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Landslide susceptibility assessment by implementing the analytical hierarchy process in GIS weight overlay tool: a case study of the Krupanj area in western Serbia

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Abstract. The aim of this paper is to show the susceptibility to sliding in the Krupanj area. Intense rainfall in May 2014 triggered many landslides in western Serbia. The Krupanj area was particularly affected by this event. The material damage occurred affected the awareness of the importance of knowing the locations that are prone to sliding. Therefore, from 2014 to 2021, field research was carried out in the Krupanj area. During this period a large amount of landslide data were collected by engineering geological mapping. These data were used for susceptibility analysis. For present study the analytical hierarchy process (AHP) and weight overlay (WO) tool were used. Nine factors were used for susceptibility analysis: slope, aspect, curvature, elevation, lithology, distance from rivers, faults, boundary's and land cover. In order to be able to make a comparison, all factors were evaluated using the Saaty scale, so that the weights of the individual factors were obtained. The weight values obtained by AHP were used in GIS tool. Final map was validated by ROC analysis. The validation results show accuracy of 77,1% (good) for model.

Key words: *Krupanj, susceptibility, AHP, landslide, analysis, weight overlay.*

Апстракт. Циљ овог рада је да прикаже подложност клижењу у општини Крупањ. Интезивне падавине у мају 2014. покренуле су многа клизишта у западној Србији. Овим догађајем посебно је погођена општина Крупањ. Настала материјална штета утицала је на свест о значају познавања локација које су склоне клижењу. Због тога су, у периоду од 2014. до 2021., изведена теренска истраживања на подручју општине Крупањ. Током овог периода инжењерскогеолошким картирањем прикупљена је велика количина података о клизиштима. Ови подаци су искоришћени за анализу подложности на клижење. За овај рад, коришћен је аналитички хијерархијски поступак (АХП) и ГИС алат за преклапање тежина (WO). За анализу подложности коришћено је девет фактора: нагиб, аспект, закривљеност, надморска висина, литологија, удаљеност од река, раседа и граница и земљишни покривач. Да би ови фактори могли међусобно да се упореде процењен је њихов значај помоћу Сатијеве скале, тако да су добијене тежине сваког фактора. Овако добијене вредности су затим коришћене за добијање карте подложности на клижење. Добијена карта подложности је затим потврђена помоћу ROC анализе. Резултати валидације показују да је њена тачност 77,1 % што значи да је модел добар.

Кључне речи: *Крупањ, подложност, АХП, клизишта, анализа, преклапање тежина.*

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Introduction

There are various methods used to define landslide susceptibility. All these methods can be grouped into qualitative or quantitative (Soeters & Van Westen, 1996; Guzzeti et al., 1999). Qualitative methods are subjective and the susceptibility is expressed in descriptive terms. Quantitative methods are based on numerical expressions of the relationship between factors and landslides (Alleoti & Chowdhury, 1999). The quantitative approaches include: analytic hierarchy process (Komac, 2006; Myronidis et al., 2016; Huang et al., 2020; Akshaya et al., 2021), analytic network process (Neaupane & Piantanakulchai 2006; Gheshlaghi & Feizizdeh, 2017), fuzzy logic (Kritikos & Davies, 2015; Palau et al., 2020), logistic regression (Abedini et al., 2017; Chen et al., 2018), multivariate statistical approach (Schicker & Moon, 2012; Vessia et al., 2020) and weight linear combination (Ayalew et al., 2004; Hung et al., 2016).

Several investigations have been carried out for the municipality of Krupanj since 2014. The first investigations were carried out for the purpose of defining locations threatened by sliding (Djokanović, 2015, 2016). Abolmasov et al. (2017) made the first assessments of the terrain`s susceptibility to landslides in the municipality of Krupanj using AHP and WoE method. Đurić et al. (2017) represent a cadaster of landslides that occurred after heavy rainfall in 2014 using satellite images. Marijanović et al. (2018) did a landslide risk assessment on the road network of the municipality of Krupanj.

The aim of the present study is to produce a susceptibility map using analytic hierarchy process (AHP) with GIS weight overlay tool (WO) in Krupanj area in the western Serbia. Intense rainfall in May 2014 triggered many landslides in western Serbia. The Krupanj area was particularly affected by this event. The material damage occurred affected the awareness of the importance of knowing the locations that are prone to sliding. Therefore, from 2014 to 2021, field research was carried out in the Krupanj area. During this period a large amount of landslide data was collected by engineering geological mapping (Đokanović, 2021, 2022). These data were used for susceptibility analysis.

The Krupanj area is located on the right bank of the Drina River and belongs to the Mačva district (Fig. 1). The area is about 341 km^2. It borders Loznica, Mali Zvornik, Ljubovija, Osečina, Koceljeva and Šabac. The area has around 17.000 inhabitants. It belongs to the hilly – mountainous terrain.

