Preliminary landslide hazard map of Serbia

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Abstract In this work a preliminary landslide hazard map of Serbia is presented as an output of a work group assignment in 2018. Simple multi-criteria approach based on experts' opinion is implemented over a set of data which are mostly publicly available. Input data included: Digital Terrain Model (and its derivatives) at 30 m resolution; Engineering geological map of Serbia at 1:300 000 scale (and its derivatives); Hydrometeorological dataset (and its derivatives); depth to bedrock model at 250 m resolution. There were seven conditioning factors which were derived from these input raster datasets. In addition, available landslide inventory on the national level was used to validate the model. The methodology first involved creating a questionnaire for domestic practitioners in the field of engineering geological mapping, to determine the sub-setting of conditioning factors into classes and individual weights of each conditioning factor in accordance with their influence on landslides. The weights were normalized in 0-100% range and then used as raster multiplicators for each reclassified conditioning factor. After their multiplication and addition in GIS environment a landslide hazard model was created. Result suggests that very high and high hazard class occupy about 12% and 28% of the territory, respectively. Administratively and spatially, the SW and W Serbia are the most affected. Validation suggests that very high and high hazard classes were confirmed in 46% of the inventory, moderate class has 31.5%, whereas remaining 22.5% can be considered as false negatives, leaving room for further improvements of this preliminary map version of the map.

Keywords landslide hazard, Serbia, multi-criteria analysis

Introduction

Landslide hazard mapping is becoming essential tool in planning and design worldwide (Mateos et al., 2020). It can be established at different levels or scales, ranging from global and continental, to national, regional, and site-specific. Naturally, the applied methodology varies accordingly, while also depending on the input data availability (Fell et al., 2008). In the case of Serbia, there were individual attempts to deal with the landslide susceptibility and hazard at different scales (Abolmasov et al., 2017b; Dragićević et al., 2012; Krušić et al., 2017; Marjanović et al. 2013; Tešić et al. 2020), but the matter was also recognized by authorities and there is a strong initiative to involve it in legislation. According to the current Law on mining and geological explorations (RS Official Gazette No. 40/2021), together with engineering geological mapping the duty to develop and update landslide hazard map of Serbia is entrusted to Geological Survey of Serbia (GSS). Under assignment of the Ministry of interior and Ministry of Mining and Energy, a Work Group involving esteemed landslide experts, steered by the GSS was assembled in 2018 with a task to develop *inter alia* a preliminary landslide hazard map on national level. This is the first map of such kind developed for the entire territory and the first one to be a joint venture of all respective landslide experts from their respective institutions, such as GSS, Faculty of Mining and Geology University of Belgrade, Highway institute Belgrade, Institute of Transportation "CIP", Institute "Jaroslav Černi", Ministry of interior Emergency Sector, and Ministry of Mining and Energy Geological investigations Department. One of the motifs for assembling such a group was the massive 2014 landsliding (Abolmasov et al, 2017ac), and constant urge to mainstream the landslide hazard issues, ever since. As indicated, the landslide hazard mapping was attempted in numerous occasions in Serbia, through different research and commercial projects. As they were mostly concentrated on local to regional level, an attempt to deliver national scale landslide hazard model is a pioneering one in Serbia. Practice and experience from these earlier projects were implemented in the national level case. The modelling was done in 2018-2019 by compiling the best international and domestic practices in large-scale studies (Abolmasov et al., 2017a). It is also important to mention that term landslide is herein considered in its widest form (Hungr et al., 2014) and includes various typology of mechanisms and materials, but primarily earth slides, and subordinately debris flows, while other types have not been considered.

Methodology

The applied methodology can be split into three sections: input data acquisition and processing; multi-criteria modelling; and validation (Fig. 1).

Input data preparation

Data repository included data on conditioning factors, i.e., factors that in combination outline zones that are likely to host landslides; triggering factors, i.e., factors that directly initiate landslide activation both spatially and temporally; and landslide inventory used for model validation.

