Vegetation growing in the water along streams has been the subject of several studies since it was recognized that it could have a significant impact on the water flow. It may increase resistance to flow and cause higher water levels. Also, it has an effect on the velocity profiles. The purpose of this paper is to investigate, and determine how aquatic vegetation influences flow resistance, water depth and discharge in the Malina stream at the Záhorská lowland area. Vegetation causes resistance to flow; it reduces flow velocities, discharge and increases water depth. Measurements performed during three years at this stream were used for an evaluation of vegetation impact on flow conditions. The Manning’s coefficient was used as one way of quantifying this impact. The results show variation of this parameter during the growing season.

KEY WORDS: Manning’s roughness coefficient, flow conditions, water-level, aquatic vegetation

Introduction

Research of the impact of aquatic vegetation is based on the investigation of the problem in laboratory conditions (Green, 2005; Manes et al., 2011). On the other side, examination of the research issues in the field conditions is more problematic (Nikora et al., 2008). Vegetation affects fluvial processes and is key in current river management and river hydraulics. Advances in understanding the behavior of flow over vegetation allow us to improve both the knowledge of flow-velocity profiles and flow resistance (James et al., 2004; Cheng, 2011; Nehal et al., 2013). 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 development of water plants progresses, the coefficient of roughness value is changed. In general, this parameter determines the extent of roughness 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 channel resistance to flow, which is typically represented by a roughness parameter, such as Manning’s n (Velisková et al., 2017). 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. Determination of the roughness coefficient n, according a seasonal variation, is an important tool in hydraulic modelling (De Doncker et al., 2009; Korichi & Hazzab, 2012).

The aim of this contribution is to demonstrate, on the basis of results from experimental field measurements on the Malina stream (Slovakia), how the sprouting of stream bed vegetation influences channel’s flow conditions and its capacity.

Theoretical background

In describing the vegetation resistance, differences have been made between submerged, emergent, flexible and rigid vegetation. It is important to distinguish between definitions of the terms ‘roughness’ and ‘resistance’. Resistance accounts for the (boundary) turbulence caused by surface properties, geometrical boundaries, obstructions and other factors causing energy losses. Therefore, a resistance coefficient reflects the dynamic behaviour in terms of momentum or energy losses in resisting the flow of the fluid. Here, flow resistance is considered to be made up of four parts: skin drag, shape drag, form drag and some other factors.

Roughness reflects the influence of the surface on the momentum and energy dissipation in resisting the flow of the fluid. Therefore, with a roughness factor the actual or effective unevenness of the boundary sur-
face is meant. Shape drag occurs as a result of the geometry of the channel. The flow has a tendency to form vortices. Form drag arises because of the form of the object. Other factors, which can influence the resistance of the flow are the presence of suspended material in the flow, wave and wind resistance from free surface distortion etc.

We know several descriptions to describe the resistance of vegetation, ranging from general roughness descriptions, to descriptions that account for various vegetation characteristics. Roughness description with constant roughness coefficient, for example Chezy formula, Darcy-Weisbach equation, Manning’s equation or roughness coefficient dependent on flow characteristics, for example Strickler and Keulegan approach. In addition we know new approach for describe the resistance of vegetation, mainly for flexible submerged vegetation (Kutija & Hong, 1996; Stone & Shen, 2002; Wilson, 2007).

Hydraulic resistance can be found in literature as:

1. Manning’s equation:

\[ v = \frac{1}{n} R^{2/3} i_0^{1/2} \]  

2. Darcy-Weisbach equation:

\[ v = \sqrt{\frac{8g}{\gamma}} \sqrt{Ri_0} \]  

3. Chezy’s equation:

\[ v = C \sqrt{Ri_0} \]

where

\( v \) – mean flow velocity [m s\(^{-1}\)],

\( R \) – hydraulic radius [m],

\( i_0 \) – water level slope,

\( n \) – Manning’s roughness coefficient [s m\(^{1/3}\)],

\( g \) – gravity acceleration [m s\(^{-2}\)],

\( C \) – Chezy’s coefficient [m\(^{1/2}\) s\(^{-1}\)].

Manning’s equation is the most widely used resistance measure among these, in particular with respect to vegetated channel. Although it expresses the resistance at the reach scale and reflects only the influence of the boundary shear on flow depth and averaged velocity, Manning’s coefficient \( n \) is often used as a lumped parameter accounting for all the various influences in a river reach. It is commonly estimated through experience from simple verbal or photograph descriptions of channels. A more advanced method is to split channel resistance into its component parts, and to determine the final value of Manning’s \( n \) from knowledge of the separate, smaller scale contributing effects using table. The determination of spatial parameters of a stream, such as the discharge area, stream bed slope, and hydraulic radius, is quite easy, but the stream bed roughness assessment could be a problem. During a year, the various degrees of in-channel sprouting could be found, and the different kinds of water plants usually grow up in stream cross-section profiles. On small longitudinal slopes, the extension of aquatic vegetation is conditional and accordingly, also on small flow velocities. The height of the vegetation with respect to the water level is important in describing vegetation resistance, because it influences the flow velocity profile (Velisková et al., 2017).

