Flow Resistance in Lowland Rivers Impacted with Distributed Aquatic Vegetation

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Flow resistance in lowland rivers impacted with distributed aquatic vegetation

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Abstract

The study addresses the research concern that the employment of fixed value for bed roughness coefficient in lowland rivers (mostly sand-bed rivers) is deemed practically questionable in the presence of a mobile bed and time-dependent changes in vegetation patches. To address this issue, we set up 45 cross-sections in four lowland streams to investigate seasonal flow resistance values within a year. The results first revealed that the significant sources of boundary resistance in lowland rivers with lower regime flow are bed forms and aquatic vegetation. Then, the study uses flow discharge as an influential variable reflecting the impacts of the above-mentioned sources of resistance to flow. The studied approach ended up with two new flow resistance predictors which simply connect dimensionless unit discharge with flow resistance factors, Darcy-Weisbach (f) and Manning (n) coefficients. A comparison between the computed and measured flow resistance values indicates that 87-89% of data sets were within the $\pm 20\%$ error bands. The flow resistance predictors are also verified against large independent sets of field and flume data. The obtained predictions using the developed predictors may overestimate flow resistance factors

to about 40% for other lowland rivers. From a different view of this research, the findings on seasonal variation of vegetation abundance hint at the augmentation in flow resistance values, both f , and n , in low summer flows when the vegetation covers river bed and side banks. The highest amount of flow resistance was observed during the summer period, July-August.

Keywords Aquatic vegetation, Flow resistance, Lowland streams, Seasonal roughness value

1 Introduction

The responsibility for catchment management in lowland areas is of paramount importance since the freshwater environment receives vast development pressures. The aquatic vegetation constitutes a substantial component of many rivers in a lowland catchment. They contribute significantly to the flow conditions and ecological function of habitat structure (Hearne and Armitage 1993; Mainstone and Parr 2002; Lacoul and Freedman 2006). Concerning flow conditions, vegetation patches on the river bed or the river bank often increase boundary roughness, decreasing velocities, and increasing river depth and cross-sectional area (Sulaiman et al. 2017). The extension of aquatic vegetation depends on many factors such as flow discharge and velocity (Riis and Biggs 2003; Schügerl et al. 2020), light accessibility (Sand-Jensen 1989), nutrient accessibility (Mainstone and Parr 2002), and material forming the river bed (Gurnell et al. 2006). Among these parameters, Franklin et al. (2008) concluded that flow velocity has the most significant impact on the presence of vegetation, and therefore, it is vital for further knowledge of better catchment management of lowland rivers.

Flow velocity can be measured by a current meter directly in natural streams or be calculated by the equation of continuity ($u = Q/A$) when both the flow discharge Q and the wetted cross-sectional area A are known. Nevertheless, in many cases, these kinds of measurements are not feasible; instead, a flow resistance predictor must be employed. Several

flow resistance equations are well acknowledged and they do not need to be calibrated when the uniform flow is deemed for a river reach. The Chezy and Darcy-Weisbach expressions, as well as the Manning formula, are widely-used equations.

Among effective parameters on flow resistance values, special attention was given to the primary source of boundary resistance, bed forms, and grain sizes (Brownlie 1981; Bathurst 2002; Yang et al. 2005; Ferguson 2007; Okhravi and Gohari 2020). However, in rivers located in low-gradient areas, the vegetation needs to be considered since it does alter roughness coefficients. In a recent study, Song et al. (2017) appraised the seasonal values of the Manning's roughness with the 1D hydraulic model in a German lowland vegetated river. According to their study, the model could predict water surface variations and flow velocities reasonably well after the seasonal roughness factor was adopted.