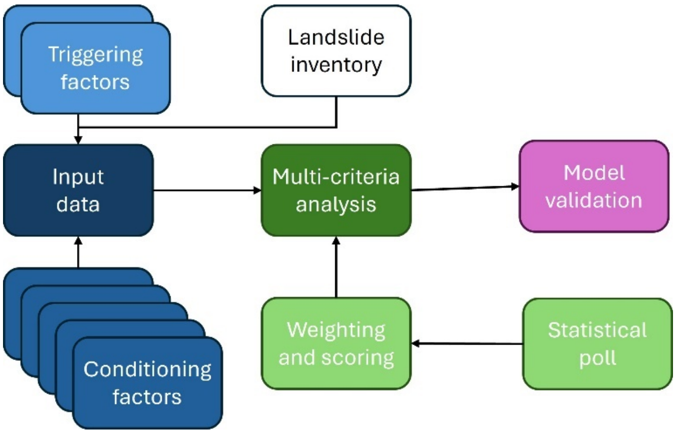

Figure 1 Methodology workflow.

A common set of conditioning factors (Tab. 1) that influence landslidng at large scales was used: Slope angle *S*; Lithology *L* (complexes of same engineering-geological features); Distance to structure *D2S*; Distance to river *D2R*; and Depth to bedrock *D2B*. Sloping indicates areas that are prone to instabilities, but not in linear fashion (steeper the slope higher the probability of landslidng), as steep angles in good rocks are not necessarily indicative of landslides, whereas gentle slopes in poor rocks can be. Therefore, lithology is another factor that can well control such combinations with slope angle. Rivers and linear structures, such as faults and joints are also commonly considered as weakened zones where weathering is intensive, groundwater is present and rock strength is weakened, therefore providing suitable conditions for instabilities. Areas closer to such lineaments are more likely to host landslides than those further away. All numerical conditioning factors (*S*, *D2S*, *D2R*, and *D2B*) were split into five classes using quantile interval splitting, to ensure them being spatially equally distributed. Nominal factor (*L*) was aggregated to a reasonable number of classes, whereby engineering-geological units with similar characteristics were generalized (Tab. 2). Subsequently these all classes in all rasters were assigned a score 1-5, wherein 1 depicts the least influence (e.g., flat slopes, good rock, areas away from lineaments and with shallow bedrock) and 5 depicts the most influence on the landsliding process (steep slopes, poor rock, areas close to rivers and faults with deep bedrock).

Table 1 Landslide conditioning and triggering factors.

Conditioning factor name and symbol	Data source	Scale/ resolution
Slope angle *S*	www.usgs.gov	30 m
Lithology *L*	https://geoliss.mre.gov.rs	1:300k
Distance to structure *D2S*	https://geoliss.mre.gov.rs	1:300k
Distance to river *D2R*	www.usgs.gov	30 m
Depth to bedrock *D2B*	https://soilgrid.org	250 m
Triggering factor name and symbol	**Data source**	**Scale/ resolution**
Long-term rain *LTR*	https://hidmet.gov.rs	NA
Short-term rain *STR*	https://hidmet.gov.rs	NA

The most common landslide triggering factor in these latitudes and climate is rainfall. Its spatial pattern delineates the areas that are more prone to instabilities, while their temporal frequency additionally impacts their probability of occurrence in time (e.g., annually). To match those two aspects the following rainfall triggering factors were defined: long-term rainfall *LTR* pattern, interpolated by using average annual sums over the baseline period 1991-2010; and short-term intensive rainfall *STR* interpolated as the number of days with rainfall exceedance of 10 mm. All interpolations were performed by using a national hydro-meteorological rain gauge network (29 stations) and resampled to 30 m resolution (https://www.hidmet.gov.rs/). Similarly to conditioning factors, these two rasters were split into equally distributed classes.

Table 2 Lithological units scoring (nominal input data type).

