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DETERMINATION OF DIMENSIONAL AND SHAPE PARAMETERS OF CROSS-SECTIONS OF NATURAL TORRENTS IN SMALL MOUNTAIN WATERSHEDS

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Abstract

The aim of this article is to assess the accuracy of estimates of geometric and shape parameters in cross-sections of natural mountain torrents using the equations of regional downstream hydraulic geometry. Equations of regional hydraulic geometry were derived for 19 natural torrents of the Western Tatras in the geomorphological unit of the Tatras. The equations for the relations between the watershed area A_W (km^2) and the bankfull channel width inside the banks B_{bf} (m), channel depth H_{bf} (m), channel cross-section area A_{bf} (m^2) and shape characteristics of the cross-section $B_{bf} : H_{bf}$ and $H_{bf} : B_{bf}$, were ascertained. At the same time, equations for the relationships between the length of the main stream L_T (km) and aforementioned dimensional and shape parameters were derived. Subsequently, the measured geometric and shape parameters of the natural cross sections of torrents were compared with the calculated values. Differences between measured and calculated characteristics were found and confirmed by pairwise selection testing.

Keywords: bankfull geometric characteristics, hydraulic geometry, torrent morphogenesis

INTRODUCTION

Observations of the hydraulic geometry of streams are widely used in fluvial geomorphological research and watercourse management. The results of research involving regional hydraulic geometry provide important information for torrent control designing, revitalization and watersheds management. In this context, we refer specially to the design of such dimensional and shape characteristics of cross-sections, that are close to nature. Powel *et al.* (2004) indicates that in the USA regional equations of hydraulic geometry are used in the designing and revitalization of watercourses. 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 these informations are 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 that features the same hydraulic geometry curves (Howell, 2009). Wilkerson (2008) noted that a physiographic region is a region in which all parts are similar in geologic structure and climate, which has a unified geomorphic history and where 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 (Julien, 2014). On the other hand, predictions concerning the development of watercourse beds and a determination of geometric and shape characteristics of their cross sections by means of hydraulic geometry equations may be characterized by a certain variability and uncertainty. The longitudinal variability in hydraulic geometry along a reach has received little attention in research literature. Harman *et al.* (2008) state that ariations in hydraulic geometry observed at sites in a given region over time are often assumed to be true variation, but measurement uncertainty may also contribute to these variations. Stewardson (2005) states that the flow profiles selected for measurement may be unrepresentative of the watercourses in which they are located. Rosgen (1994) dealt in detail with the issue of channel shapes in natural watercourses; the author states that the width/depth ratio describes the dimension and shape factor as the ratio of bankfull channel width to bankfull mean depth. The shape characteristics of natural riverbeds in connection with their development has been discussed by Osterkamp *et al.* (1983), Montgomery and Buffington (1997), Montgomery and Gran (2001), Finnegan *et al.* (2005), Milar (2005), Vianello and D´Agostino (2007), Thornton *et al.* (2007), Beechie *et al.* (2008), David *et al.* (2010), Kemp (2010), Agouridis *et al.* (2011), Buffington and Montgomery (2013), Latapie *et al.* (2014), Aisuebeogun, Ezekwe (2014), Whitbread *et al.* (2015), Choi *et al.* (2015), Allen *et al.* (2018), Ohara, Yamatani (2019).

MATERIALS AND METHODS

Analyzed torrents and watersheds are located in the Tatras National Park (TNP) in the geomorphological unit of Tatry, the subunit of Západné Tatry (Fig. 1) at altitudes from 690 to 2248 m a.s.l. The eastern border of the Western Tatras is formed by the Kôprovský torrent. The right section of the Kôprovský torrent watershed (in the direction of the flow) is already a part of the High Tatras. The highest point of this watershed is the Kriváň hill (2494 m a.s.l.).