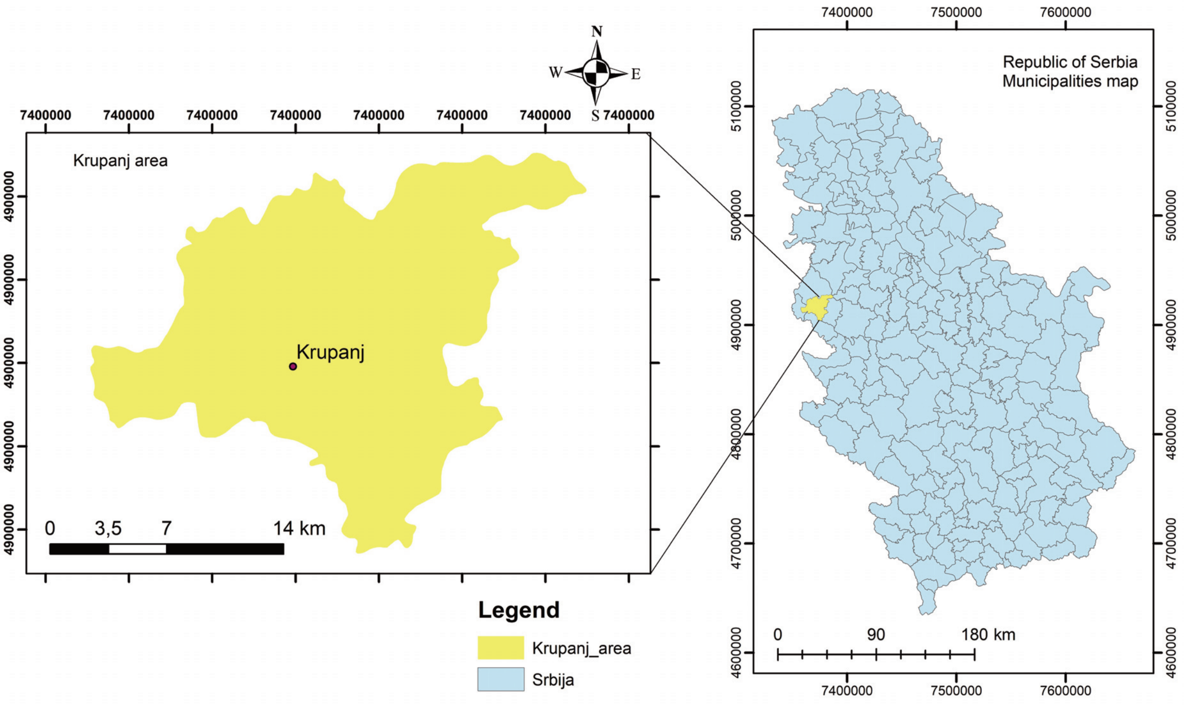

Fig. 1. Study area.

The town of Krupanj is located in the valley of the rivers Čađavica, Bogoštica, Kržava and Likodra. It is surrounded by the Boranja, Jagodnja and Sokolske mountains. This area has a moderate continental climate with elements of submountain in higher altitudes. The mean annual amount of precipitation is around 926 mm.

Methodology

The landslide susceptibility in the Krupanj area was determined using the AHP and the GIS weight overlay tool. AHP is quantitative method that allows expert evaluation. It is based on the comparison of factors and determination of their weight values. The importance of the factors is determined by the numbers 1 to 9 (Table 1). To make a decision, SAATY (2008) advises following steps: define the problem, structure the decision hierarchy, construct a set of pairwise comparison matrices and weight the elements.

Table 1. *The Saaty fundamental scale.*

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another, its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When comprise is needed

Landslide susceptibility maps without validation are less meaningful (CHUNG & FABBRI, 1998). ROC graph is a very useful tool for visualizing and evaluating data (FAWCETT, 2006). In this study both LSM maps were validated using receiver operating characteristics (ROC) analysis and area under curve (AUC). The AUC value is always between 0 and 1. A good model has a range from 0,5 to 1,0.

Landslide data

The existing landslide map is very essential for studying the relationship between the distribution of landslides and the factors (POURGHASEMI et al., 2012). Landslide inventories are essentially factual in nature (FELL et al., 2008). The map of landslides in the study area was created on the basis of data from the field study and satellite images from Google Earth. Landslide data collected from satellite images were verified in the field (ĐOKANOVIĆ, 2021). A total of 1632 landslides were registered in the investigation area (Fig. 2). The minimum area of the landslide is 1,883 m^2, the maximum 172,011 m^2. The total area of the landslides is 27,79 km^2, which is 8,15 % of the Krupanj area (Figs. 3,4). Landslides in study area are shallow to deep, with rotational, translation or complex sliding surface. Landslides data were used for validation in ROC analysis.

