Regional Debris Flow Hazard Assessment of the Grdelica Gorge (Serbia)

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Abstract

Road infrastructure development is currently very intensive in Serbia. One such example is the Grdelica Gorge, where a new highway was aligned and put into service in 2019. The Gorge has provided a very challenging engineering environment imposing high levels of several hazard types: floods; slides; debris flows; and rockfalls. In this work, the debris flow hazard for the first 15 km of the road route was in focus. The assessment included an expert-driven analysis for identifying potential source areas, coupled with deterministic modelling of the flowing process originating from these source areas, resulting in detailed simulations of the final runout distance, height of deposit, and flow velocity, which are all reliable parameters for mitigating the hazard across the road alignment. A combination of geomorphological criteria, processed in a GIS environment was used to narrow down the search of source areas containing loose, erodible material which easily mobilizes under saturated conditions. The criteria were calibrated by the outlines of the available inventory, acquired by remote sensing techniques. The Digital Terrain Model with 12.5 m resolution was used for running RApid Mass Movement Simulation (RAMMS), using estimated bulk density and friction coefficients as input parameters. Since there was no recent debris flow in the area for the appropriate back-analysis of these parameters, experience-and lab-based estimations were used. Several simulations have reached the road alignment, wherein a few imposed significant threats with respect to deposit height and velocity that require additional attention.

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Keywords

Hazard assessment · Debris flow · Runout · RAMMS · Regional scale

1 Introduction

Infrastructure development and investment strategies have put road construction in focus in Serbia in the past decade. Existing routes have been upgraded, but what is more challenging, entirely new routes have been designed through rugged terrains. One such example is the Grdelica Gorge along the South Morava River in the south of Serbia, which belongs to the international route E-75, connecting Central and South Europe. A new route with a full highway profile was designed through a relatively narrow gorge, while the previous E-75 route was recategorized as National Road No. 158. At present, the Gorge hosts the river, the previous road, a new full-profile highway, and a railway, as well as some local roads, in a corridor that is locally as narrow as 100 m, making the new highway construction a very difficult engineering task at the time. In addition, unrealistic deadlines, and legislative and political circumstances affected the usual design time frames and enforced design solutions before they were analysed from all aspects. For instance, the hazard assessment which is suitable for the feasibility and preliminary stage of the route design was undertaken at a later stage, leaving little or no possibilities for avoiding hostile sections of the route. Instead, these parts were resolved by a more complex and more costly solution, which faced constant problems during construction that had to be, and still are mitigated on the go. Hazard assessment and the downscaling investigation principle (investigating from wider to narrower area) is, therefore, imperative and must be undertaken at an early design stage to avoid at least some of the difficulties of road construction.

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1.1 Study Area

The Grdelica Gorge (Fig. 1) is located along the South Morava River, which is one of the largest river systems in the country. Stretching for more than 28 km, sloping up to 50°, and scaling significant relative altitudes from about 270 m to 900 m above sea level, the Gorge is a marble of nature, but at the same time, a very hostile terrain for any engineering endeavour. It connects the Neogene basins of Vranje (upstream) and Leskovac (downstream), which have more than 60 m of total elevation difference, indicating a strong neo-tectonic activity (relative subsidence of Leskovac and Vranje block in comparison to central Predejane block) and as a result, an intensive erosional incision into the weathered and jointed bedrock, represented mostly by low-grade crystal schists. In addition, the area was volcanically very active in early Tertiary, when numerous dacite-andesite dykes (a periphery of a large Surdulica volcanic complex to the south) penetrated the earlier gabbro intrusions and crystalline base throughout the valley (Fig. 2). The left valley slopes are capped by Cretaceous limestone, which provide a high-capacity water discharge at their contact with the impermeable schists laying below. The Gorge is echeloned along the major structural elements, i.e. NW-SE striking regional faults and anticlines, shifted by a younger set of NE-SW striking faults (Marković et al. 1995).

The abundance of water, lithologic diversity, tectonic conditions, and structural complexity are directly reflected in superficial processes (Marković et al. 1995). The high weathering rate and climatic conditions, especially in the schistose core of the valley, have produced a thick saprolitic topsoil, prone to erosional and landslide processes (Fig. 2). The entire watershed was systematically vegetated to suspend or moderate the erosion in 1970–1980, while short tributaries were featured with flood barriers to suppress torrents. Still, the slope processes are easily reactivated throughout the valley after any significant engineering activity (slope undercutting, embankment loading, tunnelling, etc.) which has been confirmed in the recent construction activities for the new highway. Seismically, the area is of no significant potential (Marković et al. 1995), whereas the climate, transiting from continental to alpine, shows common temperature and precipitation variance for such terrains, with no significant extremes. However, it is arguable whether any potential climate change could disturb such balance and introduce new aspects of the problem ahead.

The area of interest (AOI) does not encompass the entire Gorge (due to data coverage issues), but only the first 15 km