The analyses made by Ferguson (2010) through extensive field data set reflect that the use of Manning equation with the fixed value of n is not preferable for mobile river beds (sand-bed rivers mostly in lowland areas) and with relatively high submergences, $R/d_{84} > 5$ (d_{84} is the grain size which is larger than 84% of the bed material's mass and R is the hydraulic radius). The other performer types of resistance law after Manning expression are logarithmic law and power law approaches using relative submergence scaled on a d_{84} (Namaee et al. 2017). According to the data from lowland rivers, the relative submergence is usually high, and sediment motion is only initiated with low shear stress. Hence, the effects of relative submergence can be neglected on sediment transport rate (Sulaiman et al. 2017). Also, the grains forming the bed are well distributed in lowland rivers, and the median particle size (d_{50}) is usually transported as suspended load. Therefore, for sand-bed rivers, the main sources of boundary roughness are the lower regime bed forms (ripples and dunes) and the aquatic vegetation occurrence. Hence, the resistance law using relative submergence is not often the safest choice since they do not account for the bed form roughness. Since flow

discharge is the characteristic that shapes the channel and considers the irregular bed topography and water elevation variations, several authors have suggested nondimensional hydraulic geometry equations that connect dimensionless mean flow velocity (u^{**}) and dimensionless unit discharge (q^*) (Ferguson 2007; Zimmermann 2010; Rickenmann and Recking 2011). Hence, the flow discharge approach is an alternative to develop an equation for predicting flow resistance factors in lowland rivers.

Several field studies have investigated the behavior of overgrown streams on roughness coefficient in terms of improving the developed flow resistance predictors (Champion and Tanner 2000; Green 2005; Cai et al. 2020) or optimizing the model performance (Song et al. 2017). The present study aims to explore the seasonal variation of roughness coefficients in lowland streams with distributed vegetation. This research contributes to providing empirical reference data for validating the hydraulic models in which aquatic vegetation is considered in the hydraulic modeling. Besides, we tried to elaborate on developing new equations for flow resistance determination of seasonally overgrown lowland streams using collected field data. The developed flow resistance predictors take the impacts of bed form and vegetation occurrence by applying dimensionless flow discharge as an input parameter. Finally, the accuracy and applicability of the developed roughness predictors have been evaluated and compared with large sets of independent field and laboratory data.

2 Methods

2.1 Methodology Framework

Formulation of well-known flow resistance relations applied to flow velocity prediction can be presented as follows.

$$u = R^{2/3} S^{1/2} / n = C (RS)^{1/2} = (8gRS/f)^{1/2} \quad (1)$$

Here u is the mean flow velocity (LT^{-1}), C is the Chezy coefficient ($L^{1/2}T^{-1}$), n is the Manning coefficient ($L^{-1/3}T$), f (dimensionless) is the Darcy-Weisbach friction factor, S is the energy slope, and g is the acceleration due to gravity (LT^{-2}). The term $(gRS)^{1/2}$ in Eq. 1 has dimension LT^{-1} , reflecting a velocity term usually named the shear velocity and denoted by u_* . Since f is dimensionless (Eq. 2), most proposed relations under the two mentioned approaches were derived for f . The logarithmic and power law approaches connect f to the relative submergence as follows in Eq. 3 and Eq. 4.

$$f = 8 \left(\frac{u_*^2}{u^2} \right) \quad (2)$$

$$\frac{u}{u_*} = \sqrt{\frac{8}{f}} = a_1 \log \left(\frac{h}{d_{84}} \right) + a_2 \quad (3)$$

$$\frac{u}{u_*} = \sqrt{\frac{8}{f}} = \alpha \left(\frac{h}{d_{84}} \right)^\beta \quad (4)$$

where a_1 and a_2 (as well as, α and β) are empirical constant coefficients, and h is the flow depth. In low-gradient narrow streams, it is recommended to use R instead of h (Ferguson 2007).

To develop regional resistance relationships for lowland streams, watersheds with the same physiographic region should be selected. The watersheds should be similar in flow regime, precipitation, land use, bed forms, and aquatic vegetation. As briefly described before, the flow discharge is only the characteristic that shapes the channel and postulates the bed forms and submerged vegetation occurrence. Hence, the flow discharge measurements in lowland rivers are much more accurate than the relative submergence measurements. Then, the relationships based on flow discharge have higher reliability than those based on relative submergence (Eqs. 3, 4). The general form and optimal parameterization of such relationships were proposed by Rickenmann and Recking (2011):

