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Debris-flow Susceptibility Assessment in Flow-R: Ribnica River Case Study

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Abstract Debris flows are among the most dangerous erosional geohazards due to the fast rate of movement and long runout zones. Even though the initiation can be triggered in mountainous areas, inhabited and with steep slopes, their propagation and deposition can endanger not only buildings and infrastructure in the urbanized areas, but also threaten human lives. As these initiation areas usually represent unattainable terrains with rapid vegetation cover development, field observations and aerial photo analysis become high-demanding tasks. Consequently, medium-to-regional scale susceptibility assessments are increasing in interest. They allow for efficient and effective identification of the most endangered zones and can be used to propose where further detailed studies should take place. In those terms, since it can be challenging to obtain enough data for larger regions, empirical models with low data requirements represent an adequate solution to the susceptibility modelling problem. In this paper, a medium-scale debris flow susceptibility assessment has been carried out along the Ribnica River in western Serbia. Both the source areas and the propagation extent have been identified with the Flow-R empirical model based on simple probabilistic and energy calculations. The key input data used to investigate debris flow susceptibility in the study area was 10 m resolution DEM. The combination of DEM, its associated morphological derivates, landuse and lithology datasets, with Holmgren's modified propagation algorithm and the angle of reach, allowed for the 1:25000 susceptibility assessment. The results are reasonable and can be of great use for determining the areas that need to be prioritized for further detailed studies.

Keywords debris flow, Flow-R, susceptibility assessment, empirical model

Introduction

Debris flows are gravity-driven masses of poorly sorted water-saturated sediment surged down the slopes, with an unsteady and nonuniform flow. Interaction of solid and fluid forces in debris flows is not only a distinguishing factor in relation to other phenomena such as rock avalanches and sediment-laden water floods, but also a leading factor of their unique destructive power. They usually occur with little or no warning, because of slope failure in continental and seafloor environments, sometimes exerting enormous loads on objects they encounter. Similar to water floods, their fluid-phase provides them with enough energy to travel long distances in channels with modest slopes, to inundate vast areas, damage structures and endanger humans (Iverson, 1997).

Considering the material and human consequences debris flows can have, it is of great importance to conduct hazard assessment for management and reduction of the risk posed by this geohazard. However, detailed studies require numerical modelling and comprehensive field work to determine the hazard in the debris flow deposition areas (e.g., Medina et al., 2008). Difficulties in mechanical debris flow modelling and hazard assessment are a result of a very complex nature of the phenomenon, the variability of controlling factors and the uncertainty of modelling parameters (Iverson, 1997; He et al., 2003). Since it is cost and time-consuming to acquire physical parameters necessary for deterministic debris flow modelling in regional scale (Carrara et al., 2008), the modelling approach must be as simple as possible with minimum data requirements. Such characteristics seem to be best acknowledged by spatially distributed region-scale models based on empirical approaches (Rickenmann, 1999). Empirical methods seem to be the most transferable to any site because of the degree of generalisation from the data on which they were created. One of those is introduced by Horton et al. (2013) through a Flow-R model (Flow path assessment of gravitational hazards at a regional scale). "The model allows for automatic source area delineation, given user criteria, and for the assessment of the propagation extent based on various spreading algorithms and simple frictional laws. The choices of the datasets and the algorithms are open to the user, which makes it compliant for various applications and dataset availability. Amongst the possible datasets, the DEM is the only one that is really needed for both the source area delineation and the propagation assessment, with its quality being of major importance for the results accuracy" (Horton et al., 2013). The Flow-R model has been successfully applied to different case studies for which regional susceptibility maps have been generated (e.g., Horton et al., 2008; Baumann et al., 2011; Kappes et al., 2011;

Jaboyedoff et al., 2012; Fischer et al., 2012; Pastorello et al., 2017). So, the starting point of the debris flow hazard assessment at regional scale is the identification of the debris flow-prone areas, which is known as susceptibility assessment (Guzzetti et al. 2005). Two main steps in debris flow susceptibility analysis are the identification of the potential source areas and the estimation of the runout. Methods used in those purposes vary in approaches they use and data they require. For the source-area identification there are statistical methods, linking a variety of environmental factors to an inventory of past events (van Westen et al., 2006), empirical methods that analyse the environmental parameters on the experience-base (Horton et al., 2008) and physical methods that couple hydraulic models with the calculation of safety factor (Carrara et al., 2008). For the runout computation, empirical relationships are the primary approach in use, which is based on the so-called angle of reach (Corominas, 1996). Many authors express this angle as a function of the debris flow volume (Corominas, 1996; Rickenmann, 1999; Iverson, 1998).

