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BANKFULL WIDTHS IN STEEP HEADWATERS OF THE FLYSCH CARPATHIANS

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Abstract. Bankfull widths of steep headwater channels were examined in the Western Carpathian flysch midmountains. The criteria of the top of banks, scoured lines and presence of bank vegetation were helpful in the bankfull width determination. A direct downstream relationship between the parameters of the bankfull width and the watershed area and a negative downstream relationship between the parameters of the bankfull width and the channel gradient were observed in all examined channels similarly to lower gradient rivers. However, streams based in more resistant sandstone flysch and/or influenced by small debris-flows indicated much less dependence between these parameters. Significant differences in bankfull widths were found when channels of the same watershed areas, but located on leeward and windward hillslopes were compared.

Key words: Carpathians, flysch, bankfull, headwater channel

INTRODUCTION

Fluvial channels adjust their geometry to dominant discharges that are characterised by maximum sediment transportation during relatively moderate flow events rather than large floods. This is due to the fact that moderate flows occur much more frequently than high magnitude floods [Wolman and Miller 1960]. In channels controlled by fluvial processes at or near dynamic equilibrium, dominant discharge is approximately equal to the bankfull discharge [Leopold et al. 1964, Knighton 1984]. Wolman and Leopold [1957] defined bankfull as the elevation of the active floodplain and similarly, Williams [1978] described bankfull discharge as the flow which fills the channel to the tops of the banks.

While the function of discharge is the single deciding factor in the forming of the channel geometry of low gradient rivers, this is not the case for mountain streams or even

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steep headwaters [Wohl and Merritt 2008]. Their sediment transport regime and hydrodynamics differ substantially from those of low gradient rivers. The channel geometry of the headwater channel is the result of various shaping factors owing to the strong hillslope-channel coupling, occurrence of vertically oscillating bedforms, usually coarse bed sediments, influence of additional roughness parameters (bedrock outcrops, large woods) and usually limited sediment supply [Whiting et al. 1999, Gomi et al. 2003, Hassan et al. 2005, Comiti and Mao 2012]. Despite these facts, the relationship between the bankfull width (*W*) and the watershed area (*A*) expressed by the following power law with *c* and *d* coefficients [Leopold and Maddock 1953] is often used even for small mountain channels [Brummer and Montgomery 2003, Golden and Springer 2006, Vianello and D'Agostino 2007, Wohl and Merritt 2008, Galia and Hradecký 2014]:

$$W = cA^d$$

Several techniques were investigated to examine bankfull channel and bankfull discharge in alluvial streams, reflecting e.g. width/depth ratio [Wolman 1955], the first maximum of the bench index [Riley 1972], cross-sectional area and channel width relationship [Williams 1978], bank sediment parameters [Leopold and Skibitzke 1967], vegetation cover [Schumm 1960, Williams 1978] or specific invertebrates occurrence [Radecki-Pawlik and Skalski 2008]. Radecki-Pawlik [2002] provided comprehensive report of the application of several methods in mountain gravel-bed channels and pointed up, that rather a certain range of discharges should be defined as the bankfull condition. Whereas floodplain segments or benches usually missing in the steep headwaters, the parameters of the top of banks, scoured lines or discontinuity of vegetation are applicable in this part of stream network [Galia and Hradecký 2014].

The paper examines field techniques of bankfull estimations and downstream variations in the bankfull width parameter in small steep channels of flysch midmountain environment. Obtained results can be applied in forest management or restoration works of headwater steep streams.

STUDIED STREAMS

Five steep headwater streams of the midmountain flysch area of the Moravskoslezské Beskydy Mts (Czech Republic) were selected for the study (Fig. 1). From the lithological point of view, channels of Dížená, Velký Škaredý and Veřmiřovský streams contain significant amount of claystone particles (usually 10–60% based on pebble counts) in their bed sediments. By contrast, Kněhyňka and Malá Ráztoka streams are mostly based in relatively more resistant sandstones of the Godula Formation. The upper parts of Kněhyňka, Malá Ráztoka and Velký Škaredý watersheds were also influenced by small debris-flows in past centuries, although the remains of depositional forms in the Moravskoslezské Beskydy Mts indicate a greater magnitude of these processes in the Pleistocene Era [Šilhán 2014; Šilhán and Pánek 2010]. Recently, fluvial bedload transport that has dominated most of the local steep channels was characterised by low values of critical conditions for the incipient motion of grain [Galia and Hradecký 2012]. All studied channels have stepped--bed morphology [Comiti and Mao 2012], where steps, pools and rapids alternate with respect to the local channel gradient [Galia and Hradecký 2014]. Active sediment inputs are characterised by small gullies and bank failures, especially in the parts of watersheds based in the claystone members. More accessible lower gradient channel-reaches are systematically cleared of large wood by forest management, which strongly contributes to the decreasing trend of observed pieces of woody debris with increasing watershed area [Galia and Hradecký 2014].

