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CRITICAL CONDITIONS FOR THE BEGINNING OF COARSE SEDIMENT TRANSPORT IN THE TORRENTS OF THE MORAVSKOSLEZSKÉ BESKYDY MTS (WESTERN CARPATHIANS)

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Abstract: Two methods were applied in small headwater streams in the region of the Moravskoslezské Beskydy Mts: flood competence method and marked particle displacement method. The first method consisted in the measurement of the diameters of the largest boulders (200-400 mm) that had deposited in fluvial accumulations as a consequence of a Q25 flood event (5/2010). Transport of marked particles (18-152 mm) was studied in the period between 11/2010 and 7/2011, during which several minor events occurred in local torrents and maximal observed discharge was equal to the bankfull stage (Q1-Q2). The latter method was also used in two selected gullies to evaluate the intensity of coarse sediment transport in initial channels. Derived critical values (unit stream power and unit discharge) of the movement of certain grain diameters were fitted to relationships $\omega_{ci}= 0.445d_i^{1.06}$ (d_i in mm) and $q_{ci}=0.8d_i^{0.51}$ (d_i in m). Obtained critical values were generally lower than those coming from Alpine and Andine environments. The same situation was observed using a relationship obtained for dimensionless shear stress, which takes form: $\tau^*_{ci}=0.097(d_{90}/d_i)^{-0.502}$ (d_i in m). This fact may have been caused by lower bed armouring or higher sediment supply in local torrents, when compared to the magnitude of discharges in Alpine and Andine torrents. In step-pool morphology systems, the dynamics of sediment transport was higher in pools than on steps at bankfull flow (38% of grains, respectively 12% of grains, were moved), whereas the opposite was observed at lower flow. Unlike the gully more or less armoured with vegetation, the active gully void of any vegetation cover demonstrated a much higher intensity of sediment transport during both fluvial and colluvial processes.

Keywords: torrent, bed sediment, bedload transport, shear stress, unit discharge, stream power, Moravskoslezské Beskydy Mts.

1. INTRODUCTION

High gradient streams are sources of flood hazards in mountainous terrains (e.g. Chiari et al., 2010, Rickenmann & Koschni, 2010). Not long ago, floods affected the study area in 1997, 2009 and 2010. All these events were accompanied by the transport of bed material and the formation of large depositional or erosional forms in active channels. Over the past decades, critical conditions initiating grain motion in mountain headwater streams have been investigated by several authors (e.g. Costa, 1983; Bathurst, 1987; Lenzi et al., 2006). Better understanding of the triggering factors of bedload transport related to steep stream gradients is necessary for watershed management targeted at the protection of property and human lives. In the area of the Western Carpathians, sediment transport regime has been assessed by Buzek (2004, 2007) via field measurement in the Ostravice basin. Sediment transport modelling in small Beskydian basins has recently been carried out by Šír et al., (2010). However, both authors only dealt with suspended sediment transport. The modelling of bedload transport in local gravel-bed rivers has been performed in the study of Galia et al., (2012). Galia & Hradecký (2011) have evaluated morphological effects of high-magnitude floods and critical conditions for transported boulders in Beskydian headwater streams. In addition, Škarpich et al., (2010) have assessed (dis) connectivities in sediment flux in small basins.

Three critical conditions initiating bedload transport in local streams were investigated in this paper: shear stress, unit stream power and unit discharge. Critical shear stress τ_{ci} [$N.m^{-2}$] related to dimensionless critical shear stress τ^*_{ci} is one of the most commonly used conditions to describe the threshold of the incipient motion of a grain on a stream bed. It is defined in the form

$$\tau_{ci} = \tau^*_{ci}.(\rho_s-\rho).g.d_i, \quad (1)$$

where ρ_s and ρ is the density of grain diameter d_i and water respectively and g is gravitational acceleration. Critical shear stress can be substituted by bed shear stress τ_b acting on the bed surface layer at uniform flow, which leads to the relationship

$$\tau_b = \rho.g.R.S, \quad (2)$$

where S is the energy gradient usually equal to the water surface slope and R is the hydraulic radius. There is a high level of uncertainty in estimating τ^*_{ci} in gravel-bed streams. Some authors use a uniform value for τ^*_{c50} or τ^*_{84} (Buffington & Montgomery, 1997; Zimmermann & Church, 2001). Lamb et al., (2008) have introduced slope criteria to describe this parameter in steep channels, while Andrews (1983), Lenzi et al., (2006) and Mao et al., (2008) use the d_i/d_{50} or d_i/d_{90} ratio to compute dimensionless shear stress acting on a particle of a certain diameter. The d_{90} parameter is probably more appropriate for steep channels as it contributes to form resistance. For this reason, performing tests in an Alpine torrent, Lenzi et al., (2006) developed the equation:

$$\tau^*_{ci} = 0.054(d_i/d_{90})^{-0.737} \quad (3)$$

Unit stream power ω [$W.m^{-2}$] can easily be obtained when the discharge and channel geometric parameters are known:

$$\omega = (Q.\rho.S.g)/w. \quad (4)$$

W is the channel width at discharge Q. Critical values of unit stream power ω_{ci} for a grain of the central diameter d_i have been investigated in boulder bed streams since the pioneering works of Bagnold (1980), Williams (1983) and Costa (1983) appeared. Studying Alpine and Andine torrents Mao et al., (2008) identified a relationship between unit stream power and the diameter of a moved particle d_i (in mm):

