

Sediment Transport in Headwater Streams of the Carpathian Flysch Belt: Its Nature and Recent Effects of Human Interventions

Tomáš Galia, Jan Hradecký and Václav Škarpich

Abstract The paper summarizes results of both empirical and modelling research of bedload transport in headwater streams of the Czech part of the Western Carpathians. Flysch lithology (i.e. alternation of less resistant claystones and sandstones) affects bedload transport parameters in view of relatively fine-sized sediment supply resulting in low flow resistance of channels. Flood competence method (Q₂₀ flood) and marked particle displacement method (up to Q_{1–2} flow) was applied to determine critical conditions for the incipient motion of grains in channel bed. The beginning of bedload transport in flysch headwaters under lower values of critical conditions when compared to other regions was confirmed by application of the criteria of unit stream power and unit discharge. The simulated values of bedload transport intensity (1D transport model TOMSED) during a high-magnitude flood in both supply-limited and transport-limited headwaters are significantly lower than it was observed in torrents of the Alpine environment. In relation to unsuitable contemporary watershed management affecting the sediment transport (large check-dams, removing of large wood from local channels), trends of accelerated incision are observed in most headwater streams as well as in lower-gradient piedmountain gravel-bed rivers of the Flysch Belt of the Western Carpathians. Approaches of contemporary local watershed management are presented and some recommendations for the maintenance of channel stability predisposed by soft lithology (e.g. application of artificial step-pool sequences, management of woody debris in channels) are proposed.

T. Galia (✉) · J. Hradecký · V. Škarpich
Faculty of Science, Department of Physical Geography and Geoecology,
University of Ostrava, Chittussiho 10, 710 00 Ostrava, Czech Republic
e-mail: tomas.galia@osu.cz

J. Hradecký
e-mail: jan.hradecky@osu.cz

V. Škarpich
e-mail: vaclav.skarpich@osu.cz

1 Flysch Structures as a Predisposing Factor for Channel-Forming Processes

From a lithological point of view, Flysch nappe structures of the Czech part of the Outer Western Carpathian (Silesian Nappe and Magura Nappe) are generally built by two types of sedimentary rocks: sandstones and much less-resistant claystones although some other rocks such as conglomerates and limestones also occur. Such structures strictly predispose sediment delivery into local channel segments with respect to specific sediment inputs and grain-size characteristics. Heterogenous mixture of bedrock layers and tectonically weakened zones affects chronic hillslope instability, while both shallow and deep landsliding is typical of the study area which represents the most landslide-affected region within the territory of the Czech Republic (Hradecký and Pánek 2008; Pánek et al. 2011). Valleys of high-gradient streams draining out the highest mountainous areas; the steepest channels are affected by small ‘fire hose’ effect-related debris flows, which are usually connected with high-magnitude flood events.

Headwater channels based in less resistant claystones are prone to accelerated incision and large bank failures, which are activated in case of limited sediment-supply conditions. Grain-size character of sediment supply in the flysch Western Carpathians is very rarely represented by sandstone boulders of diameters >0.5 m; cobbles and smaller grain fractions prevail. Median particle-sizes are around the value of 50 mm, while d_{90} usually varies between 120 and 300 mm, depending on the lithology of sediment supply (ratio of claystones in bed sediments) and channel gradient. This implies an occurrence of channel-reach morphologies related to grain-size characteristics of stream bed; the absence of larger boulders usually prevents the formation of regular step-pool morphology sensu Montgomery and Buffington (1997). Cascades and rapid channels with absent high water scours from steps to pools implying lower form resistance are quite typical of local flysch conditions. Absence of boulder fraction directly affects total flow resistance, which leads to higher potential transport capacity of local channels. This lithology-conditioned predisposition has also strongly contributed to recent trends of accelerated incision.

