The Impact of Hydrologic Characteristics of Mountain Watersheds on Geometric and Hydraulic Parameters of Natural Torrent Beds

Matúš Jakubis[1*], Mariana Jakubisová[2]

[1] Department of Forest Harvesting, Logistics and Amelioration, Faculty of Forestry, Technical University in Zvolen, Ul. T. G. Masaryka 24, 960 53 Zvolen, Slovak Republic

[2] Borova hora Arboretum of Technical University in Zvolen, Borovianska cesta 2171/66, 960 53 Zvolen, Slovak Republic

* Corresponding author e-mail: jakubis@tuzvo.sk

ABSTRACT

The aim of the paper is to determine the geometric and hydraulic characteristics of natural torrent beds and to propose a regional hydraulic geometry equations of mountain watersheds for the High Tatras region. 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 relationships of hydraulic geometry (hitherto used without asymptote and newly proposed with asymptote) were compared. The analyses showed a strong correlation relationship between watershed area A_w (km^2) and bankfull geometric characteristics of natural cross-sections: width of the bed inside the banks B_{bf} (m), mean depth of the bed H_{bf} (m), channel cross-section area A_{bf} (m^2) and hydraulic characteristic – bankfull discharge Q_{bf} (m^3.s^{-1}). The results were tested by t-test and Shapiro-Wilk test. The determination coefficient (R^2) for the relationships without asymptote ranged between $R^2 = 0.919$ and $R^2 = 0.972$; p – values from Shapiro – Wilk test ranged between p = 0.0359 and p = 0.8027. The determination coefficient (R^2) for the relationships with asymptote ranged between $R^2 = 0.952$ and $R^2 = 0.974$; p – values from Shapiro – Wilk test ranged between p = 0.0221 and p = 0.8617. Based on the analysis we found that the new equation with the asymptote provides very good results.

Keywords: water balance equation; stream morphogenesis, High Tatras; Slovakia

INTRODUCTION

Out of the total length of the watercourses in the Slovak Republic (SR) stretching at 61,147 km, approximately 24,000 km (39.25%) are of a torrent nature. In the SR, the torrent watersheds are located in the protected areas (national parks, protected landscape areas). This fact must be taken into account in all interventions into torrent beds. Each torrent and watershed have a specific set of characteristics. There are several reasons for the acquisition of scientific knowledge in morphogenesis of torrent channels and regional hydraulic geometry of mountain watercourses and watersheds. The first is the possibility to use the results in practice (ecological torrent control, flood and erosion control, torrent revitalization, natural

torrents management etc.). Developing hydraulic geometry relationships is of great importance for different applications of stream restoration design and hydrological modeling [Osati *et al.* 2016]. The second reason is the fact that this issue has not been adequately solved in the SR. Authors [Powel *et al.*, 2004] indicate that in the USA are used in designing and revitalization of watercourses the regional equations of hydraulic geometry which are several decades old and are unsuited for existing conditions of water flows and watersheds. Author [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 a reference reach is unavailable. Regional curves can also be used in

project such as road, bridge and culvert construction. Another author [Wilkerson, 2008] states that this knowledge is essential for planners, engineers, geomorphologists, environmentalists, agricultural interests, developments situated on flood prone lands and other stakeholders in flooding and flood management. Regional curves should be applied only in projects within the same region or in the region with scientific evidence showing that it follows the same hydraulic geometry curves [Howell, 2009]. Physiographic region is a region with all parts similar in geologic structure and climate and with a unified geomorphic history [Wilkerson, 2008]. Its relief features differ significantly from those of adjacent regions. Another author [Leopold et *al.*, 1992] states that there are two types of channel hydraulic geometry: at – a – station and downstream. Regional equations represents the relationships between geomorphologic and hydrologic characteristics of watershed and geometric and hydraulic characteristics of the channel profile. An important summary of regional hydraulic geometry research in the USA was published by another authors [Bieger et *al.*, 2015] and [Blackburn – Lynch et *al.*, 2017]. These authors dealt with the relations between the watershed area A_w (km^2) and bankfull geometric characteristics of natural cross-sections: the width of the bed inside the banks B_{bf} (m), the mean depth of the bed H_{bf} (m), the channel cross-section area A_{bf} (m^2) and hydraulic characteristic – the bankfull discharge Q_{bf} (m^3.s^{-1}). We point to few authors [Jakubis, 2008, Pšida, 2014] who were involved into the problem of relations between basic hydrologic characteristics of the watershed and the bankfull regional characteristics of natural torrent beds. This article discusses a new approach to the regional hydraulic geometry issues. The superstructure and the new current direction in the research of regional hydraulic geometry is the research of relations between the basic hydrologic characteristics of the watersheds: the mean long-term annual precipitation depth in the watershed P (mm), the mean long-term annual runoff depth in the watershed Q (mm) and the mean long-term annual climatic evaporation depth in the watershed E (mm) and the above mentioned geometric and hydraulic characteristics of the natural watercourse channels. he runoff generative process is highly variable and dependent on hydrologic and climatic characteristics of a watershed. The relations of runoff formation in small mountain watersheds were analyzed by the following