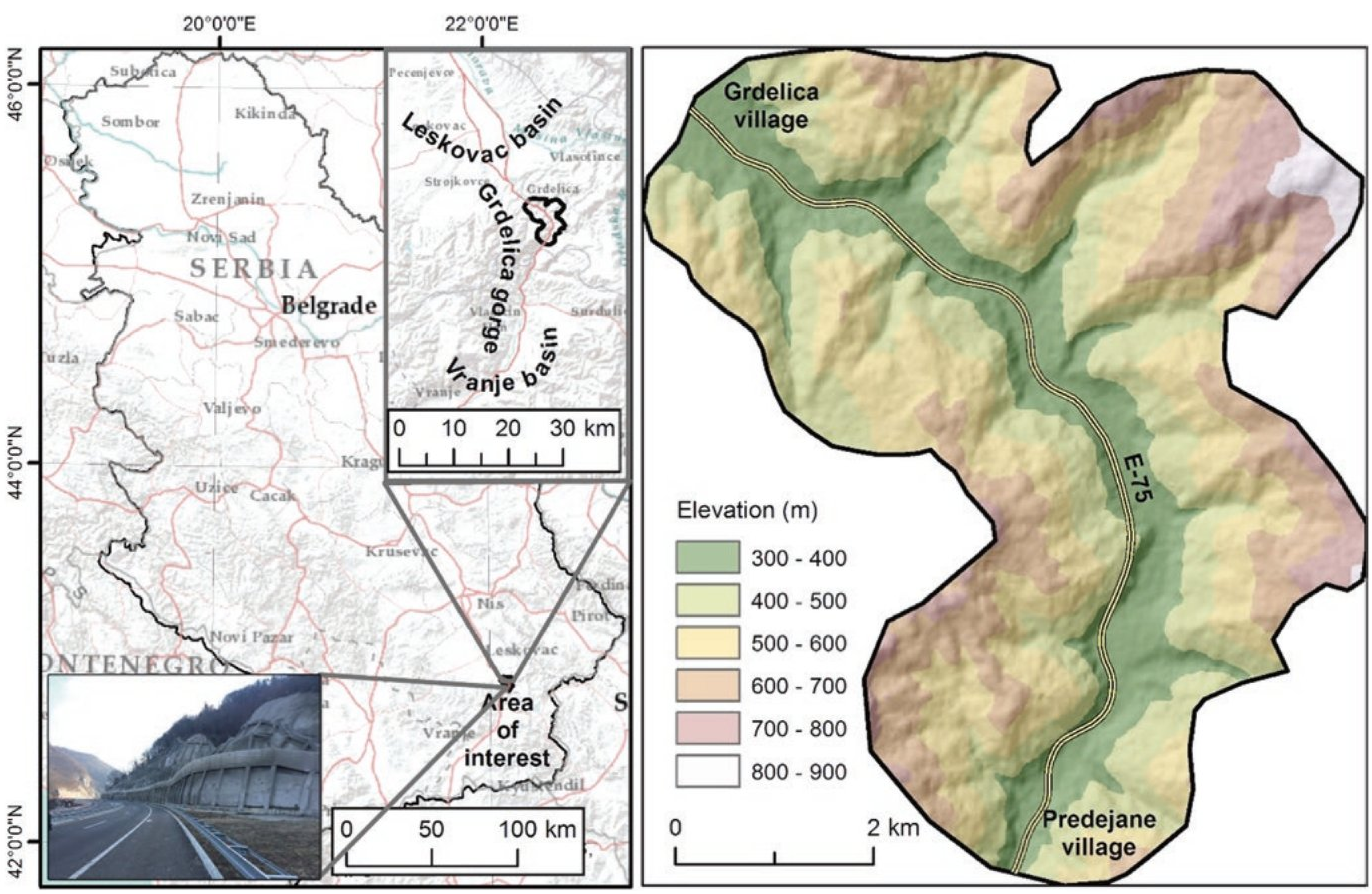


Fig. 1 Location of the AOI (left) and its Digital Elevation Model (right)