2 Bedload Transport in Small Flysch Mountain Catchments

2.1 Critical Conditions for the Commencement of Bedload Transport

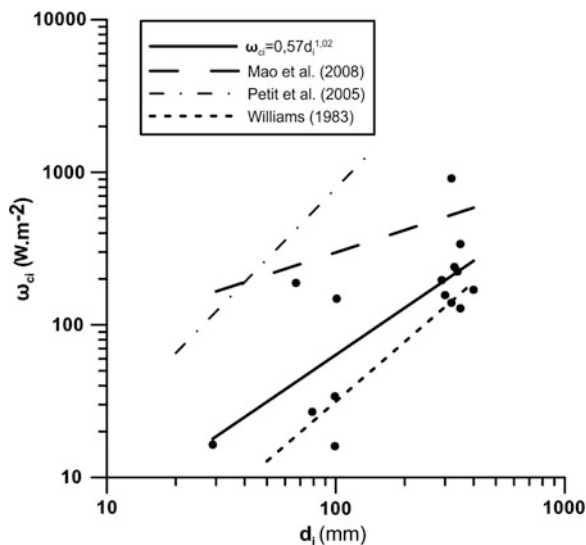
Better understanding of the trigger of bedload transport at steep stream gradients is necessary for the improvement of watershed management connected with the protection of the property and human lives. As a result of low flow resistance in flysch-based channels, critical conditions (i.e. critical unit stream power, critical

unit discharge, and critical shear stress) for the commencement of bedload transport of certain grain-size fractions have generally lower values than those obtained in other environments. Two methods were successfully used in two local steep headwater streams, the Malá Ráztoka Brook and the uppermost part of the Lubina River ($A < 2 \text{ km}^2$), to determine critical conditions for the incipient motion of grains in channel bed. Flood competence method was based both on the measurement of sizes of cobbles and boulders transported during Q_{20} discharge and the reconstruction of geometrical parameters of channel during this event. The latter approach consisted in marking individual grains and subsequent observation of their movement following lower flow events that varied between annual discharge and bankfull discharge (Q_{1-2}). A flood with Q_{20} discharge (specific discharge ca $2 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$) set in motion almost all bed material of a diameter up to 0.3–0.4 m, which corresponds to d_{95} – d_{99} size fraction of bed surface (Galia and Hradecký 2011). Transport of marked particles with maximal diameters up to 0.1 m was observed during lower flows not exceeding Q_2 (Galia and Hradecký 2012).

Using a combination of data from flood competence and marked particle displacement methods back calculations of basic bed shear stress formulas were applied: $\tau_b = \rho \cdot g \cdot R \cdot S$ and $\tau_{ci} = \tau_{ci}^* \cdot (\rho_s - \rho) \cdot g \cdot d_i$, where τ_b means shear stress acting on the channel bed; τ_{ci} means critical shear stress for the movement of particle of diameter d_i ; τ_{ci}^* means dimensionless critical shear stress or Shields parameter for d_i grain size; ρ means density of water; ρ_s means density of a solid particle; g is gravitational acceleration; R means hydraulic radius; and S means channel gradient. The application of dimensionless critical shear stress as a function of ratio d_{90}/d_i (Lenzi et al. 2006) led to the relationship $\tau_{ci}^* = 0.1(d_{90}/d_i)^{-0.52}$. The original relationship derived from the Rio Cordon torrent in Italian Dolomites ($d_{50} = 119 \text{ mm}$ and $d_{90} = 451 \text{ mm}$) by Lenzi et al. (2006) indicated a significantly lower exponent (-0.737); the influence of general lower d_{90} percentiles in flysch torrents is reflected due to relatively fine character of local sediment supply.

The beginning of bedload transport in flysch headwaters under relatively low values of critical conditions was confirmed applying the criteria of unit stream power ω_{ci} and unit discharge q_{ci} for maximal transported particle diameter d_i in forms $\omega_{ci} = a \cdot d_i^b$ (d_i in mm) and $q_{ci} = a \cdot d_i^b$ (in m). Unit stream power ω is usually defined as $\omega = (Q \cdot \rho \cdot S \cdot g)/w$, where w means channel width. Figure 1 shows a comparison between the relationship observed in Czech Carpathian headwater channels, $\omega_{ci} = 0.57d_i^{1.02}$ with respect to the boulders transported during Q_{20} flood and marked particle displacement during lower discharges, and the power trends obtained in other environments. It documents well that bedload transport of certain grain-size fraction in Alpine and Andine high-gradient channels with $a = 31.5$ and $b = 0.488$ (Mao et al. 2008) and Belgian gravel-bed streams with $a = 1.13$ and $b = 1.438$ (Petit et al. 2005) begins under much higher critical stream powers than that obtained in Carpathian flysch headwaters. Moreover, our trend is very close to the lower limit in $\omega_{ci} = a \cdot d_i^b$ relationship derived by Williams (1983) for a large worldwide set of gravel-bed streams ($a = 0.079$, $b = 1.3$).

