Geological hazards of the Gerecse Hills (Hungary)

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ABSTRACT
Landslides and related mass movement processes actively pose a threat in the Gerecse Hills (Hungary, Transdanubian Range) by endangering residential and agricultural areas. Several closed or abandoned mining sites and waste deposits are also located in the area. Most of these sites have not been fully remediated, which makes their surroundings dangerous and unsuitable for other use. A multi-hazard map (1:60,000) was prepared about the geological hazard sources of the Gerecse by collecting and synthesizing data from individual thematic maps and databases. The aim of the map is to provide a comprehensive look at the different but often-interrelated hazard sources of the area. The thematic content of the map consists of three main parts: the result of a statistical landslide susceptibility analysis marking the most landslide-prone slopes, the documented slope failure events, and the areas of hazardous mining sites and their waste deposits.

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1. Introduction
Geological hazards are geological conditions and processes that have a potential to cause harm or damage in their living or material environment, either by themselves or through their interaction with their environment (Balce & Ramos, 1988; Oszvald, 2011; UNISDR, 2009). These geological conditions and processes can be considered as the sources of geological hazards that may cause catastrophic hazard events under certain critical conditions (Canuti et al., 2001; Ye, 2017). The past events of geological hazard occurrences are collected in inventory databases. The location of potential future hazard events is estimated during a susceptibility analysis, while a geological hazard assessment also estimates the probability of occurrence within a given time frame (Fell et al., 2008).

The spatial and temporal scale on which the different geological hazards act varies greatly, but they almost always interact with each other to some extent (Gill & Malamud, 2014). Due to the interrelation of the different geohazard phenomena, it is often beneficial to follow a multi-hazard approach that addresses the geological hazards of the studied area together, instead of independently dealing with the individual hazard types. The hazard types considered during a multi-hazard study mostly depend on the characteristics of the analyzed area. The level of the zonation (inventory, susceptibility, or hazard level) and the resolution of the output product are often constrained by the quality of the available data sources (Fell et al., 2008).

Many studies have addressed the problems associated with geological hazards, but most of them have focused on only one type of geohazard. Multi-hazard approaches are less common, especially at a systematic level with large-scale maps. Hird et al. (2019) prepared a small-scale map of Saudi Arabia’s geological hazard
sources, while Gautam et al. (2021) conducted a multi-hazard analysis on a local administrative level for Nepal based on past hazard events. Oller et al. (2013) reported about the large-scale multi-hazard mapping of Catalonia that includes both susceptibility and hazard assessments. Paliaga et al. (2019) mapped the activity of landslides and the flood-prone areas around Genova and highlighted the elements of the area threatened by these phenomena.

Geological hazards also pose a threat to life and property in the Gerecse Hills, Hungary (Lóczy et al., 1989). The most common hazards in the Gerecse are related to the landslides, developing mainly on the loessy slopes of the stream valleys and along the bluffs of the Danube (Szabó, 2003). Several abandoned or closed mining waste facilities are also located in the area: quarries, clay pits, coal mines, waste heaps, tailings in the Dorog Basin, and a red mud reservoir near Neszmély village. In some cases, these sites have not been adequately remediated or maintained since their remediation; therefore, they have the potential to become problematic in the future due to their hazardous material content or unstable slope conditions (Albert et al., 2021).

It is key to know the location of the hazardous sites in order to mitigate the damages or potential future damages caused by their instability. The Mining and Geological Survey of Hungary maintains a database of landslide events (National Landslides Cadastre) and of the closed mining waste facilities. Information about landslide-related events is also available from local geologic or geomorphic maps (Gábris et al., 2018). These sources provide useful information about the most characteristic geological hazard sources of the Gerecse; however, they are often incomplete (Gerzenyi & Albert, 2021).