$$u^{**} = kq^{*m} \quad (5)$$

In Eq. 5, k and m are determined empirically, $u^{**} = u/u_* = u/(gRS)^{0.5}$ and $q^* = q/(gR^3S)^{0.5}$, q is the discharge per unit channel width ($q = Q/B$) and B is the channel width. It is worth mentioning that the final developed equation is a contribution to this work. The process of regression analysis for producing the suitable fit between data and parameters was performed by applying an iterative least-squares fitting routine. In the present method, the solver function for non-linear equations is used an iterative algorithm to determine the fitting coefficients of Eq. 5 (k and m). The quantitative comparison between the predicted and measured values of u^{**} was performed by using determination coefficient (R^2) and error-measures such as root mean square error (RMSE), scatter index (SI), and index of agreement (I_a). A similar method has been employed to extract the n flow resistance predictor in reference to q^* .

2.2 Description of Field Measurements Localities

The selected lowland streams were located in the western part of Slovakia, the city of Bratislava (Fig. 1). The annual temperature range is -0.4 (January) to 21°C (July), and the average annual rainfall is about 565 mm, mainly concentrated in the spring-summer half year (from May to July). Bratislava city is 134 m above mean sea level (amsl). In this study, four streams with a gradient of < 2 m/km were selected (Fig. 1). Besides the low slopes, the selected streams are characterized by the low grain roughness of bed, well-sorted bed material configuration, and dominated by sand-sized particles, so-call sand bed streams with uniform sediment size particle distribution (Dulovičová et al. 2020). Regarding climate conditions, extensive aquatic vegetation occurs mainly during the summer and autumn seasons but with low dense biomass during winter and spring. The vegetation coverage

around the side bank is generally grass and shrubs, while on the stream bed are the submerged or non-submerged aquatic plants.

The measured streams are surrounded by pasture and grassland or other agricultural lands (Sokáč et al. 2020). In this case, fertilizer usage increases plant growth due to the presence of nutrient concentrations in water. The corresponding effects may lead to a change in the type of vegetation growing in the streams and their surrounding area.

Four natural stream sites, namely the Malina (A), the Šúrsky channel (B), the Gabčíkovo Topoľníky channel (C), and the Chotárny channel (D) were selected for this study (Fig. 1). A typical view of the selected streams is shown in Fig. 2. Overall, 45 stream cross-section profiles were used in this study. The cross-sections not only were placed almost evenly from each other but also steady uniform flow was maintained in each stream section. Field measurements along the streams were performed to collect the necessary hydraulic data like water surface elevation, width of channel, water depth, flow discharge, and velocity profile (see Table 1). The field study was carried out from April to September at the Malina stream and from February to August at the Šúrsky channel for 2019-2020. For the case of the Gabčíkovo Topoľníky and the Chotárny channels, the field measurements were done only at June 2020. The data listed in Table 1 are the measured values during a moderate water level period (June). The flow velocity measurements were taken by SonTek FlowTracker Handheld ADV and SonTek RiverSurveyor-M9, which are proven to be accurate and applicable for the field survey (Schügerl et al. 2019).

3 Results

3.1 Roughness Variations

The monthly variations of flow resistance in terms of the Darcy-Weisbach and the Manning coefficients, f , and n , can be shown for the Malina and the Šúrsky streams. Fig. 3 indicates

the roughness condition for each measured cross-section profile during April to September for the Malina and the Šúrsky streams. It reflects the effects of aquatic vegetation on flow roughness increase in summer and early autumn, beginning from June to September. The changing trends of f and n for the Malina stream are almost similar, showing August as a month with higher roughness for study sites A1 and A2 and September for A3 and A4. However, a similar trend of results between f and n has not been obtained for the Šúrsky channel. The higher values of f for study sites B2 and B4 were observed in June, while corresponding n values show higher roughness in August. This appears to be a case of calculation methods of flow roughness since a directly measured value of Q was used for the calculation of n ; while, the measured velocity was used for the f estimation.

