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Effect of grade-control structures at various stages of their destruction on bed sediments and local channel parameters

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ABSTRACT

Grade-control structures (GCSs) represent the typical management of torrential streams, preventing massive bed erosion and bedload transport. The original and present geometric and sedimentary parameters of 18 GCSs at various stages of their destruction since the 1970s were evaluated to determine the relationship between the former and present-day components of the managed Mohelnice River (the western Carpathians, Czech Republic). The latest changes in the GCS geometry, related scour holes, and bed surface grain size of sedimentary wedges were caused by the 2010 flood event of 20–50 R.I. discharge. No relationship exists between the bed surface grain sizes and the present water drop or the present equilibrium channel slope of the sedimentary wedge. A significant downstream coarsening of the largest grain size percentile represented by D_{95} is detected through the sequence of GCSs. Also, statistically insignificant trends in downstream coarsening were observed for D_{16}, D_{50}, and D_{84} grain sizes. However, the investigated sequence is still passable for grain diameters up to 200 mm during high-magnitude floods similar to the 2010 event, as documented by the development of a confluent gravel bar downstream of the sequence. Bedload transport simulations provide the highest bedload transport rates for the initial stage of the uppermost studied channel reach without the presence of GCSs (30,000 kg min^{-1} for Q_{50}). Grade-control structures reconstruction in the 1970s significantly decreased transport rates (>2000 kg min^{-1} for Q_{50}). Owing to the erosion of GCS crests and an increase in related equilibrium channel slope, damage on GCSs can lead to an increase in bedload transport intensity (13,000 kg min^{-1} for Q_{50}). Significant linear relationships exist among the present parameters of the scour holes (length of scour hole, maximum scour depth, and horizontal distance between the point of maximum depth and the GCS crest). A statistical significant power relationship exists between the parameters of maximum scour hole depth and the present drop height, showing adjustments of maximum scours to the present stage of GCSs and the last flood event.

1. Introduction

Mountain streams are characterised by a wide variety of bed sediments from sand to boulder fraction and spatial changes in cross sections and longitudinal profiles, especially during high-magnitude flood events. Thus the management of mountain torrents involves tasks to protect against erosional processes at steep channel gradients. A traditionally used method is the stabilisation of channel beds by staircase-like sequences of cemented, boulder, or wooden grade-control structures (GCS) (Lenzi and Conesa-García, 2013). These are generally called check dams when they are 1.5–2 m above the original bed level and sills if their height is lower (Lenzi et al., 2003a,b). The principle is the reduction of the initial bed slope S to a lower equilibrium channel slope S_{eq} between individual constructions, and the value of S_{eq} generally represents the equilibrium between the potential erosion and aggradation processes in a channel reach. A variety of approaches — including empirical, geomorphic, and engineering procedures — exist to estimate S_{eq} (Wohl et al., 2013). The calculated equilibrium slope is needed to evaluate the morphological jump a_1 when the spacing L between individual GCS is chosen (Gaudio et al., 2000):

$$a_1 = (S–Seq)/L. \tag{1}$$

Once an individual GCS is constructed, the morphology and grain size parameters of the channel begin to transform to the new local flow conditions upstream and downstream of the structure. The scour occurs immediately downstream of the GCS, and its geometric parameters are usually adjusted to previous high-magnitude flood events (Lenzi and Comiti, 2003). Lenzi et al. (2003b) proposed an empirical relationship between the maximum scour depth y_s, specific critical flow energy H_s, and drop height z:

$$0.6 \le y_s(z + H_s) \le 1.4. \tag{2}$$

Specific critical flow energy can be calculated to reflect the critical flow depth H_c during the peak discharge Q at the GCS effective crest

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width B:

$$H_s = 1.5H_c = 1.5\sqrt[3]{\left(Q^2/B^2 g\right)} \tag{3}$$

where g is the acceleration owing to gravity. Lenzi et al. (2003b) also reported that bed sediment differences regarding size and lithology apparently played a minor role in determining the scour hole. However, Marion et al. (2006) evaluated the role of the sediment supply during his laboratory experiments, and he demonstrated that an increase in the upstream sediment feed led to a decrease in the maximal scour hole depth. He also showed that the effect of upstream sediment supply is included in the parameter of morphological jump influencing the resulting equilibrium slope. Marion et al. (2006) and Tregnaghi et al. (2007) reported two modes of erosional processes in scour holes with a threshold value for $a_1/H_s = 0.6$. At lower a_1/H_s ratios, scour geometry significantly depends on the jet inclination and the balance between the efficiency of the jet to remove sediment and the armouring processes to resist local erosion. D'Agostino and Ferro (2004) and Comiti et al. (2013) indicated potential three-dimensionality of scour processes, i.e., dependence of the scour hole depth on the ratio between the upstream channel width and the crest effective width. Local scour downstream of a GCS brings a risk of undermining the GCS construction and its collapse. To avoid this, the propagation of scour holes can be limited by the construction of end sills (i.e., lower secondary transversal structures). Also, close spacing of GCSs can prevent hazardous deepening of scour holes, when in case of low ratios between H_c and L, a form of geometric interference can render the scouring process less effective (Lenzi et al., 2003a). Other types of protection against deep scouring include embedding scour holes with parallel logs or large immobile boulders.