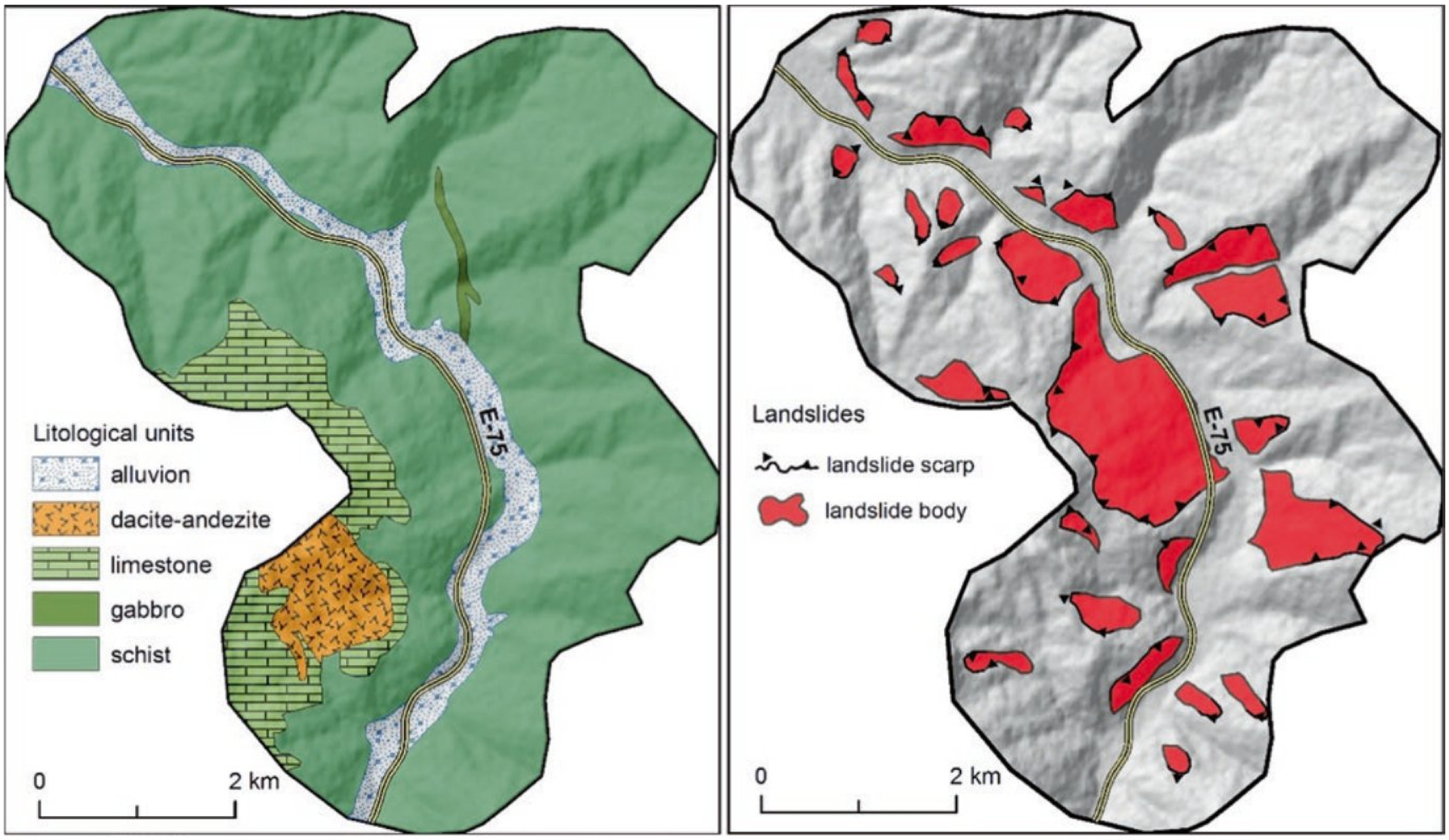


Fig. 2 Simplified geologial map (left) and Landslide inventory (right)

from its entrance, i.e., upstream of Grdelica village to Predejane village (Fig. 1), covering about 37 km2. Proliferating slope processes in this part have been investigated in the past (Marković et al. 1995), but the interest was renewed as the design of the new highway implied the use of the left valley side, which represents the inner area of interest (IAOI). The expected hazards were primarily characterized by shallow and dormant landslides, with seldom torrential floods, with associated gully erosion and alluvial fans, scree slopes, and rarely rockfalls. However, during the road construction and opening of wide and high cuts, many instabilities reoccurred (Abomasov et al. 2022). Therein, debris flows were singled out from the general landslide assessment to be separately analysed for the first time in domestic practice.

1.2 State-of-the-Art Regional Debris Flow Hazard Assessment

At regional scales (from several tens to several hundreds or thousands of km^2), debris flow models and simulations cope with uncertainty at each step of the way, beginning with accuracy of the source area inventory, input friction parameters' reliability, accuracy of the topographic surface models, level of approximation introduced in the flow models, etc. Thematic inventory focused solely on debris flows is uncommon (Guzzetti et al. 2012). They are a constitutive part of general inventories and are used in general landslide assessment practice, by implementing various approaches, from expert to deterministic (Krušić et al. 2017a), and mixed together with other landslide types, thereby inheriting a more general methodology of the assessment, which is more appropriate for short-ranged processes where source area and runout are not set far apart. This is not the case for debris flows, as they are rather long-ranged, even in regional scales, and require two-stepped analysis: (i) delineating the source areas and defining their material properties and water content, (ii) simulating the runout using appropriate flow model. Being that much different in their mechanism and that much outnumbered by slides within the general inventories, debris flows are commonly poorly represented in regional scale models. Their zone of influence is practically limited to the source areas, while their true hazard lies downslope and remains undetected.

This issue was recognized in the landslide assessment practice, and there have been numerous attempts to analyse the debris flows separately at regional scales. However, most of the authors have focused on (i), i.e., delineating and characterizing source areas using various techniques, ranging from expert-driven, statistics to deterministic, while complete (i) + (ii) procedures are rare. In fact, the debris-flow susceptibility is commonly related to (i) and includes upslope areas, while debris-flow hazard is related to both (i) + (ii) and includes the downslope areas, but primarily the runout zones (commonly, there is some infrastructure sitting in the foot of the slope or bottom of the valley where flows are terminating).

For instance, Salvetti et al. (2008) are suggesting a probabilistic approach to replace deterministic in cases when input frictional parameters cannot be estimated. A credal network is applied on a set of coupled Geological, Hydrometeorological, and Topographic thematic layers fed into the model, which is based on Takahashi's debris flow theory, thereby delineating source areas. Blahut et al. (2010) used the Weight of Evidence statistical tool to filter viable source areas from inventories that included all kinds of landslides, wherein geological and topographic features were used as filtering criteria. According to their findings, the most important indicators of the source areas are altitude, land use, geology, slope, curvature, and flow accumulation. Similarly, Kang et al. (2017), suggested debris flow source area criterion based on the geomorphological characteristics, using an Artificial Neural Network model with a modified threshold for establishing the relationship between slope and upslope contributing area. Crowley et al. (2003) used hyperspectral imagery to detect freshly exposed source areas based on their higher oxide content than the surrounding ground. Liu et al. (2020) dealt with predicting debris flow triggering thresholds on large scales considering geological and topographical variations of effective rainfall. They have also underlined that zones with more complex terrain, thicker soil, and higher sand content would be more prone to initiation of debris flows. Our previous experience (Marjanović et al. 2016; Đurić et al. 2017) involved expert-driven delineation of source areas based on the shape of the fresh debris flow footprints, using multi-resolution and multi-temporal satellite imagery and field data. Full implementation is more common at local, site-specific scales, where the source area and runout distance are known, and back-analysis is performed to establish the triggering conditions (Krušić et al. 2017b; Krušić et al. 2018; Baggio et al. 2021). At regional scales, Zou et al. (2019) reported a method based on a hydrological response unit (a subsection of a regional watershed basin) to assess the debris flow risk on a river basin level. Another important aspect is the differentiation between debris flow and debris flood by their level of fluidization due to water contents, i.e., the amount of water accumulated from recharge (rainfall, snow thaw, etc.). Ilinca (2021) has discovered that a specific range of values of topographic parameters, such as Melton number, basin relief ratio, basin length, basin area, fan slope, and source area ratio control which of those two types will develop.