L unit name	Score	Weight (%)
Igneous hard rock complex	0.5	20
Loess	1	
Alluvial sediments	1,5	
High-grade metamorphic rock	2	
Meta-clastic sediments	2.5	
Carbonate rock	3	
Marls and pyroclastic rock	3.5	
Flysch complex	4	
Low-grade metamorphic rock	4.5	
Ophiolitic mélange and clayey complex	5	

Landslide inventorying is a long-term project conducted continuously by GSS since 2007 in parallel to engineering geological mapping. So far, 67% of the territory is covered (Đokanović, 2023) and contains over 6,000 of landslide events at point level, with assigned location, date of recording, activity status and confidence level. Out of these, only the events occurring within the meteorological baseline (1991-2010) were used (2010-2018 were excluded to be consistent with the triggering data), and only active events (at the time of recording) that suggests a confident registration. In effect, a final set with 3265 landslides was used for model validation.

Multi-criteria analysis

To ensure that these datasets are used in comprehension with domestic practice, a questionnaire for assigning 1-5 scores for each factors class and overall factors weight 0-100% were created and poll was conducted within the Work Group but also including the external colleagues. After statistical analysis, i.e., by majority of votes, the final scores and weights were assigned (Tab. 3). These were used in a GIS environment as follows:

a) scores were used to reclassify original rasters using 1-5 values span;
b) weights *W* were used in multi-criteria analysis as multiplicators of each i^{th} reclassified raster (Eq.1);
c) weighted rasters were summed up (Eq.1)
   - conditioning factors *CF* subtotal;

  - o landslide hazard *H* calculation as a sum of the *CF* subtotal and the triggering factor *TF* subtotal;

d) resulting sum was normalized to 0-1 relative probability range;

e) the final hazard model was split into five classes, from very low to very high using the natural break interval (Tab. 6).

$$H = \sum_{i=1}^{5} W_i \cdot CF_i + \sum_{i=1}^{2} W_i \cdot TF_i = \\ = (0.2L + 0.18S + 0.16D2B + 0.12D2S + 0.1D2R) + (0.14STR + 0.1LTR) \quad [1]$$

Such grouping would be in line with a general theory that landslide susceptibility should consider static data while landslide hazard component should add dynamic data upon that static set (Fell et al., 2008).

Table 3 Nominal factors interval scoring and factor weights.

S intervals (°)	Score	Weight (%)
<3	1	18
3-6	2	
6-10	4	
10-17	5	
>17	3	
***D2S* intervals (m)**	**Score**	**Weight (%)**
<5	5	12
5-10	4	
10-30	3	
30-100	2	
>100	1	
***D2R* intervals (m)**	**Score**	**Weight (%)**
<50	5	10
50-100	4	
100-500	3	
500-1000	2	
>1000	1	
***D2B* intervals (m)**	**Score**	**Weight (%)**
<0.5	1	16
0.5-2	2	
2-5	3	
5-10	4	
>10	5	
***LTR* intervals (mm)**	**Score**	**Weight (%)**
<500	1	10
500-750	2	
750-900	3	
900-1000	4	
>1000	5	
***STR* intervals (days)**	**Score**	**Weight (%)**
<5	1	14
5-10	2	
10-30	3	
30-80	4	
>80	5	

Validation

A simple validation principle was applied – landslide points were plotted against the corresponding pixel values of the final hazard model, thereby revealing a distribution of true positives (which can be considered as all points correctly classified as high or very high hazard), idle (all points classified as moderate) and false negatives (all points misclassified as low or very low hazard). In addition, Mean Squared Error (Eq. 2) was calculated for relative probability *p(H)* values (generated under step d) in respect to landslide instances (*p*=1).

$$MSE = \frac{1}{n}\sum_{i=1}^{n}[p(H) - 1]^2 \quad [2]$$

Results and discussion

The preliminary landslide hazard map of Serbia was generated by using scoring and weighting based on domestic experts' opinions. Arguably, another group of experts might have come up with a different map, while using other inputs or weighting them differently. However, local knowledge is a heuristic component that is essential herein, and it is incorporated in the model indirectly, by accounting for experts' experience with landslides in various parts of Serbia, and their knowledge what conditions and what triggers landslides.

