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Channel-reach morphology controls of headwater streams based in flysch geologic structures: An example from the Outer Western Carpathians, Czech Republic

Tomáš Galia *, Jan Hradecký

Department of Physical Geography and Geoecology, Faculty of Science, University of Ostrava, Chittussiho 10, 710 00 Ostrava, Czech Republic

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ABSTRACT

A detailed measurement of 93 channel reaches that were classified with an adjusted Montgomery–Buffington (1997) reach-scale system provided comprehensive information of approximately 9 at-a-reach parameters: the channel gradient, the bankfull width, the bankfull depth, d_{90}, the percentage of resistant rocks in the bed sediment, the number of pieces of large woody debris, valley confinement, direct sediment inputs and the presence of fluvial accumulations in the stream channel. In addition, the quantified intensity of sediment transport (i.e. ratio between sediment supply and transport capacity in longitudinal stream profiles) during flood events has been estimated by the one-dimensional bedload transport model (TOMSED), which was validated in two local streams. The principal component analysis of the at-a-reach parameters did not reveal significant groups of channel-reach morphologies; thus, the selected parameters that exclude sediment transport dynamics within stream longitudinal profile cannot reliably distinguish or predict individual channel reach morphologies. Nevertheless, the channel gradient represented the most significant single explanatory variable for stepped-bed morphologies. The addition of bedload transport parameters demonstrated that limited sediment supply streams and streams with limited transport capacities featured different successions of the channel reach morphologies in terms of the channel gradient and, subsequently, the fluvial continuity. The bedrock-cascades and step-pools were significant for the first case, whereas cascade and step-rapid morphology often occurred in higher sediment supply conditions.

1. Introduction

Mountain headwater channels link slopes and the fluvial system, supplying low gradient rivers with water and sediment (Chartrand and Whiting, 2000; Kavage-Adams and Spotila, 2005). Their sediment transport regime and hydrodynamics differ substantially from those of lowland rivers owing to the common occurrence of vertically oscillating bedforms; bed sediments, including gravel, cobble, and boulder fractions, which are usually coarse; the influence of additional roughness parameters, such as large wood or bedrock outcrops; and, in most cases, a limited sediment supply character (Whiting et al., 1999; Rickenmann, 2001; Gomi et al., 2003; Hassan et al., 2005; Comiti and Mao, 2012). Thus, the channel geometry of the headwater channel is the result of various shaping factors; and endogenous processes, such as tectonic uplift and the geomorphic resistance of the bedrock lithology, also play a role (Massong and Montgomery, 2000; Kavage-Adams and Spotila, 2005; Golden and Springer, 2006). Similarly, gravitational hillslope processes, represented by mass movements (e.g., landslides and debris flows), are important forming agents, which in most cases predispose the frequency and magnitude of sediment supply into fluvial segments and the subsequent pulsing character of bedload transport (Dietrich and Dunne, 1978; Benda, 1990; Rickenmann, 2001; MacDonald and Coe, 2007; Mao et al., 2009; Yu et al., 2009; Recking, 2012). Moreover, a role of large wood in mountain channels should be accounted, when individual logs participate in formations of steps in stepped-bed morphologies (Faustini and Jones, 2003; Gomi et al., 2003; Comiti et al., 2006; Andreoli et al., 2007). A significant amount of wood in steep channels later affects grain-size parameters and sediment transport processes and often leads to 'forced' channel-reach morphologies (e.g., Montgomery and Buffington, 1997; Wohl et al., 1997; Gomi et al., 2003; David et al., 2011). Intensive forest management and anthropogenic changes of land cover in headwater watersheds can alter not only direct supply of woody debris into channels, but also sediment flux connectivity in the longitudinal profile of streams by constructing check dams (Baker et al., 2011). Also, changes in land use can have an effect on the intensity of transport processes in slope-channel systems (Harvey, 2001; Kasai, 2006; Chappell and Brierley, 2014). This observation suggests that while the function of discharge is the single deciding factor in the shaping of the channel geometry of low gradient rivers, such as those studied by Wolman and Leopold (1957) or Benson and Thomas (1966), this is not the case for mountain streams. Thus, a complex approach including nonhydrologic variables is needed to evaluate channel morphometry in steep streams (Brummer

* Corresponding author. Tel.: +420 597 092 366; fax: +420 597 092 323.
E-mail address: tomas.galia@osu.cz (T. Galia).