$$\omega_{ci} = 31.502 d_i^{0.488} \quad (5)$$

The equation in which measured discharge is divided by the channel width defines another critical parameter used in stream geomorphology - unit critical discharge q [$m^2.s^{-1}$]. Bathurst (1987) has presented a simple relationship for the incipient motion of a grain d_i (in m):

$$q_{ci} = a.d_i^b \quad (6)$$

Bathurst (1987) introduced a coefficient a ranging from 0.09-0.16 and an exponent b ranging from 0.2-0.4 for the streams of the Rocky Mountains (USA). He also proposed the calculation of b exponent: $b=1.5(d_{84}/d_{16})^{-1}$. Having analysed grain motion in an Alpine stream, Lenzi et al., (2006) substituted a with 0.641 and b with 0.641. Mao et al., (2008) used critical discharge dependent on the particle-size analysis of bed material and expressed a relationship valid for both the studied Andine and Alpine torrents:

$$q_{ci} = 0.286(d_i/d_{50})^{0.433} \quad (7)$$

In order to determine critical conditions initiating grain motion in a channel bed, two methods were successfully used in Beskydian streams: flood competition based on measuring the size of cobbles and boulders transported in a specific flow or during a flood, and the so-called (marked) particle displacement method consisting in marking individual grains and observing their movement after the flow events. Apart from that, grains were marked and monitored in two small gullies. The authors hope that new findings and conclusions of this study will contribute to the Central European mid-mountain watershed management.

2. STUDY AREA

Bedload transport was studied in two headwater streams (Fig. 1), namely in the Malá Ráztoka experimental basin (flood competition and marked particle displacement method) and the uppermost part of the Lubina River (flood competition). Both streams are located at the northern slopes of the Radhošťská hornatina Mts. The altitude varies from 530-980 m in the upper Lubina basin and 560-1080 m in the Malá Ráztoka basin respectively. Mean annual discharge corresponds to $0.061 m^3.s^{-1}$ in the Malá Ráztoka basin (2.076 km^2). 2-year recurrence discharge is equal to $0.95 m^3.s^{-1}$, 10-year recurrence discharge to $2.7 m^3.s^{-1}$, 25-year recurrence discharge to $4.4 m^3.s^{-1}$ and 100-year recurrence discharge to $8.5 m^3.s^{-1}$, as extracted from 1954-1993 time-series. Some other discharge data are known from the upper Lubina basin. Except its lowest parts, the Malá Ráztoka stream bed is predominantly of sandstone character with a minimum amount of claystone material. Due to frequent occurrence of bedrock in the channel, it is generally supplied with limited amount of sediment.

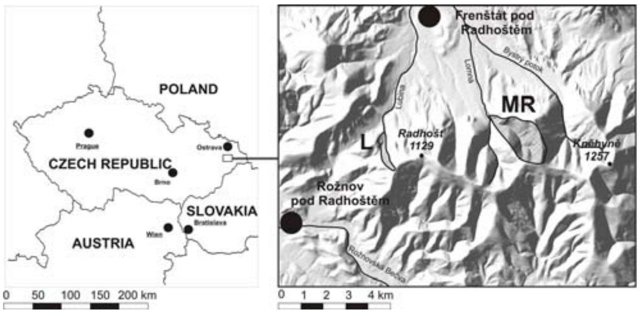

Figure 1. Basin of the upper part of Lubina stream (L; L1-L7 including reaches) and the basin of Malá Ráztoka torrent (included MR; MR1-MR4, G1 and G2 reaches).

Unlike its lower part represented by important claystone members of the Godula Formation, the Malá Ráztoka basin is mainly formed by sandstone flysch of the middle part of the Godula Formation (Cretaceous period). Still, claystone particles play a more important role in the bed structure of the upper reach of the Lubina stream where predominantly claystone formations such as the Lhoty Formation and the Veřovice Formation occur. Godula Formation sandstone cobbles and boulders are also presented, having been transported there by slope processes from the culmination parts of the Radhošťská hornatina Mts. High intensity of vertical erosional processes was observed in the upper Lubina stream related with the presence of numerous bank failures. Generally, both the basins are influenced by deep-seated slope deformations in the culmination parts of the ridges (Pánek et al., 2007). However, the relief of the Moravskoslezské Beskydy Mts. can be recognized as polygenetic (e.g. Hradecký & Pánek 2008; Šilhán & Stacke, 2011; Škarpich et al., 2011). In the Malá Ráztoka basin, average annual temperature is 6.9°C and the mean annual precipitation is 1244 mm, namely 651 mm in the warm period and 553 mm in the cold period of year (Chlebek & Jařabáč, 1995).

3. METHODS

The cobbles were marked by white non-toxic, environmentally safe paint and they were tagged by numbers representing their diameters in mm. Two sets of 60 marked cobbles in a range of 18-152 mm of b-axis were installed in two channel reaches MR3 and MR4 of the Malá Ráztoka torrent (Table 1) in November 2010. The MR3 set was situated c. 0.2 km upstream of the gauging station on the crest of a step in the step-pool reach (Montgomery & Buffington, 1997) characterised by significant occurrence of bedrock outcrops in the channel. On the contrary, the MR4 set was installed c. 0.2 km downstream from the gauging station in the reach characterised by step-pool and plane bed morphologies (Montgomery & Buffington, 1997), namely in a small pool developed under a step.

Apart from the original cobbles coming from the above mentioned reaches, the MR4 set contained also 22 claystone particles. Unfortunately, claystone cobbles were broken up 'in situ' into smaller pieces that were subsequently washed away during the experiment (11/2010-7/2011). Therefore, the only data used were those obtained observing 38 resistant sandstone cobbles.