authors in detail [Tani, 1997, Gallart et *al.*, 2002, Hrnčíř et *al.*, 2010]. Precipitation is a prerequisite for runoff formation which depends on rainfall characteristics, initial moisture conditions, soil and geological conditions, vegetation, and topographic features [Han et *al.*, 2012]. Surface runoff and later discharge in torrent channels has a significant impact on the long – term morphogenesis of torrent beds. Geometric characteristics of watercourse channels are created during long-term morphogenesis. In general, higher long-term precipitation sums in the watershed are a prerequisite for the higher runoff and consequently the for the higher discharge in torrent beds. In different natural conditions of the watersheds (hydrologic, climatic, geological, pedological, vegetation, morphology), characteristic of different physical geographic regions, exist in torrent beds specific geometric and hydraulic characteristics exist in torrent beds. There are certain regional specificities that manifest themselves in geometric and hydraulic characteristics of channels, their relations and ratios.

MATERIALS AND METHODS

Analyzed torrents and watersheds are located in the Tatras 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 (Figure 1) at altitudes from 860 to 2654 amsl. High Tatras are the highest mountains in the SR.

Between 2007 and 2017, 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 S_p = 0.25 km^2 (Važecký) to S_p = 19.34 km^2 (Poprad) with the median S_p = 3.21 km^2. The discharges Q_{100} range from Q_{100} = 1.5 m^3.s^{-1} (Važecký) to Q_{100} = 35.7 m^3.s^{-1} (Biely Váh) with the median Q_{100} = 10.25 m^3.s^{-1}. 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 analyzed area is complicated. In the High Tatras can be distinguished three main building
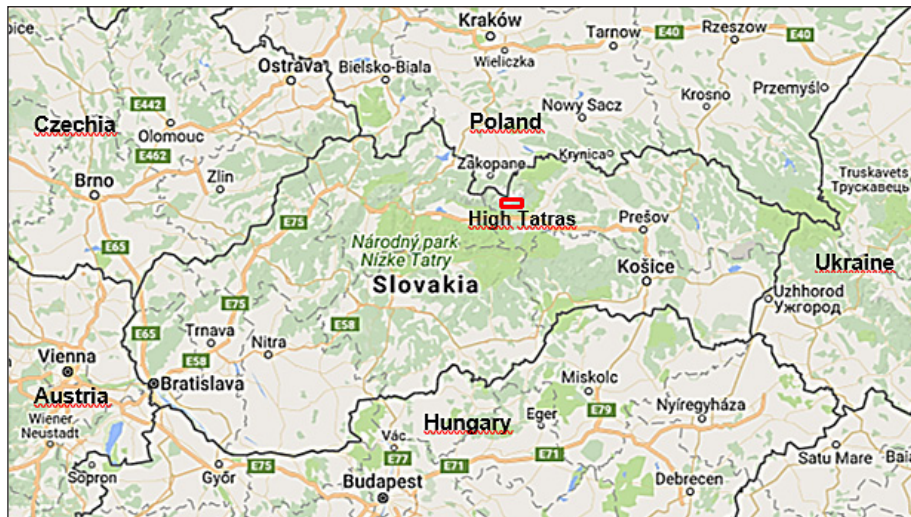
Figure 1. Map of Slovakia research area (High Tatras)

blocks: the crystalline core, mountain ranges and sedimentary cover and flysch fill adjacent depressions. Crystalline core occurs on a large part of the ridge and on the southern slopes of the mountains. In the higher parts of watersheds occurs migmatites – porphyritic granites and granodiorites. In the eastern part of the High Tatras, from the highest to middle position in a continuous strip occur porphyric granodiorites to granites, hercynian. In lower parts of analyzed watersheds forms the bedrock flysch – sandstones and calcareous claystones. From soil types are dominant in higher elevations Lithic Leptosols and others (nonrendzic) Leptosols, in lower positions Haplic Podzols to Humic Podzols. From the aspect of hydrological efficiency have the soils in the higher positions of watersheds high retention capacity with medium permeability and in the lower positions medium retention capacity and permeability [Composite Authors, 2002]. The watersheds (by the climatic regions of SR) are located in climatic region C – cold subregions: C1 – moderately cool, C2 – cool mountainous and C3 – cold mountainous. The average annual precipitation in the watersheds range from 1037 mm (Päť prameňov) to 1379 mm (Biely Váh). Average annual temperatures range from 0.9 to 3.8 °C.