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and Montgomery, 2003; Vianello and D'Agostino, 2007; Wohl and Merritt, 2008; Chappell and Brierley, 2014).

Prediction of the occurrence of channel-reach morphologies and their predisposing factors sensu Montgomery and Buffington (1997) in mountain headwater channels represents a challenge for fluvial geomorphologists, particularly owing to a large number of channel-shaping agents. Discriminant analysis (Wohl and Merritt, 2005), spatial-correlation analysis (Thompson et al., 2006), and the testing of parameters between individual morphologies (Wohl and Merritt, 2008) were conducted in order to classify mountain channel reaches into various environments. The arrangement of channel-reach morphologies in the longitudinal profile of streams was observed mainly with respect to the channel gradient. Grain size parameters also played an important role and there were significant differences between step-pools, plane beds, and pool-riffles when channel width and width–depth ratio were considered. David et al. (2010) investigated at-a-station hydraulic geometry in cascade, step-pool, and plane bed channel reaches in terms of the exponents of the velocity–discharge, the channel width–discharge, and the channel depth–discharge relationships. They indicated that the channel gradient and the average roughness area were significantly correlated to changes in the flow velocity, channel width, and channel depth with increasing discharge. In contrast, the wood volume per square metre in the channel was an independent variable when compared to observed hydraulic geometry. The recent studies of Church and Zimmermann (2007), Zimmermann et al. (2010), and Recking et al. (2012) demonstrated that unbalance between sediment supply and transport capacity in a channel and the ratio of coarsest grain diameters to bankfull channel width act as important agents for development of regular step-pool sequences.

The objective of this study was to evaluate the predicting factors for the occurrence of certain channel-reach morphologies in the mountain headwater channels draining the Flysch belt of the Western Carpathians. The heterogeneity of the local flysch lithology strongly affects the transport and shaping processes; the formations are generally composed of resistant sandstones and soft, quickly weathering claystones. Besides other things, such lithology produces a smaller grain size of bed particles as well as the absence of large boulder fractions (>630 mm), consequently affecting bed roughness and bedload transport intensity. Our innovative approach combined the statistical analysis of measured at-a-reach variables with transport processes, which were quantified by the simulated intensity of bedload transport during high magnitude flood events, to determine the behavioural patterns of local headwater channels. Character of bedload transport is not strictly related to at-a-reach variables, and it acts as a variable representing processes in the scale of stream longitudinal profile (e.g., sediment supply to some upstream channel reach). The sediment transport intensity in the local headwater channels was estimated with the one-dimensional numerical model TOMSED and validated in two reference streams.

2. Studied streams

We worked in 14 small watersheds ($A = 0.03$–$6.08\ km^2$) in the Czech region of the Flysch belt of the Outer Western Carpathians, covering local high ridges together with a piedmountain landscape with altitudes varying between 320 and 1250 m asl; these areas included the Moravskoslezské Beskydy Mts (MBM), the Podbeskydská pahorkatina Upland (PPU), and the Hostýnsko-Vsetínská hornatina Highland (HVH) (Fig. 1; Table 1). The region is characterised by the most intense precipitation regime in central Europe. The mean annual rainfall amounts vary between 800 and 1500 mm and peaks in the summer season during storm events when the overall rainfall mass is modulated by