Table 1. Summarization of observed reaches: (pf) mean parameters of channel during 5/2010 flood culmination (flood competence), (bf) bankfull parameters (marked particle displacement), (g) gullies (without predicted depth and particle-size analysis).

reach	A [km^2]	S [m.m^{-1}]	W [m]	D [m]	d_{50} [m]	d_{90} [m]	bed morphology
LU1 (pf)	0.20	0.09	2.8	0.40	0.040	0.140	step-pool
LU2 (pf)	0.20	0.11	2.8	0.30	0.045	0.140	step-pool
LU3 (pf)	0.25	0.12	2.5	0.30	0.045	0.120	step-pool
LU4 (pf)	0.25	0.11	2.8	0.40	0.045	0.120	step-pool
LU5 (pf)	0.28	0.10	3.3	0.45	0.050	0.155	cascade
LU6 (pf)	0.28	0.12	3.0	0.45	0.045	0.160	cascade
LU7 (pf)	0.35	0.06	3.0	0.35	0.045	0.155	rapid
MR1 (pf)	0.85	0.14	7.0	0.40	0.050	0.165	cascade
MR2 (pf)	1.41	0.11	3.4	0.35	0.045	0.145	cascade/bedrock
MR3 (bf)	1.95	0.08	4.0	0.27	0.045	0.160	step-pool/bedrock
MR4 (bf)	2.20	0.06	3.8	0.26	0.050	0.210	step-pool/rapid
G1 (g)	0.05	0.28	2.3	-	-	-	cascade/bedrock
G2 (g)	0.08	0.24	3.0	-	-	-	cascade/bedrock

The MR3 channel reach set was composed of sandstone rock in accordance with the local bed material. Changes in the positions of individual grains were assessed after the winter season at the end of March 2011, further in May and June after some minor storms, and finally in June 2011 after a 1-2-year flood event, when the torrent reached bankfull stage.

Similarly, four smaller sets (G1a, G1b, G2a, G2b) of marked particles were installed in two gullies (G1 and G2) situated in the upper part of Malá Ráztoka basin (Fig. 2) after the 5/2010 flood and observed in c. monthly intervals until 3/2011.

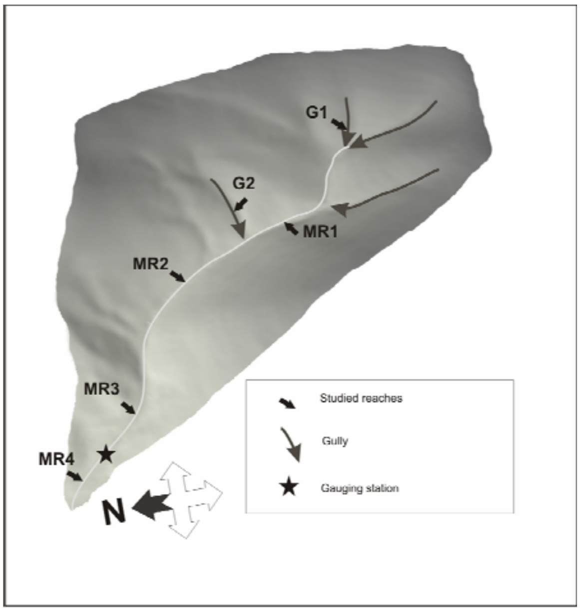

Figure 2. Schematic blockdiagram of the locations of all the studied reaches in Malá Ráztoka basin.

In study area, term 'gully' is described as V-shaped incised valley with occurrence of bedrock outcrops at its bottom and presence of ephemeral flow (e.g. Pánek et al., 2009; Šilhán & Pánek, 2010). Individual sets were arranged in stone lines painted 'in situ', in contrast to the MR3 and MR4 reaches of the torrent where the particles were picked up from the channel bed, dried and painted and finally returned to the channel. The G1 gully included the G1a set (30 particles, 25-200 mm diameters) and the G1b set of 24 marked cobbles (25-310 mm). The G1 gully, characterised by non-cohesive banks and bedrock outcrops at the bottom of its valley, is an active source of sediments for the torrent. On the other hand, being armoured with vegetation and having most of its bed material covered with moss (Fig. 3), the G2 gully is characterised by weak fluvial or colluvial transport. The G2a line contained 17 grains (40-190 mm) and the G2b line 22 particles (25-190 mm). No direct discharge measurement was conducted in the gullies during the experiment (7/2010-3/2011); the discharges are only known from the gauging station located downstream the Malá Ráztoka torrent. The transport of material in gullies was rather connected to some individual events such as storms. Not only fluvial, but also gravitational processes strongly contributed to sediment flux in these types of headwater segments.

Data from the 5/2010 flood observation were used to combine both flood competence and marked particle displacement methods. A flood event peaked Q_{25}-Q_{100} at the northern piedmont of the Moravskoslezské Beskydy Mts on 17 May 2010.

Figure 3. G1 gully (a) and G2 gully (b) showing evident morphological differences.

Culminate discharge reached the values of about $4 m^3.s^{-1}$ (c. 25-year occurrence interval) in the Malá Ráztoka basin. During this event several accumulations of bed material including large boulders (0.2-0.4 m in diameter) originated in the upper Lubina river channel reaches (LU1-LU7) and the Malá Ráztoka torrent (MR1 and MR2) (Table 1). During the flood the boulders were fluvially transported through the channel reaches upstream above the accumulations. We measured the size of stored boulders as well as the geometrical parameters of the reconstructed channel (i.e. supposed channel parameters during the flood). Furthermore, the particle-size analysis of bed material was conducted using the Wolman (1954) method. Finally, critical parameters necessary to make the boulders move were calculated according to the 5/2010 flood reconstruction (for more details see Galia & Hradecký, 2011).