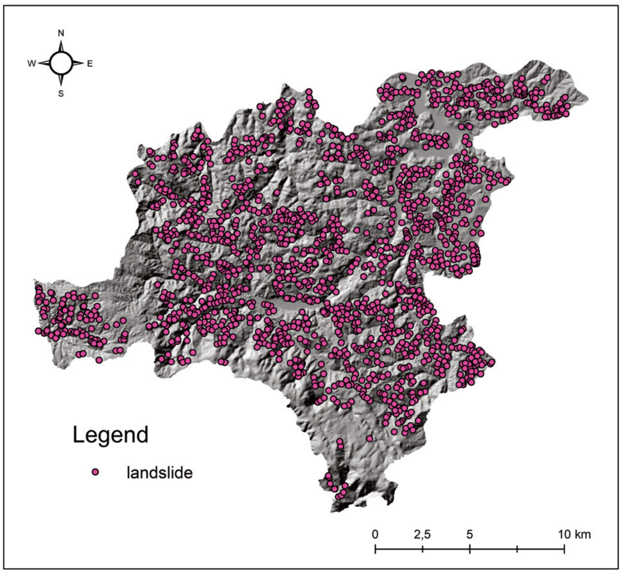

Fig. 2. *Landslide map of Krupanj area.*

Landslide factors

There are no strict guidelines for factors that must be taken into susceptibility analysis. The chosen criteria depend on the study area, its characteristics and the available data. The elements that affect slope stability are numerous and varied (VARNES, 1984). Depending on the characteristics of

Fig. 3. *Landslides in Krupanj area.*

the area, 9 factors were used for the analysis, i.e. slope, aspect, curvature, elevation, faults, rivers, lithology, boundary and land cover (Fig. 5).

Among the geomorphologic factors, slope, aspect, elevation and curvature were included in the analysis. These factors were created using a digital terrain model (DTM) with a spatial resolution of 30 m by the Geodetic Agency of the Republic of Serbia.

Slope is the most commonly used criterion for landslide susceptibility, although the relationship

Fig. 4. *Landslide locations on Google Earth (pictures are from 2016).*

between slope and stability is complex. In general, as slopes become steeper, their instability increases. Field observations show that this is not always the case. According to Varnes (1984), the steepest slopes are not always those most prone to failure. He found that many steep slopes of competent rock are more stable than comparatively gentle slopes of weak material. Therefore, the slope gradient is not a decisive

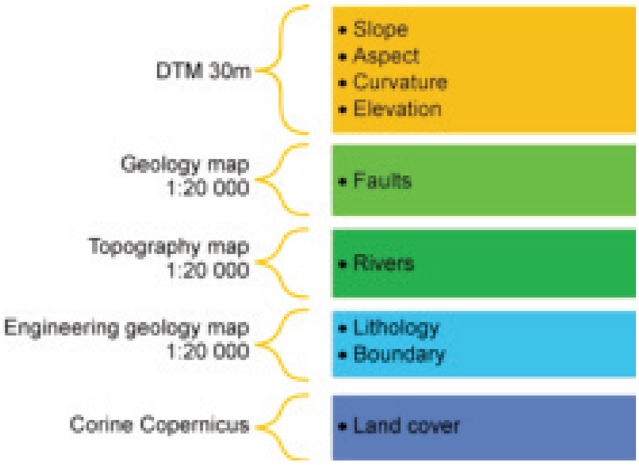

Fig. 5. *Factors for landslide susceptibility of Krupanj.*

Table 2. *Factors and classes of study area.*

Layers	Classes	Values
Slope (°)	0-5	2
	5-10	4
	10-20	5
	20-30	3
	> 30	1
Aspect	Flat	1
	N,NE,NW	5
	E,W	4
	SE,SW	3
	S	2
Curvature	Planar	1
	Concave	3
	Convex	5
Elevation (m)	< 200	1
	200-300	5
	300-500	4
	500-700	3
	> 700	2
Distance from faults (m)	0-450	5
	450-900	4
	900-1300	3
	1300-2000	2
	> 2000	1
Distance from rivers (m)	0-120	5
	120-300	4
	300-460	3
	460-550	2
	> 550	1
Lithology	Sand, gravel, clay, alluvium	1
	Limestone, dolomite, diabase-chert formation	2
	Pyroclastites	3
	Dacito-andesites, sandstone and claystone permian, granodiorites	4
	Neogen clay and sand, crystalline rocks deluvium clay and sand	5
Distance from boundary (m)	0-300	5
	300-1000	4
	1000-2000	3
	2000-3000	2
	> 3000	1
Land cover	Urban, artificial	1
	Forest, broad-leaved, coniferous, mixed	2
	Woodland, shrub	3
	Agriculture, Pastures, grasslands, arable land, complex cultivation	5

factor for landslide susceptibility. The steepest slope in the study area is 60°. Accordingly, the slopes (Fig. 5) were classified into 5 classes (Table 2).