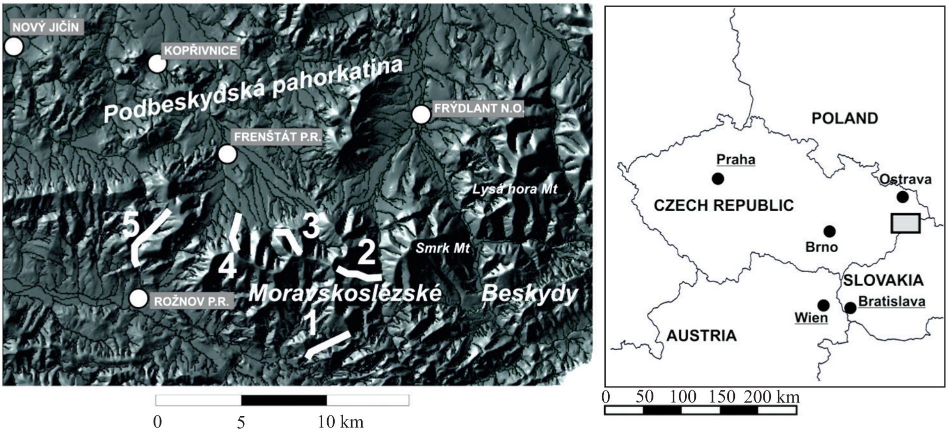

Fig. 1. Location of studied streams: 1 – Dížená, 2 – Kněhyňka, 3 – Malá Ráztoka, 4 – Velký Škaredý, 5 – Veřmiřovský

METHODS

Bankfull widths W were obtained in the morphologically consistent channel-reaches of the Dížená ($n = 9$, $0.27 \leq A \leq 3.01$ km^2, $0.15 \geq S \geq 0.06$ m · m^{-1}), Kněhyňka ($n = 10$, $0.22 \leq A \leq 3.00$ km^2, $0.40 \geq S \geq 0.08$ m · m^{-1}), Malá Ráztoka ($n = 8$, $0.20 \leq A \leq 2.20$ km^2, $0.38 \geq S \geq 0.06$ m · m^{-1}), Velký Škaredý ($n = 12$, $0.03 \leq A \leq 1.06$ km^2, $0.70 \geq S \geq 0.06$ m · m^{-1}) and Veřmiřovský ($n = 12$, $0.10 \leq A \leq 6.08$ km^2, $0.31 \geq S \geq 0.03$ m · m^{-1}) during years 2010 and 2011 and the low-flow conditions. The widths with accuracy ±0.05 m were measured at three positions in a single reach and then the mean was calculated to avoid local divergences. Channel gradients S were measured by the digital rangefinder with accuracy ±0.005 m · m^{-1} for an individual channel-reach. Watershed areas A above individual cross-sections were taken from the 1 : 10,000 topographic maps.

A great attention was paid to the estimation of bankfull marks in the field. The inflexion point in a stream bank (the top of bank criterion) was mostly considered as the bankfull width indicator in the transport or depositional channel-reaches. Also a criterion of bank vegetation discontinuity was helpful especially when limited floodplain segments occurred on lower channel gradients. For some of incised channel-reaches, the scour lines were identified in the field. A high uncertainty in bankfull width identification arose in high sediment-supply conditions, e.g. in the valleys filled by a coarse debris-flow material in Velký Škaredý. In fact, such channel-reaches can behave as a braided stream during bankfull or higher flow conditions. The bankfull flow near the Malá Ráztoka gauging station (A = 2.02 km^2) was observed 24 hours after the culmination of 5/2010 flood (Q20); the value of 0.9 m^3 · s^{-1} corresponded to 1–2 year discharge respecting 1953–2006 gauging records (Fig. 2) and such discharge reflected morphological indicators of bankfull channels (criteria of the top of banks and bank vegetation discontinuity).