4. RESULTS AND DISCUSSION

4.1. Visual observation of marked particle displacement in a torrent

Four measurements of grain motion were made between 11/2010 and 7/2011. The first one was conducted after the snow melting at the end of March 2011. The culminate discharge recorded between the installation of particles and 25 March 2011 reached $0.170 m^3.s^{-1}$ on 24 December 2010. Another two measurements followed after storm events in May and June 2011 bringing smaller culminations of $0.104 m^3.s^{-1}$ and $0.088 m^3.s^{-1}$. Finally, the culminate discharge of $0.938 m^3.s^{-1}$ was observed on 1 June, which corresponded to bankfull (1-2-year) discharge.

After the winter season, 23% and 11% of the sandstone grains moved slightly on the crest of a step (MR3) and in a pool (MR4) respectively. The sandstone grains were of maximal noticed diameters of 79 mm (MR3) and 99 mm (MR4). The grains more likely moved due to the 'settling' of grains in the bed surface layer in connection with bed armouring rather than due to the direct effect of culminate discharge (0.17 $m^3.s^{-1}$), which can be understood as a supply of 'fresh' material into an active channel, e.g. because of a bank failure. Very small activity of marked particles was noticed after the May and June storm events. In the pool (MR4), only one grain of a diameter of 29 mm was slightly moved into the distance larger than its diameter. On the crest of the step, a 99-mm- large cobble changed its position after 0.104 $m^3.s^{-1}$ discharge and a sandstone grain of a 47-mm-long b-axis was moved after the observation in June (0.088 $m^3.s^{-1}$). On the other hand, many particles of diameters smaller than 47 mm or 99 mm rested on the bed without any displacement. The same fact was observed after bankfull discharge in July (0.938 $m^3.s^{-1}$) when two particles, both of a 47-mm-long diameter, were moved to the distance smaller than the treble length of their diameter and a total of five grains of diameters in a range of 42-67 mm were transported downstream. Still, a lot of grains of a similar or smaller diameter (>18mm) were not moved (Fig.4).

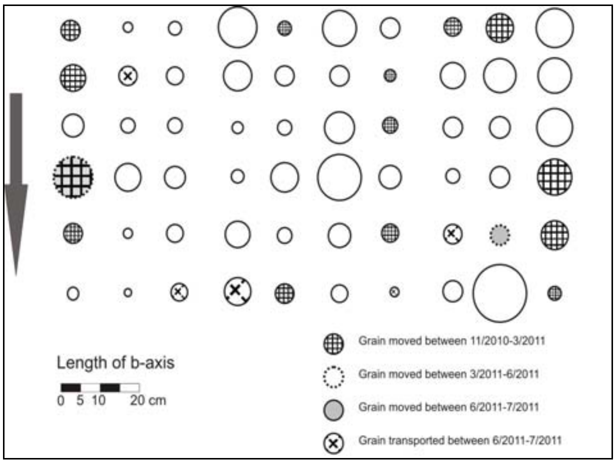

Figure 4. Illustration of grain movement in the MR3 reach between 11/2010 and 7/2011. 'Moved' means movement to the distance d_i-3xd_i, while 'transported' means movement to a distance (usually downstream from the set) larger than in the previous case.

It clearly shows that an important role in the ability of a grain to move is played by its position in relation to the flow or other particles, as it has previously been reported by some authors e.g. Bathurst (1987) or Lenzi et al., (2006). A similar situation was observed in the pool (MR4) where 38% of sandstone particles moved to a larger distance than their diameters which ranged from 26-101 mm. Some other grains of the same diameters lacked any sign of movement. Higher intensity of transport and erosive processes was observed in pools (38% of marked particles moved) than in steps (12%) during higher flows (>Q_1). During lower flows, the situation may have been opposite, as showed by the 11/2010-3/2011 results. However, more observations would have to be made in other locations to confirm this hypothesis.

4.2. Visual observation of marked particle displacement in gullies

No movement of particles was evident after several storm events in summer 2010 (culminate discharge 0.223 $m^3.s^{-1}$ at the gauging station). As it was mentioned in the above paragraphs, some bedload transport was observed in channel reaches of the torrent during lower discharges of about 0.1-0.2 $m^3.s^{-1}$. Therefore, despite much higher channel gradients in gullies, very weak fluvial transport can be observed during storm events, in contrast to the torrent. Bankfull stage (1-2-year discharge) was observed at the Malá Ráztoka basin on 31 August. After that event, marked cobbles of diameters of 20-65 mm were transported into the G1 gully (both sets) by fluvial and colluvial (creep, mass wasting, small rock-fall) processes. Moreover, a bank failure was activated and its material buried a part of both the sets by boulders of up to 0.5 m in diameter. Out of both the sets of the G2 gully, three grains of a diameter of 45, 55 and 60 mm were only moved during a 1-2-year discharge. Therefore, there was evidently a different intensity in transport processes between G1 and G2 gullies. Unlike the G2 gully that only showed weak fluvial transport, both colluvial and fluvial processes activating a bank failure strongly participated in the G1 gully. No movement was observed in both the gullies between 6 September and 26 October 2010 (culminate discharges up to 0.1 $m^3.s^{-1}$). During the winter season, the culminate discharge of 0.170 $m^3.s^{-1}$ was measured at the gauging station. Two grains of the set b were moved in the G2 gully, whereas in the G1 gully all small grains (d_i<0.05 m) gradually disappeared. During snow melting, reactivation of the bank failure along with related processes contributed to the dynamics of the transport of material in the G1 gully cross-sections.

