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Debris flows in the Hrubý Jeseník Mountains, Bohemian Massif, Czech Republic

Marek Křížek, David Krause and Tereza Raschová

Department of Physical Geography and Geocology, Faculty of Science, Charles University, Prague, Czech Republic

ABSTRACT
Debris flows in mountainous areas have a deep geomorphic impact on slope dynamics. Their activity corresponds with heavy rainfall events. The estimation of these events depends not only on meteorological prediction but also on the knowledge of their spatial occurrence. As debris flows usually occur in the same paths with different frequencies during the Quaternary period, spatial data are needed to obtain more detailed information about debris flow phenomena. This was the reason for the creation of the presented map of debris flow features in the Hrubý Jeseník Mts. A total of 95 debris flow paths and 47 debris flow accumulations (including lobes or levees) have been mapped in the field. A comprehensive spatial database of debris flow features is shown in the map, which could be helpful for future research of Quaternary geomorphic evolution of the landscape and for forest management and state administrative authorities in future planning.

1. Introduction
Very or extremely rapid slope movements of watersaturated debris occur periodically in established debris flow paths (Hungr, Leroueil, & Picarelli, 2014). They usually originate on steep slopes (over 25°), and their usual trigger is extreme rainfall. Typically, debris flow paths contain specific geomorphological phenomena such as gullies, levees on their sides and poorly sorted accumulations (Iverson, 2004). As debris flows occur on steep slopes, they are most common in tectonically active mountains around the world with high uplift and erosion rates, depending on the geological settings of each location, especially the weathering mantle thickness (Hungr et al., 2014). Debris flows cause forest and infrastructure destruction, and they endanger human lives (Costa, 1984); on the other hand, together with avalanches, they can have a positive ecological impact in some areas (Butler, 2001), and they can be the study subjects of palaeogeographical and palaeoclimatological reconstructions of landscape history (Stoffel et al., 2005). In these cases, cumulative studies have been conducted and maps of debris flow areas produced in many countries such as the USA, China and Russia (e.g. Brabb & Best, 1999; Ellen, Mark, Cannon, & Kni-fong, 1993; He et al., 2003; Perov, Chernomoretz, Budarina, Savernyuk, & Leontyeva, 2017). Recurrence of debris flows in their paths is common and has been reported from many areas around the world (e.g. Perov et al., 2017; van Steijn, 1996; Zimmermann, Mani, & Romang, 1997). Field geomorphological mapping and analysis of remote sensing data and written sources have been employed to collect debris flow spatial data in the Hrubý Jeseník Mts. (Bohemian Massif, Czech Republic), where the return period of debris flow events is quite long and the debris flow paths could get overgrown by forest before the next debris flow event (Sokol, 1965). Thus, the spatial distribution of past debris flow events (i.e. their paths and accumulations) is very important for estimating the future debris flow activity, because it occurs in the same localities. Debris flows are also a phenomenon related to environmental changes that causes risks and disasters. The presented map introduces the first complex depiction of the spatial distribution of debris flows in the study area, which is useful for future environmental planning, risk assessment and forest management, because the debris flows could occur after forest clearcutting. The map is built on a high-resolution digital elevation model (DEM) and presents the position of debris flow paths and accumulations in different catchments of the mountain range. The location properties of debris flow paths in relation to alpine timberline and infrastructure positions are presented.

