ESTIMATION OF BASIC GEOMETRIC AND HYDRAULIC CHARACTERISTICS OF NATURAL TORRENT BEDS

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Abstract

Many mountainous regions and their watersheds lack the mathematical description of their hydraulic geometry such as the High Tatras region in Slovakia. Therefore, the aim of the paper is to determine the geometric and hydraulic characteristics of natural torrent beds and to propose a regional equations of mountain watersheds for the High Tatras region. In the paper is also proposed a new equation to determine the relationships between the watershed area and the geometric characteristics of flow profiles. Derived regional equations can help in nature-friendly and ecological shaping and dimensioning of channel cross sections in torrent control designing. The research was conducted in 26 natural torrents and their watersheds on the reference sections and profiles under the sediment source zones. Two different regression equations to determine the regional relationships (hitherto used without asymptote and newly proposed with asymptote) were compared. The analyses showed a strong correlation relationship between watershed area A_w (km²) and bankfull geometric characteristics of natural cross-sections: width of the channel inside the banks B_{bf} (m), mean channel depth H_{bf} (m), channel cross-section area A_{bf} (m²) and hydraulic characteristic – bankfull discharge Q_{bf} (m³.s⁻¹). These relations were tested by t-test and Shapiro-Wilk test. The determination coefficient (R_1^2) for the relationships without asymptote ranged between $R_1^2 = 0.919$ and $R_1^2 = 0.972$; p_1 – values from Shapiro-Wilk test ranged between $p_1 = 0.0359$ and $p_1 = 0.8027$. The determination coefficient (R_2^2) for the relationships with asymptote ranged between $R_2^2 = 0.952$ and $R_2^2 = 0.974$; p_2 – values from Shapiro-Wilk test ranged between $p_2 = 0.0221$ and $p_2 = 0.8617$. At the same time, we tested and confirmed the hypothesis that the correlation coefficients R_1 from equation without the asymptote are only randomly different from the correlation coefficients R_2 from equation with the asymptote and the difference between these coefficients is also random. Derived regional equations make it possible to the gradual creation of hydrologic landscape regions in the SR. They can be also used as a valuable input to the ecological cross sections designing in torrent control and revitalization for the regions with a similar natural conditions.

Keywords: bankfull characteristics, watercourses morphogenesis, High Tatras, Slovakia

INTRODUCTION

The total length of the watercourses in the Slovak Republic (SR) is of 61,147 km. These watercourses are mostly managed by state organizations which fall under the Ministry of Environment of the SR and the Ministry of Agriculture and Rural Development of the SR. Approximately 24,000 km of watercourses (39.25%) are of a torrent nature and 19,412 km of these torrents (31.75% from total watercoure length of SR) are managed by state forestry organizations. The torrents found in geomorphological units with similar geological and other natural characteristics of the watersheds (landform, climate, vegetation), show a similar process of morphogenesis, i. e. a long-term natural development of the beds. There are several reasons why to study a long-term morphogenesis of torrent beds and regional hydraulic geometry of mountain torrents and watersheds. The first is the possibility to use the results in practice (design of cross sections in torrent control within the framework of flood protection, erosion control, torrent revitalization, natural torrents management, etc.). In the SR, all torrent watersheds occur in protected areas (national parks, protected landscape areas). This fact should be taken into account during all interventions into torrent beds and watershed because they all have specific natural characteristics. These tasks need to be addressed sensitively and ecologically, especially in protected areas such as the Tatra National Park. Research of regional hydraulic geometry provides important information on the particular stages of torrent beds designing. The fact that this problem has not been sufficiently solved in the SR encourages this type of research. Powel *et al.* (2004) indicates that in the USA, several decade-old regional equations of hydraulic geometry are used in designing and revitalization of watercourses. Regional equations of hydraulic geometry are unsuitable for existing conditions of watercourses and watersheds. Using these equations may cause various errors in designing the watercourses control and revitalization, with a negative ecological and environmental effect on the landscape. Howell (2009) suggests that regional hydraulic curves are especially useful in stream restoration projects, where the stream is so degraded that natural bankfull channel geometry can no longer be determined and no reference thereto is available. Regional curves can be used also in projects such as road, bridge and culvert construction. Wilkerson (2008) states that this information is essential for planners, engineers, geomorphologists, environmentalists, agricultural interests, developments situated on flood-prone lands, and others interested in floods and flooding. Regional curves should be applied only to projects within the same geographic region or in a region with the same hydraulic geometry curves (Howell, 2009). Wilkerson (2008) noted that physiographic region is a region, within which all parts are similar in geologic structure and climate, and which has a unified geomorphic history and its relief features differ significantly from those of adjacent regions. Regional equations represent relationships between geomorphologic and hydrologic characteristics of watershed and geometric and hydraulic characteristics of channel profile. There are two types of channel and watershed regional equations which are based on the theory of hydraulic geometry:

1. at – a – station with variations at a particular cross section and
2. downstream with variations along the length of the watercourse (more detailed Leopold *et al.*, 1992; Alexander *et al.*, 2009; David *et al.*, 2010; Julien, 2014; Gleason and Wang, 2015).

Blackburn-Lynch *et al.* (2017) mention the basic downstream regional hydraulic geometry equations:

$$W_{bkf} = aA_w^b, \tag{1}$$

$$D_{bkf} = cA_w^d, \tag{2}$$

$$A_{bkf} = eA_w^f, \tag{3}$$

$$Q_{bkf} = gA_w^h, \tag{4}$$

where:
W_{bkf} – the width of the bed inside the banks (m); D_{bkf} – mean depth of the bed (m), A_{bkf} (m²) – channel cross-section area, Q_{bkf} (m³.s⁻¹) – bankfull discharge, A_w (km²) – the watershed area; a, c, e, g – empirically derived values of absolute coefficients; b, d, f, h – empirically derived values of regression coefficients.

The problems of regional equations and their use in practice was analyzed by many authors, especially in USA. A detailed overview of the results of published articles has been summarized by Bieger *et al.* (2015) and Blackburn-Lynch *et al.* (2017). Torrents generally have three characteristics sections:

1. section with sediment formations (source zone),
2. zone of sediment transport (transport zone) and
3. sediment accumulation zone.

Boundaries between these zones can not be determined precisely, they vary depending on discharge and other factors. The shape of natural torrent beds in each zone also varies. This research paper focuses on developing relationships between watershed area and geometric and hydraulic characteristics of natural torrent beds without direct human interventions. Derived regional equations can help in nature-friendly and ecological shaping and dimensioning of channel cross sections in torrent control designing, flood and erosion control and torrent revitalization in regions for which they were derived and could be modified to be applied for similar regions in Europe.

MATERIALS AND METHODS

Analyzed torrents and watersheds are located in the Tatra National Park (TNP) in the geomorphological unit of Tatry, the subunit of Východné Tatry, the part of High Tatras and the geomorphological unit of Podtatranská kotlina, the subunit of Tatranské predhorie (Fig. 1) at altitudes from 860 to 2654 m a.s.l. High Tatras are the highest mountains in the Slovak Republic.

Between 2016 and 2019, twenty-six torrents with enclosing channel profiles near the southern border of TNP (near the northern border of the geomorphological unit of Podtatranská kotlina) were analyzed. Analyzed torrents are situated in two main river watersheds, Váh and Poprad. The watershed areas of 26 analyzed torrents range from A_w = 0.25 km² (Važecký) to A_w = 19.34 km² (Poprad) with the median A_w = 3.21 km². The discharges Q_{100} range from Q_{100} = 1.5 m³.s⁻¹ (Važecký) to Q_{100} = 35.7 m³.s⁻¹ (Biely Váh) with the median Q_{100} = 10.25 m³.s⁻¹ (Tab. I). The torrents of High Tatras are typical mountain torrents with frequent and rapid changes in discharges, sediments formation, transport of these sediments and their accumulation. Geological structure of the analyzed area is complicated. Three main building blocks can be distinguished in High Tatras: a crystalline core, mountain ranges and sedimentary cover and flysch fill adjacent depressions. Crystalline core appears on a large part of the ridge and on the southern slopes of the mountains. In the higher parts of watershed migmatites – porphyritic granites and granodiorites occur. In the eastern part of High Tatras, from the highest to central position porphyric granodiorites to granites, hercynian, occur in a continuous strip. The lower parts of the analyzed watersheds is formed by bedrock flysch – sandstones and calcareous claystones. As for soil types, in higher elevations Lithic Leptosols and other (nonrendzic) Leptosols are dominant, in lower positions, Haplic Podzols to Humic Podzols are most frequent soil types. From the aspect of hydrological efficiency the soils in the higher watershed positions have high retention capacity with medium permeability and moderate retention capacity and permeability in the lower positions (Ministry of Environment of the SR, 2002). The watersheds (by the climatic regions of the SR) are located in climatic region C – cold in subregions: C1 – moderately cool, C2 – cool mountainous and C3 – cold mountainous (Ministry of Environment of the SR, 2002). Average annual precipitation in the watersheds range from 1037 mm (Päť prameňov) to 1379 mm (Biely Váh). Average annual temperatures in watersheds range from 0.9 (Päť prameňov) to 3.8 °C (Biely Váh). Values of average annual precipitation and average annual temperatures are taken from the data of observation stations of the Slovak Meteorological Institute in Bratislava.