Final model class distribution is visually appealing (Fig. 2). Expectedly, hilly areas, long and steep valleys, and basins are characterized as high or very high hazard zones. Normalized probability threshold *p(H)* on annual level and class size *s* (in %) is matched against the hazard class:

- very low hazard, $p(H)<0.36$, $s=12.8\%$;
- low hazard, $0.37<p(H)<0.46$, $s=23.4\%$;
- moderate hazard, $0.47<p(H)<0.56$, $s=28.2\%$;
- high hazard, $0.57<p(H)<0.66$, $s=23.6\%$;
- very high hazard, $p(H)>0.67$, $s=11.9\%$.

This formally means that all high and very high hazard zones can host landslides every second year within their premisses. Although temporal probability is included through *LTR* and *STR* it is fair to note that this is only a relative annual estimate, since the frequency information is deducted, and not actually calculated. Very low and very high classes are least widespread, while all other classes are balanced in size. Administratively, the Western and SW parts of Serbia are most affected (Fig. 3), while the national road network is showing highly affected stretches along important corridors (Fig. 3). About 8% of the roads is under very high annual hazard probability, while almost 30% is under very high and high hazard combined.

The numerical validation (Fig. 2) suggests that distribution is right skewed which is encouraging outcome. Most of the actual landslides are classified as high or very high hazard (46%), while moderate class covers about 31.5%. Inconveniently, some landslides (3.5%) are misclassified as very low hazard, as well as low hazard (19%). The *MSE* is relatively low, equalling 0.06 (its root is about 0.25), although it has been tested only against the existing landslide cases, which have probability of 1.