Fig. 2. The annual flow (left) and the bankfull flow (right) immediately downstream the Malá Ráztoka gauging station

RESULTS AND DISCUSSION

The analysis between watershed area A and bankfull width W showed strong power relationships in Dížená, Velký Škaredý and Veřmiřovský streams with $R^2 > 0.80$. These streams have usually the significant proportion of claystone particles in their bed sediments up to 60% based on pebble-counts in some channel-reaches of Dížená. However, watersheds based mostly in the relatively resistant sandstone flysch (Kněhyňka and Malá Ráztoka) showed only poor relationship with $R^2 = 0.38$ and 0.13 respectively (Fig. 3). This fact may be resulted from the observations of larger diameters of sandstone bed particles and also corresponds to the occurrence of past debris-flows, which prevented from the shaping of these streams by fluvial processes during bankfull or similar discharges. By contrast, the significant proportion of less-resistant quickly weathering claystone particles allows adjustments of other studied channels even to the bankfull discharges. If we consider larger sandstone particles as resistant bed surface layer, Montgomery and Gran [2001] found out that there is no measurable difference in the channel width between alternating bedrock and alluvial reaches in channels cut into weak rocks here represented by claystones. Generally, a strong dependence between bankfull width and watershed area was reported by Golden and Springer [2006] and Vianello and D'Agostino [2007] in steep headwaters. Brummer and Montgomery [2003] also documented a strong dependence between these two parameters, although slightly lower coefficient of determination was observed in channels affected by debris-flows. Fairly good correlation in power A–W relationship (R^2 = 0.53) arose by considering larger dataset (n = 102) from the Czech part of flysch Western Carpathians [Galia and Hradecký 2014].

Similar relationships arose when the parameters of channel gradient S and bankfull width W were plotted. Again, the watersheds based also in the less resistant claystone members (Dížená, Veřmiřovský and Velký Škaredý) showed higher coefficients of determination when these two parameters were plotted ($0.49 \geq R^2 \geq 0.79$). On the other hand, such relationship for the Kněhyňka stream indicated $R^2 = 0.36$ and the Malá Ráztoka $R^2 = 0.11$ only (Fig. 4). Table 1 shows parameters of observed *A–W* and *S–W* power relationships for examined streams.

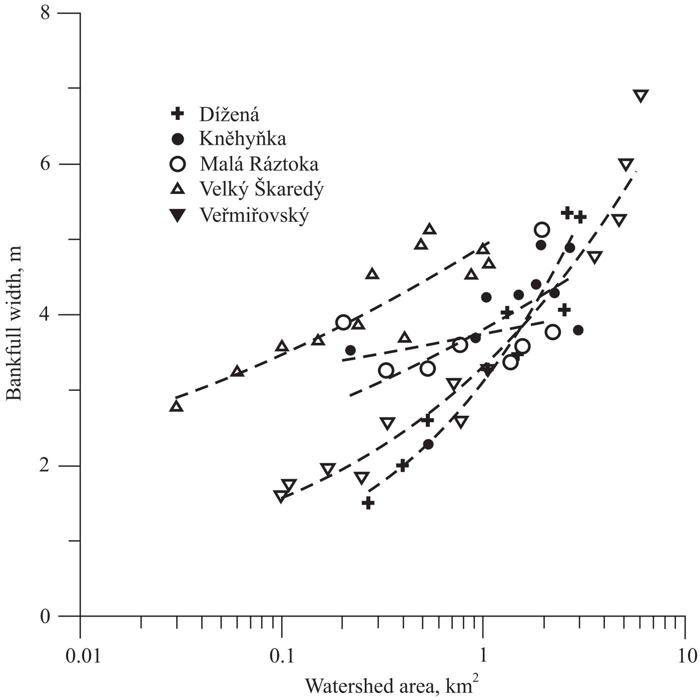

Fig. 3. Plot of the dependence of the watershed area and the bankfull width of studied channels

Table 1. Relationship between the parameters of bankfull width, watershed area and channel gradient for examined streams

Stream	n	$W = cA^d$			$W = aS^b$		
		c	*d*	R^2	*a*	*b*	R^2
Dížená	9	3.11	0.47	0.94	0.67	–0.62	0.49
Kněhyňka	10	3.80	0.17	0.38	2.30	–0.28	0.36
Malá Ráztoka	8	3.74	0.06	0.13	3.16	–0.08	0.09
Velký Škaredý	12	4.92	0.15	0.81	3.07	–0.18	0.75
Veřmiřovský	12	3.32	0.33	0.97	0.62	–0.66	0.79