This work, inspired by some of the abovementioned research, tends to use a simple combination of GIS-based data-driven analysis and expert-driven calibration to outline the source area, and subsequently, simulate the debris flows initiated from those source areas, thereby imposing hazard to the exposed road, which is quantified by the outcoming velocity, and the debris hight.

2 Materials and Methods

Regional scale assessment is commonly operated using the worldwide available raster datasets, with resolutions ranging from 30 to 250 m, which are mainly open and free data. Implementation of the flow simulation can be done using several ways and tools, from commercial to open source, which means that the analyses are becoming more available with such policies (open data and software).

2.1 Data Inputs

Data needed for the two-fold flow analysis (i + ii) included various environmental features, primarily topographic and soil properties. For delineating the source areas, i.e., task (i), a Digital Elevation Model (DEM), DEM-derived slope and curvature, and topsoil thickness were used as inputs, as suggested in Blahut et al. (2010) and Liu et al. (2020). In addition, the expert-driven landslide inventory (Fig. 2) was used to supplement this task (i). For fulfilling the second task (ii) the same 12.5 m DEM was used, as well as the map of delineated source areas (Fig. 3), which is the outcome of (i). Table 1 summarizes the data sources and other basic information.

Laboratory data inter-alia included results from 45 soil direct shear tests (performed in the investigations for the road construction), wherein residual and peak shear strength were determined. They were sampled from boreholes spread around the IAOI. Source areas encompass the first several meters of material, so it is likely that most of these tests, involving mainly the topsoil and weathered schists, can directly apply to source areas. Cohesion and internal friction angle were in the range $c = 0–20$ kPa and $\varphi = 13–34°$, respectively, as well as the range of saturated unit weight $\gamma = 19–22$ kN/m^3 which was useful for estimating the range of input values for flow material mechanical properties (Table 2). Since there was no recent debris flow reported within the IAOI, even though the area is historically well known for debris flood events (witnessed by numerous anti-flood barriers in the local gullies), lab result extrapolation was the only option to calibrate the flow model.

2.2 Methodology

Task (i) firstly required standard GIS raster processing (cropping the rasters to the AOI domain, projection harmonization, etc.), followed by a raster calculator operation which

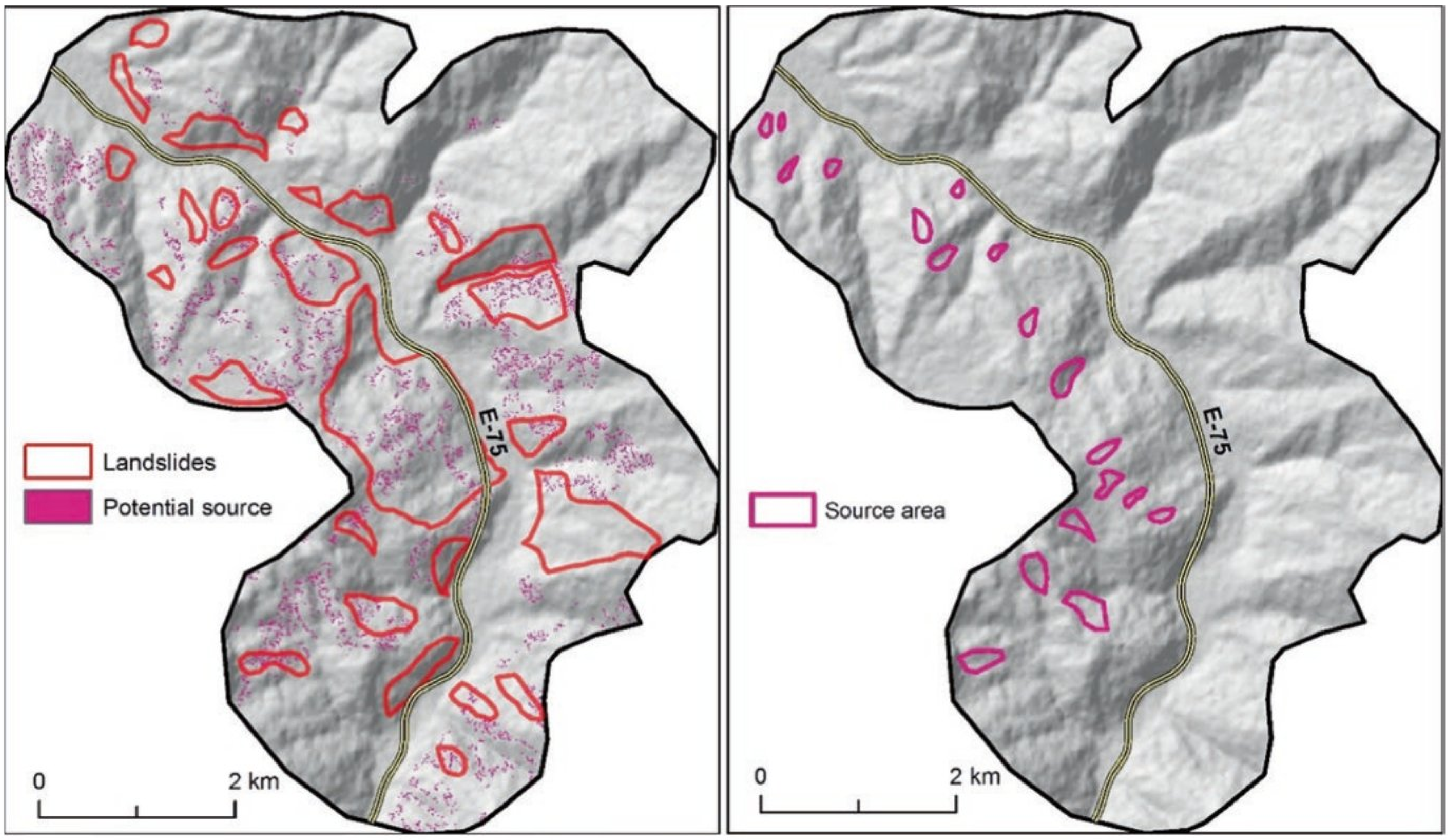


Fig. 3 Intermediate model of potential source areas with landslide inventory overlay (left) and final source area map (right)