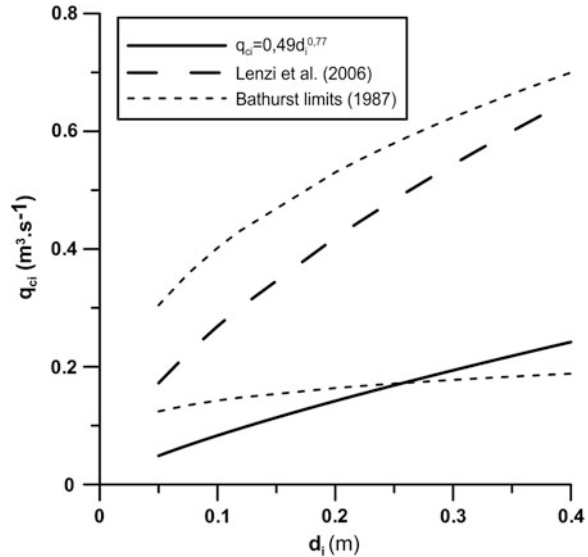
Fig. 1 Comparison of trends in critical unit stream power between flysch headwaters in the Carpathians and other environments



A similar situation arose when comparing the relationship for unit discharge $q_{ci} = Q/w$ for grain diameter d_i . Bathurst (1987) introduced coefficient a between 0.09 and 0.16 and exponent b in a range of 0.2–0.4 for the Rocky Mountains (USA) streams in $q_{ci} = a \cdot d_i^b$ relationship (d_i in mm). Lenzi et al. (2006) later substituted 1.176 for a and 0.641 for b after analysing grain motion in the Dolomitan Rio Cordon torrent (d_i in m). As for Carpathian flysch headwater streams, coefficient a was equal to 0.49 and b to 0.77 (d_i in m) when considering transport of large boulders during Q_{20} event and marked particles movement during lower discharges, again implying incipient motion of individual grain diameters under relatively low critical discharges (see Fig. 2).

Presented results document that in any case, bedload transport in flysch mid-mountains begins under relatively low discharges when compared with other small mountain streams with different predispositions. Nevertheless, a role of sediment supply in view of limited sediment supply and, on the contrary, limited transport capacity was not evaluated and our data are a combination of headwaters covering both conditions. Numerous papers documented a relationship between supply-limited conditions and the armouring of bed material resulting in a higher stability of bed surface (e.g. Whiting and King 2003; Hassan and Zimmermann 2012). In addition, higher stability of step-pool channels was observed under low sediment supply conditions (Recking et al. 2012) implying high critical conditions for the destruction of steps and incipient motion of the coarsest fraction.

Fig. 2 Comparison of trends in critical unit discharge between flysch headwaters in the Carpathians and other environments



2.2 Simulations of Bedload Transport

Direct bedload measurements in steep mountain channels are still rare. Limited sediment supply character together with important partitioning of form resistance in stepped-bed morphologies and influence of woody debris and bedrock outcrops lead to the overestimation of bedload transport volumes by conventional equations originally developed for gravel-bed rivers (e.g., Yager et al. 2007; Chiari and Rickenmann 2011). Modelling of bedload transport was conducted using the one-dimensional TOMSED model (Friedl and Chiari 2011) in two flysch headwater channels with a different regime of sediment supply. The Malá Ráztoka Brook (2.2 km²) is characterised by limited sediment supply character with a significant occurrence of resistant sandstone outcrops (up to ½ of the total length of the longitudinal stream profile). On the contrary, Velký Škaredý Brook (1.06 km²) can be described as transport limited due to a large number of sediment sources; bank failures occur in non-resistant claystone members in the downstream part of the stream profile, while debris flow accumulations are typical of the uppermost part. The modelled event was the 5/2010 flood (Q_{20}) peaking up to 4 m³ s⁻¹ in the Malá Ráztoka gauging station (2.02 km²). The sediment erosion and deposition along the studied channels were mapped in the field shortly after the flood event and compared to the situation before the event. Simulated volumes of bedload transported material and bedload discharge were verified in accordance with these erosion or deposition in channels before and after the flood event due to missing bedload transport data from direct measurements.

