vegetation in a stream bed influences channel's flow conditions and its capacity.

Theoretical background

The measured discharges and water levels are used for the calculation of the roughness coefficient of the stretch, making use of the Bresse equation and the Manning equation (Chow, 1959). Manning's equation uses a single parameter, *n*, to represent the frictional nature of a given channel cross section, and hydraulic reference manuals provide roughness guides for channels based on their composition and morphology. A channel's reference roughness is meant to be constant for all withinbank

flows; however, studies of flow in natural rivers have frequently found variability in Manning's coefficient value n, often in the form of a nonlinear, inverse relationship between n and stage or discharge. In general, hydraulic models for open channel flow are based on the Saint-Venant equations. These equations (continuity equation and momentum equation) are the one dimensional simplification of the Navier Stokes equations, which describe fluid flow in three dimensions. By calculation of the discharge and the water levels, the Saint-Venant equations allow for the calibration of the roughness of the channel (expressed by the roughness coefficient or friction factor) by comparing with field data. Here, this roughness is represented by the Manning coefficient n and it is calculated from the energy slope (Boscolo, 2014; Tuozzolo et al., 2019).
Hydraulic data as water levels and discharges are necessary, but also topographical data of the river bed and banks have to be collected. While carrying out velocity measurements in the river, the water depth and consequently, the bottom profile is registered.
There are various approaches how the roughness can be expressed, for example description with constant roughness coefficient through the Chézy formula, the Dardy-Weisbach equation, the Manning´s equation or roughness coefficient dependent on flow characteristics, for example the Strickler and Keulegan approach. In addition, there is known a new approach for determination of aquatic vegetation resistence, mainly for flexible submerged vegetation (Kutija and Hong, 1996; Stone and Shen, 2002; Wilson et al., 2007).
Most often description of hydraulic resistance can be found in literature as:

– *Manning´s equation:* $v = \frac{1}{n} R^{2/3}\, i_o^{1/2}$ (1)

– *Darcy-Weisbach equation:* $v = \sqrt{\frac{8g}{f}} \sqrt{R i_o}$ (2)

– *Chézy´s equation:* $v = C \sqrt{R i_o}$ (3)

where
v – mean flow velocity [m s^{-1}],
R – hydraulic radius [m],
i_o – water level slope,
n – Manning´s roughness coefficient [s m$^{-1/3}$],
g – gravity acceleration [m s^{-2}],
C – Chézy´s coefficient [m$^{1/2}$ s^{-1}].

The Manning´s formula is most used for expressing flow resistance (Chow, 1959). It might be determined for more complex part of a stream by empirical formula, e.g. by (Coon, 1998) who splitted channel resistance into several parts, including the bed material, presence of vegetation in the river, meandering

- $n = (n_0 + n_1 + n_2 + n_3 + n_4).m$ (4)

where
n_0 – basic value, for a straight, uniform channel,
n_1 – irregularities of the bottom,
n_2 – variations in the geometry of the channel,
n_3 – obstacles,
n_4 – vegetation,
m – correction factor for meandering.

To apply this approach, it is important that conditions already included in another parameter or element of this equation are not doubled. The equation requires an estimation of separate n factors for different channel conditions. However, the great variability of the used factors causes large degree of freedom for the precise roughness coefficient determination. Another methodology is to use a set of pictures from literature which represent a comparable situation orto make use of graphs and tables (Dyhouse et al., 2003). Photographs and descriptive data of typical type of river parts, for which the Manning coefficient is determined, can be found in (Barnes, 1967).
Channel roughness is influenced by grain size of the bedmaterial, the surface irregularities of the channel, the channel bed forms (such as ripples and dunes), erosion and deposition characteristics, meandering tendencies, channel obstructions (downed trees, exposed root wads, debris, etc.), geometry changes between channel sections, vegetation along the bankline and in the channel, etc. One single value of the roughness coefficient has to include all these parameters. Furthermore, as vegetation is strongly dependent on the season, the roughness coefficient can be fairly different for summer and winter conditions.
There are many vegetation characteristics that affect the hydraulic resistance in vegetated channels. The first important vegetation characteristic that affects the flow resistance is the geometry of the vegetation itself, concerning the taxonomy of the species as the branching index, the density of the shoots, the maximum level of growth that each species can reach in a cross section, the seasonal presence of the plant. In addition to this, there is a hydraulic parameter which considers the characteristic dimension of the vegetation in relation to flow conditions. One of the main problems in vegetated channel is the determination of the vegetation height. This can be solved if the flexural and drag properties of the vegetation are known. Flow over flexible vegetation induces bends and reduces the height of the vegetation stems. As a result, the flow-vegetation interactions are reduced. The vegetation configuration depends on flexural rigidity and density of the vegetation itself. These characteristics depend essentially on the species. The blockage factor B is the parameter that measures the portion of the channel blocked by vegetation, or equivalently the proportion of the channel containing vegetation. Several types of blockage factors have been proposed in the literature (Boscolo, 2014).
Evaluation of the impact of aquatic plants on flow conditions in a lowland stream is complicated. Nevertheless, it is possible to determine the value of the roughness coefficient n for a stream reach by using