From a methodological point of view is particurlary important the selection of reference sections and flow profiles and the determination of its geometric and hydraulic characteristics. In this regard, we follow the articles of authors [Page, 1988] and [Rosgen and Silvey, 1996]. In terrain under the source zones of torrents [Schumm, 1977, Lehotský and Novotný, 2004]

were established reference longitudinal sections (RLS) with reference cross sections (RCS). On the RCS were by leveling determined their geometric characteristic. Longitudinal slope was measured by levelung on RLS. On the RCS the sample of sediments was taken with weight at least 50 kg for granulometric analysis to determination of median grain diameter. Wetted perimeter and hydraulic radius were determined within the office processing.

To calculate bankfull discharge Q_{bf} (m^3.s^{-1}), we used the Equation according to Parker [2004]:

$$Q_{bf} = 3.732 B_{bf} H_{bf} \sqrt{g R_{bf} S} \left(\frac{R_{bf}}{D_{50}}\right)^{0.2645}$$

$$(m^3 s^{-1}) \tag{1}$$

We used the following regression Equations for analysis:
- without asymptote

$$y = a_0 . x^{a01} \tag{2}$$

- and with asymptote:

$$y = a_1 . \left(1 - e^{-kx}\right) + a_{11} . x \tag{3}$$

Equation (2) is generally used by many authors to establish hydraulic geometry relations. Equation (3) is a newly suggested means to the same end. Geometric and hydraulic characteristics of RCS are shown in Table 1.

In determination of basic elements of the water balance equation for all of the 26 analyzed

Table 1. Characteristics of RCS

Watercourse	B_{bf}	H_{bf}	A_{bf}	S	R_{bf}	D_{50}	Q_{bf}
Beliansky	3.7	0.65	2.0	2.85	0.435	0.141	4.22
Tri studničky	0.9	0.35	0.3	2.10	0.214	0.105	0.30
Mlyničná voda	2.9	0.55	1.2	2.77	0.364	0.091	2.70
Jamský	1.0	0.40	0.4	3.55	0.267	0.090	0.61
Važecký	0.8	0.30	0.2	2.90	0.154	0.077	0.24
Biely Váh	7.2	0.80	4.9	2.37	0.620	0.123	12.53
Lieskovec	2.0	0.40	0.7	3.90	0.292	0.152	1.19
Mlynica	4.5	0.65	1.9	3.93	0.413	0.129	5.93
Poprad	10.4	1.10	8.9	1.97	0.848	0.114	29.38
Veľký šum	3.2	0.60	1.5	3.72	0.417	0.131	3.80
Malý šum	1.9	0.50	1.0	2.31	0.417	0.135	1.47
Háganský	1.0	0.30	0.3	3.70	0.188	0.091	0.35
Batizovský	4.5	0.60	2.0	3.83	0.417	0.128	5.45
Hromadná voda	2.7	0.50	1.1	4.20	0.355	0.093	2.75
Velický	4.5	0.70	2.1	3.30	0.404	0.122	5.83
Slavkovský	4.0	0.60	1.7	2.20	0.370	0.099	3.58
Malý Štiavnik	1.9	0.45	0.8	0.85	0.308	0.060	0.79
Veľký Jazyk	1.9	0.40	0.8	2.18	0.348	0.065	1.21
Štiavnik	2.2	0.50	0.8	2.90	0.320	0.070	1.85
Päť prameňov	2.0	0.40	0.7	1.13	0.318	0.072	0.83
Pod Hrebienkom	2.6	0.50	1.0	1.85	0.345	0.078	1.80
Studený	9.8	1.10	7.3	2.63	0.716	0.400	20.16
Hlboký	2.4	0.55	1.3	2.53	0.464	0.069	2.68
Skalnatý	6.2	0.75	3.5	2.70	0.530	0.170	8.49
Kežm. Biela voda	9.2	1.00	6.3	2.78	0.656	0.115	23.02
Sedem prameňov	4.0	0.60	1.6	2.80	0.372	0.099	4.07

Explanatory notes: B_{bf} – width of the RCS inside the banks [m], H_{bf} – mean depth of the RCS [m], A_{bf} – RCS area [m²], S – energy gradient [m/m], R_{bf} – hydraulic radius of RCS [m], D_{50} – grain diameter [m], Q_{bf} – bankfull discharge [m³/s]

watersheds of the High Tatras, the simplified relationship was used:

$$P = Q + E \pm \Delta S \qquad (4)$$

where: *P* – mean long-term annual precipitation depth in the watershed (mm)

Q – mean long-term annual runoff depth in the watershed (mm)

E – mean long-term annual climatic evaporation depth in the watershed (mm)

ΔS – change in water storage in the watershed (mm)

Equation (4) is the simplest form of water balance equation valid only for long periods of time. It is used to calculate mean values of basic hydrologic characteristics for long periods of time. In this connection, our research proceeded from these basic assumptions:

- The basic hydrological characteristics of the watershed indentified and evaluated in the long run;

- development of torrent beds (torrent morphogenesis) is a long-time process of hundreds to thousands of years;

- component ΔS in equation (4) is not considered in analyses, change of water retention in the watershed is negligible in a long-time process;

- from precipitation in the watershed is formed runoff and subsequently discharge in watercourse beds which has a dominant effect on their development (morphogenesis),

- long-term runoff Q expresses the runoff from the watershed in all forms;

- similar natural conditions in specific regions, mostly soil and geological, vegetation, topographic features, create similar conditions for the morphogenesis (long-term development) of torrent beds;

- regional hydraulic geometry equations can be developed from these results, having a broad practical application.