1.1. Debris flows in the Hrubý Jeseník Mts.
The Hrubý Jeseník Mts. (maximal elevation Mt. Praděd, 1492 m asl), located in the northeastern part of the Bohemian Massif in Central Europe (Figure 1), consist of metamorphic rocks (gneisses, phyllites,
quartzites and mica schists – see the geological map on the Main Map). It is a Variscian fault-block mountain range influenced by the reactivation of Variscian faults under the influence of Saxonian neotectonic processes since the beginning of Alpine orogeny (Chlupáč, Brzobohatý, Kovanda, & Stráník, 2011). Tectonic activity was observed even in the current geological epoch, when vertical movements reached values of tens of metres during the Quaternary (Badura et al., 2007; Krzyszkowski & Pijet, 1993; Štěpančíková et al., 2010). Young deep valleys with steep slopes intersect Cenozoic summit planation surfaces (Křížek, 2016) located above the timberline (Treml, Jankovská, & Petr, 2008). During glacial periods of the Quaternary, periglacial (Křížek, 2016; Prosová, 1973) and locally glacial (Křížek, Vočadlová, & Engel, 2012) conditions were present in the Hrubý Jeseník Mts., which caused the formation of a thick regolith. Large old debris flow accumulations with unsorted clasts (sensu Hungr et al., 2014), observable in many valley floors (Křížek, 2016), were considered incorrectly as glacial moraines in past literature (Prosová, 1973 and references therein). Snow avalanches and debris flows are the most dynamic geomorphological processes in this mountain range (Gába, 1992; Krause & Křížek, 2018; Malik & Owczarek, 2009; Polách & Gába, 1998; Sokol, 1965; Tichavský & Šilhán, 2015) even in present climatic conditions characterized by short wet summers and long winters with long-lasting snow cover. The mean annual temperature on Mt. Praděd is +1.7°C (1960–1990; Coufal, Miková, & Langová, 1992), and the mean annual precipitation is 1231 mm (1947–1985; data of the Jeseníky Protected Landscape Area Authority). Some periglacial phenomena (ploughing blocks, earth hummocks, small sorted circles, nivation hollows and small solifluction lobes) are still active (Křížek, 2016). Since the nineteenth century, debris flow events have been observed many times, for example, in 1880, 1890, 1893, 1903, 1907, 1921, 1938, 1940, 1951, 1965, 1968, 1984, 1991, 1994, 1997, and 2006 (Gába, 1992; Krause & Křížek, 2018; Malik & Owczarek, 2009; Polách & Gába, 1998; Sokol, 1965; Tichavský & Šilhán, 2015). The last most important and fatal debris flow event occurred in the Hučivá Desná Valley (catchment no. 6 in the Main Map) after heavy rainfall on 1 July 1921 (Polách & Gába, 1998; Sokol, 1965). Approximately 50,000 m³ of regolith was removed by eight debris flows (Figure 2), and the deposit of these debris flows dammed the valley, filling up a lake that collected a huge volume of water in a short time. The dam collapsed a few hours after its formation, and the resultant flood damaged many buildings, all bridges and railway infrastructure and killed four people in villages spread along 25 km of the river. Similar events occurred in 1770 and

Figure 1. Geographical location of the Hrubý Jeseník Mts.
1813 (Schön, 1938 in Gába, 1992). The forest management authorities often tried to build erosion control fences in the debris flow paths (Figure 2) and began to grow a non-indigenous dwarf pine (*Pinus mugo*) to stabilize the convex slopes above the timberline where starting zones of debris flows are usually located (Treml, Wild, Chuman, & Potůčková, 2010). Even so, some debris flows still occur repeatedly in their paths (Gába, 1992, 2014; Sokol, 1965; Tichavský & Šilhán, 2015). As the occurrence of debris flows is still a problem in forest management and risk prevention at the present time, the spatial distribution of debris flow paths needs to be examined, yet there has been no cumulative study or map produced constraining these problems.

### 2. Methods and data collection

#### 2.1. Data collection

The map of debris flow paths is the result of (1) geomorphological field mapping of the valley floors and slopes, (2) remote sensing based on fourth generation (vertical resolution of approximately 30 cm in a 5 × 5 m grid) and fifth generation (vertical resolution of approximately 18 cm in triangulated irregular network) digital elevation models based on light detection and ranging provided by The State Administration of Land Surveying and Cadastre and historical aerial photographs from the years 1936, 1946, 1957, 1958, 1965, 1971, 1975, 1985, 1992 and 1995 obtained from The Army Institute of Geography and Hydrometeorology, and (3) analysis of written sources, e.g. dissertation thesis of Sokol (1965) and Gába (1992) paper about the last well-described debris flow event in the Keprnický potok Valley on 4 September 1991.

Recent debris flow paths and old debris flow accumulations located in valley floors and valley heads have been mapped in the field using a GPS device. Derived raster images (slope, hillshade and curvature) from the DEM have been used to compare debris flow forms observed in the field and to detect exact debris flow morphological features (such as gullies and accumulations). The positions of debris flow path borders have been validated using historical aerial photographs, as debris flows usually destroyed forest canopy, which was clearly visible in the images. Further, evidence about debris flow locations obtained from the literature (Gába, 1992; Kirwald, 1942; Sokol, 1965) has been used for discussion. Additional debris flow paths and accumulations derived from the DEM, aerial photographs and written sources have also been verified in the field.

