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Controls on log step occurrence in steep headwater streams draining Carpathian managed forests

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ABSTRACT

Instream wood in steep headwater streams impacts channel morphology and sediment fluxes via the development of log steps and related sediment storage. I investigated detailed characteristics of 73 log steps in managed temperate Carpathian forests and assessed channel- and wood-based thresholds for log step development. The limited recruitment of wood from managed forests was apparent in the low frequency of log steps (an average of 1.3 steps per 100 m channel length) in bedload-dominated channels when compared to temperate and boreal old-growth forests, and an even lower number of log steps was observed in streams recently affected by debris flows or hyperconcentrated flows. The upstream threshold of log step occurrence can be assigned to those locations in stream longitudinal profiles, where transport capacity during ordinary high flows exceeds the critical value for the initiation of bedload movement. Downstream thresholds are controlled by stream transport capacity and wood dimensions, which correspond to the limited recruitment of large wood pieces in managed forests. All log steps were found in contributing basin areas smaller than 1 km^2, and the majority of log steps (93.1%) originated in channels less than two metres in width. The development of a log step at a particular channel width or basin area was controlled by the wood length, but the resultant step parameters (step height and width, length of upstream sedimentary wedge and volume of stored sediments) were better correlated with wood diameter. The parameters of horizontal and vertical wood orientation had less importance in the development of a log step or its dimensions. Wood pieces shorter than 4 m in length accounted for 72.2% of the step-forming pieces, and the maximal diameter was less than 0.1 m for 20.5% of the pieces. These findings show the significance of relatively small wood pieces in log step development and sediment routing in steep headwater streams; the average sediment storage generated by a log step was 0.51 m^3. The support of log step development and their preservation in headwater streams draining managed forests represents an alternative low-cost approach for sediment management at the basin scale.

1. Introduction

Instream wood plays an irreplaceable role in fluvial systems, enhancing habitat heterogeneity linked to biodiversity, acting as refuge for aquatic species, serving as source of food and representing an important element of the global carbon cycle (Harmon et al., 1986; Bisson et al., 1987; Montgomery et al., 2003; Wohl et al., 2012; Livers and Wohl, 2016). Geomorphic interactions of wood with stream and river channels have been increasingly recognised during recent decades, when pioneering research also included steep channels of mountainous environments (Keller and Swanson, 1979; Marston, 1982; Bilby, 1984; Bilby and Ward, 1991; Nakamura and Swanson, 1993). A typical feature, which represents the geomorphic function of instream wood in steep headwater channels, is the formation of stable steps by individual logs spanning the channel. Such structures lead to the deposition of sediment upstream and the development of scour pools downstream as a result of water dropping from the step crest (Marston, 1982; Bilby and Ward, 1989; Nakamura and Swanson, 1993; Wohl et al., 1997; Buffington et al., 2002; Gomi et al., 2003; Słowik-Opoka et al., 2018). In this manner, log steps significantly contribute to the stabilisation of channel beds and the effective dissipation of flow energy (Swanson and Lienkaemper, 1978; Curran and Wohl, 2003; Faustini and Jones, 2003; MacFarlane and Wohl, 2003). It has also been documented that removal of instream wood from a steep channel decreases bed stability and increases sediment transport (Bilby, 1984; Díez et al., 2000).

Although the links between log dimensions and step properties (height, spacing) are recognised in the scientific literature, our knowledge regarding the minimal size of a wood piece functional as a log step and its dependence on channel geometry and hydrologic regime is still not completely understood. The number of log steps per unit longitudinal channel length is usually controlled by the channel geometry, when a higher frequency of steps is connected with steeper bed slopes

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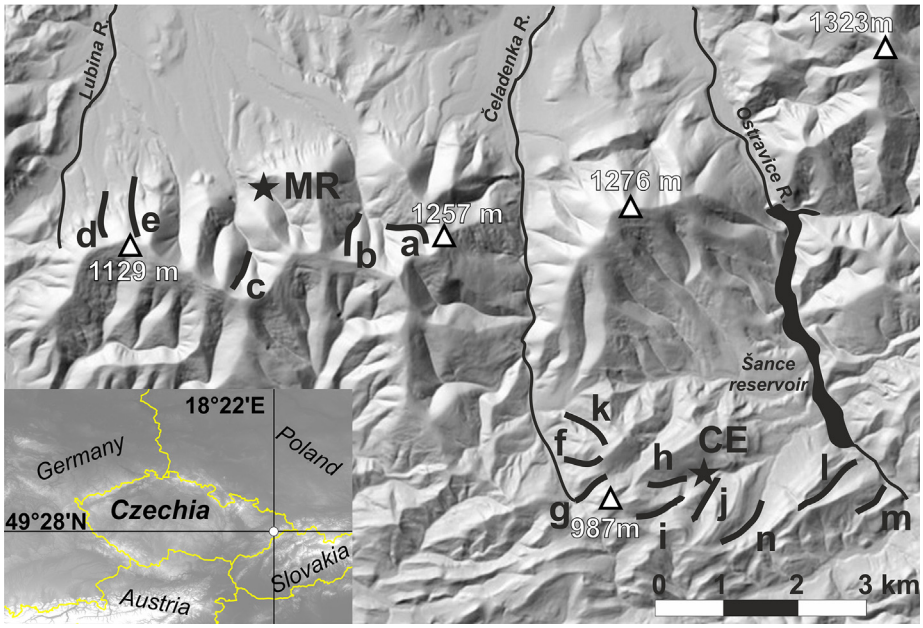