Nineteen torrents with enclosing cross-sections near the southern border of TNP (located in proximity to the northern border of the geomorphological unit of Podtatranská kotlina) were analyzed. Analyzed torrents are situated in the main river watershed Váh. The watershed areas of 19 analyzed torrents range from $A_w = 1.20\,km^2$ (Klinovaté) to $A_w = 54.61\,km^2$ (Tichý) with the median of $\tilde{A}_w = 10.14\,km^2$. The Q_{100} discharges range from $Q_{100} = 4.4\ m^3/s$ (Klinovaté) to $Q_{100} = 150\,m^3/s$ (Tichý) with the median of $\bar{Q}_{100} = 27\,m^3/s$. The streams of Western 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 variable. Magmatic rocks predominate in the analyzed area: biotite tonalites to granodiorites,

1: *Map of Slovakia with the research area (Western Tatras)* locally porphyritic. The further occurances here include porphyritic granodiorites to granites and leucocrate granitic rocks. As for soil types, in higher elevations Lithic Leptosols and other (nonrendzic) Leptosols are dominant; in the middle parts of the watersheds the most frequently occuring types are Cambic Podzols and Haplic Podzols. In lower position occur Dystric Cambisols, Cambic Umbrisols and Stagni-Dystric Cambisols. 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 elevations (Ministry of Environment of the SR, 2002). The watersheds (by the climatic regions of the Slovak Republic) are located in climatic region C – cold with the subregions: C1 – moderately cool, C2 – cool mountainous and C3 – cold mountainous (Ministry of Environment of the SR, 2002, 2002). Average annual precipitation in the watersheds ranges from 1132 mm (Suchý) to 1612 mm (Kôprový). Average annual temperatures in watersheds range from 0.19 °C (Kôprový) to 3.48 °C (Suchý). Climatic data were derived from the data of five measuring stations of Slovak Hydrometeorological Institute in the region of the Western Tatras for the years 1961–2010.

In this case the samples are the set of natural cross-sectional geometric characteristics from which the hydraulic geometry of the entire torrent network is ascertained. The watercourses in Tatras region generally have three characteristics zones: 1) zone with sediment formations (zone of erosion), 2) zone of sediment transport (transport zone) and 3) sediment deposition 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 zones also varies and is predominantly influenced by the shape of the valley. In the highest sections of the torrents, the cross-sections have a V-shape. In the middle part the profiles are U-shaped and in the lower part are broad U-shaped (Jakubis, 2000; Jakubis and Jakubisová, 2019, 2020).

On straight stretches of each natural torrents without human interventions under the erosion zone, we selected the reference longitudinal sections (RLS) with reference cross-sections (RCS) and determined their bankfull geometric and hydraulic characteristics according Page (1988) and Rosgen (1994, 2009). RLS were selected in the torrents so as to capture well the overall character of the torrent over a longer section. Subsequently, we chose RCS to represent the character of RLS

I: *Basic geometric and hydraulic characteristics of RCS*

Torrent	A_w (km^2)	φH_w (m a.s.l.)	B_{bf} (m)	H_{bf} (m)	A_{bf} (m^2)	S (m/m)	R_{bf} (m)	O_{bf} (m)	Q_{bf} (m^3/s)
Suchý	17.7	1247	10.1	1.00	8.3	1.52	0.814	10.2	13.42
Studená	3.2	1146	3.4	0.65	1.85	2.24	0.487	3.8	2.06
Jalovský	22.33	1487	11.0	1.05	9.8	1.29	0.860	11.4	16.25
Rakytie	3.06	1384	3.2	0.60	1.65	2.42	0.458	3.6	1.75
Krivý	2.48	1401	3.0	0.50	1.4	2.41	0.424	3.3	1.40
Vrbička	2.05	1411	2.9	0.45	1.15	2.69	0.371	3.1	1.04
Smrečianka	17.99	1543	9.9	1.00	8.2	1.37	0.796	10.3	12.85
Trnovec	4.55	1540	5.5	0.70	3.1	2.01	0.492	6.3	3.42
Kobylie	1.88	1444	2.9	0.50	1.3	2.12	0.394	3.3	1.12
Kamenná	2.13	1410	3.1	0.60	1.4	2.77	0.400	3.5	1.35
Klinovaté	1.20	1260	2.3	0.40	0.8	2.51	0.333	2.4	0.45
Račková	35.76	1572	13.7	1.20	15.8	0.91	1.033	15.3	29.27
Jamnícky	18.75	1576	11.7	1.15	11.2	1.31	0.903	12.4	19.38
Krivuľa	14.46	1467	7.7	0.85	5.4	1.06	0.651	8.3	6.94
Bystrá	10.22	1549	6.9	0.80	4.8	1.45	0.649	7.4	6.40
Surový	5.15	1338	4.0	0.60	2.0	1.49	0.465	4.3	2.66
Kamenistý	10.14	1571	7.5	0.90	5.8	2.03	0.707	8.2	8.63
Tichý	54.61	1639	19.7	1.50	26.5	1.07	1.318	20.1	61.30
Kôprový	30.47	1573	15.0	1.35	18.6	1.38	1.148	16.2	39.52