the Chézy – Manning equation for steady uniform flow condition (Eq. 5):

$$n_m = \frac{A_m R_m^{2/3} i_{om}^{1/2}}{Q_m} \tag{5}$$

where
i_o – water level slope,
A – discharge area [m^2],
R – hydraulic radius [m],
Q – discharge [m^3 s^{-1}],
m – means a measured value.

This approach is used also in this study.

Material and methods

Field measurements, related to the investigation of submerged vegetation impact on flow in a lowland stream, were performed along the Gabčíkovo – Topoľníky channel (Žitný Island – ŽI). It is flat area and one of the most productive agricultural region of Slovakia.
Žitný Island lies between two branches of the Danube River, on which this river is divided just below the Slovak capital Bratislava: the Danube and the Small Danube (Fig. 1). The area of the Žitný Island is approximately 2000 km^2 and represents about 4% of the Slovak territory. Its average slope is only about 2.5x10^{-4} and this was one of the reasons for building the channel network within this area. The channel network was built up for drainage and also to safeguard irrigation water. The water level in the whole channel network system has affect to groundwater level on the Žitný Island and in reverse (Dulovičová, 2019).
The Gabčíkovo – Topoľníky channel is the biggest one from three main channels of the channel network at Žitný Island (besides Chotárny and Komárňanský channel). The Gabčíkovo – Topoľníky channel was built primary for drainage, later it was used also for irrigation. The length of the Gabčíkovo – Topoľníky channel is about 30 km. Its width oscillated between 11.50–17.5 m along the channel, its depth registered maximal values up to 2.6 m (according to located cross-section profiles). Sixteen observing cross-section profiles were selected along the Gabčíkovo – Topoľníky channel, their locations are shown in Fig. 2. Measurements were carried out from rkm 1 to rkm 17 (in each kilometre, except rkm 14).
Cross-section profiles parameters – channel width, distribution of water depth along the cross-section profile width, water levels (by levelling device), discharges and velocity distribution in the cross-section profile (by ADV method – Acoustic Doppler Velocimeter – River Surveyor device) were measured (Fig. 3). This device is suitable for measurements of deeper streams. Example of record of measurement by River Surveyor device is shown on the Fig. 4 (for cross-section profile without submerged vegetation) and on the Fig. 5 (cross-section profile with submerged vegetation). All field measurements were done during one week in the begining of summer. Data used for roughness coefficient determination are from the channel segments with steady uniform flow conditions.

