Geomorphology 272 (2016) 115–126

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

# Do the coarsest bed fractions and stream power record contemporary trends in steep headwater channels?

Tomáš Galia *, Václav Škarpich

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

ARTICLE INFO

*Article history:*
Received 18 February 2015
Received in revised form 22 July 2015
Accepted 30 July 2015
Available online 12 August 2015

*Keywords:*
Headwater stream
Stream power
Bed sediments
Fluvial processes

ABSTRACT

Three stream channels that were devoid of evidence of past debris flows and one headwater channel that contained debris flow deposits in the flysch western Carpathians, Czech Republic were selected to test relationships between in-channel processes, bed sediments, and unit stream power calculated for bankfull and $Q_{20}$ flows. Contemporary depositional or erosional trends in the examined headwaters were linked with bed sediments that were represented by the coarsest cobble and boulder fraction with a mean calculated from the five largest particles. The downstream trends of the unit stream power were derived for a bankfull discharge and a well-documented 20-year flood event. In addition, the flow competences during the discharges were calculated using indirect bedload transport measurements. Downstream fining of the cobble and boulder fraction was observed in all of the studied headwaters, and unique downstream variations of the unit stream power were calculated for the longitudinal profiles. The single-thread streams that were devoid of evidence of debris flow events exhibited direct relations between the coarsest sediment size and the unit stream power, especially as calculated for the 20-year flood event and for erosional/depositional trends of the channel. The downstream coarsening of the bed material that was accompanied by an increase in the unit stream power was usually observed in the case of deeply incised (>0.5 m above the assumed bankfull depth) channel reaches. The calculated competence of the 20-year flow was up to twofold higher than that required to entrain the largest bed particle diameters in those channel reaches, and even the bankfull flow was potentially capable of transporting the coarsest bed particles in certain of the reaches. On the other hand, some depositional channel reaches evidently led to the disconnectivity of transport of the coarsest bed material even in the case of the 20-year flood event. The longitudinal profile of the channel that had evidence of past debris flows did not clearly show a direct relationship between boulder size and calculated unit stream power and contemporary channel trends. This finding reflected the presence of significantly coarser bed material, which points to a higher stability of the debris flow-influenced channel during ordinary floods when compared to fluvially dominated headwaters that are devoid of debris flows.



## 1. Introduction

Geomorphologists have long recognized that the morphology, geometry, and sediment substrate of stream channels are adjusted to a variety of inner and outer conditions. The channel geometry of alluvial undisturbed rivers, characterised by bankfull width, $W_{bf}$ (m), and depth, $D_{bf}$ (m), is related to discharges that are close to the bankfull discharge (Wolman and Leopold, 1957; Leopold et al., 1964). The regular downstream trend of the bankfull geometry parameters with increasing watershed area is often disrupted by other shaping agents, especially in confined, steep mountain streams. Endogenic processes such as tectonic uplift, bedrock resistance, gravitational hillslope processes that are represented by mass movements (e.g., landslides and debris flows), and interactions with large amounts of woody debris significantly affect the cross-sectional geometry and the channel gradient, $S$ (m/m), of streams in mountainous landscapes (e.g., Montgomery and Buffington, 1998; Massong and Montgomery, 2000; Curran and Wohl, 2003; Faustini and Jones, 2003; Gomi et al., 2003; Benda et al., 2005; Kavage-Adams and Spotila, 2005; Golden and Springer, 2006).

Since the pioneering work of Bagnold (1966), the parameter of unit stream power, $\omega$ (W m$^{-2}$), which is usually calculated as

$$\omega = (QS\rho g)/W \tag{1}$$

where $Q$ is the discharge (m$^3$ s$^{-1}$), $\rho$ is the water density (1000 kg m$^{-3}$), $g$ is the gravitational acceleration (m s$^{-2}$), and $W$ is the channel width before the evaluated flood event (m), has been often applied to calculations of bedload transport and channel response in fluvial geomorphology (Magilligan, 1992; Krapesch et al., 2011; Thorne et al., 2011; Nardi and Rinaldi, 2015). Because obtaining the input variables is easy and high-resolution digital elevation models are

* Corresponding author.
*E-mail address:* tomas.galia@osu.cz (T. Galia).

http://dx.doi.org/10.1016/j.geomorph.2015.07.047

readily available, this parameter can be used to identify dominant processes within channels (i.e., erosion or deposition reflecting relatively higher or lower values of $\omega$ during flood events), although the sediment supply from the upstream reaches should be carefully considered (Vocal Ferencevic and Ashmore, 2012; Bizzi and Lerner, 2013). A direct linkage between the unit stream power during bankfull discharge ($\omega_{bf}$) and the watershed area has been found in steep headwater channels (watershed area $A < 10$ km$^2$), when the parameter of $\omega_{bf}$ was simplified to the form

$$\omega_{bf} \approx (AS\rho g)/W_{bf} \tag{2}$$

or even

$$\omega_{bf} \approx (AS)/W_{bf} \tag{3}$$

which reflects the downstream increase of the bankfull discharge given by

$$Q_{bf} \approx cA^{d}. \tag{4}$$

The parameter $\omega_{bf}$ was found to significantly increase downstream in various mountainous environments (Brummer and Montgomery, 2003; Fonstad, 2003; Golden and Springer, 2006; Vianello and D'Agostino, 2007). On the other hand, Kavage-Adams and Spotila (2005) reported that $\omega_{bf}$ varied significantly within channels but did not change systematically with increasing watershed area of small, steep headwaters ($A < 2$ km$^2$) in the Appalachian Mountains, where channel gradients are primarily controlled by lithological resistance.