This paper presents an application of the regional-scale Flow-R empirical model for debris flow susceptibility assessment along the Ribnica River situated in mountainous area of the Zlatibor region in western Serbia. Through modelling with Flow-R, a first overview of the debris flow susceptibility of the study area has been conducted even without the records of the past events and numerous environmental data for the calibration. The main objective of this paper was to acquire preliminary information on hazard-prone areas along the Ribnica River which could be used as a base for future investigations and detailed studies on hazard and risk assessment.

Study Area

Geographical characteristics

Study area is located in the western-southwestern part of the Republic of Serbia, in the municipality of Čajetina. It extends between 43° 42' N and 43° 40' N and between 19° 37' E and 19° 34' E and covers the area of approximately 12 km² (Fig. 1, left). The territory of the municipality, including the study area, belongs to the Zlatibor district, dominated by the Zlatibor mountain. This entire domain is mountainous with its elevations ranging from 650 to 1100 m. It's characterized by a well-developed hydrological network consisting of several rivers and streams, with the most important ones being the Rzav Rivers and Ribnica hydro-accumulation. The climate of this area is dominantly humid continental with the annual precipitation average of 990 mm.

The most dominant entity of the study area is Ribnica River, the main branch of Crni Rzav River. The hazard-prone areas, common in the study area, are mainly determined by the Ribnica River flow and numerous gullies along the river.

From the geomorphological point of view, the territory of the study area belongs to Zlatibor plateau and is characterized by an elevation minimum of 606 m and a maximum of 1222 m (see Fig. 1, left). Most of the study area territory has slopes higher than 20°, especially in the parts along the Ribnica River with maximum value of 67°.

Geological setting

Study area consists of Jurassic rocks (Fig. 1, right) whose distribution is mainly associated with the Zlatibor ultramafic massif and its edges, which extend from Tara Mountain to Rzav Rivers

There are different understandings about the tectonic position, the way of appearance, the structural form, and the age of the Zlatibor massif. It is located in the central part of the Dinaridic ophiolite belt, tectonically representing a slice that rests against sedimentary rocks with high-angle contact. Ultramafic rocks composing the massif are intensively fractured and serpentinized at the base of the thrust slice, and they are weathered and cut by magnesite veins in the upper part of the massif. According to Mojsilović et al. (1971), the Zlatibor massif is predominantly of harzburgite character. In addition to the harzburgites, lerzolites, dunites and from them formed serpentinites were distinguished. All the primary rocks represent the differentiations of the harzburgite magma. Differentiation of study area's harzburgites was based on the petrological investigations, due to them macroscopically not differing from the other peridotite rocks. Serpentinites, which make up the edges of the massif, are of harzburgite and dunite character. From the lithological point of view, the study area could represent a mass movement-prone area because western-Serbia peridotite rocks are generally very jointed and prone to the weathering processes.

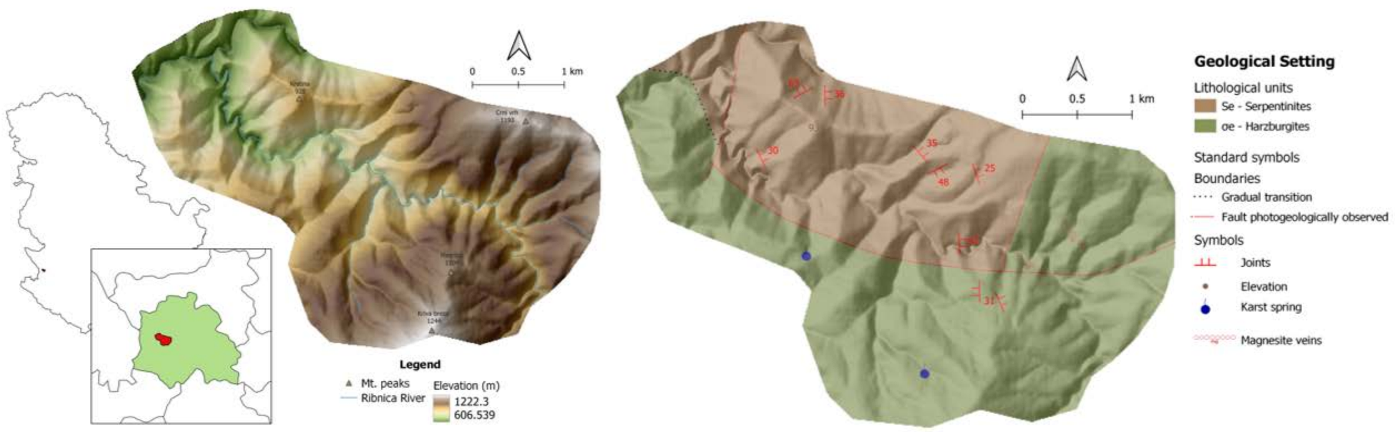

Figure *1* Study area. Its position and elevation - left. Its geological setting - right