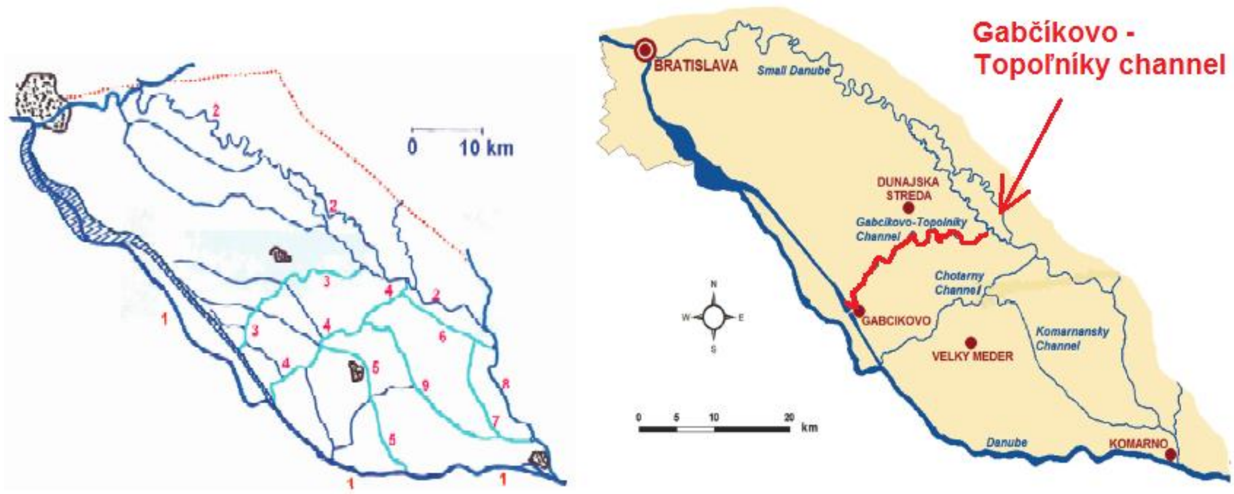

Fig. 1. Schematic map of channel network at Žitný Island (left) and three main channels of channel network at Žitný Island (right).

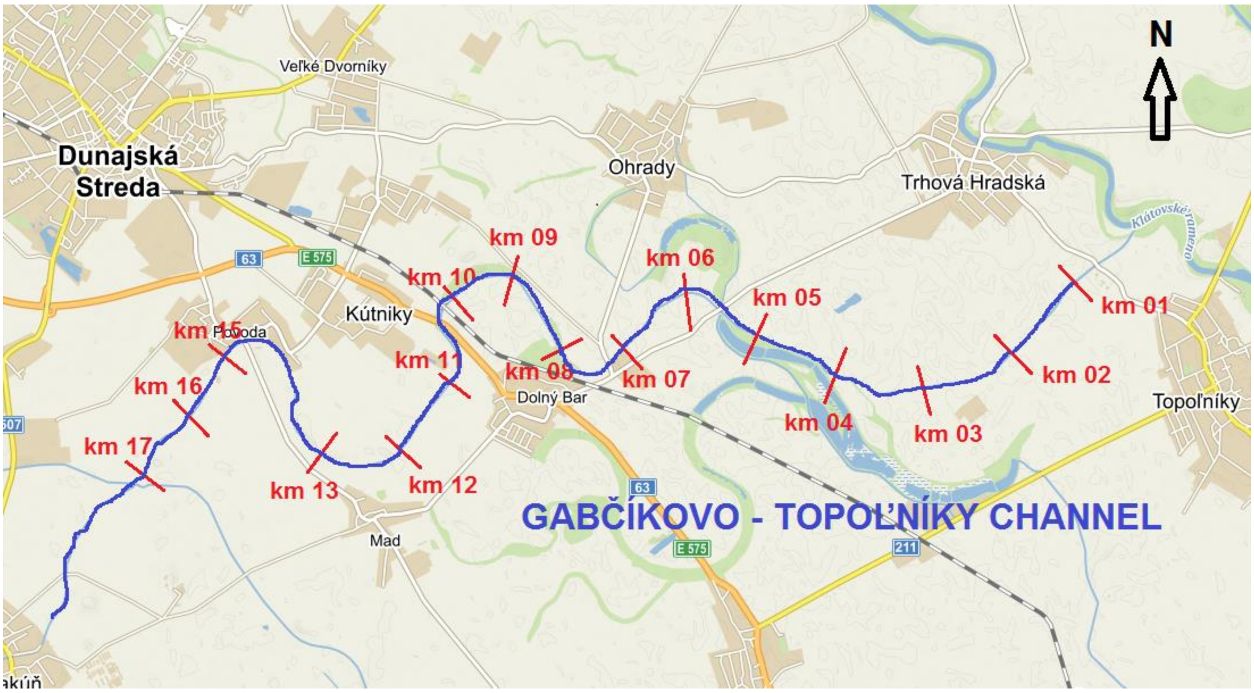

Fig. 2. Map of the Gabčíkovo – Topoľníky channel (measurements cross-section profiles in particular kilometers).

Fig. 3. Acoustic Doppler Velocimeter – River Surveyor device for measurement velocity profile and discharge.

Results and discussion

As it was mentioned, there exists a number of ways how to evaluate the influence of aquatic vegetation on flow in lowland streams. Quantification of the impact of aquatic vegetation through the roughness coefficient is one of the practically suitable methods. This roughness coefficient represents a parameter influencing discharge capacity of streams. Ranges of measured data are condensed in Table 1 (for each measured kilometer, except rkm 14). Table 1 contain number of measured cross-section profile (rkm), width (*w*), average depth (*d*), cross-section profile area (*A*), wetted perimeter (*P*), hydraulic radius (*R*), mean flow velocity (*v*) and meters above sea level (m.a.s.l.).