A_w : watershed area; φH_w : mean altitude of the watershed; B_{bf} : width of the RCS inside the banks; H_{bf}: depth of the RCS; A_{bf} : RCS area; S : energy gradient; R_{bf} : hydraulic radius of RCS; O_{bf} : wetted perimeter; Q_{bf} : bankfull discharge.

well. We chose the reference profiles under the erosion zones so that they would not be unduly affected from the sides by the slopes of the valley. The geometric characteristics of the RCS were measured by leveling. The basic characteristics of watersheds, along with the geometric characteristic of RCS: width of the bed inside the banks B_{bf} (m), channel depth H_{bf} (m), cross-sectional area A_{bf} (m^2) with the medians of B_{bf} = 6.90 (m), H_{bf} = 0.80 (m), A_{bf} = 4.80 (m^2) are listed in Tab. I. Bankfull discharge Q_{bf} (m^3.s^{-1}) with the median of Q_{bf} = 6.40 (m^3.s^{-1}) was calculated by Jarrett's equation (Rico *et al.,* 2001) in the form:

$$Q_{bf} = 3.17\, A_{bf} \times R_{bf}^{0.83} \times S^{0.12}\ (\mathrm{m^3.s^{-1}}) \qquad (1)$$

where:
A_{bf}.....cross-sectional area (m^2);
R_{bf}.....hydraulic radius (m),
S ....energy gradient of RCS (m/m).

The values of B_{bf} : H_{bf} and H_{bf} : B_{bf} ratios and morphological characteristics of the watersheds are given in Tab. II.

RESULTS AND DISCUSSION

The derived equations of regional hydraulic geometry are given in Tab. III. According to these equations, geometric (A_{bf}, B_{bf}, H_{bf}) and shape characteristics (B_{bf} : H_{bf}, H_{bf} : B_{bf}) for all of RCS were calculated. Due to the large amount of data, we present in Tab. IV. only the average values of deviations between the measured data and the data calculated according to the equations in Tab. III. A graphical representation of the curves of the individual relations are shown in Fig. 2 to Fig. 5. By analyzing the obtained results, we found that estimates of the geometric characteristics of cross-sections based on the equations of downstreram hydraulic geometry may not be accurate. By comparing the measured values of B_{bf} (m), H_{bf} (m), A_{bf} (m^2) and ratios B_{bf} : H_{bf} and H_{bf} : B_{bf} with the calculated values using the regional equations of hydraulic geometry (Tab. III), certain differences were found to occur. We used the pairwise selection method for testing and then calculated the difference for each pair comparison. Subsequently, we found the arithmetic mean and standard

II: *Shape characteristics of RCS and characteristics of watersheds and torrents*

Torrent	B_{bf} : H_{bf} (-)	H_{bf} : B_{bf} (-)	L_t (km)	$H_{max\,w}$ (m a.s.l.)	$H_{max\,t}$ (m a.s.l.)	$H_{min\,w,t}$ (m a.s.l.)	ΔH_t (m)	S_t (%)
Suchý	10.1	0.099	8.60	1804	1613	690	923	10.73
Studená	5.23	0.191	2.54	1566	1110	725	385	15.16
Jalovský	10.48	0.095	7.29	2178	1539	796	743	10.19
Rakytie	5.33	0.188	3.88	1947	1740	821	919	23.69
Krivý	6.00	0.167	3.25	1890	1705	911	794	24.43
Vrbička	6.44	0.155	1.45	1890	1339	931	408	28.14
Smrečianka	9.90	0.101	6.78	2178	1629	901	728	10.74
Trnovec	7.86	0.127	3.90	2184	1913	890	1023	26.23
Kobylie	5.80	0.172	2.18	1930	1467	957	510	23.39
Kamenná	5.17	0.194	2.22	1850	1471	970	501	22.57
Klinovaté	5.75	0.174	1.39	1630	1630	887	743	53.45
Račková	11.42	0.088	8.29	2248	1705	896	809	9.76
Jamnícky	10.17	0.098	6.88	2194	1732	959	773	11.24
Krivuľa	9.06	0.110	7.70	2043	1795	774	1021	13.26
Bystrá	8.63	0.116	6.83	2248	1845	849	996	14.33
Surový	6.67	0.150	5.15	1810	1628	855	773	14.45
Kamenistý	8.33	0.120	7.31	2248	1762	894	868	10.51
Tichý	13.13	0.076	14.17	2158	1911	977	934	6.35
Kôprový	11.11	0.090	11.96	2494	1870	976	893	7.47