Except for the cross-sectional geometry, steep mountain channels adjust their morphology by the spatial organisation of bed sediments, which contain a large range of sediment grades from sand to boulders. The coarsest fraction is especially crucial for the origin of stepped-bed morphology sensu Comiti and Mao (2012) in steep streams ($S > 0.03$), where boulder steps contribute considerably to the dissipation of the flow energy and decrease the potential of the flow for sediment transport and erosion (Reid and Hickin, 2008; Chiari and Rickenmann, 2011). The boulder steps are reorganised only during high-magnitude floods or debris flow events (Benda, 1990; Grant et al., 1990; Chin, 1998; Kavage-Adams and Spotila, 2005; Lenzi et al., 2006a; Molnar et al., 2010). This reorganisation implies the occurrence of size-selective bedload transport in steep channels during ordinary floods, as demonstrated by established power relationships between the bedload-transported grain size and unit stream power for various environments (Petit et al., 2005; Lenzi et al., 2006b; Mao et al., 2008a; Galia and Hradecký, 2012). Although a gradual downstream fining of bed sediments that follows Sternberg's exponential law, which is related to sorting processes and grain abrasion, is typical of alluvial rivers (Knighton, 1982; Powell, 1998), for mountain headwaters a downstream coarsening of bed sediments represented by changes in $d_{50}$ or $d_{90}$ has been reported (Brummer and Montgomery, 2003; Wohl and Wilcox, 2005; Vianello and D'Agostino, 2007; Johnson et al., 2010). This coarsening reflects a continuous lateral sediment supply from adjacent hillslopes or the occurrence of debris flow deposits in channels later immobile for bedload transport. However, the coarsening trend can be disrupted or terminated by changes in the lithological characteristics of the supplied sediments, influence of tributaries (Rice, 1998; Kavage-Adams and Spotila, 2005; Attal and Lavé, 2006; Golden and Springer, 2006), decoupling in the slope–channel system (Brummer and Montgomery, 2003; Golden and Springer, 2006; Galia and Hradecký, 2014), and the presence of large amounts of woody materials in the channels (May and Gresswell, 2003; Montgomery et al., 2003; Kaczka, 2008). Several studies have reported a positive correlation between $\omega_{bf}$ and bed grain size represented by $d_{50}$ or $d_{90}$ (Brummer and Montgomery, 2003; Vianello and D'Agostino, 2007) for $A < 10$ km$^2$. By contrast, Golden and Springer (2006) did not find any correlation between the size of bed sediments and $\omega_{bf}$ owing to the interaction of bed sediment lithology in the studied streams. Similarly, no significant relationship between the size of the largest boulders and cobbles and $\omega_{bf}$ was observed in flysch-based headwaters, which reflected a continuous sediment supply and an insufficient flow competence (i.e., capability of the flow to transport certain grain sizes) during bankfull flood events (Galia et al., 2015).

The crucial point is that stream power is often calculated for ordinary (i.e., bankfull) flows, although the stepped-bed morphology and channel geometry of steep headwater streams are transformed under conditions of higher flow events. Bunte et al. (2014) documented the importance of high-magnitude flood events in mountain streams when they referred to maximal discharges as effective discharges for coarse-bedded, steep channels under a snowmelt regime, except for some step-pool channels that contained a high proportion of fine sediments. Lenzi et al. (2006a) suggested definition of two dominant discharge ranges for steep headwater streams based on long-term observance of suspended and bedload transport in a steep Alpine channel. The first is related to the range of relatively frequent flows close to bankfull discharge, responsible for maintaining channel form; and the second represents the range of more rare (recurrence interval 30–50 years), high flows responsible for step destruction/creation and channel width adjustments. Moreover, additional imbalance between the sediment supply and the transport capacity leads to the spatial organisation of bed sediments, which has been demonstrated by recent studies that dealt with the regularity of step-pool morphology (Church and Zimmermann, 2007; Zimmermann et al., 2010; Recking et al., 2012). Thus, the relations between the stream power, bed sediment size, and trends of vertical channel adjustments (i.e., incision or aggradation after flood events) are still not understood in steep headwaters; and a more complex approach with an emphasis on coarse bed sediment sizes (e.g., $d_{90}$) and higher-magnitude flows is needed. The primary questions of this study are as follows:

- Does unit stream power at high-magnitude flow events reflect contemporary erosion or depositional trends in steep headwater channels?
- Do higher-magnitude flow events affect the grain-size and downstream trends of the coarsest bed fraction more than ordinary bankfull flows?

To answer these questions, we compared the size of the coarsest bed material in steep headwater channels in the flysch Carpathians with the transport competence of ordinary flows (i.e., bankfull discharges) and high-magnitude flood events, in our case with a well-documented $Q_{20}$ (where $Q_x$ denotes the flood discharge for a given recurrence interval) event. The role of contemporary trends in the channels, namely the balance between aggradation and incision, was tested and consequently confronted with the downstream variations in the coarsest bed sediment size and unit stream power calculated for $Q_{bf}$ and $Q_{20}$ flows. The analysis of the coarsest bed fraction was based on the mean boulder diameter (*MBD*), which represents the arithmetical mean of the *b*-axis of the five largest bed particles that were sampled within the active channel in a relatively short interval (10 m) in the studied stream longitudinal profiles. This approach represents a relatively less time-consuming, yet detailed method to obtain grain-size trends in the coarsest fraction of bed sediments or its connectivity along the longitudinal stream profile, when compared to classic pebble counts sensu Wolman (1954).

## 2. Studied streams

The research was conducted in four headwater channels ($0.06 < A < 1.11$ km$^2$; $0.04 < S < 0.28$ m/m) that drain the northern slopes of the Moravskoslezské Beskydy Mts, which are the part of the flysch western Carpathians with medium elevations up to 1300 m asl. The study area belongs to the locations that have the highest occurrence of shallow