Table 2 contains measured data of elevation above sea and calculated data of water level change (Δd), water level slope (i_o) and Manning´s roughness coefficient (*n*). The roughness coefficient value in the sprouted stream bed is changing during the growing season depending on aquatic vegetation growth. In consequence of raised roughness, the velocity profile is changing and thereafter the discharge capacities are also changed. Value of the Manning´s roughness coefficient by Chow (1959) for channels not maintained (dense uncut weeds, the high equals flow depth) is from 0.050 to 0.120 or channels with dense brush is from 0.080 to 0.140.

Distribution of submerged vegetation along Gabčíkovo – Topoľníky channel is different. However, because the measurements were carried out in the beginning of summer, there are a lot of reaches with large amount of submerged vegetation in cross-section profiles. In this case, the Manning´s coefficient increases rapidly with the amount of submerged vegetation.

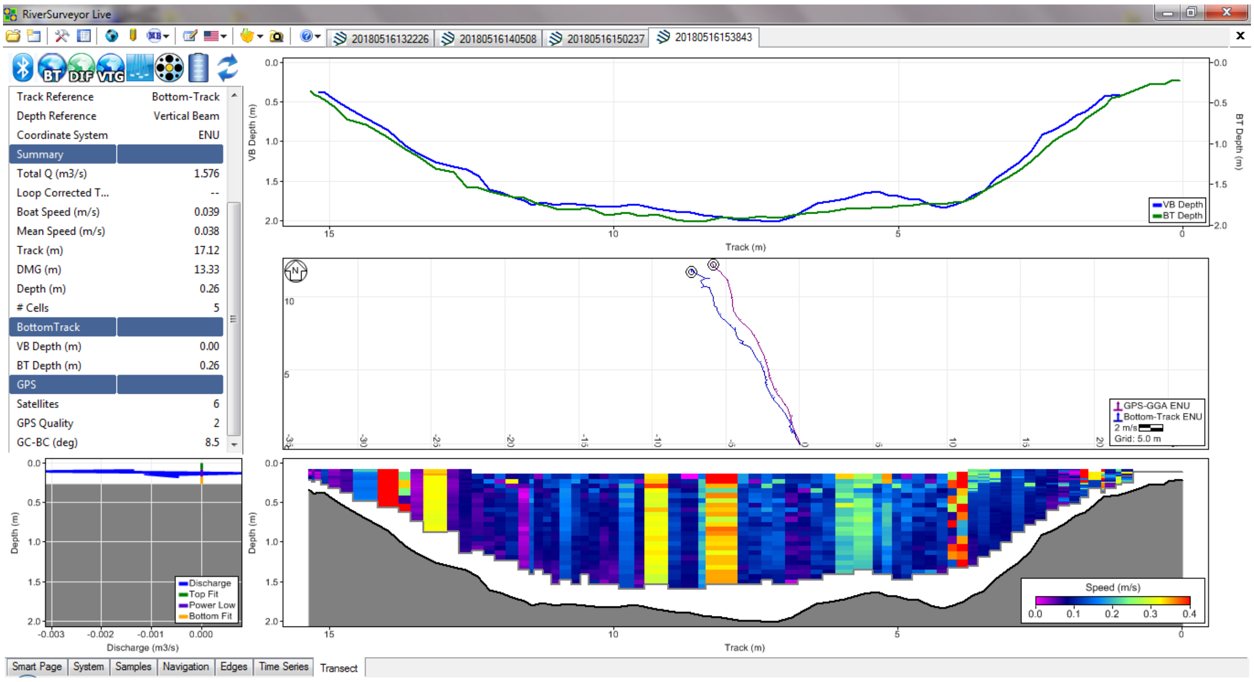

Fig. 4. Record of measurement by River Surveyor device (cross-section profile without vegetation).