Previously, a machine learning-based slope-type analysis was carried out by the authors. The analysis revealed that only a small percentage of the unstable slopes are recorded as potential threats in the landslide inventory (Albert & Gerzenyi, 2020). The affected slopes are concentrated in the central and northern parts of the Gerecse Hills and in the adjacent Dorog Basin. We have prepared a multi-hazard map of landslide and mining-related geological hazard sources in the Gerecse Hills with the aim to collect and supplement the information already available from different maps and databases. The map incorporates data from the inventories of the local geological survey, geothematic maps and the results of a statistical landslide susceptibility analysis.

Reichenbach et al. (2018) provide a review about the wealth of different existing statistical landslide susceptibility models and emphasize the importance of the input data selection, the choice of the analysis method, and the testing of the model predictions. Our analysis was conducted with a frequency ratio type approach (Chung, 2006; Davis et al., 2006; Lee & Talib, 2005). The model used the vicinity of the landslide scarps as training areas and analyzed the distribution of geologic and morphometric variables to yield estimates for landslide susceptibility (or relative hazard, Parise, 2001). The estimates show to what extent a certain area is similar to the already landslide-affected training areas.

Displaying the data related to the different types of geological hazards together on a multi-hazard map can lead to the better understanding of these often-interrelated threats to the human environment.

2. Study area

The study area is in the northern central part of Hungary close to the Danube River. It covers the central and northern parts of the Gerecse Hills and the western parts of the Dorog Basin. The surface is covered mostly by Quaternary loess and siliciclastic alluvial and colluvial formations. Freshwater limestones (travertines) are also representative sediments in the area (Figure 1). Outcrops of Neogene marls, Paleogene limnic coal, marls, limestones, and Mesozoic carbonates and sandstones are found on the higher territories (Gyalog & Síkhegyi, 2005). The morphology and the occurrence of the geological formations are characterized by the paleo-tectonic directions and by the erosional valleys cutting into the fluvial terraces of the paleo-Danube (Gábris et al., 2018).

The windborne Pleistocene loess covers the footslopes of the hills and the paleo-morphology of the partly eroded fluvial terraces. The thickness of loess varies between 1 and 15 m, as it is being intensely eroded at the fringes of the plateaus (Scharek et al., 2000). The linear erosion is dominant, but due to the undercutting, slope failures often occur in the sides of the incising valleys.

The oldest formations of the Gerecse are the Late Triassic shallow-marine carbonates forming the bulk of the larger hills. Jurassic ammonitico rosso limestone is quarried as decorative stones, while Cretaceous marine marls are used as raw materials for the cement industry. The Paleogene limnic coal was tunnelled in the Dorog Basin from the nineteenth century. Fire clay was excavated from open pits in small quantities. The occurrence of the Quaternary travertine is bound to the Danube terraces. Quarries of this porous limestone are present in the area since the Roman age. All mining activity in the area was terminated by the end of the last century, except for the quarrying of the building materials, such as the travertine limestone. The residues of the mining industry are most typical around the old coal mines in the Dorog Basin, forming large waste heaps there.
3. Materials and methods

The geological hazard map is made up of a topographic base and multiple thematic layers dealing with the different geological hazard sources of the area. The topographic base of the map focuses on representing the characteristic terrain and hydrological features of the Gerecse, while also marking the residential areas and local transport routes. Our consideration for this design choice was to help identify hazard-affected areas and to facilitate route planning for the more detailed field surveys. The thematic part follows a multiple hazard approach by displaying information about the different geological hazard-related phenomena in the study area. The displayed thematic information is a composite of the results of a statistical landslide susceptibility analysis, the documented events of mass movements, and the mining-related hazard sources. The used data sources and the analysis methods are described in the following parts. Figure 2 shows how the main map was composed from the different data sources.

3.1. Geothematic maps and databases

While geological features are not displayed on the map directly, the study is reliant on data gathered from the geological maps of the Mining and Geological Survey of Hungary. Categorized geologic features serve as an input layer for the landslide susceptibility analysis, landslides marked on the geological maps were used to supplement the landslide inventory, and large-scale field maps aided the identification of waste heaps. The following geological maps were used as a part of the research project:

- Geological map of the Gerecse Mountains (1: 50,000; Budai et al., 2018)
- Geological Map of Hungary (1: 100,000; Gyalog & Síkhegyi, 2005)
- Field geological maps (1: 10,000)

The Mining and Geological Survey of Hungary also maintains a landslide inventory and a mining waste inventory.