On straight stretches of each streams, we selected the reference longitudinal sections (RLS) with reference cross-sections (RCS) and determined their geometric and hydraulic characteristics according Page (1988) and Rosgen and Silvey (1996). We established RLS and RCS in the terrain under the torrents sediments source zones without direct human interventions. The source zone boundary cannot be specified exactly. RLS were established in sections that well represented the overall character of the torrent bed in relatively balanced longitudinal gradient in the envisaged transport zone. We determined the geometric characteristics of the RCS by leveling. Basic characteristics of watersheds and geometric and hydraulic characteristic of RCS: width of the bed inside the banks B_{bf} (m), mean channel depth H_{bf} (m), cross-sectional area A_{bf} (m²)

1: *Map of Slovakia with designation of research watersheds area*

and bankfull discharge Q_{bf} (m³.s⁻¹) with medians of B_{bf} = 2.80 (m), H_{bf} = 0.55 (m), A_{bf} = 1.25 (m²) and Q_{bf} = 2.73 (m³.s⁻¹) are listed in Tab. I. To calculate bankfull discharge Q_{bf} (m³.s⁻¹), we used the Equation according to Parker (2004):

$$Q_{bf} = 3.732 B_{bf} H_{bf} \sqrt{gR_{bf}S} \left(\frac{R_{bf}}{D_{50}} \right)^{0.2645} \quad \text{(m³.s⁻¹).} \qquad (5)$$

The author confirmed the suitability of using equation (5) to calculate the total discharge in natural gravel beds. In the examples solved by the author, the possibilities of using equation (5) for very similar values of geometric and hydraulic characteristics, which occurred in our research, are presented. ($Q_{bf} \geq 2.7$ m³.s⁻¹, $B_{bf} \geq 5.24$ m, $H_{bf} \geq 0.25$ m, D_{50} = 0.027–0.167 m, S = 0.00034–0.031, etc.).

The longitudinal slope of RLS was calculated from altitude differences of RLS determined by leveling, too. A sediment samples were collected on each RCS in order to conduct of sieve granulometric analyses used to determine the grain diameter D_{50} (m) with median of D_{50} = 0.102 (m). The weights of the sediment samples ranged from 52.3 to 57.2 kilograms for the individual RCS. We also determined the hydraulic radius R_{bf} (m) with the median of R_{bf} = 0.371 (m) during the office-run processing. Watersheds areas with up to the RCS as enclosing profiles were from the maps with GIS methods determined with median of A_w = 3.21 (km²).

We used the following regression Equations for analysis:
• Equation without the asymptote hitherto generally used to development of hydraulic geometry relations:

$$y = a_0 \times x^{a01} \qquad (6)$$

I: *Characteristics of watersheds and RCS to bankfull discharge calculation in High Tatras torrents*