Materials and Methods

Debris-flow modelling in Flow-R

Flow-R is an empirical debris flow susceptibility model, developed under Matlab®, with a clear and user-friendly interface. It allows for the simulation and hazard assessment at a regional scale for different types of natural hazards such as debris flows, snow avalanches and rockfalls. Trough modelling with Flow-R, regional debris flow susceptibility maps can be generated with low-data requirements and satisfying accuracy, at the same time.

The This GIS-based susceptibility tool processes the input data in order: 1) to delineate the potential source areas by means of morphological and user-defined criteria, and 2) to compute the propagation of the debris flow on the basis of the frictional laws and flow direction algorithms (Horton et al., 2013). Important to emphasize, such regional-scale computation processes cannot take the debris flow volume or mass into account.

The computational phase number 1 – source area identification consists of an index-based approach in which multiple spatial data is incorporated, such as Digital Elevation Model (DEM), slope gradient, flow accumulation, lithology etc. Importation of the entering datasets requires the definition of the computation criteria or thresholds for each one of them. The source area assessment consists of classifying the input datasets grid cells as either favourable, excluded or ignored, if the initiation is possible, unlikely or no decision can be made, respectively. A grid cell can be marked as potential source area if it has been selected as favourable at least once, and never excluded.

The computational phase number 2 – assessment of the propagation is based on the spreading algorithms which control the path of the debris flow, and the friction laws which determine the runout distance. Even though there are several different direction algorithms to choose from, Horton et al. (2013) recommend the application of Holmgren's or Holmgren's modified version, since it allows reproducing most of the other algorithms and parametrizing the spreading. Runout distance can be assessed by implementing one of the two available algorithms: the friction model from Perla et al. (1980) – originally developed for avalanches, that calculates the runout distance as a function of the coefficient of friction μ and the mass-to-drag-ratio ω, and the simplified friction-limited model (SFLM) characterized by a minimum travel angle.

Input datasets

According to Takahashi (1981) and Rickenmann and Zimmermann (1993), three critical factors for debris flow initiation are: terrain slope, water input, and sediment availability. While the first two factors refer to the general disposition, the water input plays a role of a triggering factor.

To represent these critical factors in the source area assessment, the following datasets have been imported to the Flow-R – all with the same resolution (10 m), coordinates and in ASCII format:

- Digital elevation model, as the only essential data to model the debris flow susceptibility;
- Slope gradient and plan curvature, to take into account the slope shape influence;
- Flow accumulation, to take into account the water input related to the upslope contributing area;
- Lithology, to take into account the debris production related to the material characteristics;
- Land use – vegetation classification, to take into account the forested areas.

Digital elevation model (DEM) with a resolution of 10 m, smoothened and filled, has been used to assess the debris flow susceptibility of the study area. This elevation raster has also been used to derivate the other morphological and hydraulic input datasets - slope gradient, plan curvature and flow accumulation. According to many studies (e.g., Zhang and Montgomery, 1994; Quinn et al., 1995; Horton et al., 2013) 10 m grid size represents an adequate resolution for simulating different geomorphic and hydrological processes, without missing some significant areas (finer resolution), or enlarging the extents (lower resolution).

An orthophoto image has been used to generate the vegetation classification needed to represent the land use, or to be more precise, to include the forested areas in the source assessment procedure. The vegetation cover has been segmented by a vegetation index generated from red, green and blue band of the orthophoto image (eq. 1):

$$I = \frac{Red+Blue}{Green} \quad [1]$$

where I represents the vegetation index, and *Red*, *Green* and *Blue* are the orthophoto image's bands.

Lithology data has been extracted from the Geological Map of the Republic of Serbia (1:100 000), by digitising it for the study area's extent, and converting it into a raster file with 10 m resolution. Both serpentinites and harzburgites have been included in the modelling process.