For the other two lowland streams, the Gabčíkovo - Topoľníky and the Chotárny channels, similar measurements have performed one time in June. Calculated values of f and n for June are presented in Table 2. The range of n values at the same measuring time varied from 0.068-0.145, 0.022-0.272, 0.019-0.085, and 0.01-0.053 for Malina, Šúrsky, Gabčíkovo Topoľníky, and Chotárny streams, respectively. This result clarifies that the sources of boundary resistance in the lowland streams can be highly variable along a stream. The seasonal changes in flow velocity and aquatic vegetation alter the stream bed morphology. The velocity reduction during summer could probably enhance the sedimentation within submerged vegetation. Later, high flows during winter remove much of the deposited sediment. These processes, along with river bank alterations, would express the changes of the river bed topography, resulting in different values of flow resistance.

Table 2 clearly shows that the roughness of points C1 and C23 were the highest in the selected reach at Gabčíkovo Topoľníky channel, with a value of 0.084. The same for the Chotárny channel was observed at points D5, D4, and D8 with a variation from 0.05 to 0.053. In general, for the study sites with low flow velocity and full coverage of vegetation patches

at the bed and stream banks, the roughness reached near the peak values. During summer, submerged vegetation beds acted like semi-permeable dams, diminishing flow velocity, increasing flow depth, and wetted cross-sectional area (Fig. 4). Also, the presence of vegetation beds causes great variation range of flow velocity, resulting in habitat heterogeneity. The observations revealed that the abundance and diversity of aquatic vegetation are restricted at higher water velocities.

3.2 Development of New Equations

As it was mentioned and showed before, the rate of flow resistance can vary along lowland streams. Its value depends mainly on the formation of bed materials and dense aquatic vegetation. Its correct value is significant for practice, but the determination is complex. By propose of a new relationship, we tried to contribute to the solution of this problem.

The new flow resistance equations are developed on the basis of field data at stable and alluvial stream cross-section profiles. As a design tool, the new predictor considers two influential aspects of flow resistance in lowland streams: bed and bank vegetation and bed forms. Hence, the new equation is not only valuable for predicting flow velocity and flow resistance in lowland streams but also it is helpful in the proper design of stable channel geometry in similar physiographic areas.

To determine the mean flow velocity and therefore f , using a new flow resistance predictor, the formula structure of Eq. 5 is applied to the field data set for four natural streams in studied lowland regions located near the city of Bratislava. Using a power function in the form of Eq. 5 and flow discharge as an input parameter, the following equation is proposed. The corresponding variables are already described under Eq. 5.

$$u^{**} = 0.9785q^{*0.9529} \quad (6)$$

Fig. 5 shows the relationship between u^{**} and q^{*} depending on flow discharge as a controlling factor. The value of the determination coefficient (R^2) is calculated at about 0.97,

showing the perfect correlation made by the power equation. According to the results of statistical error analysis, the new predictor indicates a good performance because of the high value of I_a and the low values of RMSE and SI (Fig. 6). Also, the value of u^{**} calculated by Eq. 6 gives an acceptable prediction for most cross-section profiles. The accuracy of the prediction of u^{**} values was assessed by counting the number of results surrounded between two asymmetric bounds ($\pm 20\%$ concerning the perfect agreement line (45-degree line)), i.e., considering an overestimation of 20% and an underestimation of 20%, respectively. In accordance with this method, more than 87% of the predicted values (64/73) are within the boundaries, as shown in Fig. 6. The result provides evidence of similarity in the streams and watershed characteristics in those stream reaches used to develop Eq. 6 for predicting flow velocity and friction factor since data scatter around the regression line lie within reliable $\pm 20\%$ errors. It is worth noting that the new predictor not only takes flow discharge into account but also considers hydraulic radius and surface variations of water.

The power equation was also showed an appropriate fit for n estimation in relation with the q^* , so the next predictor was extracted to estimate n as:

$$n = 0.32q^{*-0.978} \quad (7)$$

Fig. 7 shows the scattering between the values of n and q^* . The statistical analysis showed that the low values for RMSE and SI along with high correlations (R^2) and I_a , indicating good predictions for n was obtained by Eq. 7. In Fig. 8, 89% of the predicted values (65/73) are surrounded by the same referred bounds ($\pm 20\%$).