To determine the elements of the equation (4), relationships was derived by authors [Szolgay et *al.*, 1997]. The authors drew on the knowledge that the mean annual climatic evaporation depth E (mm) can be determined as a function of potential evaporation index EP_i and of the mean long-term annual precipitation depth P (mm):

$$E.EP_i^{-1} = f(P.EP_i^{-1}) \qquad (5)$$

On the basis of the relation (4) and (5) and the data measured at 54 meteorological stations in the SR, authors [Szolgay et *al.*, 1997] derived for the conditions of SR the following empirical relationships:

$$Q = P - \frac{P}{\sqrt{0.809 + \left(\frac{P}{EP_i}\right)^2}} \text{(mm)} \qquad (6)$$

and

$$Q = P.\left(1 - \frac{EP_i}{\sqrt{0.809.EP_i^2 + P^2}}\right) \text{(mm)} \qquad (7)$$

The potential evaporation index EPi was calculated using the relation:

$$EP_{iSR} = 260.822 + 37.920\overline{T} + 0.077\overline{T}^3 \qquad (8)$$

where $\overline{T}$ – mean long-term annual temperature in the watershed (ºC)

The values of the mean long-term annual precipitation depth P (mm) and the mean long-term annual temperature $\overline{T}$ (ºC) for all of the analyzed watersheds were derived from the data measured at 8 meteorological stations of the High Tatras (Table 2), Figures (2) and (3).

Table 2. Mean annual precipitation and temperature in the High Tatras stations

Station	SA	P	T
Tatranská Lomnica	832	833	5.2
Starý Smokovec	1018	930	4.9
Vyšné Hágy	1140	864	4.3
Hrebienok	1285	1132	3.5
Štrbské pleso	1360	976	3.6
Popradské pleso	1530	1319	2.2
Skalnaté pleso	1778	1380	1.6
Lomnický štít	2634	1855	-3.7

Explanatory notes: SA station altitude [m a. s. l.], P – long-term annual precipitation [mm], T – long-term annual temperature [ºC]

Using the results of equations (4), (6), (7) and (8), respectively, the coefficient QA_w as: $QA_w = (Q.A_w).1000^{-1}$ was calculated. Hydrological characteristics of reference watersheds are shown in Table 3.

RESULTS AND DISCUSSION

The analyses showed a strong correlation between the coefficient QA_w and the bankfull geometric characteristics of the torrents´ natural cross-sections: the width of the bed inside the banks B_{bf} (m), the mean depth of the bed H_{bf} (m), the channel cross-section area A_{bf} (m²) and hydraulic characteristic – the bankfull discharge Q_{bf} (m³.s⁻¹). The results were tested by the t-test and the Shapiro-Wilk test. The determination coefficient (R^2) for the relationships without the asymptote ranged between $R^2 = 0.921$ and $R^2 = 0.968$; p – values from the Shapiro – Wilk test ranged between $p = 0.0080$ and $p = 0.5379$. The determination coefficient (R^2) for the relationships
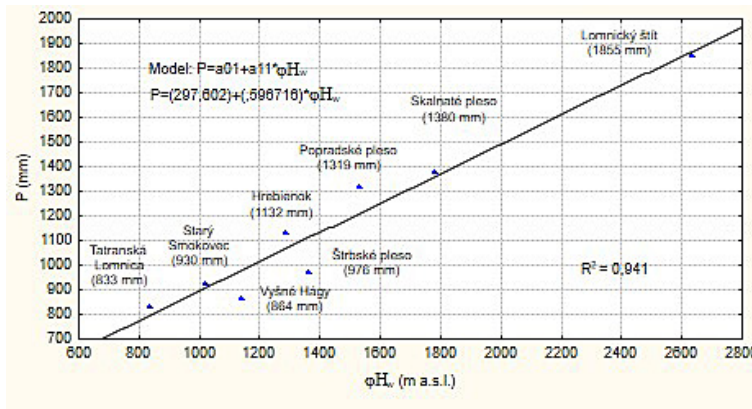

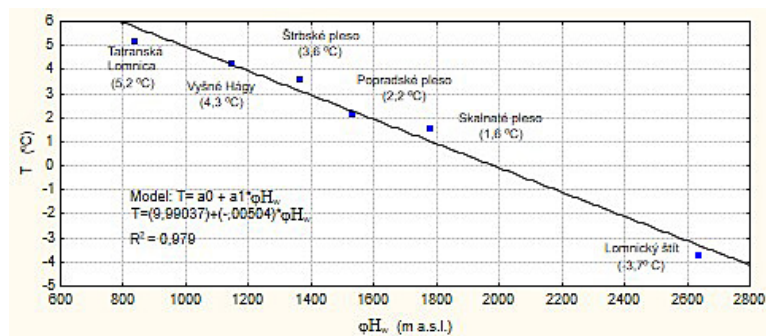**Figure 2.** Relation between φH$_w$ and the mean annual precipitation depth P