In contrast, depositional processes occur upstream of the GCS where sedimentary wedges develop up to the achievement of the lower equilibrium channel slope and lead to a local decrease in D_{50} of the surface bed sediments (Boix-Fayos et al., 2007; Bombino et al., 2009; Zema et al., 2014). Overall, the sequences of bed sills and check dams decelerate or interrupt the sediment connectivity, especially coarser bed fractions. This often implies the downstream narrowing and incision of the channel and the downstream coarsening of the bed sediments (Martínez-Castroviejo and García-Ruiz, 1990; Gaudio et al., 2000; Castillo et al., 2007; Boix-Fayos et al., 2007; Martín-Vide and Andreatta, 2009; Wohl et al., 2013; Zema et al., 2014) where forms of these adjustments can be comparable to the effects of large dams before the sedimentary wedges of GCSs become completely silted (Kondolf, 1997; Petts and Gurnell, 2005). Such altered conditions strongly affect aquatic habitat diversity and riparian vegetation, which are indicators of ecosystem health (Bombino et al., 2008, 2009; Kang and Kazama, 2013, 2014). However, completely silted check dams have their trap efficiency reduced, allowing the connectivity of fine grain size fractions in dependence on reached equilibrium slope (Boix-Fayos et al., 2007).

To minimise environmental impacts and preserve the protection against erosional processes and massive bedload transport, novel approaches in stream bed stabilisation have been tested and applied in Alpine countries, the USA, and Japan during the last decades. Lenzi (2002) described hydraulic and ecological functions of cemented and uncemented boulder check dams that copy natural step-pool sequences in steep Alpine torrents. Similar techniques of artificial step-pool sequences are also widely applied within the torrent restorations in the USA (Chin et al., 2009). Filtering-retention check dams enable connectivity for finer bedload transport or allow downstream transport of a certain volume of sediments, whereas debris flows, large boulders, and floating wood are trapped (D'Agostino, 2013). In addition, representing environmentally friendly bed-stabilisation elements with preserved high-energy dissipation, block ramps are often constructed in less steep gravel-bed rivers instead of conventional GCSs (Pagliara, 2007; Pagliara and Palermo, 2013; Radecki-Pawlik, 2013; Thomas et al., 2013).

The study presents an evaluation of the effect of grade-control structures at various stages of their destruction on local channel geometry (including scour holes and upstream channel slopes), and on bed surface grain size parameters of the present or former sedimentary wedges. The most recent destruction of local GCSs was observed during the last large flood event in 2010 with 20–50 discharge R.I., and we assume adjustments of scour holes and grain size parameters to the flow competence of this event. Unlike a variety of studies evaluating the scour hole geometry (e.g., Lenzi et al., 2002, 2003a,b; Marion et al., 2006), we were not able to calculate the critical flow depth at the GCS central crest during that event for further depth analysis because of the often highly irregular cross-profile geometry of the damaged GCSs and their gradual destruction during flood events. Nevertheless, we proposed a pilot study on the dynamic adjustment of channel parameters to changes in bed stabilisation elements, and we tried to find significant relationships between the former and present-day components of the managed gravel-bed stream.

2. Study area

2.1. Regional settings

The Mohelnice River is a left-side tributary of the Morávka River, found in the Outer Western Carpathians, Czech Republic. It is a typically torrential gravel-bed stream with a length of 13.1 km. The drainage area of the Mohelnice River watershed is 40.5 km^2. The highest and lowest sites within the basin are, respectively, Lysá Hora Mt at 1323 m asl, and the mouth of the Morávka River at 410 m asl (see Fig. 1). This study focused on the 2.6-km-long river reach that runs from the mouth of the Morávka River to km 2.6. The annual precipitation in the basin ranges from 1000 to 1800 mm (data source: Czech Hydrometeorological Institute). The Mohelnice River is characterised by high discharge variation. In particular, frequent floods of moderate magnitude owing to snow melting or high-intensity rainfalls during storm events and rare, large floods caused by summer rains associated with cyclones occur in the Mohelnice River watershed. The mean annual discharge of the river amounts to 1.13 m^3 s^{-1} at the Raškovice-Mohelnice gauging station (at km 1.85, see Fig. 2), where the basin area is 35.38 km^2 (data source: Povodí Odry State Enterprise, Czech Hydrometeorological Institute). Table 1 shows the recurrence intervals of flood discharges.

The study area belongs to the boundary of the Moravskoslezské Beskydy Mts and Podbeskydská Pahorkatina Hillyland. It was built by the Silesian unit of the Outer Carpathian Group of nappes and formed by flysch Cretaceous rocks dominated by Quaternary sediments (Menčík et al., 1983; Menčík and Tyráček, 1985). The flysch rocks of the Cretaceous period belong to a partial nappe of the Těšín-Hradiště Formation (lower Cretaceous) with a characteristic representation of sandstones and the Godula Member–Mazák Formation (Upper Cretaceous) with the occurrence of the Ostravice sandstone (Menčík et al., 1983). These lithological conditions are prone to bedload transport under relatively low discharges and to the incision of channels in the case of limited sediment supply (Galia and Hradecký, 2012; Škarpich et al., 2013). Most hillslopes of the studied watershed are under heavy forest management; reforestation took place at the turn of the nineteenth and twentieth centuries after significant deforestation during the so-called Pastoral and Wallachian colonisation (sixteenth–seventeenth centuries). The forest cover consists mainly of Norway spruce (*Picea abies*) and beech (*Fagus sylvatica*). Extensive agriculture with gardens, pastures, and meadows prevail in lower valley segments. Although the downstream part of the Mohelnice River (ca. 0.0–1.5 km) runs through the built up area of Raškovice village, at many places the river banks are currently accompanied by dense riparian vegetation (Fig. 3B).