Table 1 Input data types and sources

Input data	Data source	Resolution	Purpose
DEM	ALOS PALSAR mission	12.5 m	Task (i) source area delineation and task (ii) terrain surface for placing simulations
Slope	DEM-derived	12.5 m	Task (i) source area delineation
Curvature	DEM-derived	12.5 m	Task (i) source area delineation
Depth to bedrock	ISRIC world soil information	250 m	Task (i) source area delineation
Landslide inventory	Marković et al. (1995)	NA	Task (i) source area calibration
Source areas	From (i)	12.5 m	Task (ii) flow initiation points
Mechanical properties	From associated lab works	NA	Task (ii) input parameters for flowing material
Road section	Public Enterprise roads of Serbia	NA	Task (iii) exposure assessment

Table 2 Combinations of input parameters of the flow model

Combin. No.	μ	ξ (ms^{-2})	γ (kN/m^3)	Combin. No.	μ	ξ (ms^{-2})	γ (kN/m^3)
1	0.1	200	2200	12	0.35	200	1900
2	0.15	200	2200	13	0.1	500	2200
3	0.2	200	2200	14	0.15	500	2200
4	0.25	200	2200	15	0.2	500	2200
5	0.3	200	2200	16	0.25	500	2200
6	0.35	200	2200	17	0.3	500	2200
7	0.1	200	1900	18	0.35	500	2200
8	0.15	200	1900	19	0.1	500	1900
9	0.2	200	1900	20	0.15	500	1900
10	0.25	200	1900	21	0.2	500	1900
11	0.3	200	1900	22	0.25	500	1900
12	0.35	200	1900	23	0.3	500	1900

was used to narrow down the search for delineating optimal locations as source areas within IAOI (Fig. 3), using the following condition: (680 m > DEM > 400 m) & (23° > Slope > 13°) & (2.8 m > Depth to bedrock>2.4 m) & (−0.1 > Curvature> − 0.8). This condition implies that higher altitudes with moderately steep slopes and moderate topsoil thickness and concave relief are preferable. In the cases where these potential source areas coincided with the main scarp zone of the historical landslides, the local upstream micro basin (outlining the local ridge lines) is manually contoured as a source area (Fig. 3).

The second task was to simulate the flow over available terrain surface (DEM) using delineated source areas and estimated mechanical properties, friction coefficient $\mu = \mathrm{tg}\varphi$, unit weight γ, and viscose-turbulence drag coefficient ξ. Table 2 summarizes all tested combinations of input parameters, which is in accordance with lab results and common practice (Sosio et al. 2008). The implemented frictional resistance bulk flow model was the Voellmy-fluid friction model, implemented through RAMMS: DEBRISFLOW software (Christen et al. 2012). There was no available local hydrographic data to model the saturation condition realistically. The same applies to the level of entrainment due to erosion of the flow itself. In effect, the modelling was performed solely by calibrating frictional properties under saturated conditions assuming that there was no entrainment erosion. This is on the safe side since such an approach is more conservative (volume is enlarged by entrainment, the mass is densified, while conditions do not need to be necessarily saturated). The output of the model includes the runout of the bulk flow (when the resistance forces in the flow overpower the kinetic), its velocity distribution along the way, as well as its debris deposit height in raster format, which are all convenient for quantifying the level of hazard and exposure to a road segment that sits below designated source areas.

The final task (iii) was to assess the hazard exposure along assigned road sections in vector format, obtained from the official road management service. The resulting distribution of relevant features (runout, velocity, heights) of the flows that have their runouts reaching beyond the road line is performed by segmenting the road vector into 50 m sections and performing statistical analysis of feature values (statistics of pixels of resulting rasters) that intersect the road in a GIS environment.

3 Results and Discussion

The outlining of the source areas resulted in 18 designated areas of various sizes (7–100 ha), hosted primarily in schists (12), but also in limestone (4) and dacite (2). For the convenience of the analysis, simulations were run according to these three groups, assuming that flows hosted in the same material will behave the same in the simulation. Vegetation and other land-use features were not considered. As indicated, local hydrograph information was not available, so the saturation threshold under extreme conditions was taken from the research on general landslide thresholds experienced in Serbia in 2014 (Marjanović et al. 2018).