Figure 3. Relation between φH_w and the mean annual temperature T

Table 3. Hydrological characteristics of experimental watersheds

Torrent	A_w	φH_w	P	T	EP_i	Q	E	QA_w
Beliansky potok	3.17	1614	1261	1.9	333.40	937	324	2.97
Tri studničky	0.36	1278	1060	3.6	400.93	680	380	0.24
Mlyničná voda	2.18	1544	1219	2.3	348.97	881	338	1.92
Jamský potok	0.60	1407	1137	3.0	376.66	776	361	0.47
Važecký potok	0.25	1350	1103	3.2	384.69	736	367	0.18
Biely Váh	10.62	1812	1379	0.9	295.01	1089	290	11.57
Lieskovec	1.57	1434	1153	2.8	368.69	799	354	1.25
Mlynica	6.90	1740	1336	1.3	310.29	1032	304	7.12
Poprad	19.34	1789	1365	1.0	298.82	1072	293	20.74
Veľký šum	4.86	1548	1221	2.3	348.97	883	338	4.29
Malý šum	3.07	1665	1291	1.7	325.66	973	318	2.99
Háganský potok	0.71	1277	1060	3.6	400.93	680	380	0.48
Batizovský p.	5.69	1696	1310	1.5	317.96	999	311	5.68
Hromadná voda	3.25	1510	1199	2.4	352.89	858	341	2.79
Velický potok	6.16	1736	1333	1.3	310.29	1029	304	6.34
Slavkovský p.	5.31	1655	1285	1.7	325.66	967	318	5.13
Malý Štiavnik	0.88	1273	1057	3.6	400.93	678	379	0.60
Veľký Jazyk	1.19	1306	1077	3.5	396.84	700	377	0.83
Štiavnik	1.64	1528	1209	2.4	352.89	868	341	1.42
Päť prameňov	0.98	1239	1037	3.8	409.14	651	386	0.64
Pod Hrebienkom	2.73	1308	1078	3.5	396.84	701	377	1.91
Studený potok	18.13	1793	1367	1.0	298.82	1074	293	19.47
Hlboký potok	4.88	1304	1076	3.5	396.84	699	377	3.41
Skalnatý potok	9.37	1506	1196	2.5	356.83	851	345	7.97
Kež. Biela voda	18.29	1612	1259	1.9	333.40	935	324	17.10
Sedem pram.	4.58	1241	1038	3.8	409.14	652	386	2.99

Explanatory notes: A_w – watershed area [km^2], φH_w – mean altitude of the watershed [m a. s. l.], P – mean annual precipitation depth [mm], T – mean annual temperature [°C], EPi – potential evaporation index, Q – mean annual runoff depth [mm], E – mean annual evapotranspiration depth [mm], QAw – coefficient calculated as $(Q.Aw).1000^{-1}$

with asymptote ranged between $R^2 = 0.953$ and $R^2 = 0.970$; p – values from the Shapiro – Wilk test ranged between $p = 0.0016$ and $p = 0.8625$. Derived regional regression equations for analyzed correlation relations are listed in Tables 4 and 5 also contains the absolute and the regression coefficients for particular regional equations.

S_r: $\sqrt{\dfrac{1-R^2}{n-2}}$, t: $\dfrac{R}{S_r}$, RMSE: root mean square error, SWp: p – value by Shapiro-Wilk test

Table 5 contains the statistical characteristics and testing of particular relations. In all cases, the number of root mean standard errors using the equation with the asymptote, is lower than when

Table 4. Regression regional equations by equations (2) and (3)'

Correlation relation	Regression equation
$B_{bf(1)} = f(QA_w)$	$B_{bf(1)} = 1.5993*(QA_w)^{0.6087}$
$H_{bf(1)} = f(QA_w)$	$H_{b(1)} = 0.4162*(QA_w)^{0.2949}$
$A_{bf(1)} = f(QA_w)$	$A_{bf(1)} = 0.4135*(QA_w)^{0.9823}$
$Q_{bf(1)} = f(QA_w)$	$Q_{bf(1)} = 0.6630*(QA_w)^{1.2162}$
$B_{bf(2)} = f(QA_w)$	$B_{bf(2)} = 1.7983*(1-EXP(-(2.1980)*QA_w))+0.4262*QA_w$
$H_{bf(2)} = f(QA_w)$	$H_{bf(2)} = 0.4375*(1-EXP(-(4.6409)*QA_w))+0.0333*QA_w$
$A_{bf(2)} = f(QA_w)$	$A_{bf(2)} = 0.1935*(1-EXP(-(10.992)*QA_w))+0.3779*QA_w$
$Q_{bf(2)} = f(QA_w)$	$Q_{bf(2)} = -61.642*(1-EXP(-(0.0306)*QA_w))+2.6885*QA_w$

Explanatory notes: $B_{bf(1)}$, $H_{bf(1)}$, $A_{bf(1)}$, $Q_{bf(1)}$ – characteristics calculated by equation (2) without the asymptote, $B_{bf(2)}$, $H_{bf(2)}$, $A_{bf(2)}$, $Q_{bf(2)}$ – characteristics calculated by equation (3) with the asymptote

the equation without the asymptote was used. The graphic representation of the regional curves are shown in Figures. (4) – (7).