Aspect is also considered as a landslide-related factor (POURGHASEMI et al., 2012) and is often used in susceptibility analysis. The orientation of slopes is important because they are exposed to the sun, wind, snow and precipitation. Therefore, north-facing slopes are more prone to landslides than south-facing slopes. This is because south-facing slopes receive more sun and therefore evaporation is higher. The aspect map (Fig. 6) was created in the GIS and then divided into 5 classes (Table 2).

Curvature is one of the factors influencing the occurrence of landslides (POURGHASEMI et al. 2012). The term curvature is defined as the rate of change of slope gradient or aspect usually in a particular direction (WILLSON & GALLANT, 2000). According to SHARMA & MAHAJAN (2019), curvature represents the susceptibility of slopes to erosion and the current slope morphology. Both profile and planar curvature are used in the susceptibility analysis. The profile curvature is the curvature in the vertical plane parallel to the slope direction. It is the measure of the rate of change of the slope gradient. The planar curvature has an influence on the convergence or divergence of water during runoff (NEFESIUGLU et al., 2008; POURGHASEMI et al., 2012). Planar curvature was used in this study. The classification for the curvature is concave, planar and convex (Fig. 6).

Altitude is also one of the most important factors for slope stability. According to DAI & LEE (2001), rocks at very high elevations usually have a very high shear strength, at medium elevations the slopes are covered with a thin diluvium layer that is more prone to landslides, and at very low elevations the landslide risk is very low because the terrain is gentle and covered with a thick diluvium layer and residual soil. The elevations were derived from the DEM with a pixel size of 30 x 30 m using the ArcMap tool. The study area has an elevation ranging from 144 to 967 m, which is classified into five classes using the natural brakes method (Fig. 6).

Faults are structural elements that represent weakened parts. Fault zones increase landslide potential by creating steep slopes and sheared, weakened rock (WACHAL & HUDAK, 2000). In general, the