4 Discussion

4.1 Seasonal Roughness in Similar Physiographic Regions

Flow velocity, hence flow discharge, has long been recognized as a major factor controlling the growth extension and distribution of aquatic vegetation in rivers (Wilby et al. 1998; Franklin et al. 2008). Typically, aquatic vegetation growth is restricted at higher flow velocities (Riis and Biggs 2003). As the flow velocity in the summer season is less than in other months of the year, the growth conditions are pretty stimulating for vegetation establishment. Since there is a positive relationship between the percentage of vegetation abundance and bottom roughness in lowland rivers, the values of n or f are higher in the summer period. Following this result, a similar trend was reached by Champion and Tanner (2000) and Song et al. (2017), showing that the flow resistance values were higher in summer and early autumn for cases of lowland rivers in New Zealand and northern Germany, respectively.

The field study in lowland streams near Bratislava, Slovakia, revealed that n values are increased from 0.016 to 0.373 with the increase of aquatic vegetation abundance from 0 to 100%. The corresponding range for the field survey of Champion and Tanner (2000) was between 0.05 to 0.5. Also, O'Hare et al. (2010) reflected $\pm 50\%$ variations of the Manning roughness coefficient value from the annual mean values for the cases of lowland river reaches in England and Scotland. The present study confirmed the findings stated by Ferguson (2010) about the variations of the Manning roughness coefficient for sand-bed rivers located in lowland areas due to great changes in bed forms and vegetation abundance. Hence, the calibrated seasonal roughness coefficient for the actual aquatic vegetation condition is highly recommended to better model flow resistance and calculate flow velocity.

4.2 Assessment of Flow Resistance Predictors

To verify the application of the developed equations for predicting flow resistance in the form of the Manning (n) and the Darcy-Weisbach (f) expressions, a series of data sets from the literature were used (Brownlie 1983; Song et al. 2014, 2017).

According to the field-measured data, Eq. 6 was developed to predict the Darcy-Weisbach friction factor in lowland streams with bed forms and submerged aquatic vegetation. To estimate the value of f by Eq. 6, the dimensionless value of q as q^* must first be calculated. To predict the accuracy of Eq. 6, field data from a lowland river located at the Upper Stör catchment in northern Germany were used (Song et al. 2014, 2017). According to the results mentioned above, the seasonal variations of roughness values presented in this study were similar to the German lowland catchment since they both located at the same physiographic area. The comparison of calculated f values by Eq. 2 with predicted f by Eq. 6 has been shown in Fig. 9. The results show that most of the data were between the perfect agreement line and a band specified by +40%. In fact, 92% of the predicted values (82/89) are included by the above-referred bounds. The good predictions by Eq. 6 are due to the similarity of hydraulic and sediment characteristics of the selected German catchment and the resemblance of the distributed vegetation throughout a yearly field study.

Data scattering of the Manning roughness coefficient with q^* has concluded the similar form of power equation presented in Eq. 7. In order to assess whether Eq. 7 developed on collected field data from the lowland streams near Bratislava, Slovakia is applicable for other lowland rivers (sand-bed rivers), a database consisting of 420 flume and field data have been used. The data sets were extracted from a database compiled by Brownlie (1981). Each data set was selected based on similar hydraulic and sediment conditions and flow regimes with the lowland streams in the study area. The database contains comprehensive records of flow discharge, channel width, water depth, bed slope, median grain size of bottom material, sediment gradation, and specific gravity of the sediment. The hydraulic and sediment

parameters of the selected data sets are listed in Table 3. To verify the validity of Eq. 7, the results were compared with the Manning roughness predictions obtained by the equation of Brownlie (1983):

$$n = 0.034d_{50}^{0.167} \left[1.893 \left(\frac{R}{d_{50}} \right)^{0.1374} \times S^{0.1112} \right] \quad (8)$$

The predictor of Brownlie (Eq. 8) for the Manning roughness coefficient is recommended for sand-bed streams, and it takes into account both aquatic vegetation and bed forms.