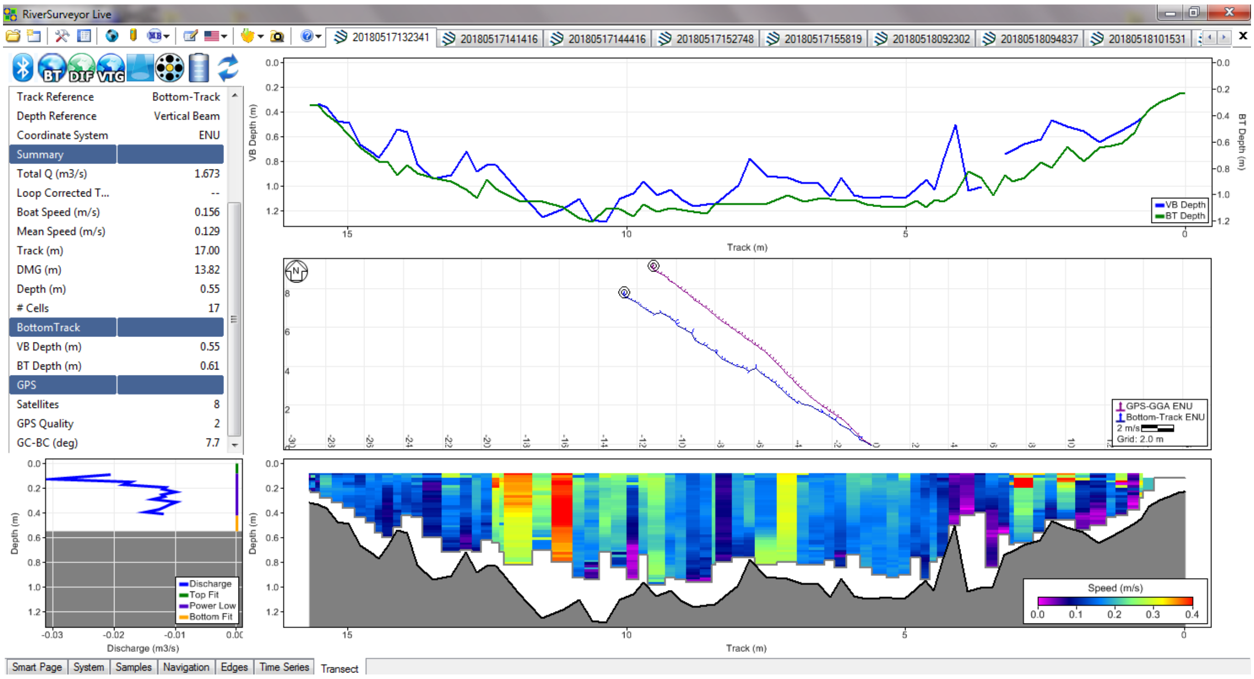

Fig. 5. Record of measurement by River Surveyor device (cross-section profile with submerged vegetation – peaks on the bed- stream indicated growing up vegetation).

Table 1. **Summary of measured and calculated data for Gabčíkovo – Topoľníky channel (for measured rkm)**

rkm	width [m]	average depth [m]	area [m^2]	wetted perimeter [m]	hydraulic radius [m]	flow velocity [$m\ s^{-1}$]	meters above sea level [m.a.s.l.]
01	15.5	0.72	24.49	20.25	1.210	0.084	110.632
02	14.5	0.41	19.88	18.25	1.089	0.097	110.671
03	16.5	0.39	17.11	16.50	1.037	0.118	110.685
04	16.0	0.68	19.22	18.31	1.050	0.100	110.689
05	13.5	0.67	15.50	15.65	0.990	0.112	110.732
06	16.0	0.32	10.70	17.87	0.599	0.170	110.776
07	17.5	0.21	15.17	18.34	0.827	0.118	110.808
08	17.0	0.48	11.52	18.15	0.635	0.165	110.905
09	15.0	0.46	10.10	14.50	0.697	0.128	110.935
10	14.5	0.33	11.75	15.91	0.739	0.155	111.060
11	16.5	0.55	12.21	17.82	0.685	0.137	111.168
12	15.5	0.36	11.51	17.18	0.670	0.126	111.214
13	16.0	0.43	11.96	16.59	0.721	0.132	111.305
15	11.5	0.38	9.51	8.87	1.072	0.139	111.462
16	14.5	0.40	6.98	13.24	0.527	0.128	111.612
17	16.0	0.26	19.76	17.32	1.141	0.080	111.670
Average	**15.375**	**0.44**	**14.21**	**16.54**	**0.856**	**0.124**	**111.020**