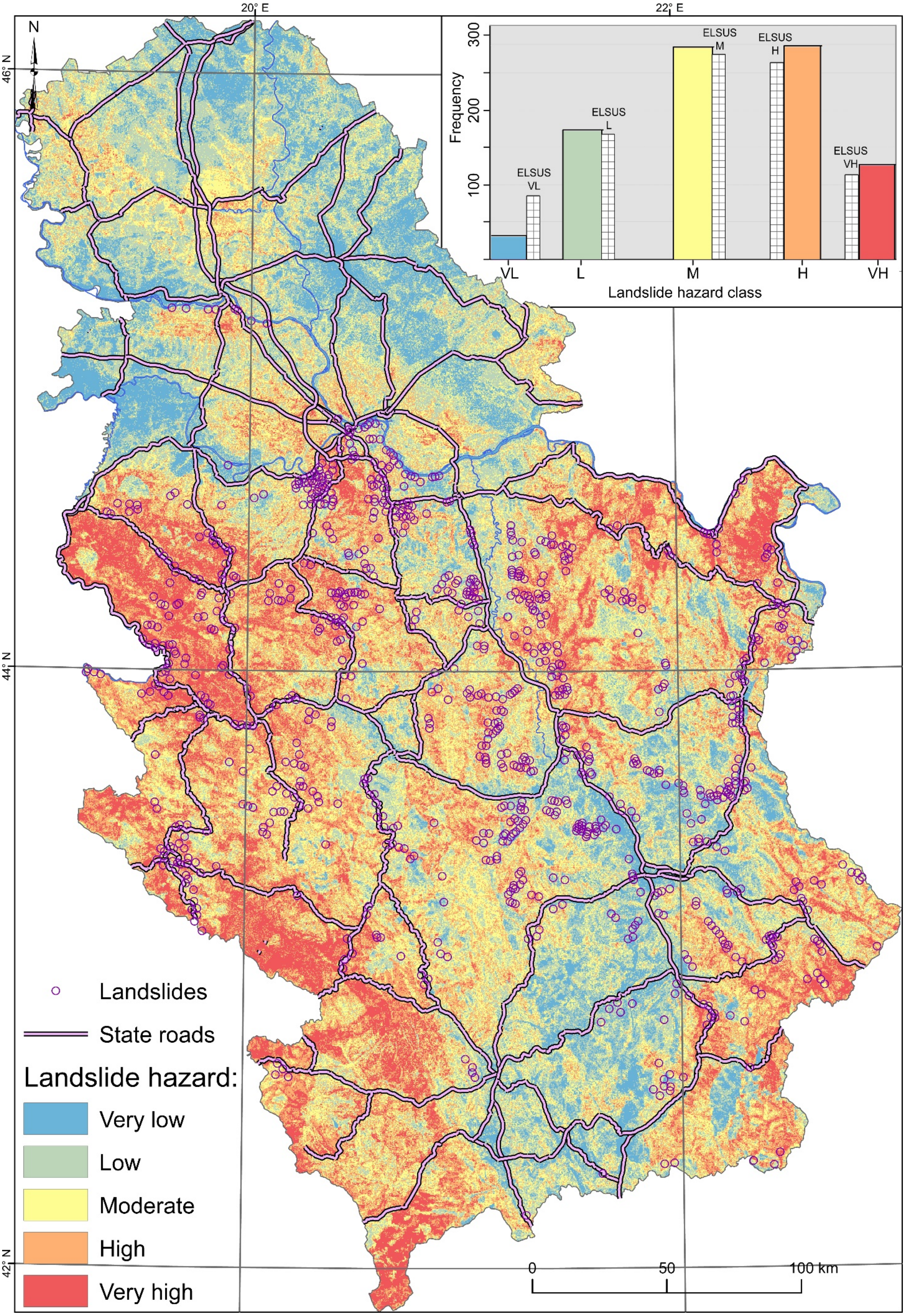

Figure 3 Preliminary landslide hazard map of Serbia with validation histogram in the upper right.

When compared against even higher-level (open) map of continental scale, ELSUS2 (Wilde et al., 2018), which has coarser (200 m) resolution, but is based on similar multi-criteria methodology, the preliminary map brings some improvements, and should be preferred over ELSUS2 output. In particular, the false negative rate is higher in the ELSUS2, while all other classes have similar distribution (Fig. 2). False negatives are the most severe type of errors in landslide assessment, as they suggest landslide-safe area at location which is an actual landslide. In addition, MSE of the ELSUS2 model is considerably higher (0.18) than in the case of the preliminary national model.

The Preliminary landslide hazard map of Serbia is for now published as a static document in PDF format on the GSS web page https://gzs.gov.rs/doc/portali/inz-geomehanika/2_Karta%20Hazarda%20od%20klizista.pdf, but it is in plan to create a web service on the Ministry of Mining and Energy portal, i.e., Geological Information System of Serbia (https://geoliss.mre.gov.rs/) as an interactive map.

Conclusions

In this pioneering work, it has been shown that a proper landslide hazard assessment at national level requires an institutional support and guidance regarding both, connecting the group of most relevant experts in the field and providing the necessary data. Legislation could be directed further to bylaws and rulebooks which will more closely define standards of developing landslide hazard maps at national or regional scales.

Although encouraging, results leave room for further improvements by introducing other potentially relevant inputs for condition factors, such as land use or other DTM derivatives. Strategies for class intervals selection and scoring can also be based on data approach (statistical assessment, calibration with independent inventory subset, etc.) instead of expert-driven one, or perhaps their combination. Also, triggering factors can be improved by using advanced climate indices or even climate change projections to ensure the applicability of the hazard map beyond the climatic baseline.

The applicability of such output can be versatile, but primarily oriented towards general levels of planning and design. It can be also used for upscaling for wider regions analysis (e.g., the Western Balkan Region), which is common investment framework (especially in climate change context) and will require such kind of inputs for further developments or reconstruction, mitigation etc. It is not suitable to be used at municipal or more detailed levels, due to its input data which are too coarse, and landslide inventory which is point based (at municipal level or finer, polygon based is more appropriate).