4.3. Critical shear stress – methods of flood competition and marked particle displacement

The methods of marked particle displacement (11/2010-7/2011) and flood competition (5/2010) were used. Having introduced the Eq. 2, we obtained values of shear stress acting on bed particles during bankfull discharge in the MR3 and MR4 locations and values of bed shear stress resulting from the post-flood channel observations (5/2010) in the other studied reaches (Table 2).

Table 2. Bed shear stress obtained by Eq. (2) (τ_b), related dimensionless shear stress for d_{90} (τ^*_{c90}) and for d_{iMAX} diameter of the largest transported cobble/boulder in the observed reach (τ^*_{cmax}), back-calculated by Eq. (1). For comparison, results of Lenzi et al., (2006) relationship based on Eq. (3) is also displayed (τ_{bLen} and $\tau^*_{cmax\text{-}Len}$). 'pf' means post-flood and 'bf' bankfull channel reaches.

reach	τ_b [N.m^{-2}]	τ_{bLen} [N.m^{-2}]	$\tau^{\square}_{c90}$	d_{max} [m]	$\tau^{\square}_{cmax}$	$\tau^{\square}_{cmax\text{-}Len}$
LU1 (pf)	274.7	147.4	0.129	0.35	0.052	0.028
LU2 (pf)	266.6	141.9	0.125	0.30	0.058	0.031
LU3 (pf)	284.8	129.7	0.156	0.33	0.057	0.026
LU4 (pf)	335.7	125.0	0.184	0.29	0.076	0.028
LU5 (pf)	346.9	164.5	0.147	0.40	0.057	0.027
LU6 (pf)	407.5	160.9	0.167	0.34	0.079	0.031
LU7 (pf)	167.0	154.4	0.071	0.32	0.034	0.032
MR1 (pf)	493.0	165.5	0.197	0.35	0.093	0.031
MR2 (pf)	313.2	146.2	0.142	0.32	0.064	0.030
MR3 (bf)	186.7	102.1	0.079	0.07	0.183	0.100
MR4 (bf)	134.5	140.7	0.043	0.10	0.088	0.092

Obtained values of bed shear stress and dimensionless shear stress of transported boulders in post-flood reaches are c. two-three times higher than those computed introducing the d_i/d_{90} relationship of Lenzi et al., (2006) (Eq. 3). The results correspond to the assumption of Zimmermann & Church (2001) assessing the basic Eq. (2) as overestimating in case of rough bedforms at steep gradients and turbulent flows because the Eq. (2) was originally developed for uniform flows. An exception was identified in the LU7 reach (post-flood) where computed values were almost equal due to a lower (0.06 m/m) local channel gradient and less developed vertically oscillating bedforms in rapid morphology. In case of smaller sizes of particles obtained by the particle displacement method, the values obtained by means of the Eq. (2) and back-calculation of Lenzi et al. (2006) relationship (Eq. 3) are more similar than those computed using the flood competence approach.

Similar values of τ_b and τ^*_{cmax} computed by both the methods (Eq. (2)+Eq. (1) and Eq. (3)+Eq. (1)) for the morphology of rapids of LU7 channel reach showed that the concept of critical shear stress is more appropriate for lower channel slopes (≤0.06 m/m) with less developed bedforms where grain resistance is significant. Nevertheless, Buffington & Montgomery (1997) pointed out the difficulties in determining exact values of dimensionless shear stress in gravel-bed streams. They determined a relatively wide range of 0.03-0.086 for τ^*_{c50} for well-sorted bed materials. By contrast, high-gradient torrents are distinguished by poorly sorted bed material and thus much higher uncertainty in the τ^*_{c50} estimation. Moreover, steep channels are characterised by a high ratio of form resistance due to step-like bed morphology (Chiari & Rickenmann, 2011) and the application of Eq. (2) based on uniform flow clearly overestimates the resulting shear stress values even in case of large flood events.

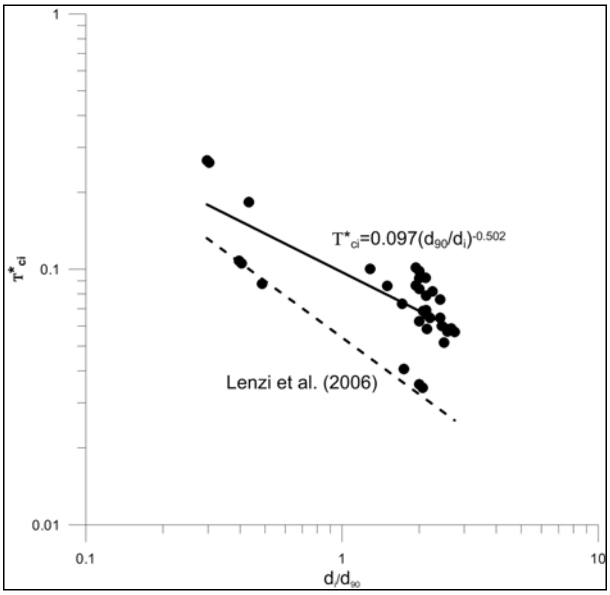

Figure 5. Dimensionless critical shear stress as a function of the d_{90}/d_i ratio. Compared to the trend observed by Lenzi et al., (2006).