3.1.1. National landslides Cadastre

The Hungarian landslide inventory database, the National Landslides Cadastre (Mining and Geological Survey of Hungary, 2019), collects events related to mass movements since the 1970s (Kertész & Schweitzer, 1991). Data was first gathered on survey sheets, today the database is available online. The inventory marks the sites of mass movements in a point or...
polygon form, where sufficient data was available. Supplementary information about the activity, movement type, geological and morphological characteristics, possible triggering factors, and the landslide mitigation measures are also recorded in the database. Van Den Eeckhaut and Hervás (2012) reported 50–75% completeness of the Hungarian inventory in their review of European landslide databases. The work of Józsa et al. (2019) provides a review of the National Landslides Cadastre’s recent state. According to our field observations (Gerzsenyi & Albert, 2021), the database in the Gerecse area contains some inaccuracies, and these inaccuracies had to be corrected before the inventory could be used for further analysis.

3.1.2. Closed mine waste facilities

The closed mine waste facilities of Hungary were collected in an openly available risk-based inventory (Kiss & Jordán, 2020). The collection and ranking of the mining waste deposits was carried out in accordance with the guidelines described by Stanley et al. (2011). The facilities underwent a pre-selection procedure that ruled out the waste deposits that were not considered harmful to their environment. The risk-ranking was performed on the facilities that needed further examination according to the pre-selection works. The parameters considered during the ranking were the type of the waste, the size of the deposit, the slope inclination of the area, and the existence and completeness of remediation works (Kiss & Jordán, 2020). Waste heaps and tailings were sorted into five hazard categories (descending hazard level):

- Z-1/M-1: large size, without remediation
- Z-2/M-2: small size, without remediation
- Z-3/M-3: large size, remediated
- Z-4/M-4: small size, remediated
- Unknown

Sites without sufficient information to determine the hazard level were assigned with ‘unknown’ rank. Later the database was supplemented with waste deposits of inert materials (Kiss & Jordán, 2020). Inert materials pose no or minimal risk of releasing pollutants, but their heaps are often unstable or prone to landsliding (Albert et al., 2021). Therefore, these areas are also unsuitable for other use. The number, hazard level, and type of mining waste facilities in the inventory for the area is given in Table 1.

Table 1. The number and hazard level of the sites in the official Closed mining waste facilities inventory.

| Hazard category                  | Tailings | Heaps | Inert heaps | All type |
|----------------------------------|----------|-------|-------------|----------|
| Large size, without remediation  | 1        | 0     | 10          | 11       |
| Small size, without remediation  | 0        | 0     | 1           | 1        |
| Large size, remediated           | 0        | 1     | 0           | 1        |
| Small size, remediated           | 0        | 1     | 0           | 1        |
| Unknown                          | 0        | 29    | 3           | 32       |
| All level                        | 1        | 31    | 14          | 46       |

3.2. Landslide susceptibility estimations

Landslide susceptibility maps show the likelihood of landslide occurrence in the study area based on the analyzed terrain and environmental conditions (Brabb, 1984; Parise, 2001). They show where the landslide-prone slopes are located, but they do not
assess the time of recurrence (Fell et al., 2008). The probability of landslide occurrence within a given time can be estimated with landslide hazard assessment (Varnes, 1984) that builds on the susceptibility analysis.

### 3.2.1. Data preparation

A statistically based landslide susceptibility analysis was conducted with a frequency ratio-type model (Lee & Talib, 2005) based on the likelihood ratio functions approach (Chung, 2006; Davis et al., 2006) to find the most landslide-prone slopes. The model analyzes the distribution of a geological and five geomorphometric variables. The susceptibility estimates of the model explain to what extent a certain area is similar to the landslide sites used as sample areas. The model was implemented as a Python script that works with raster grid data (Gerzsenyi, 2020).