The Manning equation with separated grain and form resistance to lower energy gradient (Rickenmann 2005) was applied to obtain mean velocities in channel

Table 1 Simulated bedload transport in Malá Ráztoka Brook and Velký Škaredý Brook during 5/2010 flood event

	Malá Ráztoka	Velký Škaredý
Basin area (km ²)	2.2	1.06
Peak discharge (m ³ s ⁻¹)	4	2
Peak bedload transport intensity (m ³ h ⁻¹)	10–40	25–50
Total bedload transport volume (m ³)	370–860	500–1,240

cross-sections. Limited erosional depth and estimation of direct sediment inputs from sediment sources (i.e. bank failures and hollows) during the flood event were also included in the simulations. Bedload transport equations of Rickenmann (2001) and Bathurst et al. (1987) were used to calculate bedload discharge. Table 1 shows resulting ranges of values of simulated bedload transport discharge and total bedload transport volumes during 5/2010 flood for selected channel cross-sections of Malá Ráztoka Brook (sediment supply limited) and Velký Škaredý Brook (transport limited). It implies that bedload transport intensity in small watersheds is dependent rather on direct sediment supply than on absolute value of peak discharges. The TOMSED model calculated lower values of maximal bedload transport intensity and total volumes of transported material for supply limited stream despite the occurrence of twofold peak discharge in the stream outlet.

The reconstruction of bedload transport in Austrian Alpine streams with slightly larger basin areas (6–10 km²) and much higher peak discharges (up to 25 m³ s⁻¹) has been done by Chiari and Rickenmann (2011) by means of the SETRAC numerical model (Rickenmann et al. 2006), a predecessor of the TOMSED model. They indicated much higher intensity of bedload transport with total volumes of transported sediments 16,000 and 33,000 m³ during flood events than those simulated in our case (maximum 1,240 m³ at some cross-sections of transport-limited Velký Škaredý Brook). Such a comparison is necessary for the understanding of contemporary management of local torrents, because the approach of torrential check dams traditionally used in local streams comes from the Austrian Alps. Relatively small volumes of potentially transported material together with low critical conditions for the beginning of bedload transport make channels predisposed by flysch lithology very prone to accelerated incision. Also, oversized check dams and bank stabilisation strongly contribute to such trends in many of local channels.

3 Contemporarily Watershed Management and Its Effect on Stream Hydromorphology

Since permafrost degradation in the early Holocene, forest cover has gradually developed in the whole area of Czech Carpathians. At the beginning of 16th century, the Wallachian colonisation brought the deforestation even of the ridge parts

of the mountains and the establishment of the large grasslands for pastoral farming. Together with higher precipitation during Little Ice Age, this led to an increase in sediment delivery into stream segments, higher activity of debris flows in the steepest channel gradients, accumulative tendencies on alluvial cones and some of lower gradient gravel-bed streams were transformed from single-thread pattern into anabranching pattern (Šilhán and Pánek 2007; Wistuba and Sady 2011; Škarpich et al. 2013). Experience with such tendencies which were naturally accompanied by higher intensity of bedload transport at that time, probably led to fast adoption of Alpine torrential check dams since the beginning of 20th century. Nevertheless, approximately at the same time pastoral farming gradually declined and major parts of the Czech Carpathians were covered by spruce and beech agricultural forests again. Decrease in sediment supply caused by afforestation and, on the other hand, construction of channel stabilisation works resulted in accelerated incision of most local channel reaches during 20th century. Similar tendencies were also observed in lower gradient gravel-bed rivers in the forefields of the Western Carpathians (e.g. Lach and Wyźga 2002; Wyźga 2008; Škarpich et al. 2013). Mentioned changes in sediment supply and watershed management of headwaters is one of the important factors that trigger accelerated incision of these rivers.