Zimmermann & Church (2001) suggested including 'pool gradient' as the lowest energy level that cobbles go through during bedload transport. Chiari & Rickenmann (2011) proposed the application of a reduced energy gradient whose computation is related to grain resistance only. Back calculation of the basic bed shear stress formula (Eq. 2) and application of observed ratio of d_{90}/d_i after Lenzi et al. (2006) led to the following relationship with good correlation R^2=0.57:

$$\tau^*_{ci}=0.097(d_{90}/d_i)^{-0.502} \quad (8)$$

The resulting trend observed by us is significantly higher than the one developed using the original Eq. (3), which can point to lower bed armouring or higher sediment supply in evaluated Beskydian torrents (Fig. 5). At present, we are lacking data from Q_2-Q_{25} flood events to make the reported trend more specific. These observations could fill the gap of not measured diameters $0.11<D_i<0.20$ m for the largest transported particles and related critical shear stresses.

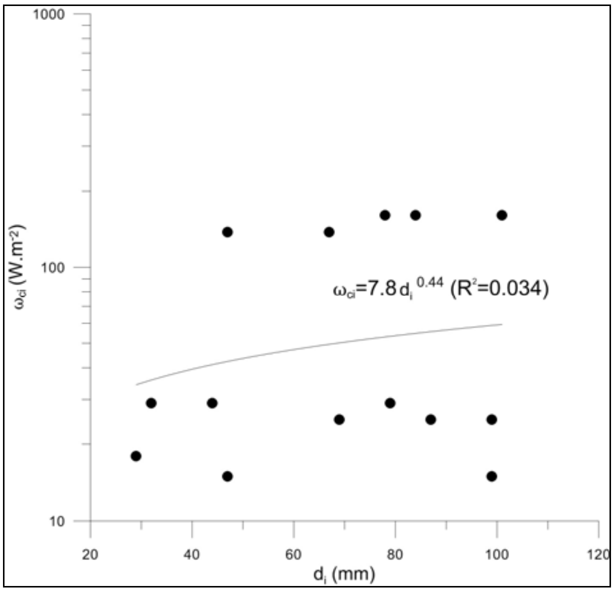

Figure 6. Relationship between unit stream power and three maximal diameters of a moved grain during individual culminations - marked particle displacement method in the MR3 and MR4 reaches (data from 5/2011 and 6/2011 discharge were put together because of a lack of observed movement)

4.4. Critical unit stream power – methods of flood competition and marked particle displacement

Known discharge data and geometrical channel parameters of the Malá Ráztoka torrent made it simple to compute critical unit stream power in the MR3 and MR4 reaches. A specific discharge method was used for post-flood channel reaches. Plotting the observations based on the marked particle displacement method only (Fig. 6) brought no significant trend (R^2=0.03). Unit stream power for current discharges in the MR3 and MR4 reaches (11/2010-6/2011) ranged from 15-30 W.m^{-2}; during bankfull discharge it increased up to 138 W.m^{-2} in the MR3 and 161 W.m^{-2} in the MR4 reach.

The 5/2010 flood indicated unit stream power in a range of 120-240 W.m^{-2} in the uppermost part of the Lubina river and 339 and 911 W.m^{-2} for the MR1 and MR2 reaches respectively. Computed unit stream power for downstream MR3 and MR4 reaches reached values of about 600-800 W.m^{-2} due to lower gradients than presented in MR1 and MR2 reaches. There was notable difference in the extent of particle movement evaluated by both the methods. As for the marked particle displacement method, we recorded particle movement for distance larger than d_i diameter. Flood competition generally supposes active transport of particles. Despite this fact, the combination of these two approaches resulted in a relatively good correlation (R^2=0.57) between the largest moved cobble/boulder and unit stream power (Fig. 7). The relationship with d_i in mm takes the form:

$$\omega_{ci} = 0.445 d_i^{1.06} \quad (9)$$

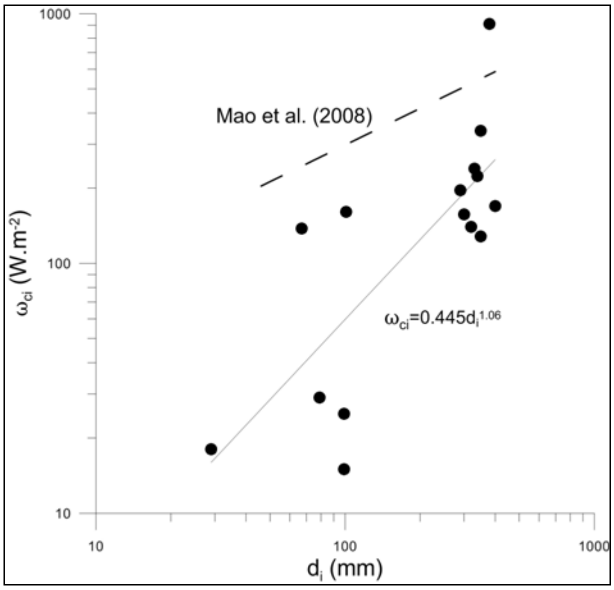

Figure 7. Trend between unit stream power and maximal diameter of a moved particle compared to the trend observed by Mao et al., (2008).

As figure 7 indicates, the trend under study contains a bit lower critical values than those reported by Mao et al., (2008) from Alpine and Andine environments, mainly at lower unit stream power (lower discharges). This can be caused by a higher sediment supply connected with weaker bed armouring related to hydrological conditions (see Barry et al., 2008) in local Beskydian streams. However, omitting the data between 30-120 W.m^{-2} and above 250 W.m^{-2} would also play some role in the inaccuracy of the dependence observed by us.