Watercourse	A_w	φH_w	B_{bf}	H_{bf}	A_{bf}	S	R_{bf}	D_{50}	Q_{bf}
Beliansky	3.17	1614	3.7	0.65	2.0	2.85	0.435	0.141	4.22
Tri studničky	0.36	1278	0.9	0.35	0.3	2.10	0.214	0.105	0.30
Mlyničná voda	2.18	1544	2.9	0.55	1.2	2.77	0.364	0.091	2.70
Jamský	0.60	1407	1.0	0.40	0.4	3.55	0.267	0.090	0.61
Važecký	0.25	1350	0.8	0.30	0.2	2.90	0.154	0.077	0.24
Biely Váh	10.62	1812	7.2	0.80	4.9	2.37	0.620	0.123	12.53
Lieskovec	1.57	1434	2.0	0.40	0.7	3.90	0.292	0.152	1.19
Mlynica	6.90	1740	4.5	0.65	1.9	3.93	0.413	0.129	5.93
Poprad	19.34	1789	10.4	1.10	8.9	1.97	0.848	0.114	29.38
Veľký šum	4.86	1548	3.2	0.60	1.5	3.72	0.417	0.131	3.80
Malý šum	3.07	1665	1.9	0.50	1.0	2.31	0.417	0.135	1.47
Háganský	0.71	1277	1.0	0.30	0.3	3.70	0.188	0.091	0.35
Batizovský	5.69	1696	4.5	0.60	2.0	3.83	0.417	0.128	5.45
Hromadná voda	3.25	1510	2.7	0.50	1.1	4.20	0.355	0.093	2.75
Velický	6.16	1736	4.5	0.70	2.1	3.30	0.404	0.122	5.83
Slavkovský	5.31	1655	4.0	0.60	1.7	2.20	0.370	0.099	3.58
Malý Štiavnik	0.88	1273	1.9	0.45	0.8	0.85	0.308	0.060	0.79
Veľký Jazyk	1.19	1306	1.9	0.40	0.8	2.18	0.348	0.065	1.21
Štiavnik	1.64	1528	2.2	0.50	0.8	2.90	0.320	0.070	1.85
Päť prameňov	0.98	1239	2.0	0.40	0.7	1.13	0.318	0.072	0.83
Pod Hrebienkom	2.73	1308	2.6	0.50	1.0	1.85	0.345	0.078	1.80
Studený	18.13	1793	9.8	1.10	7.3	2.63	0.716	0.400	20.16
Hlboký	4.88	1304	2.4	0.55	1.3	2.53	0.464	0.069	2.68
Skalnatý	9.37	1506	6.2	0.75	3.5	2.70	0.530	0.170	8.49
Kežm. Biela	18.29	1612	9.2	1.00	6.3	2.78	0.656	0.115	23.02
Sedem prameňov	4.58	1241	4.0	0.60	1.6	2.80	0.372	0.099	4.07

Explanatory notes to Tab. I: A_w (km²) – watershed area; φH_w (m a.s.l.): mean altitude of the watershed; B_{bf} (m) – width of the RCS inside the banks; H_{bf} (m) – mean depth of the RCS; A_{bf} (m²) – RCS area; S (m.m⁻¹) – energy gradient; R_{bf} (m) – hydraulic radius of RCS; D_{50} (m) – grain diameter; Q_{bf} (m³.s⁻¹) – bankfull discharge

- and newly designed Equation with the asymptote:

$$y = a_1 \times (1 - e^{-kx}) + a_{11} \times x, \tag{7}$$

k – parameter expressing the stepness of regression curve to the asymptote.

RESULTS AND DISCUSSION

Characteristics of watersheds and RCS to bankfull discharge Q_{bf} (m³.s⁻¹) calculation in High Tatras torrents are listed in Tab. I.

The results and derived regional regression equations for analyzed relationships are listed in Tab. II which also contains the absolute and regression coefficients for particular regional equations.

The results were tested by t-test and Shapiro-Wilk test. Statistical testing by these tests and values of root mean square errors (RMSE) are listed in Tab. III. The determination coefficient (R_1^2) for the relationships by regression eqation (2) without the asymptote ranged between $R_1^2 = 0.919$ and $R_1^2 = 0.972$; p_1 – values from Shapiro-Wilk test ranged between $p_1 = 0.0359$ and $p_2 = 0.8027$. The determination coefficient (R_2^2) for the relationships by regression equation (3) with the asymptote ranged between $R_2^2 = 0.952$ and $R_2^2 = 0.974$; p_2 – values from Shapiro-Wilk test ranged between $p_2 = 0.0221$