#### 2.2. Map creation

The **Main Map** is designed as a physical wall map in dimensions of A1 format, for which the map scale is 1:40,000. Elevation data in the map have been derived from the Digital Terrain Model of the fourth generation (State Administration of Land Surveying and Cadastre): contours with an interval of 50 vertical metres and hillshade tinting (illumination azimuth 315°, altitude 45°) with 50% transparency are used to underline topography on the **Main Map**. The streams, rivers and summit points have been derived from the

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**Figure 2.** Debris flow paths in the Hučivá Desná catchment (6) in the year 1921 (old photograph from a postcard on the left), and technical protection built in debris flow paths in order to stabilize the slopes (on the right, photo D. Krause).
digital terrain model and named according to the GEO- NAMES database (The State Administration of Land Surveying and Cadastre). The roads, forests and buildings have been visualized by the OpenStreetMap data. The colours used in the map are those commonly used in topographic maps (Kraak & Ormeling, 2013). Highlighted features (debris flow paths and accumulations) are visualized in violet and orange to be easily visible on the basic map. The Projected Coordinate System used in the map is the Czech National System S-JTSK – Krovak East-North. Collected spatial data are visualized in the presented map, which contains two categories of debris flow spatial data in the study area:

(a) debris flow paths with observable transportation zone (polygon features). Most of these debris flows were active since the beginning of the twentieth century, as the morphological forms of whole paths are still visible in the field or were observed on the historical aerial photographs and checked in the field. Many of these paths are overgrown by forests in the present time, but their reactivation in the future is possible;

(b) debris flow accumulations on the valley floors (point features). These landforms are relics of older debris flow activity with no more morphological evidence about the transport zone, only large accumulations composed by unsorted deposits (Figure 3). Even though these features are remains of older debris flow events, their surroundings could be prone to debris flows in the future.

The debris flow features are located in 11 catchments – sections, shown in the map with unique numbers. Information about the elevation parameters of all debris flow features and about the area of debris flow paths is given in tables next to the map. Two small thematic maps of the same spatial extent as the Main Map are added in the scale of 1:120,000. The geological map depicts the different lithologies within the mountain range, and the slope map shows the locations of the highest surface slope. These maps should enable the reader to compare the distribution of debris flow features to their geological and morphological settings when all studied catchments and debris flow features are printed.

3. Conclusions

Field geomorphological mapping, with the support of remote sensing and previous studies, allowed for the creation of a database of debris flow paths and accumulations for the Hrubý Jeseník Mts. A total of 95 debris flow paths and 47 debris flow accumulations have been mapped and visualized in the Main Map. Most of them are located in the northern part of the study area (catchments no. 1–7). This is caused particularly by geological (see the geological map) and climatic differences between these two parts of the mountains. In the northern part of the study area, the rocks (predominantly gneiss, mica schists and phyllites) are foliated. This foliation forces the speed of weathering, especially when the foliation plane has the same inclination as the surface slopes. The total area of observed debris flow paths in the mountains is 67 ha, which represents 0.25% of the whole study area. The greatest area, 23 ha, covered by debris flow paths is located in the Hučivá Desná catchment (no. 6), predominantly on the slopes of Mt. Červená hora (1333 m asl), as well as on the eastern slope of this mountain in catchment...
In many cases, the debris flow paths coalesce with other paths in their lower parts. This is observable in catchments no. 1, 3, 4, 5, 6 and 7.

Debris flow starting zones occur between 948 and 1318 m asl. In all catchments except for catchment no. 10, the starting zones of debris flow paths are located above 1000 m asl. This confirms that the debris flows are usually caused by steep slopes in convex upper sections of valley slopes with sufficient amount of regolith. The lowest parts of debris flow paths are located between 703 and 1001 m asl. In catchment no. 6, where the largest debris flow paths active in 1921 are located, there is the highest starting point of debris flows, and this catchment has the highest range of elevations, over 500 vertical metres, containing debris flow paths. Debris flow accumulations on valley floors occur between 617 and 1110 m asl, with the lowest one located in catchment no. 6 and the highest one in catchment no. 8 (Table 1). Most of the recent debris flows originated in the forest, with only some debris flows on Mt. Červená hora (catchment no. 6) having their starting zones above the timberline.