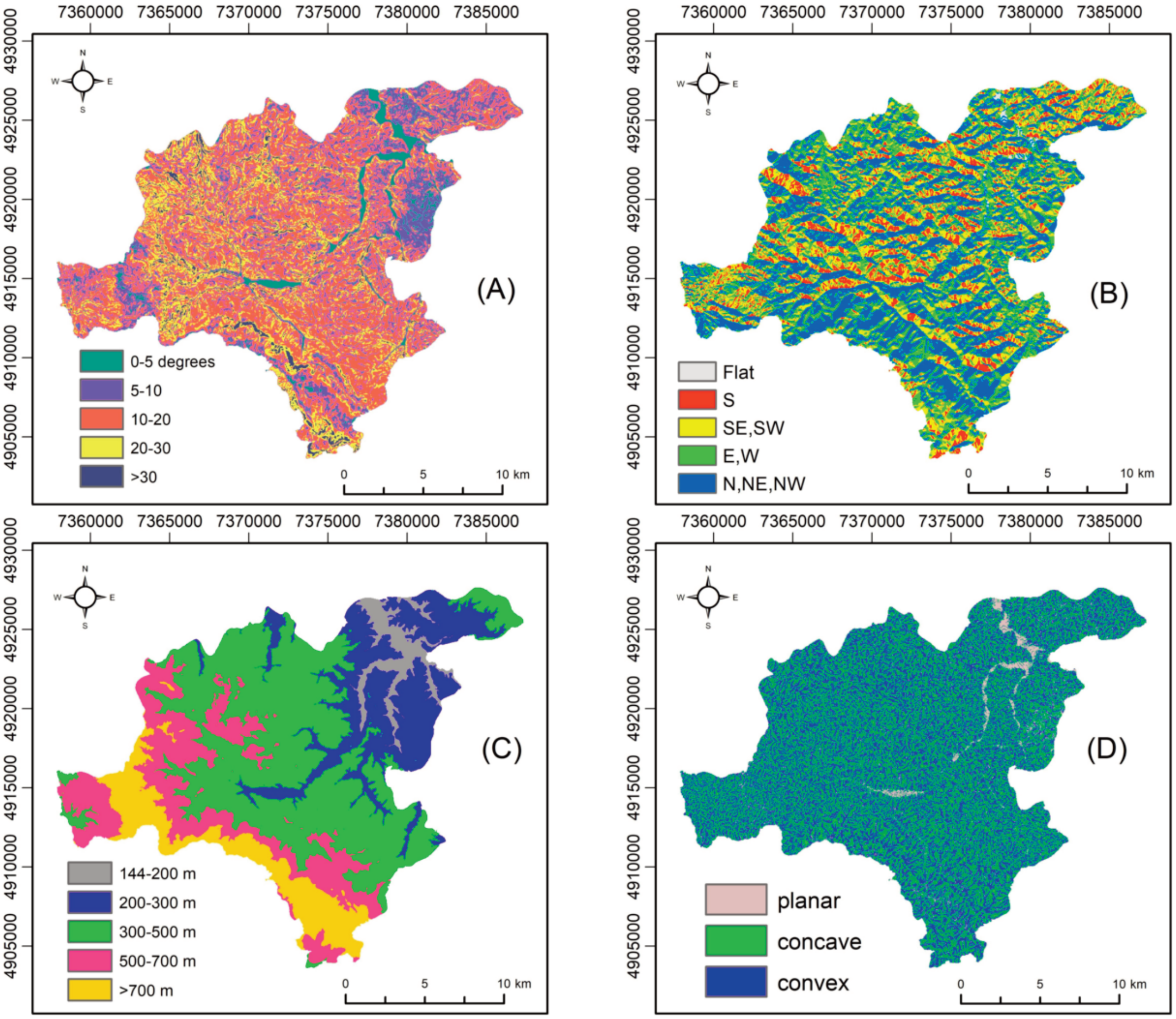

Fig. 6. *Thematic maps of various factors: a. slope, b. aspect, c. elevation, d. planar curvature.*

frequency of landslides decreases with increasing distance from faults (Sarkar et al., 1995). Different authors use different buffer zones. For example, Abedini et al. (2017) use 1500 m, Aksaya et al. (2021) and Gökhan (2019) 100 m, Jazouli et al. (2019) 200 m buffer, Biswas et al. (2023) 2 km and Bahrami et al. (2021) different buffer zones. For the study area, the faults were obtained from the geological map at a scale of 1:25.000. The buffer zones are subdivided according to the frequency of occurrence. It is found that the zones near the boundaries are more susceptible to sliding. The map of the distance of faults (Fig. 7) was divided into 5 classes (Table 2).

Water is a major factor in the behavior of slopes (Leroueil, 2001). **Rivers** affect slope stability by eroding the toe of the slope, saturating the slope and causing the water level to fluctuate (Janjić, 1979; Gökceoglu & Aksoy, 1996). Therefore, the distance to rivers is one of the controlling factors for the stability of a slope (Pourghasemi et al., 2012). In general, the frequency of landslides decreases with increasing distance from the drainage line. This can be attributed to the fact that the increased groundwater level during storms and the terrain modification caused by gully erosion can influence the initiation of landslides (Dai & Lee, 2001). There is no consensus in the literature on the width of the buffer zone. Some authors such as Abedini et al. (2017) use 50 m buffers, Gökhan (2019) uses 100 m and Bahrami et al. (2021) use a 200 m zone. The study area was affected by heavy rainfall that caused numerous landslides (2014). The map of the rivers was created from the topographic map at a scale of 1:25.000. This map shows that the study area has a very dense drainage network. It is assumed that the zones near the boundaries are more susceptible to sliding. The distances to the rivers (Fig. 7) were divided into 5 classes (Table 2).

Landslides are greatly controlled by lithology. **Lithology** is the most important parameter in landslide studies, as different lithological units have different susceptibilities (Dai et al., 2001; Yalcin, 2007). Lithology includes the composition, fabric, texture or other attributes that influence the physical behavior of rocks and engineering soils (Varnes, 1984). These properties are very important for determining the shear strength, permeability, weathering and other characteristics of soils and rock that affect slope stability (Varnes, 1984). The lithologic map was created from the engineering geological map of the study area at a scale of 1:25.000 (Fig. 6). The main lithological units in this study are low crystalline rocks of Paleozoic age, represented by phyllites, Permian sandstones and mudstones, lime-stones, granodiorites, dacito–andesites, pyroclastites, Neogene clays and sands, and Quaternary sands, gravels and clays. In the south there is a small area dominated by cherts, mudstones and sandstones within the “diabase – chert formation”.

Another factor that affects the occurrence of landslides is the boundaries between the lithological units where landslides frequently occur. Field observations in the study area show that some landslides occur in this zone. The boundaries were taken from the engineering geological map of the study area (Fig. 6). It is assumed that the zones near the boundaries are more susceptible to sliding. The distance from the boundaries was divided into 5 classes (Table 2).

Land cover also has an effect on slope stability (Wachal & Hudak, 2000). In general, vegetation increases slope stability. Varnes (1984) emphasizes the importance of vegetation: forests retain a considerable amount of rainwater, remove a large amount of water from the soil through evapotranspiration and reduce erosion and runoff. In addition, the root system increases the shear resistance of the mass and soil cohesion and reduces the effect of climatic influences by protecting the mass from sun, rain and wind. However, some landslides were triggered in the forest area during recent events (2014). The land use map was created using Corine Land Cover from the Copernicus Land Monitoring Service. Based on this data, forest areas cover 46 % of the study area (Fig. 6). The land cover was divided into 4 classes (Table 2).

Results and discussion

To create WO map each factor is assigned a weight in percentage determined by AHP (Table 3). The consistency ratio for the comparison matrix is 0,094, which is less than 0.1. Based on the weighting values obtained, we see that lithology (27,8%) and slope (22%) are of the greatest importance. This is followed by land cover (18,5%), distance from rivers (12,2%), distance from boundaries (7,6%), distance from faults (5,1%) and elevation (3,1%). Aspect (2 %) and curvature (1,4 %) are the least important, mainly due to their high variability, and are therefore, not a decisive factor in susceptibility analysis. The low importance of aspect and curvature in Serbia is also confirmed in the research by Tešić et al. (2020).