and $p_2 = 0.8617$. The graphical representation of the regional curves by equations (2) and (3) is shown in Figs. 2–5. Based on the results (Tab. III), we found that the determination coefficients (R_2^2) for the correlation relations $B_{bf(2)} = f(A_w)$, $H_{bf(2)} = f(A_w)$, and $Q_{bf(2)} = f(A_w)$ are higher than for relations $B_{bf(1)} = f(A_w)$, $H_{bf(1)} = f(A_w)$, and $Q_{bf(1)} = f(A_w)$; the determination coefficient (R_1^2) for the relation $A_{bf(2)} = f(A_w)$ is almost identical to the (R_1^2) for the relation $A_{bf(1)} = f(A_w)$. Shapiro-Wilk test (that is appropriate for the files with $n \leq 50$) to analyse of residuals distribution was used. We found (Tab. III) that the p_2 – values for relations $B_{bf(2)} = f(A_w)$, $H_{bf(2)} = f(A_w)$ are significantly higher than p_1 – values for relations $B_{bf(1)} = f(A_w)$, $H_{bf(1)} = f(A_w)$. The p_1 – values for the relations $A_{bf(1)} = f(A_w)$, $Q_{bf(1)} = f(A_w)$ are almost identical to the p_2 – values for the relations $A_{bf(2)} = f(A_w)$, $Q_{bf(2)} = f(A_w)$. Based on our analysis, we can recommend the use of newly proposed regression equation (3) with the asymptote to determine of regional equations, too.

Regional curves by equation (3) with the asymptote reflects very well bankfull characteristics B_{bf}(m), H_{bf}(m), A_{bf}(m²) and Q_{bf}(m³.s⁻¹) especially for larger watershed areas. The importance of variant solutions in the development of regional hydraulic geometry equations and curves can be ilustrated in Fig. 3. In comparing the course of the curves

II: *Regression equations of analyzed relations*

Correlation relation	Regression equation
$B_{bf(1)} = f(A_w)$	$B_{bf(1)} = 1.3366 \times (A_w)^{0.6787}$
$H_{bf(1)} = f(A_w)$	$H_{b(1)} = 0.3800 \times (A_w)^{0.3305}$
$A_{bf(1)} = f(A_w)$	$A_{bf(1)} = 0.3288 \times (A_w)^{1.0712}$
$Q_{bf(1)} = f(A_w)$	$Q_{b(1)} = 0.4738 \times (A_w)^{1.3475}$
$B_{bf(2)} = f(A_w)$	$B_{bf(2)} = 1.4676 \times (1\text{-EXP}(-1.9013 \times A_w)) + 0.45678 \times A_W$
$H_{bf(2)} = f(A_w)$	$H_{bf(2)} = 0.4107 \times (1\text{-EXP}(-3.9534 \times A_w)) + 0.0359 \times A_W$
$A_{bf(2)} = f(A_w)$	$A_{bf(2)} = 0.0115 \times (1\text{-EXP}(-49.8164 \times A_w)) + 0.3950 \times A_W$
$Q_{bf(2)} = f(A_w)$	$Q_{bf(2)} = -84.304 \times (1\text{-EXP}(-k \times 0.0327 A_w)) + 3.3779 \times A_W$

III: *Statistic characteristics and testing of analyzed relations*

Correlation relation	$R_{1,2}$	$R_{1,2}^2$	S_R	t	>; =; <	$t_{0.01\,(24)}$	RMSE	$SWp_{1,2}$
$B_{bf(1)} = f(A_w)$	0.980	0.961	0.0403	24.32	>	2.797	0.55	0.0394
$H_{bf(1)} = f(A_w)$	0.959	0.919	0.0581	16.51	>	2.797	0.06	0.0359
$A_{bf(1)} = f(A_w)$	0.978	0.956	0.0428	22.85	>	2.797	0.48	0.8027
$Q_{bf(1)} = f(A_w)$	0.986	0.972	0.0342	28.83	>	2.797	1.29	0.0265
$B_{bf(2)} = f(A_w)$	0.984	0.967	0.0378	26.03	>	2.797	0.51	0.3319
$H_{bf(2)} = f(A_w)$	0.976	0.952	0.0447	21.83	>	2.797	0.05	0.8617
$A_{bf(2)} = f(A_w)$	0.977	0.954	0.0438	22.31	>	2.797	0.51	0.7949
$Q_{bf(2)} = f(A_w)$	0.987	0.974	0.0329	29.73	>	2.797	1.27	0.0221