The presented map summarizes all above-mentioned mapping results and provides an overview of the spatial distribution of debris flow paths and accumulations in the Hrubý Jeseník Mts. All these features could be compared to geological and slope properties of the studied area. The importance of the map is for palaeogeographical studies as well as for future environmental planning. Because the map data are stored as shapefiles, they could be used in the future for further mapping of geomorphological processes in the area using geographic information systems, which is important for forest and nature protection management, as well as for risk assessment.

### Table 1. Catchments in the Hrubý Jeseník Mts. with their debris flow features.

<table>
<thead>
<tr>
<th>Catchment number and name</th>
<th>Number of debris flow paths</th>
<th>Number of debris flow accumulations</th>
<th>Area of debris flow paths (m²)</th>
<th>Maximal elevation of debris flow paths (m asl)</th>
<th>Minimal elevation of debris flow paths (m asl)</th>
<th>Maximal elevation of debris flow accumulations (m asl)</th>
<th>Minimal elevation of debris flow accumulations (m asl)</th>
<th>Documented debris flow activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Vražedný potok</td>
<td>3</td>
<td>1</td>
<td>48,050</td>
<td>1277</td>
<td>983</td>
<td>772</td>
<td>772</td>
<td>twentieth century</td>
</tr>
<tr>
<td>2: Javohlíčky potok</td>
<td>3</td>
<td>2</td>
<td>14,300</td>
<td>1169</td>
<td>1001</td>
<td>824</td>
<td>789</td>
<td>twentieth century</td>
</tr>
<tr>
<td>3: Klepáčovský potok, Jelení potok</td>
<td>26</td>
<td>7</td>
<td>14,2650</td>
<td>1271</td>
<td>1040</td>
<td>886</td>
<td>709</td>
<td>twentieth century</td>
</tr>
<tr>
<td>4: Keprnický potok</td>
<td>4</td>
<td>5</td>
<td>33,755</td>
<td>1311</td>
<td>980</td>
<td>955</td>
<td>779</td>
<td>1921, recent</td>
</tr>
<tr>
<td>5: Rudohorský potok</td>
<td>8</td>
<td>6</td>
<td>74,152</td>
<td>1310</td>
<td>832</td>
<td>1005</td>
<td>780</td>
<td>1921, recent</td>
</tr>
<tr>
<td>6: Hučivá Desná, Poníkový potok</td>
<td>13</td>
<td>6</td>
<td>23,400</td>
<td>1310</td>
<td>795</td>
<td>886</td>
<td>617</td>
<td>1921</td>
</tr>
<tr>
<td>7: Černý potok, Červenohorský potok</td>
<td>17</td>
<td>0</td>
<td>88,950</td>
<td>1274</td>
<td>866</td>
<td>–</td>
<td>–</td>
<td>1921</td>
</tr>
<tr>
<td>8: Studený potok, Bukový potok</td>
<td>0</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>9: Divoká Desná, Divoký potok, Hladový potok, Česnekový potok</td>
<td>11</td>
<td>20</td>
<td>34,625</td>
<td>1126</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>twentieth century</td>
</tr>
<tr>
<td>10: Tříramený potok</td>
<td>2</td>
<td>0</td>
<td>750</td>
<td>948</td>
<td>809</td>
<td>–</td>
<td>–</td>
<td>twentieth century</td>
</tr>
<tr>
<td>11: Merta, Kamenný potok, Divoký potok</td>
<td>6</td>
<td>1</td>
<td>3425</td>
<td>1076</td>
<td>767</td>
<td>–</td>
<td>–</td>
<td>recent</td>
</tr>
</tbody>
</table>
Supplemental data

The shapefiles of debris flow paths and accumulations could be provided on request by the authors. The shapefile of the paths is a polygon feature, and the shapefile of debris flow accumulations is a point feature.

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ORCID

Marek Křížek ORCID iD http://orcid.org/0000-0001-5791-571X
David Krause ORCID iD http://orcid.org/0000-0001-5224-8954

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