All weights are added up to 100 percent. The WO map was classified into four classes: very low, low, high and very high (Fig. 7). The results show that the high class is the most represented and covers an area of 206 km^2 or 55,70 % of the total study area. The very high class and the low class are equally represented. The very high class covers an area of 78 km^2, which corresponds to 21,13 % of the total study area. The low class covers an area of 80 km^2 or 21,73 % of the total study area. The very low class is the least represented, covering 5 km^2 or 1,43 % of the total study area.

The landslide susceptibility maps (LSM) were evaluated using ROC analysis. The analysis was performed using the ARCSDM toolbox for ArcGis. After installing the tool in the ArcGis toolbox, the raster landslide map was taken as the true positive and the raster LSM map was taken as the classification model and the area under the curve (AUC) was calculated (see Fig. 8). The LSM map with an existing landslide is shown in Fig. 9. The AUC value for the

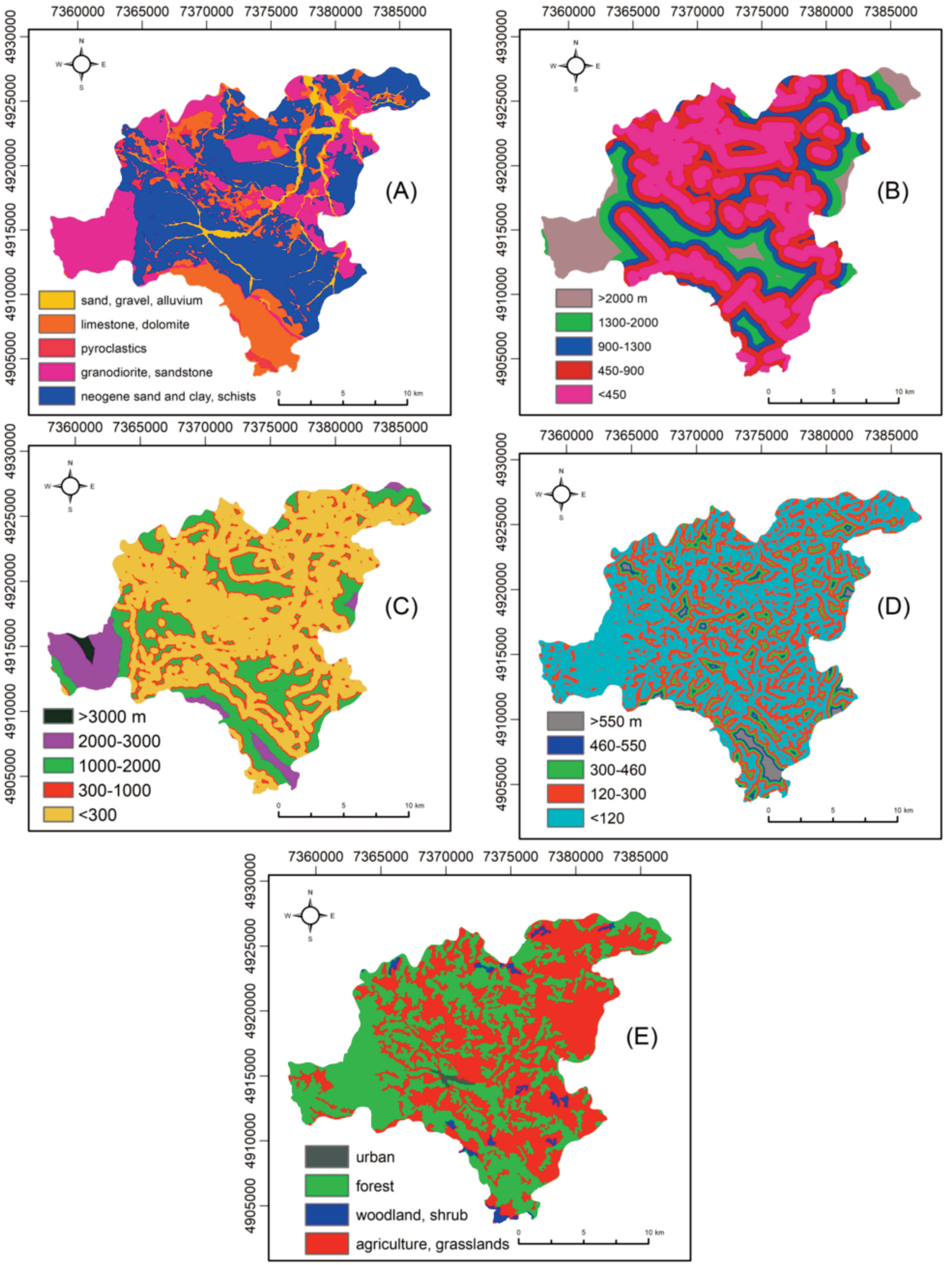

Fig. 7. *Thematic maps of study area of various factors: a. lithology, b. fault distance, c. boundary distance, d. river distance, e. land cover.*