Explanatory notes to Tab. III: $R_{1,2}$ – correlation coefficient; $R_{1,2}^2$ – determination coefficient; $S_r - \sqrt{\dfrac{1-R^2}{n-2}}$; $t - \dfrac{R}{S_r}$; RMSE – root mean square error; $SWp_{1,2}$ – value by Shapiro-Wilk test

which were derived by the equation (2) withouth the asymptote and by the equation (3) with the asymptote, it is clear that for larger watershed areas, the equation (3) with asymptote significantly better reflects the relation between watershed area A_w (km²) and mean depth of the RCS H_{bf}(m). In other cases (in relations $A_{bf} = f(A_w)$, $B_{bf} = f(A_w)$ and $Q_{bf} = f(A_w)$), the course of both curves is similar. For the above reasons, we propose in design optimization of geometric characteristics of channel

cross sections the use of both methods, their mutual comparison and evaluation. The source zone boundary cannot be specified exactly. RLS were established in sections that well represented the overall character of the torrent bed in relatively balanced longitudinal gradient in the envisaged transport zone.
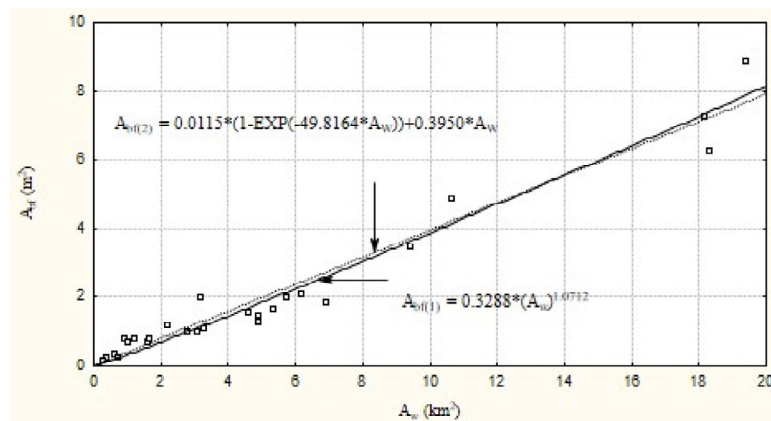
At the same time we tested the hypothesis that the correlation coefficients $R_{(1)}$ from equation (2) are only randomly different from the correlation
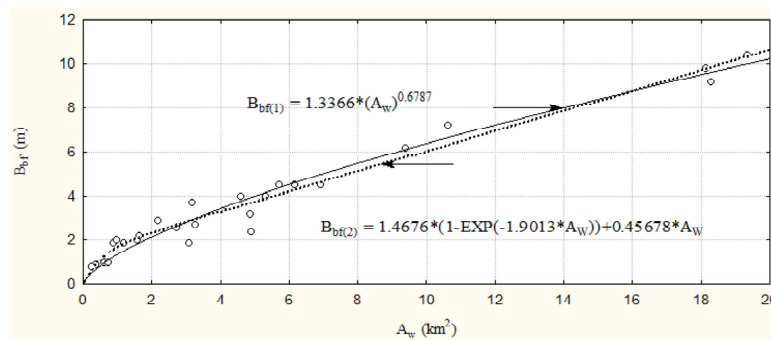
2: *Regional equations and curves for the relation between A_w (km²) and B_{bf} (m)*
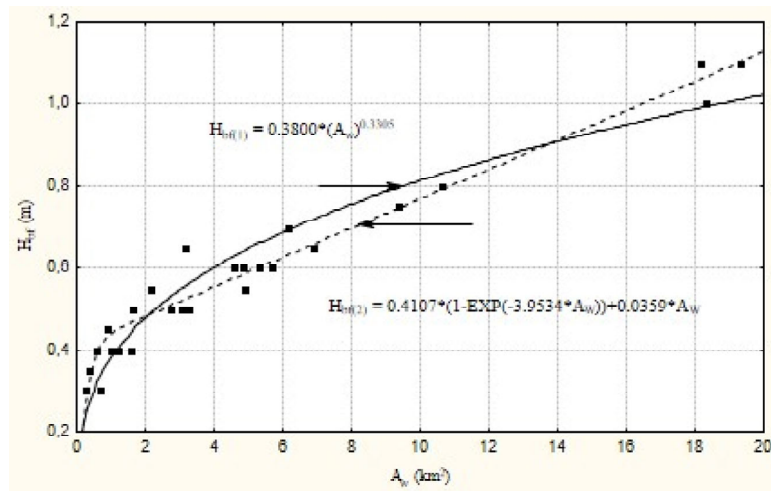
3: *Regional equations and curves for the relation between A_w (km²) and H_{bf} (m)*