4.5. Critical unit discharge – methods of flood competition and marked particle displacement

The last evaluated parameter, unit critical discharge, was relatively successfully used in some previous studies conducted in high-gradient streams

(Bathurst, 1987; Lenzi et al., 2006; Mao et al., 2008). Applying the marked particle displacement method only, no significant trend was observed again between the three largest moved grains and measured discharge. After both the methods have been combined (Fig. 8), a fairly good correlation is evident (R^2=0.47) and the relationship with d_i in meters takes the form:

$$q_{ci}=0.8d_i^{0.51} \quad (10)$$

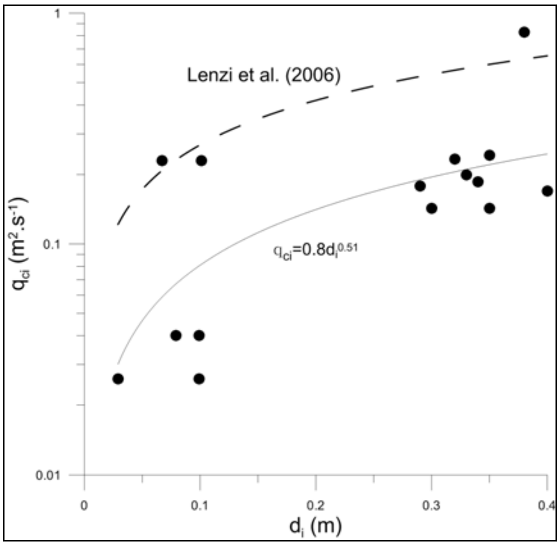

Figure 8. Unit discharge plotted against the maximal diameter of a moved particle using the methods of marked particle displacement and flood competence.

Bathurst (1987) reported generally lower power exponents in a range of 0.2-0.4 in gravel-bed streams with bed gradients between 0.03-0.06. Our displayed trend between unit discharge and diameter of transported grain is again lower than the trend obtained by the observation of an Alpine stream (Lenzi et al., 2006). Further investigations are necessary to validate and specify values of the coefficients in Eq. (10). However, as it was mentioned above, local channels can be characterised by a less stable bed or a larger relative sediment supply than the Alpine studied stream. Plotting q_{ci} dependent on d_i/d_{50} ratio, we got a fairly well correlated (R^2=0.46) relationship:

$$q_{ci}=0.046(d_i/d_{50})^{0.77} \quad (11)$$

For comparison, Mao et al., (2008) reported a lower value of the exponent (0.62) for an Alpine stream and 0.37 for an Andine torrent. He also noticed some variance between the approaches used (marked particle displacement vs. flood competence).

5. CONCLUSIONS

Critical conditions initiating the motion of cobbles and boulders in Beskydian headwater channels were evaluated by the combination of two methods – flood competence and marked particle displacement method. Some trends between the size of individual particles and the magnitude of a critical condition (shear stress, unit stream power and unit discharge) were investigated and compared to the results observed in other mountainous areas. Higher sediment supply and a lower degree of bed armouring related to discharge characteristics in local streams resulted in lower values of critical conditions causing the movement of grains than those reported from other environments. On the other hand, more field observations need to be performed in local torrents with both high and low sediment supply patterns in order to verify these trends.

Higher dynamics of sediment transport and erosional processes was observed in a pool than on the crest of a step during bankfull flow, whereas the opposite situation occurred during lower flows. High intensity of sediment transport was observed in the active gully (G1) where also colluvial processes strongly interacted. On the contrary, only a small amount of moved particles was noted in the G2 gully where bed material was armoured with moss and other vegetation even during bankfull flow observed downstream in the torrent.

The results were derived from Q_a-$Q_{1\text{-}2}$ and Q_{25} observations in Beskydian headwater streams. However, long-term measurement is necessary to make these trends more accurate and to complete the discharge data and thus critical conditions initiating bedload transport. Methodological differences between the two methods may have caused some inaccuracies in reported relationships, as Mao et al., (2008) warned. Apart from that, the Malá Ráztoka torrent has rather limited sediment supply character resulting from frequent occurrence of bedrock in its active channel, which is in contrast to the upper Lubina reaches where high recent vertical erosion is observed connected to bank failures and related relatively high sediment supply. As some authors reported previously (e.g. Mueller & Pitlick, 2005; Yu et al., 2009), sediment supply affects the intensity of bedload transport related to the change in values of critical conditions initiating bed particle movement in headwater streams. We assume that our results are valuable for the management of local midmountain basins in a sense of the first monitoring of bedload transport in small headwater streams in the Czech Western Carpathians.

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REFERENCES

Andrews, E.D., 1983. *Entrainment of gravel from naturally sorted riverbed material*. Geological Society of American Bulletin 94, 1225–1231.

Bagnold, R.A., 1980. *An empirical correlation of bedload transport rates in flumes and natural rivers*. Proc. R. Soc. Lond. A 372, 453-473.

Barry, J.J., Buffington, J.M., Goodwin, P., King, J.G. & Emmett, W.W., 2008. *Performance of bed-load transport equations relative to geomorphic significance: Predicting effective discharge and its transport rate*. Journal of Hydraulic Engineering. 134(5), 601-615.

Bathurst, J.C., 1987. *Critical conditions for bed material movement in steep, boulder-bed streams*. Erosion and Sedimentation in the Pacific Rim (Proceedings of the Corvallis Symposium, August, 1987), IAHS Publ. no. 165, 309-318.

Buffington, J.M. & Montgomery, D.R., 1997. *A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers.* Water resources research 33, 1993-2029.

Buzek, L., 2004. *The suspended load regime as a signpost of the intensity of water erosion in the mountain forested catchments (on the example of the Moravskoslezské Beskydy Mts.)* J. Hydrol. Hydromech. 52, 1, 24–40 (in Czech language).