Check dams and their maintenance together with bank stabilisation works still prevail in the contemporary management of local high-gradient channels, although some modern hydraulic rapid structures begin to appear. Check dams and road sluices act as barriers in sediment transport causing the discontinuity in sediment flux in the local longitudinal stream profiles. The accelerated incision and coarsening of bed material are usually observed downstream of these objects (Škarpich et al. 2010). In relation to contemporary watershed management, one should note again proneness of local channels to erosional processes due to low flow resistance connected with low critical conditions for the commencement of bedload transport and relatively small amounts of potentially transported material, as we documented in the previous chapter. Figures 3 and 4 show the situation during 5/2010 flood event (ca Q_{20}) when an undersized sluice was jammed by coarse material as it was unable to transport coarse fraction of sediments during flood culmination (Fig. 3). At the same time, the channel incised significantly downstream the sluice partially destroying the sluice due to backward erosion (Fig. 4). Gravel extraction from the upstream channel-reaches and bank stabilisation works downstream the sluice started immediately after the flood event.

A similar role is played by oversized concrete check dams, especially in headwater streams with recent limited sediment-supply conditions and bedrock outcrops occurrence in channel bed. Due to this deficiency in potential sediment sources, accelerated incision trends are usually observed downstream the constructed dams. In case of the presence of soft claystone bedrock lithology in downstream channel-reaches, incision continues into this bedrock and many difficulties arise concerning the stabilisation of the channel-reaches (Fig. 5).

Large woody debris has for a long time been recognised as an additional bed roughness element affecting sediment transport dynamics in small steep streams when individual logs act as steps in the stream longitudinal profile. These steps are



Fig. 3 A road sluice acting as a barrier to bedload transport during 5/2010 flood event due to its jamming (Lubina watershed). The *arrow* shows flow direction



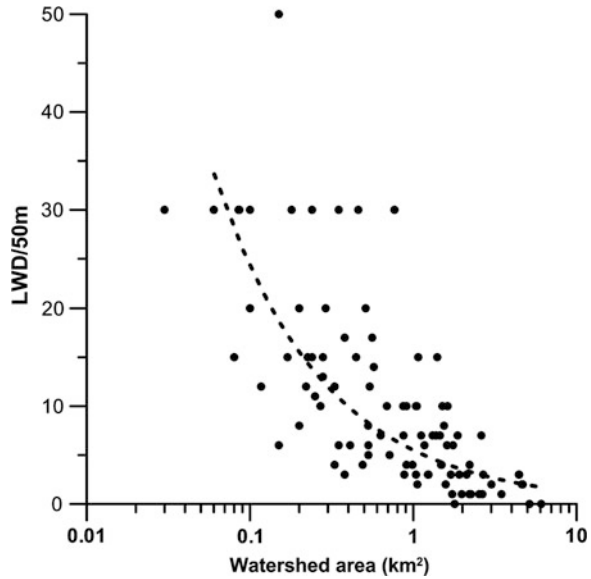
Fig. 4 Accelerated incision downstream the sluice during 5/2010 flood event (Lubina watershed)



Fig. 5 A channel-reach incised 6 m into claystone bedrock downstream check dams in the Malá Ráztoka watershed (the upstream view)

important energy dissipators in nature streams, when they significantly reduce bedload transport intensity during high flow events. Presence of woody debris also improves stabilisation of sediment accumulations in channels (e.g. Gomi et al. 2003; Faustini and Jones 2003). Nevertheless, local channels are systematically cleaned from woody debris by forest management, especially at well-accessible sites related to lower channel gradients ≤ 0.1 m/m. The removal of large woody debris by local people resulted in a significant decrease in individual logs (minimal size 0.5×0.1 m) in active channels with the increase in watershed area when we tested 102 channel-reaches in the Czech part of the Western Carpathians (Fig. 6). A lack of woody debris in channels causes further decrease in total flow resistance, which probably also contributes to the acceleration of bed degradation. Moreover, ecological potential of woody debris in channels should not be neglected.

Fig. 6 Relationship between the amount of large woody debris on 50 m distance of the channel and watershed area



4 Recommendation for the Management of Flysch Headwaters

The following recommendations are based on our research and observations in flysch-predisposed watersheds; however, they can be applied in any of small channels predisposed by relatively soft lithology prone to accelerated erosional processes. The previous chapter demonstrated some unsuitable examples of watershed management in local headwaters. Classic torrent control works are probably still a functioning solution for channel-reaches in densely built-up areas to protect the property and lives during high-magnitude flood events. Nevertheless, modern rapid hydraulic structures should be adopted widely due to their better effect for aquatic habitats. Bank stabilisation works should only be implemented in sites of necessary protection (e.g. bridge constructions, road and railway communications). Such stabilisation works are contemporarily widely used in stream longitudinal profiles without reasonable arguments. Moreover, decreased connectivity in sediment fluxes between channels and adjacent hillslopes naturally contributes to the acceleration of erosional processes in local streams.