4: *Regional equations and curves for the relation between A_w (km²) and A_{bf} (m²)*

coefficients $R_{(2)}$ from equation (3) and the difference $|R_{(1)} - R_{(2)}|$ is also random. The test criterion is the characteristic:

$$Z' = \frac{\left| Z'_{R(1)} - Z'_{R(2)} \right|}{\frac{1}{\sqrt{n-3}}}. \tag{8}$$

Testing characteristics Z' are in all cases lower than the critical values $Z'α$. This means that we accept the hypothesis, that the differences between $R_{(1)}$ and $R_{(2)}$ are only random and therefore not significant (Tab. IV).

By permeability and resistance to water flowing in the torrent beds, Valtýni (1981) declared geomorphological value of 5 various bedrocks in the SR and confirmed that the bedrock greatly affects morphogenesis and natural geometric characteristics of torrent beds. Wolock *et al.* (2004) divided the USA into 20 Hydrologic Landscape regions (HLR) on the basis of similar natural characteristics. Vianello and D'Agostino (2007) evaluated variations in bankfull cross-sections along a steep stream in dolomites (Northern Italy). The relations between watershed area A_w (from 0.040 to 7.084 km²) and bankfull width of the channel inside the banks W_{bkf} (from 0.35 to 5.10 m) were ewaluated with $R^2 = 0.620$.

Jakubis (2008) analyzed natural geometric characteristics of torrent beds on 25 torrents in a geomorphological unit of Poľana (Central Slovakia, neovolcanites) with the bankfull characteristics medians of $A_w = 4.47$ (km²), $B_{bf} = 2.40$ (m), $H_{bf} = 0.55$ (m), $A_{bf} = 1.05$ (m²), $Q_{bf} = 1.14$ (m³.s⁻¹) and the determination coefficients ranged between $R^2 = 0.907$ and $R^2 = 0.989$. Pšida (2014) evaluated the relationships of bankfull regional hydraulic geometry in four geographic regions – geomorphologic units in the SR with different bedrocks with the bankfull characteristics with the medians of $A_w = 18.81$ (km²), $B_{bf} = 8.10$ (m), $H_{bf} = 0.83$ (m), $A_{bf} = 4.53$ (m²), $Q_{bf} = 8.02$ (m³.s⁻¹) where the determination coefficients ranged between $R^2 = 0.723$ and $R^2 = 0.977$. Both authors confirmed varying and specific natural geometric and hydraulic characteristics of torrent beds and their long – term morphogenesis in watersheds with different bedrocks and natural characteristics (climate, vegetation, landform). Galia and Hradecký (2014) evaluated 120 bankfull cross-sections of 14 mountain streams in flysch bedrock of Outer Western Carpatians in the relations between watershed area (A_w from 0.45 km² to 2.59 km²), width of the channel inside the banks (W_{bkf} from 2.17 m to 3.96 m) and mean channel depth (D_{bkf} from 0.23 to 0.30 m). Observed reaches showed a fairly good correlation ($R^2 = 0.53$)
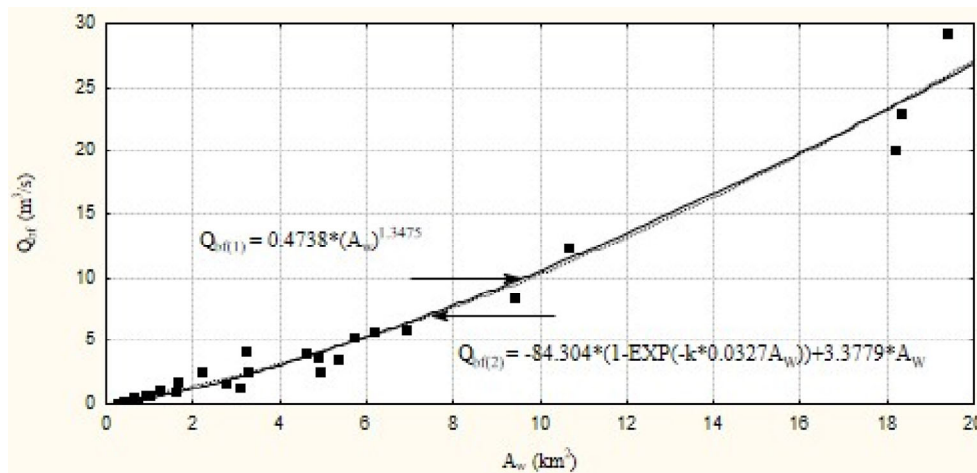
5: *Regional equations and curves for the relation between A_w (km²) and Q_{bf} (m³.s⁻¹)*