The graphic presentation of residuals for each relations of the Shapiro-Wilk test are shown in Figures. (8) – (15). Based on our analysis, we recommend the use of the regression equation (3) with theasymptote to determine regional equations of hydraulic geometry.

In relation to bankfull geometric and hydraulic characteristics, coefficient QA_w was evaluated for the first time in the SR [Jakubis, 2008] in geomorphological unit Poľana (Central Slovakia, neovolcanites) in 25 torrents with characteristics with the medians $A_w = 4.47$ (km^2), $B_{bf} = 2.40$ (m), $H_{bf} = 0.55$ (m), $A_{bf} = 1.05$ (m^2), $Q_{bf} = 1.14$ (m^3.s^{-1}). The determination coefficients in these relationships ranged between $R^2 = 0.907$ and $R^2 = 0.989$. Author [Pšida, 2014] evaluated the relationships between the QA_w coefficient and the-above mentioned bankfull characteristics of four torrents in four different geographic regions – geomorphological units in the SR with different bedrocks with characteristics with the medians $A_w = 18.81$ (km^2), $B_{bf} = 8.10$ m, $H_{bf} = 0.83$ (m), $A_{bf} = 4.53$ (m^2),

$Q_{bf} = 8.02$ (m^3.s^{-1}). The determination coefficients ranged between $R^2 = 0.705$ and $R^2 = 0.960$. Both authors confirmed varying and specific natural geometric and hydraulic characteristics of torrent beds and their long – term morphogenesis in watersheds with different bedrocks.

CONCLUSION

The torrents are often located in protected areas. Therefore, a very sensitive approach to interfering with the torrent, flood and erosion control is needed. If such principles are not respected, various errors in torrent control designing and revitalization may occur, with negative ecological and environmental consequences in the landscape. Derived regional equations and curves make it possible to come up with a valuable input to the ecological designing and dimensioning in torrent control, flood and erosion control and torrent revitalization in the areas from which they were derived and, at the same time, to the gradual creation of hydrologic landscape regions. The results of research in regional hydraulic geometry provides these options.

Table 5. Statistic characteristics and testing of analyzed relations

Correlation relation	R	R^2	S_R	t	> = <	$t_{0.01(24)}$	RMSE	SWp
$B_{bf(1)} = f(QA_w)$	0.980	0.960	0.0408	24.02	>	2.797	0.55	0.2177
$H_{bf(1)} = f(QA_w)$	0.959	0.921	0.0574	16.71	>	2.797	0.06	0.1551
$A_{bf(1)} = f(QA_w)$	0.983	0.966	0.0376	26.14	>	2.797	0.43	0.5379
$Q_{bf(1)} = f(QA_w)$	0.984	0.968	0.0365	26.96	>	2.797	1.38	0.0080
$B_{bf(2)} = f(QA_w)$	0.984	0.968	0.0365	26.96	>	2.797	0.51	0.6974
$H_{bf(2)} = f(QA_w)$	0.976	0.953	0.0443	22.03	>	2.797	0.05	0.8625
$A_{bf(2)} = f(QA_w)$	0.985	0.970	0.0353	27.9	>	2.797	0.41	0.7569
$Q_{bf(2)} = f(QA_w)$	0.985	0.969	0.0359	27.44	>	2.797	1.37	0.0016