The proper selection of the sample areas is a crucial part of the analysis, since the estimates are based on the level of similarity to the sample areas. To predict the occurrence of a certain landslide-related phenomenon, only those areas should be selected where that certain phenomenon occurred in the past (Chung & Fabbri, 2003). Our aim was to predict the initiation areas of the landslides, i.e. the scarps; therefore, the vicinity of landslide scarps had to be selected instead of the whole landslide scars.

Landslides scarps marked in the National Landslides Cadastre inventory and on the Geological map of the Gerecse Mountains (1: 50,000; Budai et al., 2018) provided the initial data for selecting the sample areas. Landslide scarps, transitional areas, and runout areas (debris) were delineated from these datasets based on our field observations (Albert & Gerzsenyi, 2020). On the field, we were looking for visible markers to distinguish between the different areas using inventory mapping methods (IAEG Comission on Landslides, 1990; McCalpin, 1984; Varnes, 1984). The criteria included the level of degradation of the outcrop, the texture of the revealed material, and the condition of the vegetation. The scar and transitional areas were used as sample areas for the susceptibility analysis, while the runout (debris) areas were omitted.

The five geomorphometric input variables of the model were derived from the SRTM 1 Arc-second DEM (Farr et al., 2007) with SAGA GIS modules (Conrad et al., 2015). The SRTM data was transformed into a 31 m resolution grid in HD72/EOV (EPSG: 23700) projection prior to the analysis. The grid was then smoothed with a Gaussian filter to reduce the impact of artifacts on the model. The geomorphometric variables and the methods used for their calculation were the following:

- Elevation – SRTM 1 Arc-second DEM
- Slope (Zevenbergen & Thorne, 1987)
- General curvature (Zevenbergen & Thorne, 1987)
- TWI – SAGA Wetness Index (Boehner & Selige, 2006)
- Geomorphons – 10 terrain units (Jasiewicz & Stepinski, 2013)

Categorized geological features of the Geological Map of Hungary (1: 100,000) were used as a qualitative input variable. The features of the map were sorted into fourteen categories based on their rheological stability and physical characteristics (Table 2).

The vector polygon layers of the categorized geological variable and the sample landslide areas were converted into raster grids of the same grid system as the geomorphometric variables. Cells overlapped by categorized geological feature polygons were assigned with the respective category number. Cells covered by the sample landslide scarps were marked with value ‘1’, while the remaining non-landslide area was marked with ‘0’.

### 3.2.2. Frequency ratio analysis

The steps of the frequency ratio analysis used for the susceptibility modelling were the following (Figure 3):

1. Separate the sample landslide (L) and the non-landslide (NL) areas.
2. Compute the distributions of the six analyzed variables (elevation, slope, curvature, TWI, geomorphons, geology) for both the landslide (Lvariable) and non-landslide areas (NLvariable) as relative frequency histograms.
3. Compute the ratio of the histogram bin values of the landslide (L) and non-landslide (NL) distributions (frequency ratio) for each variable:

\[
FR_{variable} = \frac{L_{variable}}{NL_{variable}} \quad (1)
\]

\(FR_{variable}\) in (1) is a set of ratios linked to the histogram bins of the distributions. These frequency ratios are

| ID | Category | Percentage of total area | Frequency ratio weight |
|----|----------|--------------------------|------------------------|
| 1  | Clay     | 2.24%                    | 0.00000                |
| 2  | Silt (Loess) | 62.23%               | 1.33504                |
| 3  | Travertine | 0.77%                   | 1.00000                 |
| 4  | Sand     | 3.84%                   | 0.00000                 |
| 5  | Sand, silt | 4.18%              | 0.00000                 |
| 6  | Sand, silt, clay | 0.96%            | 1.51402                 |
| 7  | Pre-Quaternary carbonates | 7.83%             | 0.33439                |
| 8  | Gravel   | 0.12%                   | 0.00000                 |
| 9  | Gravel, sand | 0.02%            | 0.00000                 |
| 10 | Gravel, sand, silt, clay | 13.08%        | 0.76154                 |
| 11 | Consolidated mixed debris | 0.01%            | 0.00000                 |
| 12 | Stratified sandstone | 0.50%             | 0.08721                 |
| 13 | Stratified mixed debris | 1.01%            | 0.17206                 |
| 14 | Mixed debris | 3.22%             | 0.97902                 |
also conceivable as weights. Values with \( FR_{\text{variable}} < 1 \) are less characteristic in the landslide (L) areas and values with \( FR_{\text{variable}} > 1 \) are more characteristic there.