Simulation parameters

For the source area delineation, the model elaborates the input datasets using different threshold values and classifies every grid cell as explained above. Considering the fact that most debris flows occur in terrains with a slope gradient higher than 15° (Rickenmann and Zimmermann, 1993; Takahashi, 1981; Bathurst et al. 1997), this value has been taken as the lower initiation threshold. Since the plan curvature can contribute to localizing hollows, gullies and channels, by its negative values indicating a concave morphology (Carrara et al. 2008), for the triggering value -2/100 m^{-1} has been chosen. Horton et al. (2013) recommend this value as an optimum for the 10 m resolution DEM (for western Switzerland). For defining the flow accumulation threshold, based on the relationship between the upslope contributing area and the terrain slope, Horton et al. (2008) suggest two curves, combining the work of Rickenmann and Zimmermann (1993) and of Heinimann (1998) – one for the extreme and one for the rare events, respectively. For the computation process in this paper the 'extreme events' equation has been applied:

$$\begin{cases} tan\beta_{tresh} = 0.31 S_{uca}^{-0.15} & if \quad S_{uca} < 2.5\ km^2 \\ tan\beta_{tresh} = 0.26 & if \quad S_{uca} \geq 2.5\ km^2 \end{cases} \quad [2]$$

where $tan\beta_{thresh}$ is the slope threshold, and S_{uca} the surface of the upslope contributing area.

Probabilistic energy-based propagation calculation, for the previously delineated source areas, uses a variety of flow direction algorithms, depending on user's needs and preferences. Developed and recommended by Horton et al. (2013), modified Holmgren's (1994) multiple flow direction method has been used for the debris flow spreading assessment in this paper. It is expressed by the equation 3:

$$p_i^{fd} = \frac{(tan\beta_i)^x}{\sum_{j=1}^{8}(\tan\beta_j)^x} \forall \begin{cases} tan\beta > 0 \\ x \in [1; +\infty[\end{cases}, \quad [3]$$

Where i, j are the flow directions, p_i^{fd} the susceptibility proportion in direction i, $tan\beta_i$ the slope gradient between the central cell and the cell in direction i, and x the variable exponent. For x = 1 the spreading simulates the multiple flow direction by Quinn et al. (1991), whereas for when x increases in its value, the divergence is reduced up to resulting into the single direction for x → ∞ (O'Callaghan and Mark 1984). Horton et al. (2013) introduced the *dh* variable which enables the central cell of the computational window (3x3 matrix) to be risen up to 70 m, and to allow for the flow to be guided by the general topography. The authors suggest that a 10 m resolution DEM is not very sensitive to the *dh* parameter and recommend the usage of exponents in range from 4 to 6. Following the stated above, the *dh* variable has been set to 1 m, whereas for the x exponent the value of 4 has been used. An additional parameter being considered in the computation is the persistence function (inertial parameter), that represents the change of the flow direction angle between the two consecutive cells. The one implemented in this paper is the Gamma (2000) function.

The runout distance computation doesn't take into account a source mass, so it is based on a simple energetic balance between a cell and the next one, represented by the equation 4:

$$E_{kin}^i = E_{kin}^0 + \Delta E_{pot}^i - E_f^i, \quad [4]$$

where E_{kin}^i is the kinetic energy of the cell in direction i, E_{kin}^0 is the kinetic energy of the central cell, ΔE_{pot}^i is the change in potential energy to the cell in direction i, and E_f^i is the energy lost in friction to the cell in direction i.

There are two frictional models available for use: Perla et al. (1980) and the simplified Friction Limited Model (SFLM). SFLM is based on the maximum possible runout distance, which is characterized by a minimum travel angle, also named the angle of reach (Corominas, 1996). It is the angle of the line that connects the source area to the most distant point reached by the debris flow. For this paper's purpose, the angle of reach has been set to 11°, and to ensure there are no improbable runout distances produced, the velocity limit has been set to 15 m/s.

Threshold values implemented in the source area delineation and propagation assessment for the Ribnica study area are summarized in Tab. 1.

Table 1 Flow-R modelling parameters for the study area

Source area delineation	
imported dataset	*criteria*
Digital elevation model	above 600 m
Slope gradient	above 15°
Flow accumulation	extreme events for 10m DEM
Plan curvature	-2/100m^{-1}
Land use	default
Lithology	default
Propagation assessment	
algorithm / function	*criteria*
Holmgren (1994) modified	dh=01m; exp=04
Inertial parameter	Gamma (2000)
SFLM (travel angle)	11°
Velocity	15 m/s

Results

Simple, yet effective empirical medium to regional scale debris flow model Flow-R allowed for the delineation of debris flow source areas and estimation of propagation extent in medium scale of 1:25000 for Ribnica study area.