L_t : length of main stream; $H_{max,\,w}$: maximal altitude of the watershed; $H_{max,\,t}$: maximal altitude of the torrent (spring); $H_{min\,w,t}$ minimal altitude of the watershed and torrent; ΔH_t : absolute heigth difference in the watershed; S_t : torrent gradient.

deviation s_d of these differences (Tab. IV). We tested the null hypothesis: H_0: $\mu_1 - \mu_2 = 0$; the difference is only randomly different from zero. The test criterion is the characteristic:

$$t = \frac{\bar{d}}{s_{\bar{d}}} \tag{2}$$

and

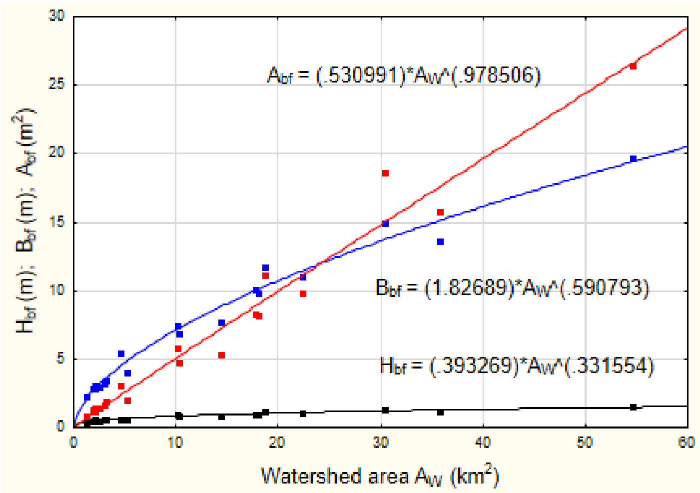
$$S_{\bar{d}} = \frac{s_d}{\sqrt{n-1}}. \tag{3}$$

We accept hypothesis H_0 if $t \le t_{\alpha;f}$ and reject if $t > t_{\alpha;f}$.

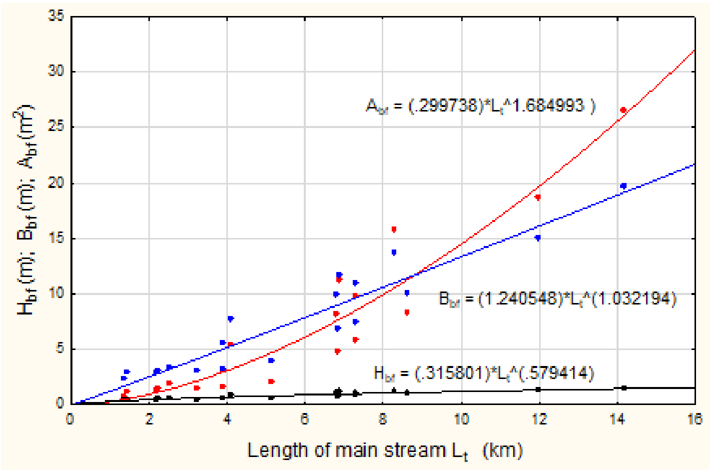
From the detailed results (Tab. IV) it is clear that we reject the null hypothesis H_0 in all cases. This means that the differences between the measured characteristics B_{bf} (m), H_{bf} (m), A_{bf} (m²) and ratios $B_{bf} : H_{bf}$ and $H_{bf} : B_{bf}$ and characteristic estimated using the equations of regional hydraulic geometry