Explanatory notes: R – index of correlation, R^2 – index of determination,
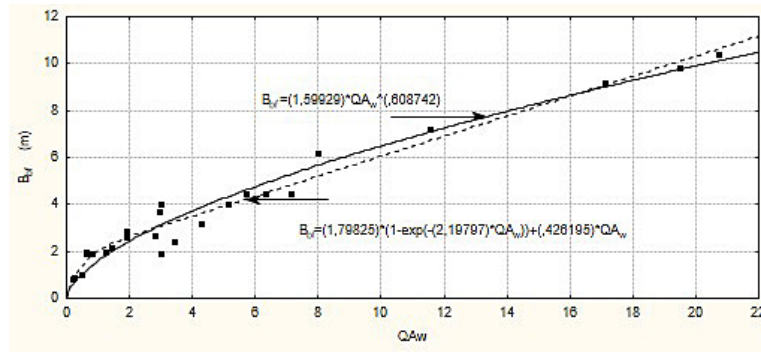
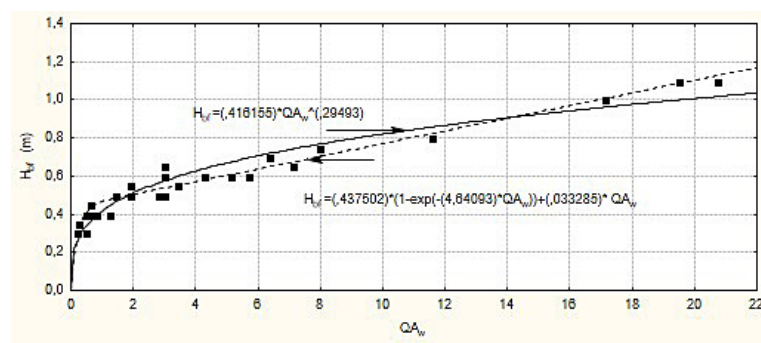**Figure 4.** Relation between QAw and B_{bf}

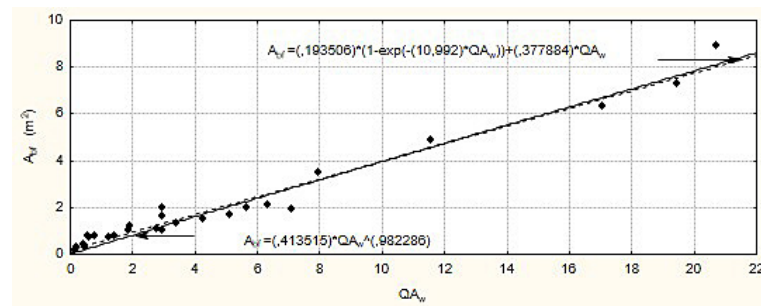**Figure 5.** Relation between QAw and H_{bf}

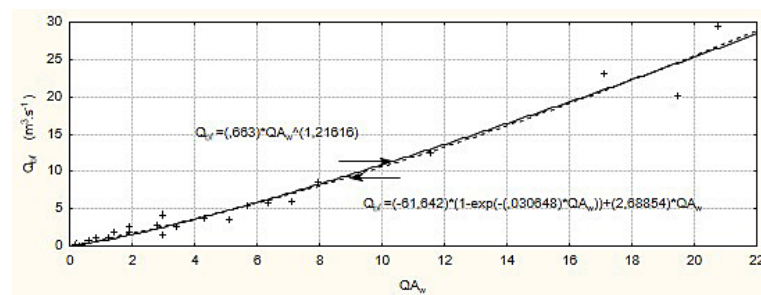**Figure 6.** Relation between QAw and A_{bf}
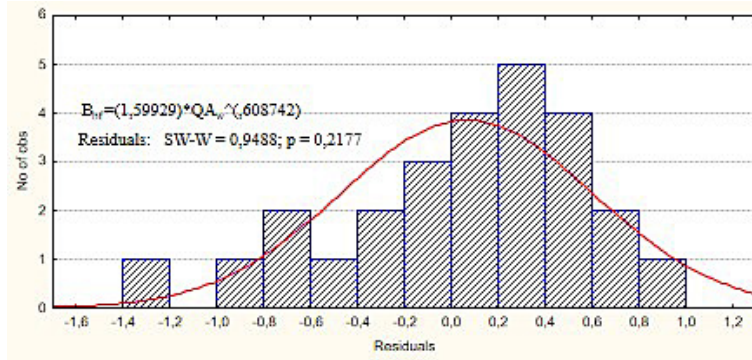

Figure 7. Relation between QAw and Q_{bf}

Figure 8. Residuals for the relation $B_{bf} = f(QAw)$ by equation (2)
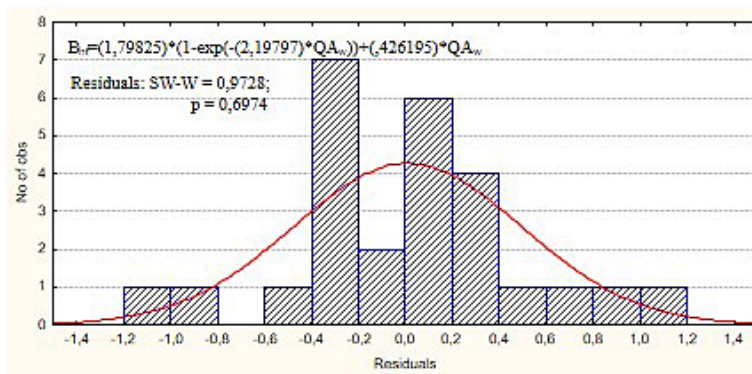