Table 2. **Summary of calculated data for Gabčíkovo – Topoľníky channel (between cross-section profiles – rkm)**

rkm	Δ water level [cm]	water surface slope	**Manning´s coefficient [$m^{-1/3}\ s$]**
01–02	3.9	0.000039	**0.075**
02–03	1.4	0.000014	**0.036**
03–04	0.4	0.000004	**0.018**
04–05	4.3	0.000043	**0.063**
05–06	4.4	0.000044	**0.037**
06–07	3.2	0.000032	**0.031**
07–08	9.7	0.000097	**0.051**
08–09	3.0	0.000030	**0.028**
09–10	12.5	0.000125	**0.056**
10–11	10.8	0.000108	**0.050**
11–12	4.6	0.000046	**0.039**
12–13	9.1	0.000091	**0.058**
13–15	15.7	0.000157	**0.058**
15–16	15.0	0.000150	**0.079**
16–17	5.8	0.000058	**0.065**
Average	**6.92**	**0.000069**	**0.049**

Variation of Manning´s coefficient along the Gabčíkovo – Topoľníky channel is summarized in Table 2. The highest value is in between river kilometers 15–16 (0.079), the lowest value is in rkm 03–04 (0.018). Average value for all cross-section profile is 0.049. Diaz (2005) claimed that the variations in the *n* values diminish when the slope increases. For intermediate flows in which the flow depth is greater than the height of vegetation (the grasses submerged), the *n* values decrease as average velocity increases. The decrease of *n* is regarded as a result of the increase of plant bending and submergence when velocity increases. For unsubmerged vegetation, Ding et al. (2004) hypothesized that an increase in flow depth less than that required to top the vegetation causes little change in the mean velocity. Therefore, flow resistance tends to increase with the depth. The roughness coefficients *n*, varies with the type of vegetative cover, longitudinal slope, and average flow depth. Fig. 6 shows the variation of the Manning´s coefficient and slope values along the evaluated channel reach. Fig. 7 shows growth of the slope value with value of the Manning´s coefficient at all evaluated cross-section profiles along Gabčíkovo – Topoľníky channel. Trend is relatively steep, when we compared this trend with other interdependences between Manning´s coefficient and flow velocity (Fig. 8) or average depths (Fig. 9). At the same time, there is the opposite course of the trend.

When it comes to flow velocity values (from 0.080 $m.s^{-1}$ for rkm 17 to 0.170 $m.s^{-1}$ for rkm 06), we observe a relatively small decline in the trend of the measured data (Fig. 8). We can state, that with decreasing values of the flow velocities are higher values of the Manning´s coefficient. On the Fig. 4 and 5 we see the course of velocity in cross-section profile (biggest value of flow velocity is recorded by red colour, smallest value of flow velocity is recorded by purple colour).

As regards average depth (Fig. 9), these values are from 0.21 to 0.72 m (maximum depth is 2.2 m for rkm 02). Average depths were obtained by River Surveyor device. We observe minimum decline of trend for values of the average depth. This trend is very similar with trend of the interdependence between values of flow velocity and Manning´s coefficient. Of course, depth in the measured cross-section profiles can be influenced by aquatic vegetation (Fig. 5. – peaks on the bed-stream), and for this reason, the depth recorded by the River Surveyor device can be a little bit different from the actual depth.

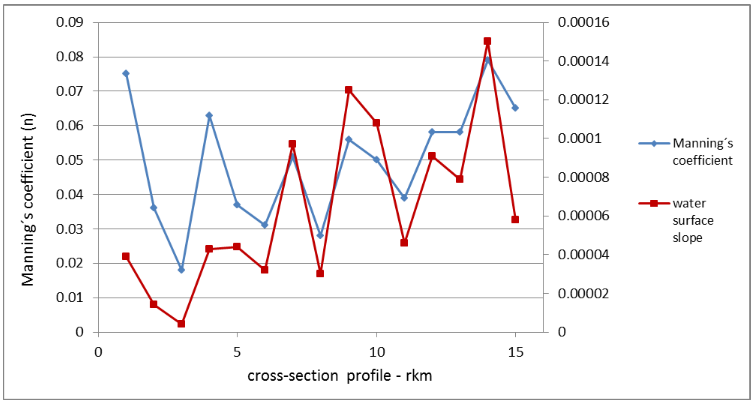

Fig. 6. Variation of Manning´s coefficient and slope along evaluated reach of the Gabčíkovo – Topoľníky channel.