III: *Derived equations of regional hydraulic geometry*

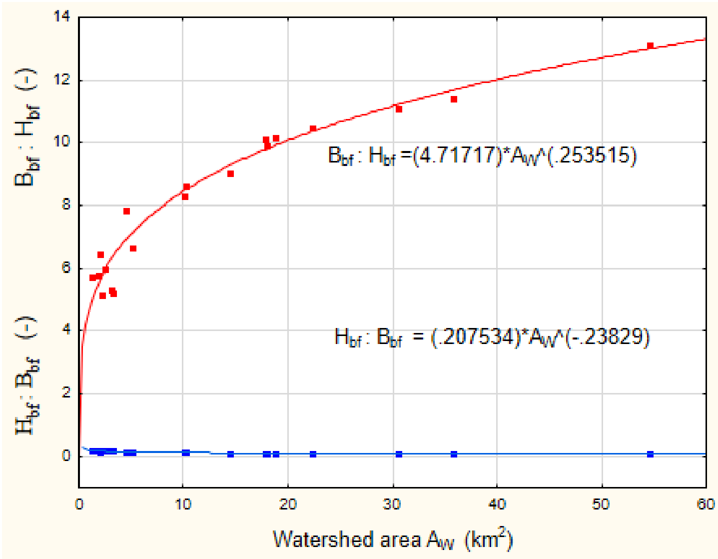
Correlation relation	Regression equation
$B_{bf} = f(A_w)$	$B_{bf} = 1.8269 \times A_w^{0.5908}$
$B_{bf} = f(L_t)$	$B_{bf} = 1.2405 \times L_t^{1.0322}$
$B_{bf} = f(H_{bf})$	$B_{bf} = 9.6027 \times H_{bf}^{1.778}$
$H_{bf} = f(A_w)$	$H_{bf} = 0.3933 \times A_w^{0.3316}$
$H_{bf} = f(L_t)$	$H_{bf} = 0.3158 \times L_t^{0.5794}$
$H_{bf} = f(B_{bf})$	$H_{bf} = 0.2757 \times B_{bf}^{0.5689}$
$A_{bf} = f(A_w)$	$A_{bf} = 0.5310 \times A_w^{0.9785}$
$A_{bf} = f(L_t)$	$A_{bf} = 0.2997 \times L_t^{1.6850}$
$B_{bf} : H_{bf} = f(A_w)$	$B_{bf} : H_{bf} = 4.7172 \times A_w^{0.2535}$
$B_{bf} : H_{bf} = f(L_t)$	$B_{bf} : H_{bf} = 4.1441 \times L_t^{0.4208}$
$H_{bf} : B_{bf} = f(A_w)$	$H_{bf} : B_{bf} = 0.2075 \times A_w^{-0.2383}$
$H_{bf} : B_{bf} = f(L_t)$	$H_{bf} : B_{bf} = 0.2176 \times L_t^{-0.3385}$



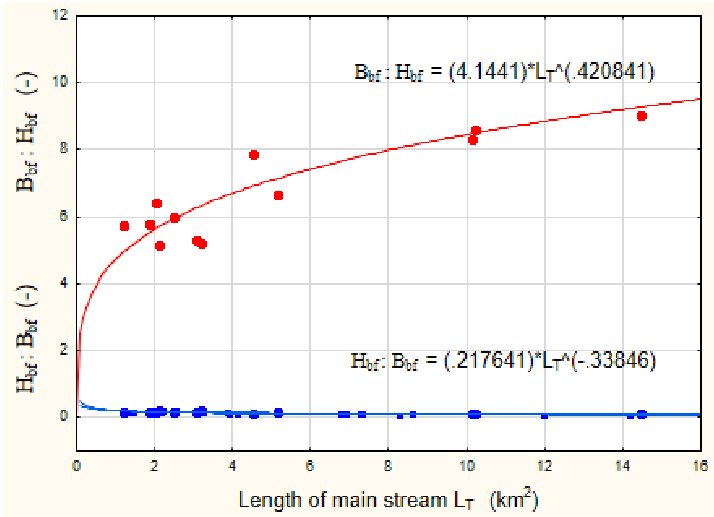
2: *Relations between watershed area A_w and geometric characteristics of RCS – B_{bf}, H_{bf}, A_{bf}*



3: *Relations between length of main stream L_t and geometric characteristics of RCS – B_{bf}, H_{bf}, A_{bf}*



4: *Relations between watershed area A_w and relations – $B_{bf} : H_{bf}$, $H_{bf} : B_{bf}$*



5: *Relations between length of main stream L_t and relations $B_{bf} : H_{bf}$, $H_{bf} : B_bf$*

are found to be significant. Therefore, other factors need to be taken into account when estimating these characteristics, e.g. valley morphology, sediment type, sediment transport regime channel stability, riparian vegetation, etc.