Each source area was geometrically defined (length, width, depth to bedrock, natural slope angle). The natural slope angle was used as a control to define the range of friction values that are used for defining combinations in Table 2. The average natural slope angle equals 13 ± 3° which can be theoretically assumed as the upper friction angle value $\varphi = 13°$ ($\mu = 0.23$). This is justified given that in direct shear lab tests, the residual angle lower bounds were exactly 13°. Since there was no back-analysis example available, it was not possible to evaluate the best model, but the most hazardous one in terms of runout, velocity and deposited height. The worst-case scenario included the following input combination: $\mu = 0.1$, $\xi = 500\ \mathrm{ms}^{-2}$, $\gamma = 22\ \mathrm{kN/m}^3$. Higher values of solid friction coefficient increase the friction with the ground and within the material itself, while higher values of viscose friction do the opposite, and too high values, e.g., 1000 ms^{-2} or higher that are rarely used in practice (Mikoš and Bezak 2021), might lead to over-fluidization and switch to debris flood scenario, which is considered as a different phenomenon that does not correspond to the methodology used for designating source areas, adopted soil saturation principle, and the involved bulk fluid model (mixed phases, while in floods fluid phase is more dominant). The worst-case scenario (Fig. 4) included debris runout distances between 0.5 and 2.5 km, maximum velocities of 27.3 m/s, and deposit heights up to 21.8 m. Such events were not recorded within the wider area, but in climate-changing conditions, they might become realistic. As indicated before, it is difficult to define a realistic model without a back-analysis option, therefore, a trial and error using 200 and 500 ms^{-2} was used in various combinations with other parameters (Table 2).

Further analysis involved exposure assessment for the worst-case scenario. The level of fluidization in the worst case was such that debris flows of almost all source areas have reached the road line and beyond. However, not all of them introduced the same hazard level, as some would flow in too slowly to the road to leave any effect on the construction, while some did not create sufficient volume to reach significant height (road embankment height is 5–28 m). To identify the actual hotspots and sections of the road that are most exposed, a segmented road vector was introduced, and per each of its 313 sections (all 50 m long) the maximum value of the overlapping raster (both, velocity and height) was calculated (Fig. 5).

The hazard along the exposed road is divided into five classes, guided by the Natural Breaks Intervals of respective

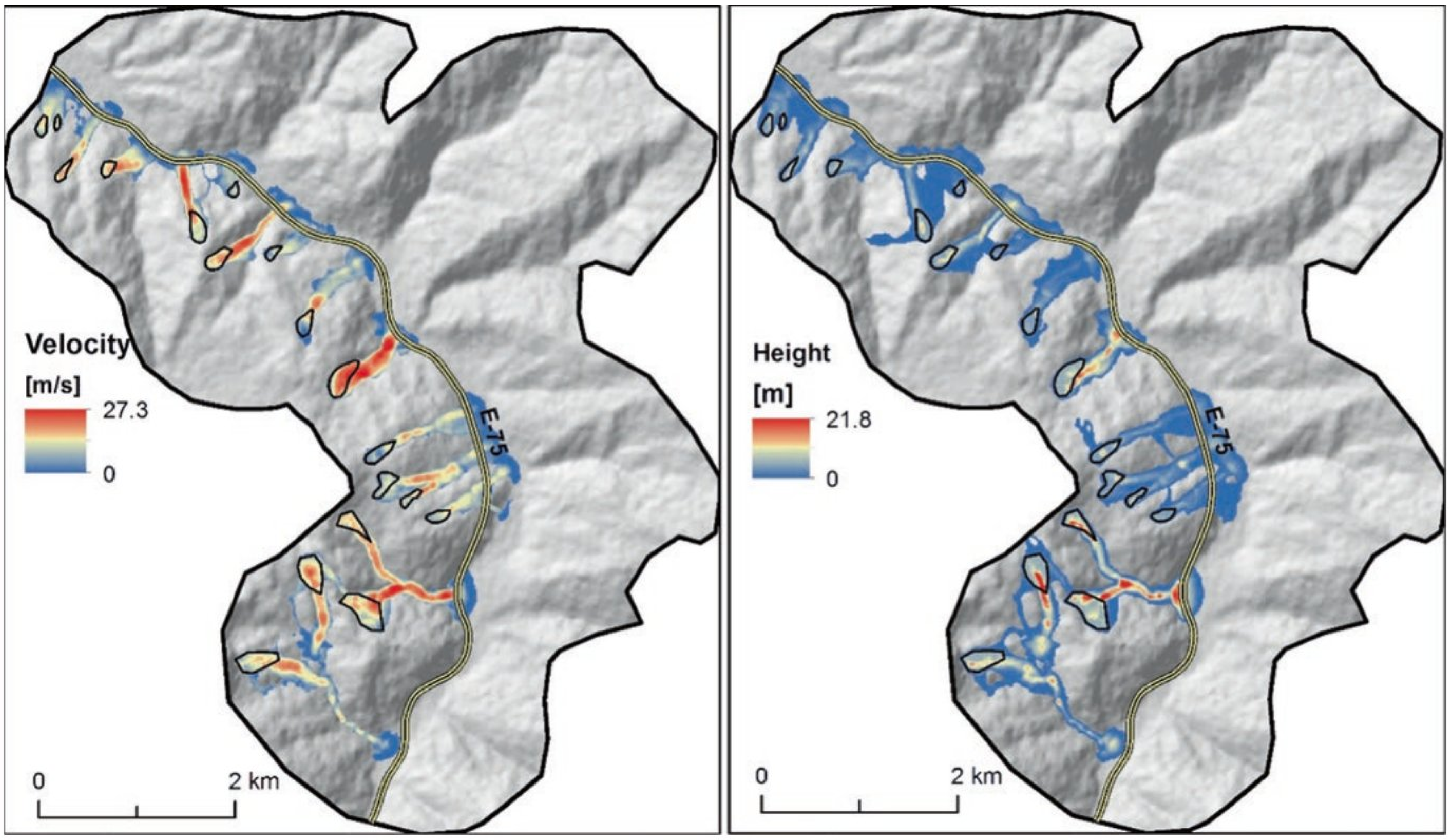


Fig. 4 The worst-case model simulation per velocity (left) and deposit height (right)