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).

All factors mentioned above can be quantified only under laboratory conditions. Evaluation of the impact of water 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 Chezy–Manning equation for steady uniform flow condition (Eq. 4):

\[ n_m = \frac{h_m R_{m}^{2/3} i_{w,m}^{1/2}}{Q_m} \]

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.

Material and methods

Field measurements, related to the investigation of aquatic vegetation impact on flow in a lowland stream, were performed along the Malina stream in the Záhorská lowland. Záhorská lowland area – and Malina stream - was chosen, it is one of the most productive agricultural areas of Slovakia. Malina stream is a sewer river in Záhorie low-land, flows through the territory of Malacky district. It is a left tributary of Morava river, has a length of 47.75 km. Catchment area is 516.6 km\(^2\) and her discharge is 0.828 m\(^3\) s\(^{-1}\) in Jakubov village 2.234 m\(^3\) s\(^{-1}\) in the estuary. Four observing cross-section profiles were selected along the Malina stream, their locations are shown in Fig. 1. Measurement were carried out in the first section with distance 1140 meters (from gas profile to Suchý stream profile) and in the second section with distance 2140 meters (from railway bridge profile to road bridge profile). Cross-section profile parameters (channel width, distribution of water depth along
the cross-section profile width), water levels (by levelling device), discharges and velocity distribution along the cross-section profile width (by ADV – Acoustic Doppler Velocimeter device Flow Tracker) were measured. Measurements were performed in the channel segments with steady uniform flow conditions. In general, field measurements were done in April, during summer time (July–August) and during autumn (October) and winter (November and February). Accordingly, we try to detect if any changes occur in different periods of the growing season.

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 from each year are condensed in Table 1 for section 1 (from gas profile to Suchý stream profile) and Table 2 for section 2 (from railway bridge profile to road bridge profile). Tables contain mean flow velocity (v), discharge area (A), wetted perimeter (l), hydraulic radius (R), water level change (∆h), 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. The rate of the vegetations impact on flow regime during the vegetation season differed in each year. The reason is that each year had different climatic conditions, which stimulated aquatic vegetation growth to a different extent. Furthermore, the activities concerning the maintenance of the channel network (mowing, water level regulation, etc.) also influenced the degree of aquatic vegetation growth, as it was mentioned above. For example, in the third year of observation, the differences of n values along the channel varied in the most extensive range (0.021–0.195) for the first section, for the second sector the differences of n values along the channel varied in the most extensive range (0.020–0.138 vs. 0.015–0.133) in the second and third year.

Aquatic vegetation recording by means of camera during the year 2018 (April vs. August) are shown in Fig. 4 (gas profile) and Fig. 5 (railway bridge profile). The mean flow velocity values decrease with increasing roughness coefficient and are lower during the summer season than during spring or autumn for the same discharge sub-range.

Value of Manning’s roughness coefficient by Chow (1959) belong to channels not maintained, weeds and brush uncut with dense weeds, high as flow depth is from 0.050 to 0.120 or with dense brush, high stage is from 0.080 to 0.140. Calculated datas are in the our case is higher.

Change of discharge and water-level during three years for section one (from gas profile to Suchý stream profile) and section two (from railway bridge profile to road bridge profile) are shown in Fig. 2 and Fig. 3. Ranges of measured data for section 1 and section 2 are condensed in Table. The results show, that when is recorded biggest discharge value, then water-level value is smallest (for all measured cross-section profile). On the other side, when discharge value is smallest, water-level value is not biggest.

Figure 4 and figure 5 show growing of aquatic vegetation in the Malina stream during the season from April 2018 and from August 2018 (figure 4 for gas profile and figure 5 for railway bridge profile).

Fig. 1. Location of observed cross-section profiles along the Malina stream.
Table 1. Summary of measured and calculated data of first section experiment (from gas profile to Suchý stream profile)

| Date of measur. | v [m s⁻¹] | A [m²] | l [m] | R [m] | v [m s⁻¹] | A [m²] | l [m] | R [m] | Δh [m] | i₀ | n |
|-----------------|-----------|-------|-------|-------|-----------|-------|-------|-------|--------|----|---|
| 08/2016         | 0.095     | 4.09  | 5.8   | 0.705 | 0.091     | 3.75  | 6.49  | 0.578 | 0.048  | 0.000422 | 0.156 |
| 11/2016         | 0.153     | 3.96  | 6.7   | 0.59  | 0.158     | 2.52  | 6.59  | 0.382 | 0.028  | 0.000246 | 0.052 |
| 02/2017         | 0.315     | 2.92  | 5.67  | 0.515 | 0.351     | 2.62  | 6.8   | 0.385 | 0.014  | 0.000128 | 0.017 |
| 07/2017         | 0.061     | 2.83  | 5.64  | 0.502 | 0.059     | 2.39  | 6.31  | 0.379 | 0.020  | 0.000171 | 0.115 |
| 04/2018         | 0.221     | 1.46  | 5.08  | 0.287 | 0.262     | 1.25  | 5.91  | 0.211 | 0.029  | 0.000257 | 0.021 |
| 08/2018         | 0.052     | 3.73  | 5.99  | 0.622 | 0.045     | 4.22  | 8.55  | 0.493 | 0.023  | 0.000198 | 0.195 |
| 12/2018         | 0.128     | 3.58  | 6.32  | 0.566 | 0.35      | 2.71  | 6.63  | 0.408 | 0.035  | 0.000309 | 0.027 |
| 04/2019         | 0.201     | 2.71  | 5.35  | 0.505 | 0.375     | 1.45  | 5.79  | 0.25  | 0.056  | 0.000492 | 0.023 |