Despite the fact that the model essentially only requires the digital elevation model as input data, morphological, vegetational and lithological characteristics have also been taken into account for this study case.

Source areas have dominantly been identified in two main parts of the study area, as shown in Fig. 2. Majority of them is located along Ribnica River, in central to eastern parts of the study area, characterized by elevations ranging from 850 to 1000 m, mostly at north-facing slopes with angles of inclination ranging from 30 to 40°. Other source area cluster is located in NW part of the study area. It is characterized by the lowest elevations of the study area, ranging from 620 to 700 m, mostly north-facing slopes with angles of inclination ranging from 20 to 40°. Through visual orthophoto image interpretation, Flow-R delineated source areas have been found to be reasonably outlined, with majority of them being placed in river gullies at high elevations, as expected.

As it comes to assessing the spreading of debris flow material, modified Holmgren's algorithm in combination with SFL model and velocity limitations allowed the calculation from all the determined source areas. The results are shown in Fig. 3 and represent rational outcomes in regard to estimated size of runout zones.

Since there is no inventory map to be taken into account for the validation process, the results can be observed as a preliminary debris flow spatial prediction of sufficient accuracy.

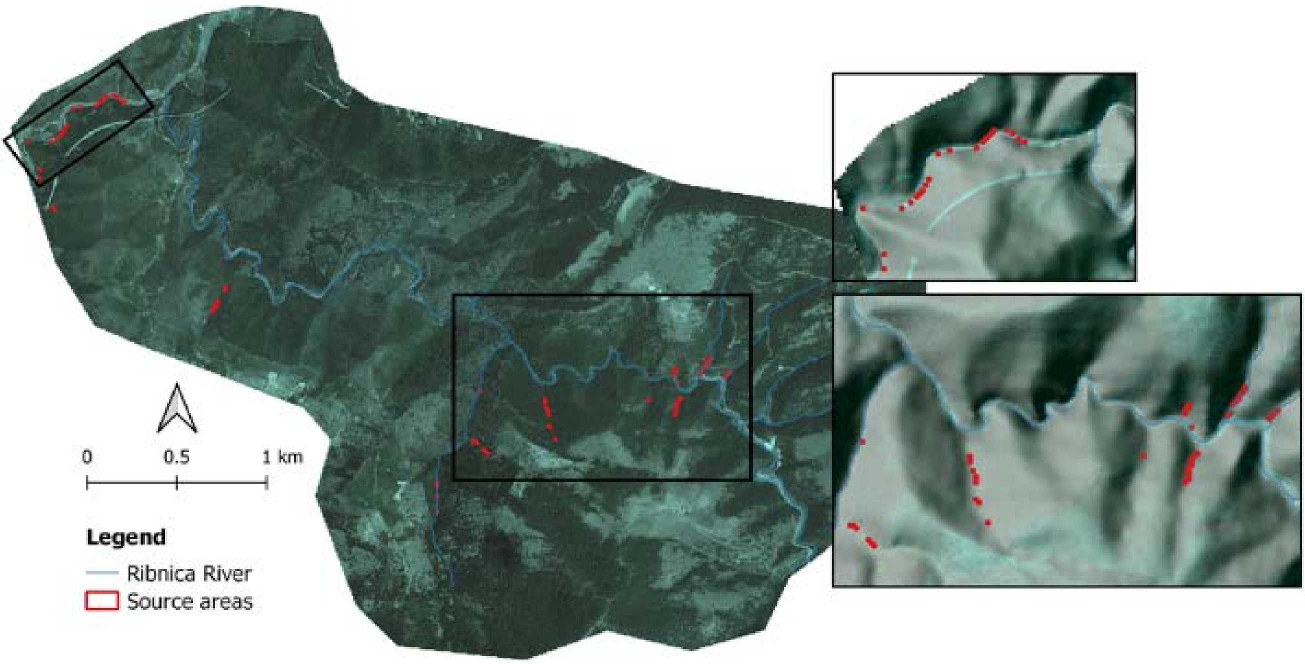

Figure 2 Delineated source areas with amplifications of two major cluster zone

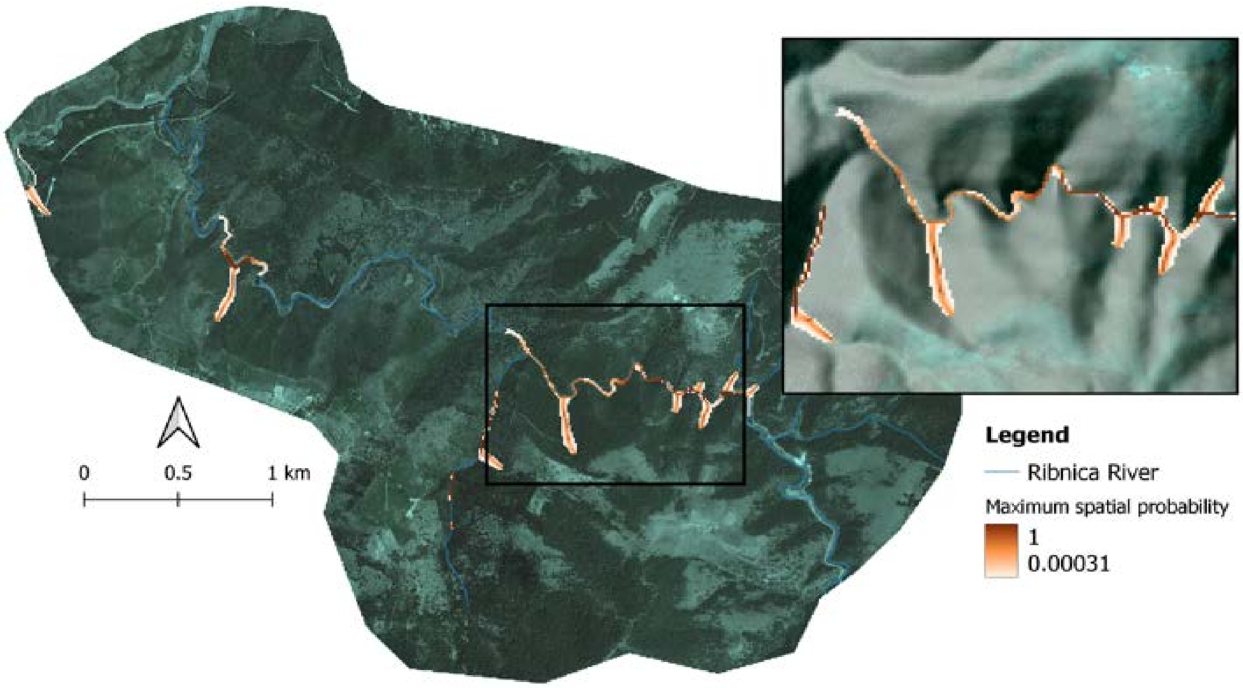

Figure 3 Calculated propagation extent with amplified debris flow prone zones in eastern parts of the study area

Conclusion