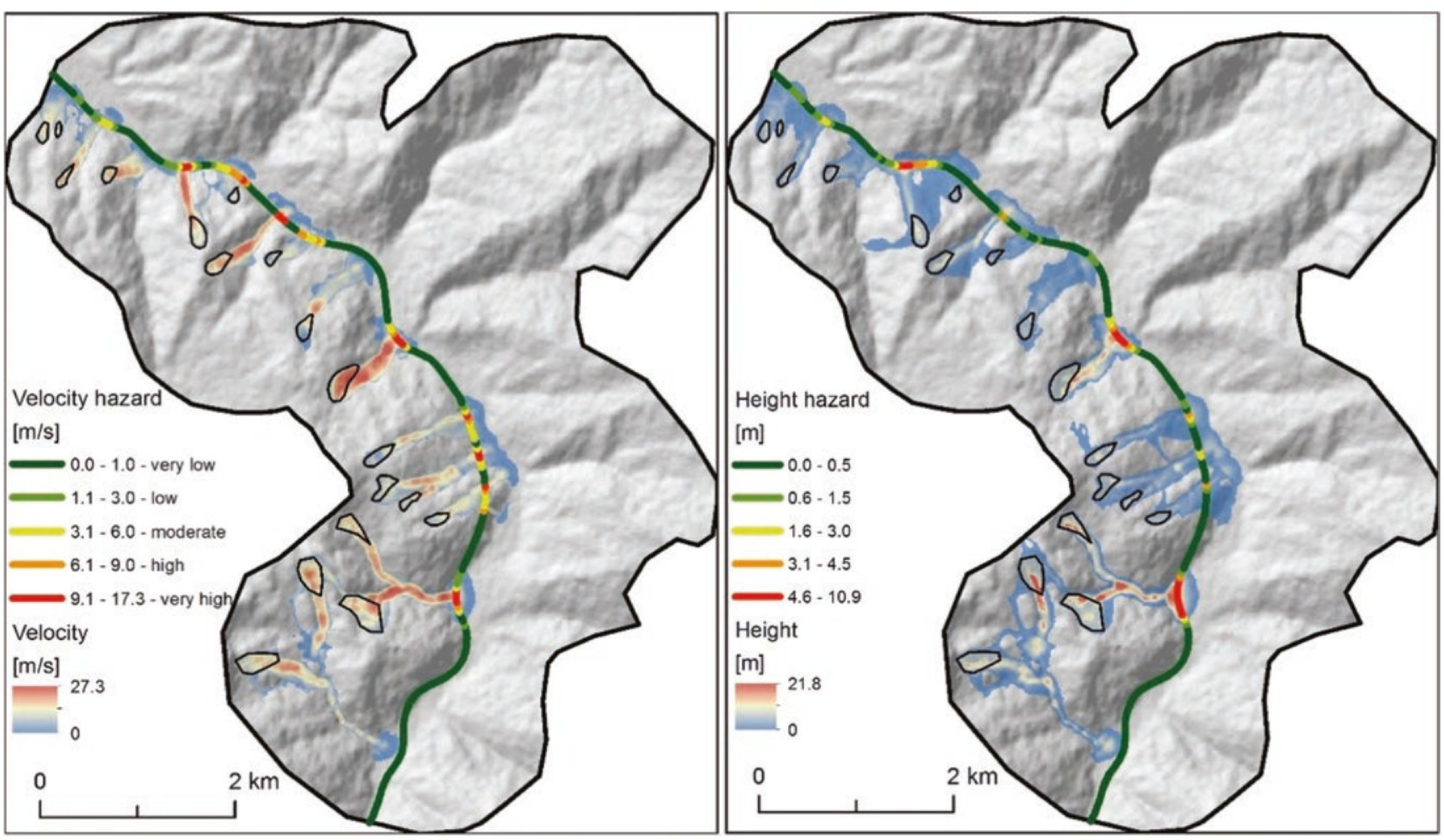


Fig. 5 Road exposure to hazard due to velocity (left) and deposit height (right)