Table 3. *Comparison matrix of landslide factors.*

	Lithology	Slope	Land cover	Rivers	Boundary	Faults	Elevation	Aspect	Curvature
Lithology	1	2	3	3	5	5	7	9	9
Slope		1	2	3	5	5	7	7	9
Land cover			1	3	5	5	7	7	8
Rivers				1	3	3	5	5	7
Boundary					1	3	5	5	7
Faults						1	3	5	6
Elevation							1	3	5
Aspect								1	3
Curvature									1
Weight	27,85	22,05	18,52	12,24	7,60	5,15	3,15	2,03...	1,42

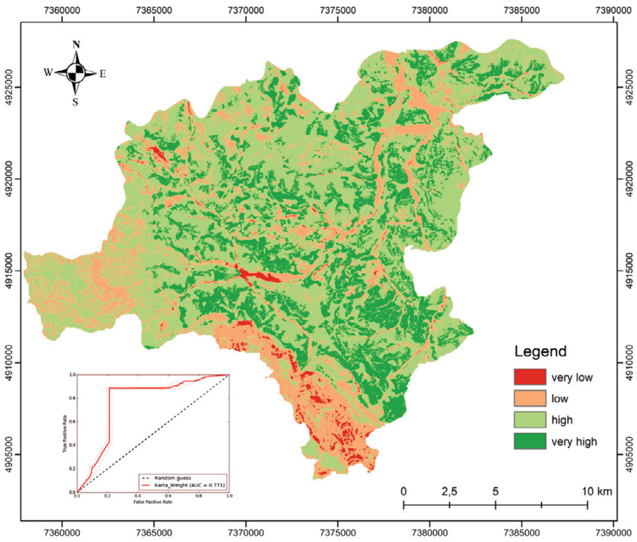

Fig. 8. *Landslide susceptibility map.*

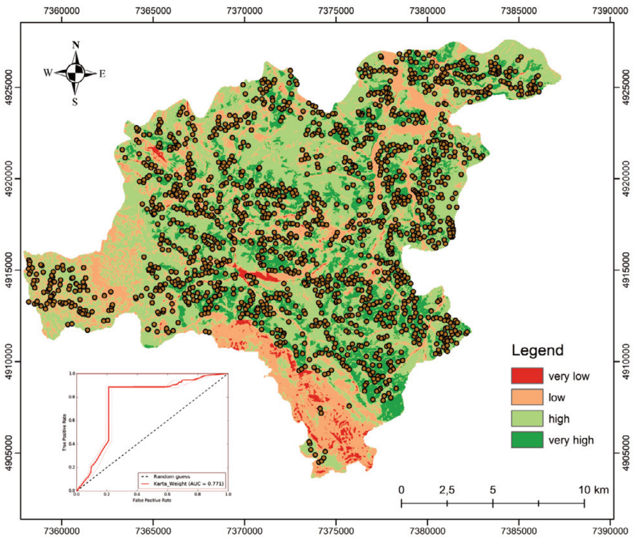

Fig. 9. *Landslide susceptibility map with existing landslides.*

LSM map is 0,771, which indicates that the model has a good accuracy (77,1%). Based on the shape of the ROC curve, we can say that it is a discrete model. The statistical representation of the landslide classes is shown in Fig. 10.

Conclusions

This paper presents the application of the AHP method with the ArcGis weight overlay tool to create a landslide susceptibility map of the Krupanj area in western Serbia. This area was particularly affected by intense rainfall in 2014. Since then, numerous investigations have been carried out. In the period 2014-2021, about 1632 landslides were registered in this area. Nine factors were ana-

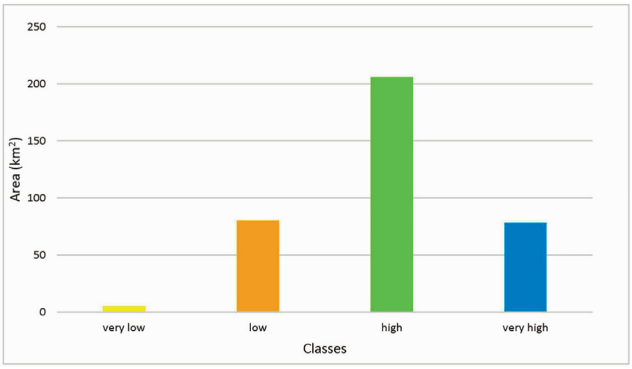

Fig. 10. *Landslide classes.*

lyzed to create susceptibility map: slope, aspect, curvature, elevation, lithology, distance to rivers, faults, boundaries and land cover. The landslide susceptibility map was obtained by expert AHP and GIS weight overlays. The results show that lithology and slope are the most important factors in the study area. Aspect and curvature are the least significant factors in the area. On the LSM map, almost 77% of the study area belongs to the very high and high susceptibility areas. The areas where the risk is high require more detailed investigations and engineering prevention measures.