In view of the downstream bankfull geometry and potential stream restorations of steep headwaters, a relatively high variety in bankfull width existed between individual channels at equal upstream watershed areas. For example, Dížená and Veřmiřovský streams, both located on the leeward side of mountain ridges indicated bankfull width ≤ 2 m by considering ca. 0.2 km^2 upstream watershed area. On the other hand, Velký Škaredý and Malá Ráztoka, located on the windward hillslopes showed values about 4 m by considering the same watershed areas. It is obvious, that also a character of precipitation regime and hydrogeologic conditions of watersheds play important role in derived bankfull geometry of geographically neighbouring headwaters. Geomorphologic processes related to hillslope-channel coupling (e.g., landsliding, debris-flows) are typical for headwaters and they strongly influence sediment-supply conditions in their frequency, magnitude and resistance of bed sediments. In our case, it was resulted into the lower degree of the adjustment of bankfull width to the upstream watershed area in debris-flow influenced headwater channels. It implies fact, that potential stream restorations cannot calculate with unique regional values of bankfull width for this type of channels (e.g. $W = 3.19\ A^{0.22}$ reported for the flysch Western Carpathians [Galia and Hradecký 2014]), but individual headwaters should be individually carefully evaluated.

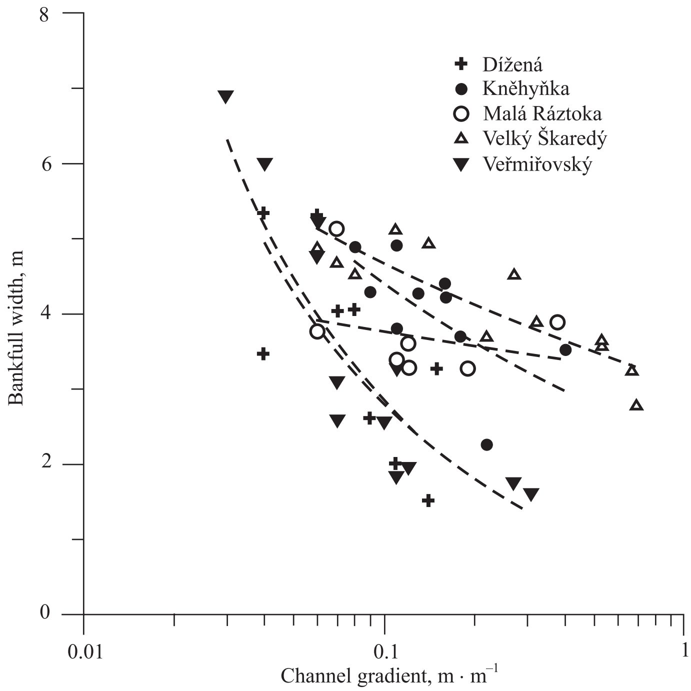

Fig. 4. Logarithmic plot of the dependence of the channel gradient and the bankfull width of studied steams

CONCLUSIONS

In steep fluvially-dominated channels, the top of banks, scoured lines or vegetation discontinuity criteria were helpful to estimate bankfull stage. High sediment supply conditions (e.g., presence of debris-flow accumulations in valley floor) made difficult to exactly determine the bankfull width. Positive downstream trend between the parameters of bankfull width and watershed area was observed in steep flysch-based headwaters showing a similarity to the lower gradient streams. However, such trend was much less significant for channels containing a higher amount of relatively resistant sandstones and for channels affected by debris-flows. Differences in absolute values of measured bankfull widths were obtained by considering the same upstream watershed area when channels on leeward and windward slopes were compared. Thus, a detailed evaluation of individual headwater watershed is recommended for potential stream restorations and designs of steep channels.

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PRZEPŁYWY BRZEGOWE NA STROMYCH TERENACH GÓRNYCH BIEGÓW RZEK FLISZU KARPACKIEGO

Streszczenie. W pracy badano przepływy brzegowe na stromych terenach górnych biegów strumieni na obszarze fliszu w środkowej części Karpat Zachodnich. W określeniu przepływów brzegowych przydatne były kryteria dotyczące wierzchnich fragmentów brzegowych, linii przebiegu erozji oraz obecność wegetacji brzegowej. Bezpośredni stosunek pomiędzy parametrami przepływów brzegowych w dół rzeki oraz obszaru zlewni, a także ujemny stosunek między parametrami przepływów brzegowych a nachyleniem koryta zaobserwowano we wszystkich badanych ciekach, podobnie jak w rzekach o niższym stopniu nachylenia. Jednak strumienie usytuowane na terenach zbudowanych z bardziej wytrzymałego piaskowca fliszowego oraz/lub będące pod wpływem cieków z małym rumowiskiem wykazywały mniejszą zależność między tymi parametrami. Istotne różnice w przepływach brzegowych znaleziono porównując koryta z tej samej zlewni, lecz występujących na zboczach leżących po stronie zawietrznej oraz nawietrznej.

Słowa kluczowe: Karpaty, flisz, przepływ brzegowy, górny bieg rzeki

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