Fig. 1. Map of the study area: a–e are the northern studied streams (a – Bystry 1, b – Bystry 2, c – Lomna, d – Maly Skaredy, e – Velky Skaredy), f – n the southern studied streams (f – Celadenka 1, g – Celadenka 2, h – Cervik 1, i – Cervik 2, j – Cervik 3, k – Destansky, l – Rika 1, m – Rika 2, n – Sustkula), CE and MR are gauging stations of small experimental basins.

and narrower channels (Wohl et al., 1997; Gomi et al., 2003). Nevertheless, very confined narrow valleys can produce suspended wood pieces on opposite hillslopes and above the bankfull channel depth, which may decrease the potential of a piece of wood to form a log step (Nakamura and Swanson, 1993; Bahuguna et al., 2010). In addition to wood diameter (Wohl et al., 1997; Faustini and Jones, 2003), the total height of steps is also determined by the presence of boulders participating in the formation of steps (Scott et al., 2014). The size of recruited wood into steep channels is reflected by the trees living in the riparian corridor and adjacent hillslopes, because downstream redistribution of wood by fluvial transport is limited in this part of the fluvial net (Bilby and Ward, 1991; Gurnell et al., 2002; Hassan et al., 2005; Beckman and Wohl, 2014; Wyżga et al., 2015). As a consequence, log steps in these channels are expected to be relatively stable elements and they are formed rather by immobile wood that is recruited directly from the bank or adjacent hillslope (Wohl et al., 1997). However, extraordinary floods and debris-flow events can be responsible for the sudden transport of wood accompanied by evacuation of almost all wood pieces from the channel bed and by destruction of present log steps (May and Gresswell, 2003; Lucía et al., 2015; Comiti et al., 2016).

Clustered wood pieces spanning the channel, referred to as (log) jams, can play a similar geomorphic role to that of log steps, although they probably more effectively alter the longitudinal connectivity of sediments. They are also responsible for enhanced hydrologic floodplain-channel connectivity in less confined channels (Abbe and Montgomery, 2003; Wohl, 2013; Wohl and Beckman, 2014). Such clustering of wood pieces is connected with active wood transport during high-flow events (Abbe and Montgomery, 2003). Thus, the importance of jams at the expense of steps increases by increasing channel width in relation to the potential for wood mobility, whereas log steps are often leading representatives of instream wood geomorphic function in steep headwater channels with limited wood transport.

Old-growth forests usually supply channels with a high number of wood pieces of large dimensions, which may suppress relations among critical wood size, channel geometry, and possible development of a log step. Therefore, limited wood recruitment in managed forests in terms of lengths and diameters of supplied pieces (Bilby and Ward, 1991; Rigon et al., 2012; Benda and Bigelow, 2014) represents a suitable opportunity to more clearly investigate links between channel parameters and the characteristics of a single wood piece spanning the channel that is able to form a stable log step. I hypothesise that although wood dimensions will likely be the key factors to consider regarding the geomorphic function of a wood piece, channel parameters (e.g., bankfull channel and valley floor width, bed slope, and intensity of sediment transport processes) will also influence possible development of log steps. The main hypotheses of the study are as follows:

- the frequency of log steps in channels surrounded by managed forests will be lower than log step frequencies reported previously from old-growth forests throughout the world;
- the frequency of log steps in channels subject to intensive hydrogeomorphic processes (i.e., debris or hyperconcentrated flows) will be lower than log step frequencies in streams void of these processes;
- upstream and downstream threshold values of the selected channel parameters will exist for the occurrence of log steps created by a single piece of wood;
- the aforementioned thresholds will have a direct relationship with the dimensions of a piece of wood, and
- the volume of sediments accumulated upstream of a log step will be controlled by the dimensions of the step-forming wood.

To assess these relationships, I investigated log steps in two neighbouring medium-high mountainous areas of the Western Carpathians under similar second-growth forest canopy and, thus, similar dimensions of recruited wood, but with contrasting characteristics in terms of sediment transport processes predisposed by the windward precipitation effect and different channel gradients.

2. Study area

Fourteen first- and second-order studied streams drain the medium-high Moravskoslezské Beskydy Mountains (reaching elevations of 1200–1300 m a.s.l.) of the outer Western Carpathians (Fig. 1; Table 1). The flysch-nappe structure (alteration of rigid sandstones and soft shales) predisposes the area to both shallow and deep landslide activity (Pánek et al., 2013; Březný and Pánek, 2017). The sediment supply into the fluvial system is realised by bank failures in incised channel reaches or by shallow landslides, whereas the steepest valleys are prone to debris or hyperconcentrated flows (Šilhán and Galia, 2015; Galia and Škarpich, 2016). In addition, episodic bedrock landslides act as sediment supply agents in some steep confined valleys (Šilhán et al., 2013).