1. Assign the corresponding \( FR_{\text{variable}} \) weights to the cells of the six analyzed variable grids to get the \( W_{\text{variable}} \) weighted grids.
2. Landslide susceptibility \( (S) \) is then computed by averaging the weighted grids of the six analyzed variables:

\[
S = \frac{W_{\text{elevation}} + W_{\text{slope}} + W_{\text{curvature}} + W_{\text{TWI}} + W_{\text{geomorphons}} + W_{\text{geology}}}{6}
\]  

Susceptibility \( (S) \) values are then ranked and the ranked values are converted into a percentile form. Susceptibility in a percentile form \( (S_{\text{percentile}}) \) shows the percentage of cells in the study area that have lower susceptibility than \( n \). For example, \( S_{\text{percentile}} = 80\% \) (or 0.8) means that 80\% of the study area is less susceptible to landslides than cells with \( S_{\text{percentile}} = 80\% \) susceptibility.

4. Results

4.1. Landslide susceptibility map

A landslide susceptibility map was prepared with the frequency ratio method. The input variables for the analysis were the landslide sample areas and the six variables described in the Materials and methods section (elevation, slope, general curvature, TWI, geomorphons, categorized geology). The accuracy of the model predictions was tested with 5-fold cross validation (Figure 4). The landslide sample area was first randomly divided into five equal parts (folds), then the analysis was carried out with four parts in the (L) sample (train) area and one part in the (NL) non-landslide (test) area. This process was repeated for each set of four train, one test area folds. The accuracy of the model was evaluated by checking the distribution of the test landslide cells in the susceptibility
classes for each fold. Figure 5 shows the average of the distributions for the five validation folds.

Susceptibility values give information about the estimated level of threat for a grid cell relative to the other parts of the area (Parise, 2001). They do not provide the absolute level of threat or estimate the time of landslide recurrence (Fell et al., 2008). During a susceptibility analysis, it is up to the interpreter to decide on the range of values considered prone to landslides. After analyzing the cumulative distribution of Figure 5, we considered cells with 85–100% susceptibility as prone to landslides. This category corresponds to the 16% of the total study area with the highest susceptibility values. According to the cross validation, 50% of the test landslide cells fell into this category. The most susceptible 16% is displayed in two categories on the main map: S(96–100%) containing 14% of the test landslides and S(85–95%) containing 36% of them.

According to the model predictions, 93.4% of the landslide-prone areas are located on loessy (silt) slopes. These slopes are in the lower areas of the Gerecse (mean elevation: 214 m, std.: 40.6 m) and their average slope inclination is 8.5° (std.: 2.08°). The most susceptible areas include the narrow stream valleys along the Danube (e.g. the Nyáraska Valley south to Neszmély), the sides of the larger valleys, and the slopes of the smaller hills. Many of the most susceptible slopes are in populated areas. For example, Neszmély, Dunaszentmiklós, Bajót, MogyorósBánya, Annavölgy, and Sárisáp villages are especially affected. The quarries at the higher, inner parts of the hills do not fall into the susceptible zones, but several waste deposits in the eastern, lower part of the study area are on landslide-prone slopes.

4.2. Collection of mining waste facilities

The closed mine waste facilities are marked only as point features in the inventory of the Mining and Geological Survey of Hungary (MGSH, 2020). The 1:60,000 scale of the geohazard map allows displaying the areas linked to the points. Therefore, we reviewed the large-scale (1:10,000) topographic and geological maps of the study area and digitized the areal extent of waste deposits. The waste type and the reliability of the source were also recorded. The largest possible areal extent of the waste facilities was digitized in the cases where the site boundaries on the different data sources did not overlap.

