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Increased gully activity induced by short-term human interventions – Dendrogeomorphic research based on exposed tree roots

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ABSTRACT

The recent acceleration of gully erosion caused by environmental factors and human impacts has led to an enhanced demand for applied research in risk-prone areas worldwide. We investigated the dynamics of gullies that have recently threatened dwellings and railways in the foreland of the Eastern Sudetes (340–390 m a.s.l. in the NE part of Czechia). Flood countermeasures in a residential area above the study site created conditions conducive to accelerated erosion in the gullies; thus, the main aim of this study was to determine how human interventions changed the spatio-temporal dynamics of the gullies during a short period. Twenty two gullies (with a mean length 48.5 m) have developed on a 1-km-wide escarpment (with a mean slope 25°) composed of glaciogenic sediments of various sizes. Dendrogeomorphic techniques were applied on 23 exposed roots of *Tilia cordata* Mill. (a tree species that has never been used to detect root exposure). Microsections were prepared using a G.S.L.1 sledge microtome and analysed using the WinCELL Reg software to determine the timing of root exposure.

Approximately 90% of the eroded sediments (1287.4 m^3) were transported across the railway onto the floodplain and caused damage to dwellings, while approximately 10% created bare accumulations at the gully floors. The most significant pulses of gully erosion occurred during the last 10 years (2007, 2009, 2010, and 2014). The maximum identified gully erosion occurred in 2014 (max. incision: 154 cm; maximum widening: 160 cm). In contrast, the development of the bank failures has been slowly progressing since the early 1990s, with a mean bank eroded area between 0.07 and 0.12 $m^2\,year^{-1}$. The analysis of the precipitation characteristics (1963–2016) with the Mann-Kendal trend test revealed no significant trend. However, the last strong erosion event, in May of 2014, was triggered by an extraordinary rainstorm with an hourly intensity of 41.3 $mm\,h^{-1}$ (maximum intensity of 2.8 $mm\,min^{-1}$). Therefore, the recent increase in gully erosion is the consequence of extreme precipitation and human interventions that have been performed in the study site since 2007 (i.e., damming of the ditches and building of new culverts). The dendrogeomorphic research of exposed *T. cordata* roots significantly contributed to the identification of the gully erosion pulses and thus can be further applied in other localities.

1. Introduction

Gully development and the recent increase in gully erosion is a popular scientific topic worldwide, especially studies concerning natural hazards and risk assessment in the most vulnerable localities (Hamandawana, Nkambwe, Chanda, & Eckardt, 2005; Poesen, Nachtergaele, Verstraeten, & Valentin, 2003; Valentin, Poesen, & Li, 2005; Vanmaercke et al., 2016; Yitbarek, Belliethathan, & Stringer, 2012). Gullies represent an integral part of the catchment connectivity, through the sediment supply from hillslopes to the channels and channel floodplains, and thus, gullies influence the local sediment balance through varying rates of erosion and deposition. Consequently, gullies may negatively impact the hydrological functioning of catchments and, in extreme cases, strong gully erosion may lead to extensive damage of the infrastructure, causing considerable financial losses (Boardman, Poesen, & Evans, 2003; Vanmaercke et al., 2016).

Gully dynamics are controlled by various factors relating to different environments. Local topography characteristics such as slope

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gradient and the size and shape of the contributing upstream area draining into the gully headcut influences the time lag of the hydrological response after rainfall events and peak discharge values (Rossi, Torri, & Santi, 2015; Vandaele, Poesen, Govers, & van Wesemael, 1996). Soil characteristics (such as cohesion, permeability, and the amount of organic matter) influence potential soil erodibility and contribute to changes in the volume of transported sediments/soil. Conversely, the presence of vegetation may increase soil stability and infiltration capacity (Torri & Poesen, 2014; Vanmaercke et al., 2016). In addition, the geomorphic effect of high-magnitude rainfall events, the most common triggering factor of accelerated gully erosion, strongly depends on rainfall intensity, antecedent soil moisture condition (e.g., influenced by antecedent rainfall and/or snow melting) (Li & Fang, 2016) or the specific mineralogical content of eroded material (e.g., presence of smectite; Valentin et al., 2005).

Furthermore, human impact is considered the critical aspect contributing to gully development; human impact may change the properties of the abovementioned natural factors (Ionita, Fullen, Zgłobicki, & Poesen, 2015). Both long- and short-term unsuitable land-use and land management (e.g., deforestation, land abandonment, soil compaction caused by agricultural machinery, irrigation/tile drainage systems, overgrazing) may lead to the initiation and evolution of rill and gully erosion, even on a large scale (Valentin et al., 2005; Lesschen, Kok, Verburg, & Cammeraat, 2007; Menéndez-Duarte, Marquínez, Fernández-Menéndez, & Santos, 2007; Martínez-Casasnovas, Ramos, and García-Hernández, 2009). In addition, road and railway construction, including culverts, influence the development and geometry of gullies and may significantly increase the erosion rate downstream (Archibold, Levesque, De Boer, Aitken, & Delanoy, 2003; Croke & Mockler, 2001; Galia, Šilhán, & Škarpich, 2017; Nyssen et al., 2002).