Following the aforementioned results, Fig. 10 compares values of n computed by using the two methods (Eqs. 7 and 8). The obtained results were bounded by two defined lines, -30% and +50%. The values of the Manning roughness coefficient using both equations showed that these two methods are in acceptable agreement. A closer look specifies that most field data lie within +50% and the perfect agreement line. The consistency of data is reasonably good considering the usually large degree of uncertainties in field measurements. Part of the scatter in the data could be a result of the dissimilarity in rivers and catchment characteristics, abundance and density of submerged vegetation, land use, sediment load and gradation, and geographic areas. The presence and percentage of cohesive sediment in the bottom and, or aquatic vegetation on the bottom and bank significantly affect the roughness values (Hey and Thorne 1986; Franklin et al. 2008).

It is necessary to mention that Eq. 7 takes non-uniformity in flow (sourcing by bed forms and vegetation) into account by using q^* , needless to have d_{50} . The new predictor benefits from the calculation of flow discharge as the main characteristic, which considers the effects of primary sources of boundary resistance in lowland streams (bed forms and vegetation). The results confirm that Eq. 7 is an excellent choice for predicting the Manning roughness coefficient for low flows through distributed aquatic vegetation.

5 Conclusion

In the present study, field data from 45 cross-section profiles of four streams were collected at Slovakian lowland areas near Bratislava city during different seasons of the year. The study aims to first explore the effects of submerged aquatic vegetation on flow resistance coefficient, Darcy-Weisbach, and Manning and, then contribute to developing new simple flow resistance predictors in lowland streams. The main findings emerge:

- The primary sources of flow resistance in lowland rivers with lower flow regimes are bed form and aquatic vegetation.
- Seasonal variations of flow resistance, both in f , and n , showed the dominant impact of vegetation patches during summer months when stream discharge is low. Two roughness coefficients revealed similar trends during the year, leading to the maximum value in the second-half summer (July-August) and the minimum value in the first-half spring (March-April).
- A new equation for flow resistance determination was developed based on the recommended structure form of Rickenmann and Recking's study, using flow discharge as the input, to predict mean flow velocity and therefore Darcy-Weisbach friction factor, f (Eq. 6). The same structure was also applied to connect flow discharge with Manning roughness coefficient n , and the results led to a generation of another flow resistance predictor (Eq. 7). Both predictors showed a perfect fit with the data set of the present study in which 87-89% of all data was surrounded within $\pm 20\%$ error bounds in respect to the perfect agreement line.
- To verify the suitability and applicability of the above-referred flow resistance predictors, Eqs. 6 and 7 were evaluated using another extensive field database from similar physiographic lowland areas (for Eq. 7, the flume database is also employed). The statistical analysis of the predicted values of f and n represented a reasonable

agreement with those corresponding values obtained from series of data sets. The results concluded that both flow resistance predictors could be employed for lower flow regimes in lowland rivers.

The present study provides reference field data for validating hydraulic models in which the characteristics of lowland streams are considered. The improvement of model performance by taking the composition of river beds and side banks into account will be practical to simulate flood events better and reduce flood risks.

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Author Contributions

Saeid Okhravi: Study conception and design, Formal analysis and investigation, Methodology, Data curation, Visualization, Writing - original draft, Writing - review and editing. **Radoslav Schügerl:** Material preparation, Data collection, curation, and analysis. **Yvetta Velísková:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing - review and editing.

Data Availability

Some or all data and models that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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Figures

Figure 1

The location of lowland streams in western Slovakia and study points

Figure 2

Typical view at lowland streams presented in the study

Figure 3

Time variations of f and n at each cross-section, a) Malina stream b) Šúrsky stream

Figure 4

Measurements at the Gabčíkovo Topoľníky channel and photograph of submerged aquatic vegetation

Figure 5

Relationship between u^{**} and q^{*} for field data

Figure 6

Comparison of u^{**} values predicted using the Eq. 6 and ones calculated from measured data

Figure 7

Relationship between n and q^* for field data

Figure 8

Comparison of n values predicted using the Eq. 7 and those calculated in the present study

Figure 9

Comparison of calculated and predicted friction factor

Figure 10

Comparison of n values estimated using the new developed predictor (Eq. 7) and the Brownlie's equation (Eq. 8)

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