The facilities were sorted into four categories based on waste type:

- Mining waste heap
- Quarry and rock heap (inert materials)
- Red mud reservoir
- Tailing

Based on the reliability of the source, three categories were distinguished:

- Surveyed and ranked in the official inventory
- Surveyed but not ranked in the official inventory
- Other source, only marked on other maps

The number of polygons in the waste type and source reliability categories is given in Table 3. The areal extent (km²) of the respective categories is given in Table 4. On the geological hazard map, areas from all reliability categories are marked, and mining waste facilities are categorized by their waste type. Most of the quarries and rock heaps are located on the hillsides and footslopes of the Gerecse Hills. The tailings and waste heaps of the non-inert materials are mostly in the Dorog Basin, around Dorog, Tokod, TokodalTáró, MogyorósBánya, Annavölgy, Sárisáp, and Csolnok settlements. These sites are mostly associated with the former coal mines in the area.

5. Discussion

We prepared a multi-hazard map describing the landslide and mining-related geological hazards of Gerecse Hills in 1:60,000 scale (Main Map). The map synthesizes data from the landslide and mining waste inventories of the local geological survey, topographic and geological maps, field work, and the estimations of a statistical landslide susceptibility model. The map consists of three main thematic parts: the documented events related to mass movements, the closed or abandoned mining waste facilities, and the results of the landslide susceptibility analysis.

The closed mining waste facilities inventory holds record of 46 sites for the area. Official hazard assessment was only carried out for 11 of them and only two of these sites have been knowingly remediated. To supplement the database, the type and areal extent
of 113 mining waste deposits covering 5.19 km² were collected from large scale topographic and geological maps. We found a significant number of mining waste deposits in the area that were not marked in the official inventory. The level of remediation for these deposits or the threats they pose are mostly unknown. While the maps that were used for data collecting provided useful information for the analysis, they might be outdated. The reliability of the information gathered from the maps should be checked on the field or evaluated by comparing the results to recent remote sensed data. Further research should aim to complete the database and continue the evaluation of the potentially dangerous sites.

The landslide susceptibility model analyzed the distribution of five geomorphometric variables and the geological features of the area with the frequency ratio approach. The results mark the areas that are the most susceptible to landslides compared to the other parts of the study area. The accuracy of the model predictions was checked with 5-fold cross validation. The results were accurate enough to be displayed on the map according to both our field experiences and the validation tests. On the map, 16% of the study area with the highest estimated susceptibility level is marked as prone to landslides.

The landslide-prone areas are mostly the steeper, loessy slopes of the study area. The populated areas of many municipalities fall within the susceptible zones; moreover, several mass movement events have already been reported from these locations, according to the local landslide inventory. We also found that the landslide susceptibility assessment indicates that several mining-related sites, mostly waste heaps and quarries, are located on landslide-prone slopes, or themselves form a high-risk morphology. The combined representation of the mining-related sites and the landslide-related phenomena on the map helps to identify areas where both hazard sources are present. Researchers and local planners both should pay attention to these areas to prevent hazardous events, especially if these sites are close to populated or otherwise vulnerable areas.

The findings of the study collect and supplement the data already available from different sources, while also highlighting the existing gaps in the thematic databases. The map will be a useful tool for

**Table 3.** The number of collected mining waste facility polygons and the reliability of their sources.

| Facility type        | Reliability |          |          |          |
|----------------------|-------------|----------|----------|----------|
|                      | Other source| Surveyed | Surveyed and ranked | All category |
| Mining waste heap    | 27          | 31       | 4        | 62       |
| Quarry and rock heap | 30          | 6        | 11       | 47       |
| Red mud reservoir    | 0           | 0        | 1        | 1        |
| Tailing              | 0           | 3        | 0        | 3        |
| All facilities       | 57          | 40       | 16       | 113      |