Buzek, L., 2007. *Water erosion of the watershed of the upper Ostravice river from 1976 to 2000.* Moravian geographical reports, 15, 4, 2-12.

Chiari, M., Friedel, K. & Rickenmann, D., 2010. *A one-dimensional bedlou transport model for steep slopes.* Journal of Hydraulic Research 48, 2, 152-160.

Chiari, M. & Rickenmann, D., 2011. Back-*calculation of bedload transport in steep channels with a numerical model*. Earth Surface Processes and Landforms 36, 805-815.

Costa, J.E., 1983. *Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range.* Geological Society of America Bulletin 94, 986-1004.

Galia, T. & Hradecký, J., 2011. *Bedload transport and morphological effects of high-magnitude floods in small headwater streams - Moravskoslezské Beskydy Mts (Czech Republic)*. Journal of Hydrology and Hydromechanics 59, 4, 238-250.

Galia, T., Škarpich, V. & Hradecký, J., 2012. *Bedload sediment transport in connection to geomorphological transition of the gravel-bed streams in the Moravskoslezské Beskydy mountains*. Geografie 117, 1, 95-109 (in Czech language).

Hradecký, J. & Pánek, T., 2008. *Deep-seated gravitational slope deformations and their influence on consequent mass movements (case studies from the highest part of the Czech Carpathians)*. Natural Hazards 45, 235-25.

Chlebek, A. & Jařabáč, M., 1995. *Evaluation of dependence of forest vegetation growth on climate in the Beskydy Mts. by using factor analysis.* Lesnictví, 41, 9, 426–431 (in Czech language).

Lamb, M., Dietrich, W. & Venditti, J., 2008. *Is the critical shear stress of incident sediment motion dependent on channel-bed slope?* J. Geophys. Res.–Earth Surface 113. F02008, doi:10.1029/2007JF000831.

Lenzi, M.A., Mao, L. & Comiti, F., 2006. *When does bedload transport begin in steep boulder-bed stream?* Hydrologic. Process., 20, 3517-3533.

Mao, L., Uyttendaele, G.P., Iroumé, A. & Lenzi, M.A., 2008. *Field based analysis of sediment entrainment in two high gradient streams located in Alpine and Andine environments.* Geomorphology 93, 368-383.

Montgomery, D.R. & Buffington, J.M., 1997. *Channel reach morphology in mountain drainage basins.* Geological Society of America Bulletin 109, 596–611.

Mueller, E.R. & Pitlick, J., 2005. *Morphologically based model of bed load transport capacity in a headwater stream.* Journal of geophysical research 110, F02016, doi:10.1029/2003JF000117.

Pánek, T., Tábořík, P. & Hradecký, J., 2007. *Gravitational disintegration of the Čertův Mlýn Mt. (Moravskoslezské Beskydy Mts.)* Geologické výzkumy na Moravě a ve Slezsku v roce 2006, 124-129 (in Czech language).

Pánek, T., Hradecký, J., Minár, J., Hungr, O. & Dušek, R., 2009. *Late Holocene catastrophic slope collapse affected by deep-seated gravitational deformation in flysch: Ropice Mountain, Czech Republic.* Geomorphology 103, 414-429.

Rickenmann, D. & Koschni, A., 2010. *Sediment loads due to fluvial transport and debris flow during the 2005 flood events in Switzerland.* Hydrological Processes 24, 993-1007.

Šilhán K. & Pánek T., 2010. *Fossil and recent debris flows in medium-high mountains (Moravskoslezské Beskydy Mts, Czech Republic).* Geomorphology 124, 238-249.

Šilhán K. & Stacke V., 2011. *The present-day geomorphic activity of alluvial fan (a case study from the Moravskoslezské Beskydy Mts. based on dendrogeomorphological methods).* Moravian Geographical Reports 19, 18-29.

Šír, B., Richnavský, J., Bobál, P., Unucka, J., Ďurica, M. & Podhorányi, M., 2010. *Sediment transport modelling within small catchments of Beskydy Mts.* In: Geografie pro život ve 21. století: Sborník příspěvků z XXII. sjezdu České geografické společnosti pořádaného Ostravskou univerzitou v

Ostravě 31. srpna - 3. září 2010, pp. 43-48. Ostravská univerzita v Ostravě, Ostrava. ISBN 978-80-7368-903-2.

Škarpich, V., Galia, T., Hradecký, J. & Peč, J., 2010. *Identification of stream (dis)connectivity with the use of macrogranulometric analysis of channel bed sediments (the Moravskoslezské Beskydy Mts.)* Geol. výzk. Mor. Slez. v r. 2010, 199-204 (in Czech language).

Škarpich, V., Tábořík, P. & Hradecký, J., 2011. *Structure and genesis of the quaternary filling of the Slavíc River valley (Moravskoslezské Beskydy Mts., Czech Republic).* Moravian geographical reports 19, 30-38.

Williams, G.P., 1983. *Paleohydrological methods and some examples from Swedish fluvial environments*. Geografiska Annaler 65A, 227-243.

Wolman, M.G., 1954. *A method of sampling coarse river-bed material*. Transactions American Geophysical Union, 35, 6, 951-956.

Yu, G., Wang, Z., Zhang, K, Cchang, T. & Liu, H., 2009. *Effect of incoming sediment on the transport rate of bed load in mountain streams.* International Journal of Sediment Research 24, 260-273.

Zimmermann, A. & Church, M., 2001. *Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel of mountain streams.* Geomorphology 40, 311-327.

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