To prevent the increased risk of gully erosion and the resulting damage, it is necessary to quickly determine the predisposition to erosion and erosion-triggering factors, which can vary, even within a small area. Long-term monitoring and modelling of transported sediments need to be carried out to calculate or assess the erosion rates and sediment yields (Brazier, 2004; Haregeweyn et al., 2013). Dendrogeomorphic approaches are alternative methods of estimating gully dynamics and erosion rates in forested hydrological response units (Alestalo, 1971; Vandekerckhove, Muys, Poesen, De Weerdt, & Coppé, 2001). Dating and quantification of the erosion processes is based on analysis of the timing of the exposed living tree roots and has been successfully applied worldwide (please see next). Based on the wood-anatomical changes that occur almost immediately after the root exposure, we can determine the year of an erosion event and, broadly, the rate of gully retreat and bank erosion (Corona et al., 2011; Gärtner, 2007; Gärtner, Schweingruber, & Dikau, 2001; Stoffel, Corona, Ballesteros-Cánovas, & Bodoque, 2013). With this approach, Bodoque et al. (2005, 2011), Lopez-Saez et al. (2011) and Ballesteros-Cánovas, Corona, Stoffel, Lucia-Vela, and Bodoque (2015) quantified the sheet erosion rate on slopes in the French Alps and in Central Spain. Rovéra, Lopez Saez, Corona, Stoffel, and Berger (2013) and Morel et al. (2017) dated the shore erosion and cliff retreat in Mediterranean regions. Malik (2006, 2008) obtained the chronology of erosion events and gully retreat rates in low-gradient gullies of Poland, and similarly, Šilhán and Galia (2015) and Šilhán, Galia, and Škarpich (2016a) tried to quantify the volume of material supplied to a stream channel from bank failures using the combination of root exposure dating and bedload transport modelling in the Western Carpathians. In contrast, there are not many papers on gully incision rates due to the limited number of localities with a dense network of exposed roots that can be dated (Ballesteros-Cánovas et al., 2017).

In this paper, we investigated gully development on a 1-km-wide section of escarpment built by unstable glacial sediments, where the occurrence of strong erosion events has increased during the last few years and caused considerable damage to the railway embankment and dwellings located below the escarpment. The drainage area of the gullies has been used for agriculture and subjected to human interventions. Therefore, the main aim of this study was to determine how human interventions change the spatio-temporal dynamics of gullies in a relatively small area during a short period. Along several gully profiles, a dense root network has been exposed and thus created a suitable site for the reconstruction of gully incision and widening. Dendrogeomorphic research (including research on erosion processes) still mainly focuses on coniferous tree species at the expense of broadleaved trees. This study outlines the possibility of using small-leaved lime trees (*Tilia cordata* Mill.), a common broadleaved tree species that has never been used to quantify erosion processes. The research aims to (i) produce a detailed map of the gully system and quantify the volume of the eroded and accumulated material, (ii) date the erosion events using a tree ring analysis of the exposed roots and calculate the gully incision and widening rate, and (iii) analyse the triggering rainfall threshold. Furthermore, we discuss recent gully evolution with respect to known human interventions and known flash flood events.

2. Study site

Our research focused on the gully network located near the city of

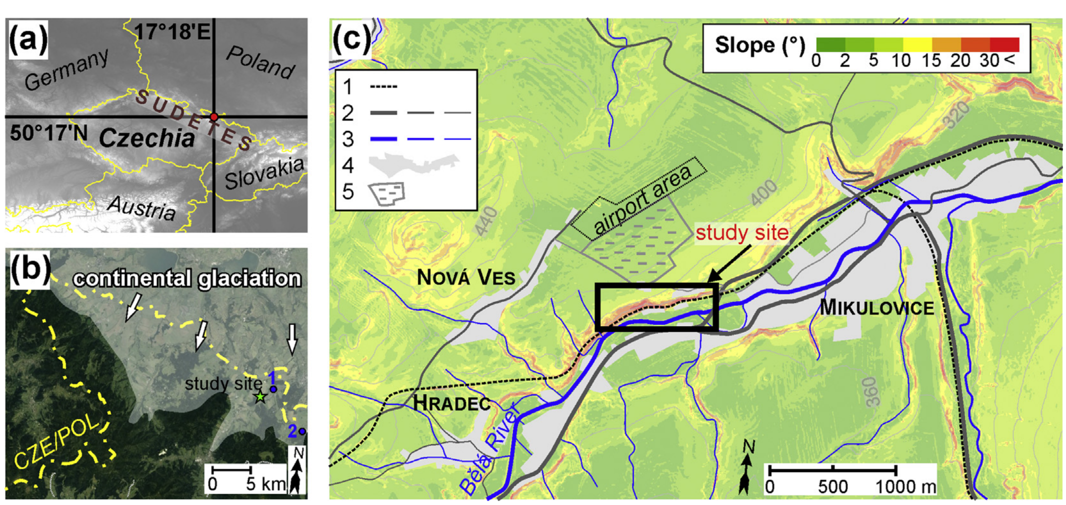

Fig. 1. Study site location: (a) position within Czechia; (b) position within the Eastern Sudetes, with the approximate direction and boundary of the last continental glaciation according to Gába (1981) and Hanáček (2014) (meteorological stations: 1 – Mikulovice, 2 – Zlaté Hory); and (c) study site and surroundings (1 – railway, 2 – roads, 3 – rivers and streams, 4 – residential area, 5 – tile drainage).