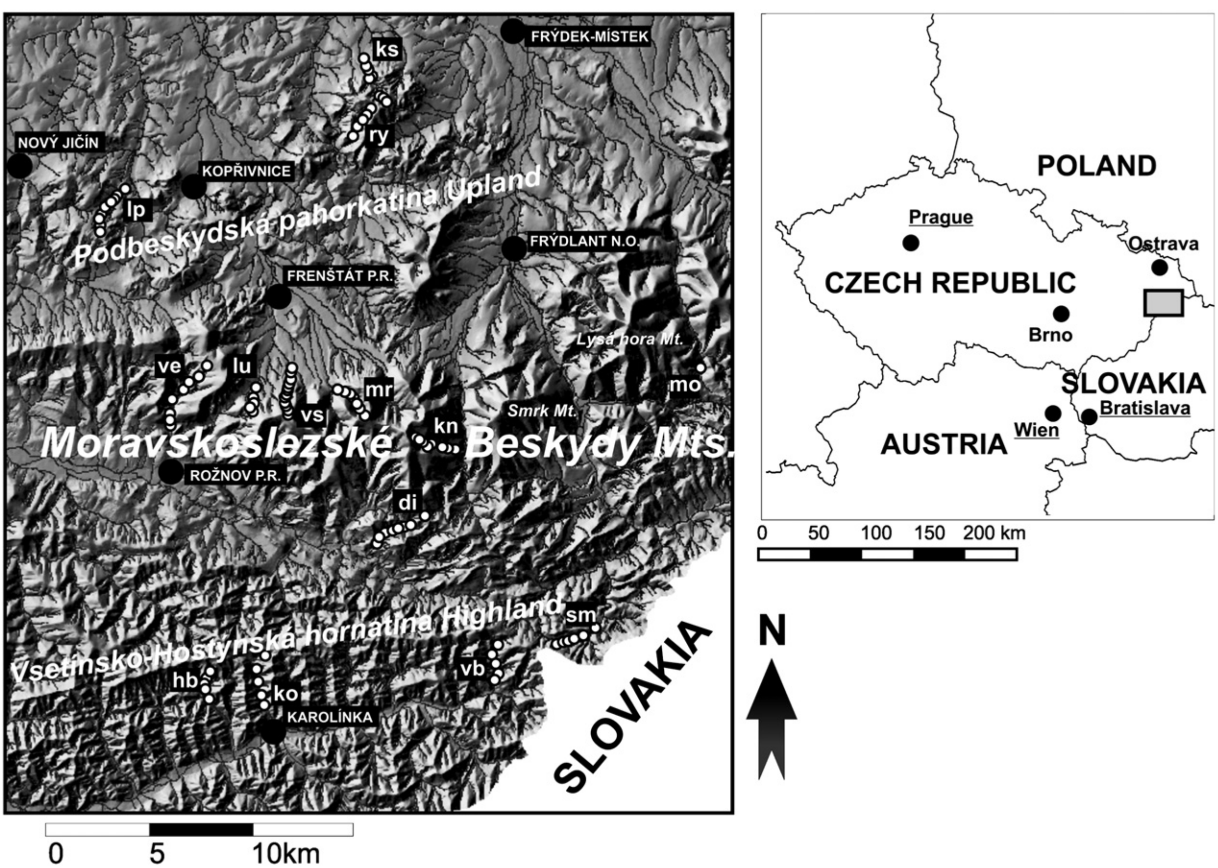

Fig. 1. Study area and evaluated headwater channel reaches, where the variables for the PCA analysis were obtained: di — Dížená, hb — Hrubá Brodská, kn — Kněhyňka, ko — Kobylská, ks — Košice, li — Libotínský, lu — Lubina, mo — Mohelnice, mr — Malá Ráztoka, ry — Rybský, sm — Smradlava, vs — Velký Škaredý, Ve — Veřmiřovský, vb — Vsetínská Bečva. Streams with a simulated intensity of bedload transport are highlighted.