Harman *et al.* (2008) state that the results from an individual cross-section may not be representative of the geometry of the entire reach nor do can they indicate the degree of local variability along the reach. The authors point out that of the many possible sources of uncertainty in hydraulic observations, two significant groups can be distinguished: sample error and model error. Alexander *et al.* (2009) state that hydraulic geometry relations assist in an understanding of the channel adjustments process, but are limited in their predictive capabilities and require cautions application when used for such purposes.

Only few authors (Whitbread *et al.,* 2015; Beechie *et al.,* 2007; Thornton *et al.,* 2007; Kemp, 2010) have dealt with the research of the shape characteristics of natural river beds, although this issue is very important from an ecological point of view. A comparison of our results with the those of other authors is given in the Tab. V. We confirmed that estimates of geometric parameters of natural cross-sections, which are based on the equations of regional hydraulic geometry, informative can be used only in the regions from which these equations were derived.

IV: *Statistical characteristic and testing of the results*

Correlation relation	R	R^2	$\overline{d}$	S_d	t	> = <	$t_{0,01\ (18)}$	RMSE
$B_{bf} = f\ (A_w)$	0.989	0.979	0.5386	0.4657	4.872	>	2.878	0.744
$B_{bf} = f\ (L_t)$	0.944	0.890	1.3475	0.8915	6.413	>	2.878	1.690
$B_{bf} = f\ (B_{bf})$	0.992	0.984	0.5213	0.3311	6.679	>	2.878	0.648
$H_{bf} = f\ (A_w)$	0.978	0.956	0.0545	0.0372	6.214	>	2.878	0.069
$H_{bf} = f\ (L_t)$	0.939	0.882	0.0902	0.0589	6.504	>	2.878	0.113
$H_{bf} = f\ (B_{bf})$	0.989	0.978	0.0380	0.0269	5.996	>	2.878	0.165
$A_{bf} = f\ (A_w)$	0.985	0.969	0.8131	0.9019	7.408	>	2.878	1.265
$A_{bf} = f\ (L_t)$	0.953	0.908	1.5473	1.4254	4.606	>	2.878	2.197
$B_{bf} : H_{bf} = f\ (A_w)$	0.976	0.952	0.4042	0.3411	5.027	>	2.878	0.553
$B_{bf} : H_{bf} = f\ (L_t)$	0.898	0.806	0.9231	0.5145	7.612	>	2.878	1.110
$H_{bf} : B_{bf} = f\ (A_w)$	0.927	0.859	0.0100	0.0107	3.966	>	2.878	0.015
$H_{bf} : B_{bf} = f\ (L_t)$	0.820	0.672	0.0185	0.0124	6.304	>	2.878	0.023

RMSE: Root mean square error

V: *Comparison of results with the results of other authors*

Correlation relation	Author	Study Area	Regression equation
$B_{bf} : H_{bf} = f\ (A_w)$	Whitebread *et al.* (2015)	Scottish Highlands Scotland	$B_{bf} : H_{bf} = 4.45 \times A_w^{0.07}$
	Beechie *et al.* (2007)	Blue Mountains USA	$B_{bf} : H_{bf} = 7.90 \times A_w^{0.16}$
	Thornton *et al.* (2007)	Kangaroo river catchment Australia	$B_{bf} : H_{bf} = 16.01 \times A_w^{0.06}$
	Jakubis, Jakubisová (2021)	West Tatras Slovakia	$B_{bf} : H_{bf} = 4.72 \times A_w^{0.25}$
$B_{bf} : H_{bf} = f\ (L_t)$	Kemp (2010)	Lachlan river catschment Australia	$B_{bf} : H_{bf} = 10.3 \times e^{-0.004Lt}$
	Jakubis, Jakubisová (2021)	West Tatras Slovakia	$B_{bf} : H_{bf} = 4.14 \times L_t^{0.421}$

CONCLUSION

Equations of regional hydraulic geometry were derived for 19 natural torrents of the Western Tatras in the geomorphological unit of the Tatras. We used these data for the analysis of the basic shape (geometric) cross-sections of these torrents. Evaluation of shape characteristics of natural cross-sections has more practical uses, the first of which is the acquisition of data for the application of nature-friendly river design and torrent control in the context of both flood and erosion protection of the landscape. Another possibility is the use of these data in the classification of watercourses, as well as in the processes involved in river and land management and watercourses restoration activities, which is considered of impertance, especially in protected areas.

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