Experiments with stream bed stabilisation using artificial step-pool sequences have been performed since 1990s in the torrents of the Italian Alps. Such structures imitate natural step-pool morphology *sensu* Montgomery and Buffington (1997) and there is an effort to replace traditional concrete check dams with these low boulder check dams. Artificial step-pool structures are built for the safety degree for Q_{20-30} and provide sufficient connectivity for aquatic organisms and sediment transport (Lenzi 2002). Restored step-pool channels are increasingly common also



Fig. 7 Artificial step-pool sequence in the Malá Ráztoka Brook

in the USA (Chin and Phillips 2007; Chin et al. 2009). Since May 2013 a similar experiment has been taken place in flysch Carpathians (the Malá Ráztoka watershed) through a construction of 13 step-pools from local sandstone boulders (Fig. 7). Key boulders in each step exceed a diameter of 0.4 m; this corresponds to the largest grain-size fraction transported during flood 5/2010 (Q_{20}) in the examined channel (Galia and Hradecký 2012). The geometry of artificial step-pool sequence is related to the relationship obtained for natural step-pool sequences $1 < (H/L/S) < 2$, where H is step height, L means distance between crests of steps and S means channel gradient (e.g. Lenzi 2001; Wohl and Wilcox 2005). The channel gradient of experimental channel-reach varies between 0.08 and 0.12 m/m; bankfull width is about 4 m and the height of artificial steps varies between 0.4 and 0.6 m. One hundred limestone grains of diameters $20 < d_i < 40$ mm were placed in the most upstream pool. They represented fine grain-size fraction and enabled us to observe the dynamics of this fine fraction through an artificial step-pool channel-reach. During two months, until June 2013, ca 2/3 of limestone grains were transported downstream from the uppermost pool. The longest travel distance was three step-pool sequences during ordinary Q_a – Q_1 flows. That implies that these structures provide efficient connection of fine grain-size fractions during lower flows. It is planned to continue the experiment in order to monitor the stability of steps during higher flow events. Erosional and depositional trends in constructed step-pool sequences will be evaluated within repeated geodetic measurement.

We expect that artificial step-pools can play an important role in mountain stream restoration. They can be an alternation to larger concrete dams in areas with

a lower degree of flood protection for their low cost demands and functional connectivity for aquatic organism migrations and sediment transport. Moreover, accelerated incision as it is observed downstream of larger check dams is not expected if these much lower boulder dams are used.

There is also great potential for the application of individual logs in order to enhance aquatic environment. The topic of clearing the channels of woody debris by local people has been discussed in the previous chapter. We suppose that the presence of logs in headwater channels with relatively fine bed sediments may lead in view of sediment dynamics to (i) the deceleration of erosional processes in headwater streams by an increase in total bed roughness, although steep mountain channels are undoubtedly understood as erosion and transport segments of the fluvial network, and to (ii) a significant decrease in bedload transport intensity in specific channel-reaches with relatively unlimited sediment sources due to stabilization of channel accumulations by woody debris.

A detailed evaluation of active sediment sources is the main goal for the determination of quality watershed management not only in view of heterogeneous geologic predispositions. Even neighbouring small headwater basins can significantly differ in the criteria of potential sediment supply during high flow events (i.e. their magnitude and grain-size parameters) consequently related to the intensity and total volumes of bedload transport. Streams with a wide occurrence of relatively resistant sandstone bedrock outcrops in beds have much smaller potential for the transport of larger volumes of sediments than streams based in soft claystone formations usually accompanied by shallow landslides and bank failures. In addition, the lithology of bed sediments strongly affects the development of bed resistance formations (i.e. steps or large boulders). Predisposition to debris-flow scours should carefully be assessed at channel gradients exceeding 0.20 m/m since this channel gradient is widely understood as a boundary between prevailing fluvial and colluvial processes (e.g. Gomi et al. 2003; Šilhán and Pánek 2010).

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