Table 2. Summary of measured and calculated data of second section experiment (from railway bridge profile to road bridge profile)

| Date of measur. | v [m s⁻¹] | A [m²] | l [m] | R [m] | v [m s⁻¹] | A [m²] | l [m] | R [m] | Δh [m] | i₀ | n |
|-----------------|-----------|-------|-------|-------|-----------|-------|-------|-------|--------|----|---|
| 08/2016         | 0.096     | 4.24  | 6.21  | 0.632 | 0.085     | 3.341 | 7.108 | 0.471 | 0.056  | 0.000263 | 0.115 |
| 11/2016         | 0.15      | 4.74  | 6.46  | 0.733 | 0.188     | 3.86  | 8.466 | 0.455 | 0.065  | 0.000303 | 0.054 |
| 02/2017         | 0.401     | 2.79  | 6.03  | 0.463 | 0.393     | 2.928 | 5.824 | 0.502 | 0.036  | 0.000169 | 0.020 |
| 07/2017         | 0.069     | 2.57  | 6.35  | 0.404 | 0.059     | 3.021 | 6.508 | 0.464 | 0.040  | 0.000185 | 0.138 |
| 04/2018         | 0.243     | 1.52  | 6.01  | 0.253 | 0.239     | 1.708 | 7.456 | 0.229 | 0.021  | 0.000011 | 0.015 |
| 08/2018         | 0.047     | 4.102 | 7.79  | 0.526 | 0.052     | 3.668 | 9.044 | 0.405 | 0.034  | 0.000016 | 0.133 |
| 12/2018         | 0.131     | 3.714 | 6.31  | 0.588 | 0.14      | 3.519 | 7.604 | 0.462 | 0.045  | 0.000211 | 0.061 |
| 04/2019         | 0.248     | 2.295 | 6.71  | 0.342 | 0.283     | 2.045 | 6.627 | 0.307 | 0.068  | 0.000318 | 0.028 |

**Fig. 2.** Change of discharge and water-level of the Malina stream during three years for section one.

**Fig. 3.** Change of discharge and water-level of the Malina stream during three years for section two.
Table 3. Summary of measured data of the discharge and water-level on the four cross-section profile

| Date of measur. | gas profile | Suchý stream profile | railway bridge profile | road bridge profile |
|----------------|-------------|----------------------|-----------------------|--------------------|
|                | Q [m$^3$/s$^1$] | w-l [m a.s.l.] | Q [m$^3$/s$^1$] | w-l [m a.s.l.] | Q [m$^3$/s$^1$] | w-l [m a.s.l.] |
| 08/2016        | 0.384       | 141.559              | 0.408                | 141.077           | 0.418               | 141.077         | 0.486               | 140.514             |
| 11/2016        | 0.609       | 141.260              | 0.633                | 140.979           | 0.714               | 140.979         | 0.726               | 140.331             |
| 02/2017        | 0.929       | 140.910              | 0.949                | 140.764           | 1.117               | 140.621         | 1.165               | 140.260             |
| 07/2017        | 0.161       | 140.981              | 0.175                | 140.785           | 0.177               | 140.721         | 0.182               | 140.325             |
| 04/2018        | 0.323       | 141.304              | 0.328                | 141.010           | 0.370               | 140.942         | 0.409               | 140.727             |
| 08/2018        | 0.201       | 141.415              | 0.191                | 141.189           | 0.194               | 141.003         | 0.193               | 140.661             |
| 12/2018        | 0.451       | 141.350              | 0.486                | 140.997           | 0.513               | 140.745         | 0.476               | 140.293             |
| 04/2019        | 0.511       | 141.282              | 0.543                | 140.815           | 0.572               | 140.646         | 0.583               | 140.281             |

Fig. 4. Aquatic vegetation in the Malina stream during season (April 2018 versus August 2018) – gas profile.

Fig. 5. Aquatic vegetation in the Malina stream during season (April 2018 versus August 2018) – railway bridge profile.
Conclusion

Vegetation in natural streams influences the flow field and related characteristics and phenomena, such as discharge capacity, velocity profile, roughness, 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 Malina stream. The roughness coefficient n was used as a way of quantifying the impact. A summary of relevant measured and calculated values is given in Tables 1 and 3.

An analysis of the obtained data revealed that the roughness coefficient value changes during the growing season. A consequence of vegetation growth in the channel is a changing velocity profile and water level. The rate of these hydraulic parameters divergences, in comparison to summer and non-summer seasons, decreases with increasing discharge. 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 into this problem.

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