IV: *Testing of differences significance between correlation coefficients $R_{(1)}$ and $R_{(2)}$*

Correlation coefficient		Fischer's transformed variable		$\left|Z'_{R(1)} - Z'_{R(2)}\right|$	Z'	>; =; <	$Z'α$
$R_{Bbf(1)}$	0.980	$Z'_{RBbf(1)}$	2.298	3.363	1.741	<	2.807
$R_{Bbf(2)}$	0.984	$Z'_{RBbf(2)}$	1.935				
$R_{Hbf(1)}$	0.959	$Z'_{RHbf(1)}$	2.257	0.250	1.199	<	2.807
$R_{Hbf(2)}$	0.976	$Z'_{RHbf(2)}$	2.507				
$R_{Abf(1)}$	0.978	$Z'_{RAbf(1)}$	2.437	0.221	1.060	<	2.807
$R_{Abf(2)}$	0.977	$Z'_{RAbf(2)}$	2.216				
$R_{Qbf(1)}$	0.986	$Z'_{RQbf(1)}$	2.094	0.306	1.468	<	2.807
$R_{Qbf(2)}$	0.987	$Z'_{RQbf(2)}$	2.542				

between increasing A_w (km²) and W_{bkf} (m). By contrast, bankfull mean depth D_{bkf} (m) indicated its independence on increasind watershed area A_w (km²) with $R^2 = 0.03$. Blackburn-Lynch *et al.* (2017) reported results of regional equations from 2856 sites for 20 various HLR in the contiguous USA with the natural characteristics medians of A_w = 71.2 (km²), B_{bf} = 10.5 (m), H_{bf} = 0.7 (m), A_{bf} = 7.0 (m²) and Q_{bf} = 19.5 (m³.s⁻¹). The determination coefficients varied from $R^2 = 0.410$ to $R^2 = 0.710$. The authors confirmed: a) the importance of regional hydraulic geometry research, b) the existence of relationships between watershed area A_w (km²)

and B_{bf} (m), H_{bf} (m), A_{bf} (m²), Q_{bf} (m³.s⁻¹) and c) the differences between the regional equations and curves of hydraulic geometry for various HLR of the USA. All cited authors used to determination of regional bankfull hydraulic geometry eqations a regression equation (2) without asymptote. Different results are brought about by specific natural characteristics of each region (Powel *et al.*, 2004). We can confirm that the regional hydraulic geometry equations provide reliable results only for specific regions and can be used in practice only in these regions from which the data originated.

CONCLUSION

Despite the fact that numerous papers are published throughout the world about regional hydraulic geometry relationships, there are very few studies focused on this problem in the SR and other countries of Central Europe. A wide range of applications of the research of regional equations in torrent control and revitalization confirm the need of further findingds in this field of science because it has not been properly addressed in Central Europe so far. Consequently, in future we can derived the regional equations of the other regions of the SR with different natural characteristics. The results of presented research can be used as an important basis for the dimensioning, design and shape optimization of cross sections of the beds in ecological torrent control within the flood protection, erosion control, revitalization and watershed management in protected area of the High Tatras region. Also, the developed equations could be used for application to other similar regions with similar natural characteristics of watersheds for example in Central Europe.

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