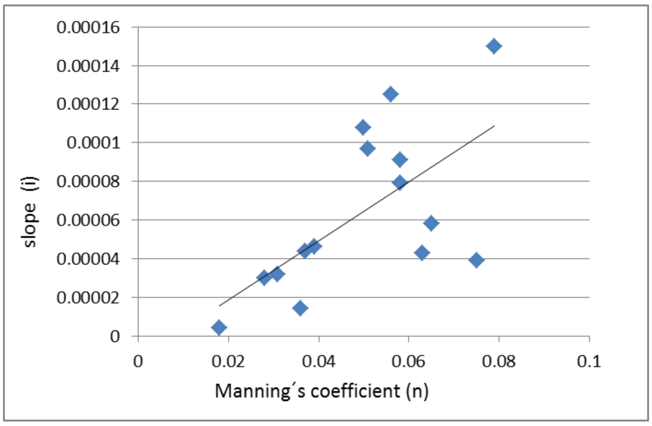

Fig. 7. Interdependence between values of slope and Manning´s coefficient at all evaluated cross-section profiles along Gabčíkovo – Topoľníky channel.

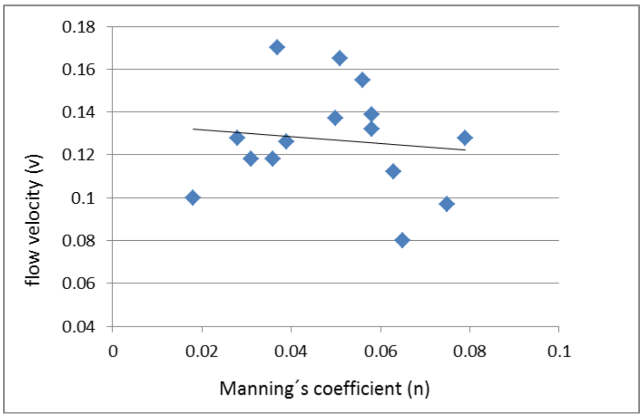

Fig. 8. Interdependence between values of flow velocity and Manning´s coefficient at all evaluated cross-section profiles along Gabčíkovo – Topoľníky channel.

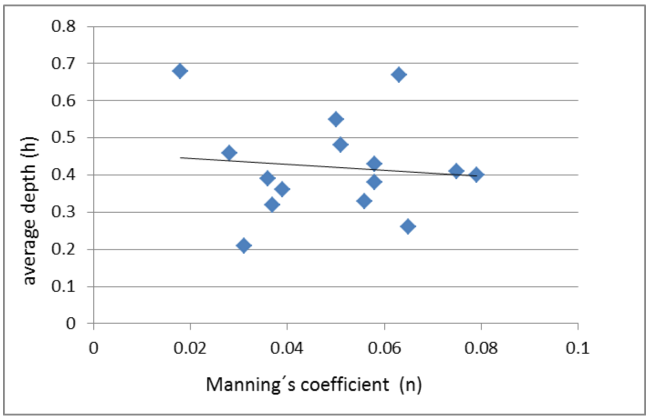

Fig. 9. Interdependence between values of average depth and Manning´s coefficient at all evaluated cross-section profiles along the Gabčíkovo – Topoľníky channel.

Conclusion

Vegetation in natural streams influences the flow and related characteristics and phenomena, such as roughness, discharge capacity, velocity profile, but also erosion and sedimentation, pollutant transport and water biota. The aim of this paper was to investigate and determine the impact rate of aquatic vegetation on flow conditions, based on field measurements along the Gabčíkovo – Topoľníky channel. The roughness coefficient n was used as a way of quantifying the impact. An analysis of the obtained data revealed that the roughness coefficient value changes along the channel, ant that the *n* value increases with the decreasing of flow depth. There were determined ranges of Mannings´s roughness coefficient values for relevant period of year with aquatic vegeration occurrence. Manning's coefficient value found in this study is in the range of 0.020 to 0.079. The analyses of measured data showed and confirmed the complexity of the impact of in-channel vegetation on stream flow, and the necessity to continue investigation of this problem.

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Mgr. Radoslav Schügerl, PhD. (*corresponding author, e-mail: schugerl@uh.savba.sk)
Ing. Yvetta Velísková, PhD.
Ing. Valentín Sočuvka, PhD.
Ing. Renáta Dulovičová
Institute of Hydrology SAS
Dúbravská cesta 9
84104 Bratislava
Slovak Republic