Susceptibility assessment, through an empirically distributed approach implemented within the Flow-R modelling framework, seems to be an appropriate first step in hazard and risk analysis. Even though Flow-R cannot integrate local controlling factors and actual behaviours, it is still characterized by many advantages in hazard susceptibility assessment. It enables the user to conduct a regional to medium scale analysis with minimum input data requirements and short computation time, by adapting the functions and algorithms to the needs of the case study. Also, as a topography-based model, it results in propagation areas larger than observed in the field, which allows for more precaution.

This study represents the first debris flow susceptibility assessment along the Ribnica River in western Serbia. Unlike most of the similar analysis in Flow-R, for Ribnica study case there hasn't been an inventory map to take into account for validation of the generated results. This lack shouldn't seem to be an issue in assessing the debris flow susceptibility of the study area, because the key objective of this paper was to delineate the possible hazard prone zones. Generated results should be considered as a first phase of the hazard analysis in the study area that provides information on where field investigations should be conducted in the future. They should be used as a base for the next phase, which should consist of detailed studies needed to be performed in order to propose adequate mitigation measures.

The combination of available input datasets and chosen algorithms for debris flow susceptibility modelling in the study area has shown realistic results. Delineated source areas and propagation extents are in good agreement with expected outcomes based on study area's morphological features and the orthophoto visual evaluation. Most of them are found to be located along the Ribnica river in the eastern part of the study area, which is characterized by the highest elevations and slopes between 30 and 40°.

For the future work, it would be of great interest to perform detailed studies on the hazard assessment in the study area, conduct field investigations, and compare the results and conclusions with modelling results generated with limited input data.

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