**Table 4.** The area (km²) of collected mining waste facility polygons and the reliability of their sources.

| Facility type        | Reliability |          |          |          |
|----------------------|-------------|----------|----------|----------|
|                      | Other source (km²) | Surveyed (km²) | Surveyed and ranked (km²) | All category (km²) |
| Mining waste heap    | 0.6243      | 0.8452   | 0.1221   | 1.5917   |
| Quarry and rock heap | 0.6934      | 0.0565   | 2.4379   | 3.1878   |
| Red mud reservoir    | 0.0000      | 0.0000   | 0.2914   | 0.2914   |
| Tailing              | 0.0000      | 0.1227   | 0.0000   | 0.1227   |
| All facilities       | 1.3177      | 1.0244   | 2.8514   | 5.1935   |
raising awareness to the problems and threats posed by the geological hazard sources in the central and northern parts of the Gerecse Hills and in the Dorog Basin.

Software

Raster data processing was done with SAGA GIS (7.6.4). The susceptibility analysis was done with Python scripts developed by D. Gerzsenyi (https://github.com/gerzsd/frmod). QGIS (3.10.7-A Coruña) was used for vector data processing and preliminary map design. The final map sheet was prepared with Inkscape 1.1.

Geolocation information

Geographic coordinates (WGS84, EPSG: 4326) of the boundaries of the study area:

- Longitude: West: E18.2906763398559, East: E18.731702020612591
- Latitude: South: N47.6423927776676, North: N47.77697358862431
- Center: E18.511611, N47.70971

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Disclosure statement

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Data availability statement

The final products of the analysis (sample landslide polygons, landslide susceptibility raster, mining waste polygons) that support the findings of this article are openly available in figshare (figshare.com) at https://doi.org/10.6084/m9.figshare.13625936.v1.

OpenStreetMap made by OpenStreetMap contributors (2019) is available from: http://download.geofabrik.de/europe/hungary.html. NASA’s SRTM 1 Arc-second Global DEM is available through EarthExplorer (https://earthexplorer.usgs.gov/).

The National Landslides Cadastre (https://mbfsz.gov.hu/hatosagi-uyegy/nyilvantanartasok/orszagos-felzsimozgaskataszter), the Closed Mining Waste Facilities database (https://mbfsz.gov.hu/hatosagi-uyegy/nyilvantanartasok/bezart-banyaszati-hulladekkezelok), the Geological Map of Hungary (1:100,000; Gyalog & Sikhegyi, 2005, https://map.mbfsz.gov.hu/fdt100/), and the Geological Map of the Gerecse Mountains (1:50,000; Budai et al., 2018, https://map.mbfsz.gov.hu/gerecse50/) are available from the Mining and Geological Survey of Hungary. Derived data based on these original data sources are available from D. Gerzsenyi upon reasonable request.

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No potential conflict of interest was reported by the authors.

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Data availability statement

The final products of the analysis (sample landslide polygons, landslide susceptibility raster, mining waste polygons) that support the findings of this article are openly available in figshare (figshare.com) at https://doi.org/10.6084/m9.figshare.13625936.v1.

OpenStreetMap made by OpenStreetMap contributors (2019) is available from: http://download.geofabrik.de/europe/hungary.html. NASA’s SRTM 1 Arc-second Global DEM is available through EarthExplorer (https://earthexplorer.usgs.gov/).

The National Landslides Cadastre (https://mbfsz.gov.hu/hatosagi-uyegy/nyilvantanartasok/orszagos-felzsimozgaskataszter), the Closed Mining Waste Facilities database (https://mbfsz.gov.hu/hatosagi-uyegy/nyilvantanartasok/bezart-banyaszati-hulladekkezelok), the Geological Map of Hungary (1:100,000; Gyalog & Sikhegyi, 2005, https://map.mbfsz.gov.hu/fdt100/), and the Geological Map of the Gerecse Mountains (1:50,000; Budai et al., 2018, https://map.mbfsz.gov.hu/gerecse50/) are available from the Mining and Geological Survey of Hungary. Derived data based on these original data sources are available from D. Gerzsenyi upon reasonable request.
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