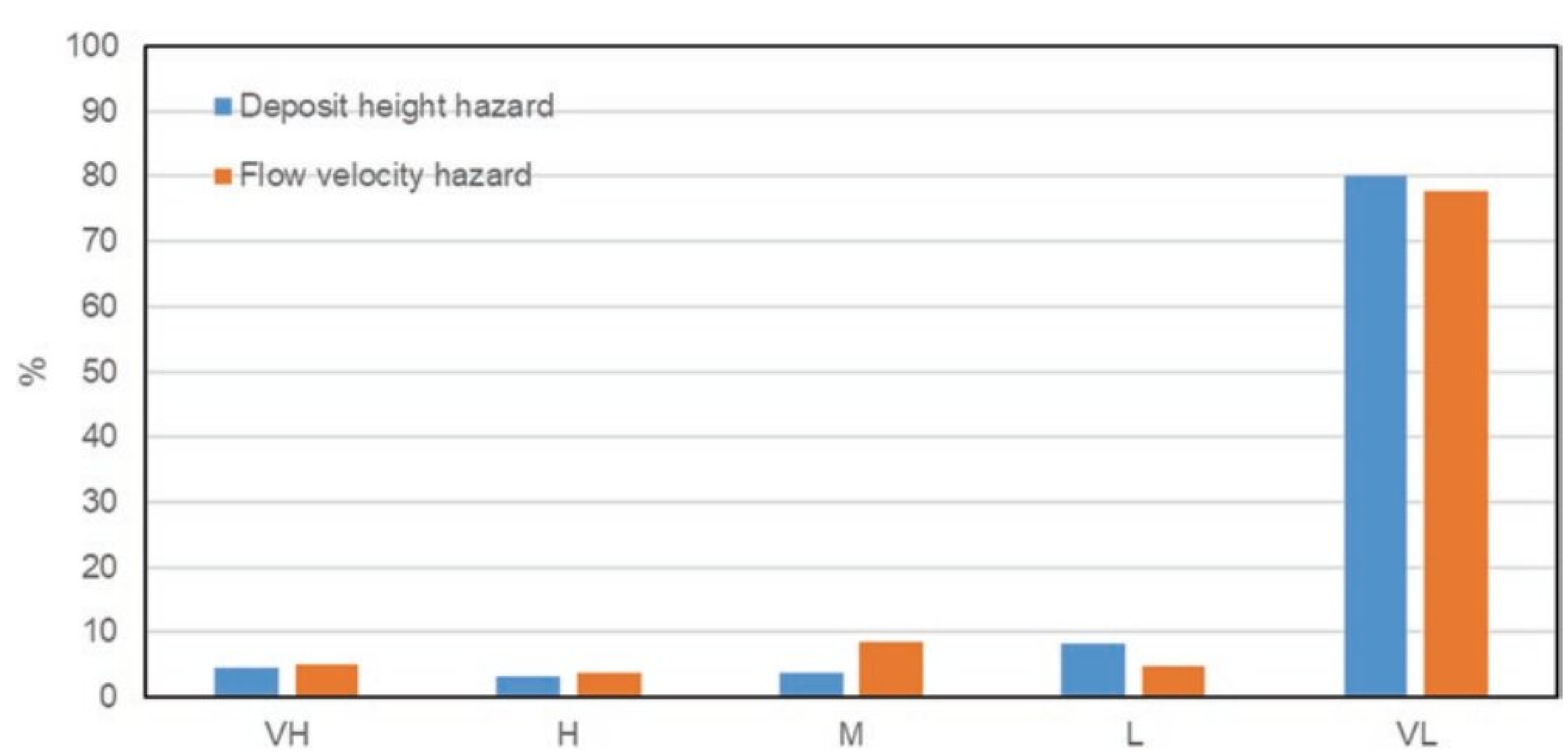
values (maximum height and maximum velocity), ranging from very low hazard, low hazard, moderate, high, and very high class. The intervals are further adjusted according to the actual conditions. For instance, a simulated deposit height that is nearly reaching the minimal embankment height (5 m) must be considered as a very high hazard class, so all heights over 4.5 m were classified as such. Similarly, the flux capacities of road culverts were used for adjusting the velocity hazard interval. Assuming culvert diameter R = 2 m and length L = 30 m (double track full profile highway), a flux of 90 m^3/s is obtained. When back-calculated, the flow velocity that corresponds to such flux is 9 m/s (assuming that the flow channel and culvert cross-sections are equal), which was taken as the lower bond for the very high hazard class. If the culvert to channel cross-sectional area is for example 2, the required velocity (high hazard) is decreased to 6 m/s and so forth (for moderate, low and very low hazard).

The hazard exposure model outlines the areas that are highly affected as bright red stretches of the road versus dark green stretches which are hazard-free (Fig. 5). Along the road route which is 15.6 km long, very high hazard due to the flow deposit height occupies 4.5% (700 m), high hazard 3.2% (500 m), moderate hazard 3.8%, (600 m), low hazard 8.3% (1300 m), and very low hazard 80.2% (12,500 m) (Fig. 6). There are three very high hazard instances along the route. Among them, the longest continuous very high-hazard stretch of the road equals 400 m. Very high hazard due to flow velocity occupies 5.1% (800 m), high hazard 3.8% (600 m), moderate hazard 8.6% (1350 m), low hazard 4.8% (750 m), and very low 77.7% (12,100 m). Along the route, here are eight very high-hazard instances due to velocity. The longest stretch of the road affected by the very high hazard due to velocity is 150 m. The most adverse scenario is the spatial overlap of velocity- and height-related very high-hazard segments. Such overlap is found along 1.5% (400 m) of the road route.

4 Conclusion

In this work, a regional scale debris flow hazard assessment was demonstrated in a case study in Southern Serbia, covering about 37 km^2 of hilly-mountainous landscape, with a relatively simple geological setting, but intensively tectonized and weathered rock. The recently constructed highroad, that runs through the valley was in the focus, i.e., its 15.6 km long subsample. It was necessary to demonstrate at a specific design stage how the road is potentially affected by hazardous phenomena, the debris flows in this case. The approach involved three tasks (i) delineating theoretical source areas (ii) running simulations with calibrated parameters, and (iii) quantifying hazard exposure along the road route. In total, 18 source areas were used for running 24 simulations, based on 24 combinations of input flow friction parameters. It has been shown that there are several relatively large hot spots. The approach shows that it is possible to micro-locate and quantify the hazardous phenomenon, by simulating its impact velocity and deposit height at road level. In addition, it was possible to discern parts of the road route which are most affected by one of the two hazards, or both acting simultaneously. This implicates the possibility of planning the maintenance and other budgeting aspects, e.g., remediation, more precisely, by knowing the length or surface of the road affected and approximate remediation costs common in domestic practice per area or length (Radić et al. 2018). Further research can be directed toward fitting friction parameters per each source area separately, appending additional useful parameters, such as stress and pressure, and furthering the analysis from debris flow exposure to debris flow risk by using available traffic frequency data. It is important to demonstrate such tools, which can be used by road managing enterprises not only for planning budgets dedicated to existing roads but for hazard prevention prior to construction of the new corridors. The approach allows for avoiding or

Fig. 6 Distribution of hazard classes (Very High—VH, High—H, Moderate—M, Low—L, Very Low—VL) along the exposed road



reducing the number of road intersections with high and very high hazard zones at regional scales, which is convenient for early road design stages, and should become a common practice, especially in developing societies.

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