Finally, it is important to note that landslide hazard map is a dynamic one in nature, and it can vary considerably. One reason is the dynamic nature of the landslide inventory itself, so that in case of data-driven approach it can change as knew locations are reported. It can especially vary if climate-change projections are introduced for specific time splits in the future. Therefore, it can be fix-termed to a span ranging from anything between several years to a decade. It is well matching period with its potential application in spatial planning at national or regional levels, because these plans also expire after five years or more. New version of the national landslide hazard map is already in progress.

References

Abolmasov B, Damjanović D, Marjanović M, Stanković R, Nikolić V, Nedeljković S, Petrović Ž (2017) Project BEWARE—landslide post-disaster relief activities for local communities in Serbia. In Advancing Culture of Living with Landslides: Volume 3 (pp. 413-422). Mikoš, Arbanas, Yin, Sassa (eds). Springer International Publishing. (ISBN 978-3-319-53500-5).

Abolmasov B, Krušić J, Andrejev K, Marjanović M, Stanković R, Đurić U (2017). Application of AHP and WoE methods for landslide susceptibility assessment on Krupanj municipality. Izgradnja. 7(10):239-46.

Abolmasov B, Marjanović M, Đurić U, Krušić J, Andrejev K (2017) Massive landsliding in Serbia following cyclone Tamara in May 2014 (IPL-210). In Advancing Culture of Living with Landslides: Volume 1 ISDR-ICL Sendai Partnerships 2015-2025 (pp. 473-484). Sassa, Mikoš, Yin (eds). Springer International Publishing. (ISBN 978-3-319-53500-5).

Đokanović S (2023) Basic engineering geological map of Serbia project achievement. Tehnika. 78(6): 673-678.

Dragićević S, Carević I, Kostadinov S, Novković I, Abolmasov B, Milojković B, Simić D (2012) Landslide susceptibility zonation in the Kolubara river basin (western Serbia) - analysis of input data. Carpathian journal of earth and environmental sciences. 7(2): 37-47.

Fell R, Corominas J, Bonnard C, Cascini L, Leroi E, Savage W Z (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering geology. 102(3-4): 85-98.

Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. Landslides. 11: 167-194.

Krušić J, Marjanović M, Samardžić-Petrović M, Abolmasov B, Andrejev K, Miladinović A (2017) Comparison of expert, deterministic and Machine Learning approach for landslide susceptibility assessment in Ljubovija Municipality, Serbia. Geofizika. 34(2): 251-273.

Marjanović M, Abolmasov B, Đurić U, Bogdanović S (2013) Impact of geo-environmental factors on landslide susceptibility using an AHP method: A case study of Fruška Gora Mt., Serbia. Geološki anali Balkanskoga poluostrva. 74(1): 91-100.

Mateos R M, López-Vinielles J, Poyiadji E, Tsagkas D, Sheehy M, Hadjicharalambous K, Liscák P, Podolski L, Laskowicz I, Iadanza C, Gauert C, Todorović S, Jemec Auflič M, Maftei R, Hermanns R L, Kociu A, Sandić C, Mauter R, Sarro R, Béjar M, Herrera G (2020) Integration of landslide hazard into urban planning across Europe. Landscape and urban planning. 196: 103740.

Tešić D, Đorđević J, Hölbling D, Đorđević T, Blagojević D, Tomić N, Lukić A (2020) Landslide susceptibility mapping using AHP and GIS weighted overlay method: a case study from Ljig, Serbia. Serbian Journal of Geosciences. 6(1): 9-21.

Wilde M, Günther A, Reichenbach P, Malet J P, Hervás J (2018) Pan-European landslide susceptibility mapping: ELSUS Version 2. Journal of maps. 14(2): 97-104.