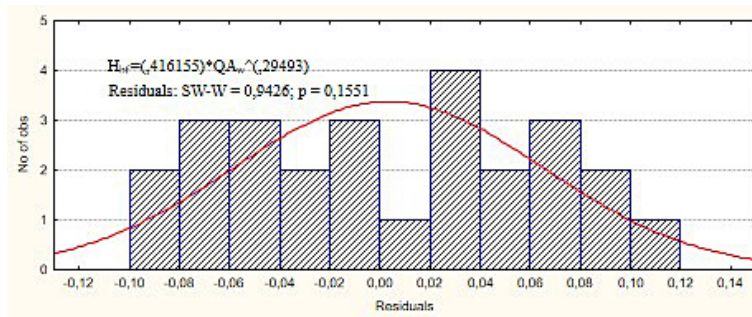**Figure 9.** Residuals for the relation $B_{bf} = f(QAw)$ by equation (3)

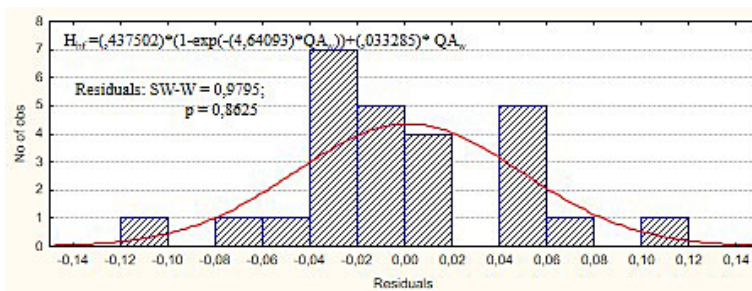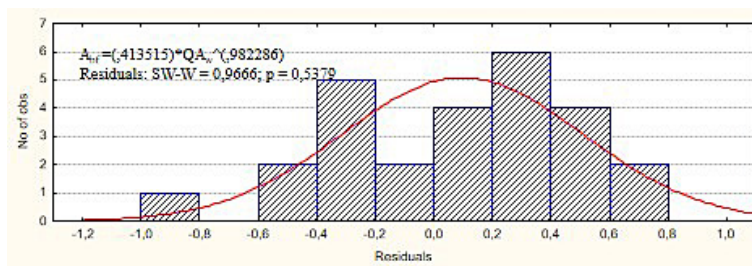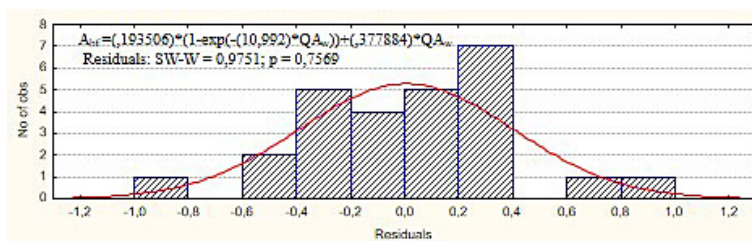**Figure 10.** Residuals for the relation $H_{bf} = f(QAw)$ by equation (2)

Figure 11. Residuals for the relation $H_{bf} = f(QAw)$ by equation (3)

Figure 12. Residuals for the relation $A_{bf} = f(QAw)$ by equation (2)

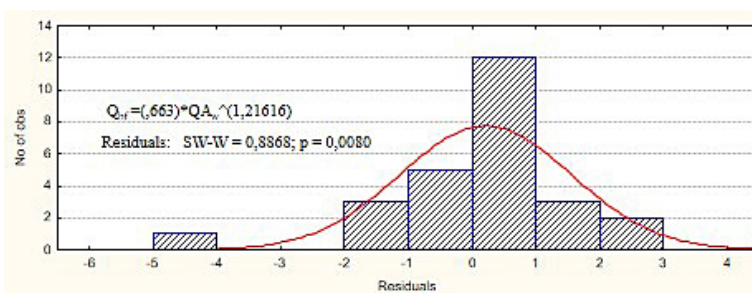**Figure 13.** Residuals for the relation $A_{bf} = f(QAw)$ by equation (3)

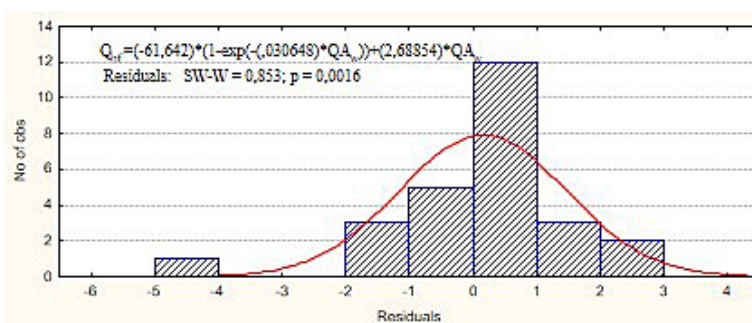**Figure 14.** Residuals for the relation $Q_{bf} = f(QAw)$ by equation (2)

Figure 15. Residuals for the relation $Q_{bf} = f(QAw)$ by equation (3)

Acknowledgements

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