The LSM map was validated using the ROC graph and AUC value. The accuracy of the LSM obtained by WO is good. Four classes could be distinguished on the WO map. The map produced in this study can be used by spatial planners and experts for decision making. Susceptible zones required for construction purposes need further engineering geological and geotechnical considerations. The behavior of the models used to generate the susceptibility map can be affected by the selection of influencing factors and landslide information.

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References

Abedini, M., Ghasemyan, B. & Mogaddam, R.M.H. 2017. Landslide susceptibility mapping in Bijar city, Kurdistan Province, Iran: a comparative study by logistic regression and AHP models. *Environmental Earth Sciences,* 76: 308.

Abolmasov, B., Krušić, J., Andrejev, K., Marjanović, M., Stanković, R. & Đurić, U. 2017. Primena AHP i WoE metode u proceni podložnosti terena na kliženje za područje opštine Krupanj [*Application of AHP and WoE methods for landslide susceptibility assessment on Krupanj municipality* – in Serbian, with an English abstract]. *Izgradnja,* 71: 239–246.

Akshaya, M., Danumah, J.H., Saha, S., Ajin, R.S. & Kuriakose, S.L. 2021. Landslide susceptibility zonation of the Western Ghats region in Thiruvananthapuram district (Kerala) using geospatial tools: A comparison of the AHP and fuzzy-AHP methods. *Safety in extreme environments,* 3: 181–202.

Alleoti, P. & Chowdhury, R. 1999.Landslide hazard assessment summary review and new perspectives. *Bulletin of Engineering Geology and Environmental*, 58: 21–44.

Ayalew, L., Yamagishi, H. & Ugawa, N. 2004. Landslide susceptibility mapping using GIS based weighted linear combination, the case in Tsugawa area of Agano river, Nigata prefecture, Japan. *Landslides,* 1: 73–80.

Bahrami, Y., Hassani, H. & Maghsoudi, A.2021. Landslide susceptibility mapping using AHP and fuzzy metho sin the Gilan province, Iran. *GeoJournal*, 86: 1797–1816.

Biswas, B., Rahaman, A. & Barman, J. 2023. Comparative assessment of FR and AHP models for landslide susceptibility mapping for Sikkim, India and preparation of suitable mitigation techniques. *Journal of Geological Society of India*, 99: 791–801.

Brabb, E. 1984. Innovative approaches to landslide hazard mapping. *4th International symposium on Landslides*, 307–324.

Chung, C.J.F. & Fabbri, A.G. 1999. Probabilistic prediction models for landslide hazard mapping. *Photogramm Engineering Remote Sensing*, 65: 1389–1399.

Dai, F.C. & Lee, C.F. 2001. Terrain-based mapping of landslide susceptibility using a geographical information system: a case study. *Canadian Geotechnical Journal*, 38: 911–923.

Demir, G. 2019. GIS-based landslide susceptibility mapping for a part of the north Anatolian fault zone between Reşadiye and Koyulhisar (Turkey). *Catena*, 183.

Đokanović, S. 2015. Landslides induced by intensive rainfall in western Serbia (May 2014). *Proceedings of the 2nd Regional symposium on landslides – ReSyLab, Beograd*, 175–180.

Đokanović, S. 2016. Landslides and damage to buildings as a result of intense rainfall in Krupanj. *Tehnika*, 1: 48–55 (in Serbian).

Đokanović, S. 2021. Osnovna inženjersko-geološka karta 1:100 000 – list Zvornik [*Basic engineering geological map 1:100 000 – sheet Zvornik* – in Serbian]. Geološki zavod Srbije, Beograd.

Đokanović, S. 2022. Osnovna inženjersko-geološka karta 1:100 000. Tumač za list Zvornik L34-123 [*Basic engineering geological map 1:100 000. Explanatory booklet for the sheet Zvornik* – in Serbian]. Geološki zavod Srbije, Beograd.

Đokanović, S. & Trbojević, Đ. 2018.Damage caused by landslides in Serbia from 2009-2016 (in Serbian). *17th Serbian Geological Congress*, Vrnjačka Banja, 663–667.

Đurić, D., Mladenović, A., Pešić-Georgiadis, M., Marijanović, M. & Abolmasov, B. 2017. Using multiresolution and multitemporal satellite data for post-disaster landslide inventory in the Republic of Serbia. *Landslides*, 14: 1467–1482.

Facett, T. 2006. An introduction to ROC analysis. *Pattern Recognition Letter*, 27: 861–874.

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: 85–98.

Firomasa, M. & Abay, A. 2019. Landslide assessment and susceptibility zonation in Ebantu district of Oromia region, western Ethiopia. *Bulletin of Engineering Geology and Environmental,* 78: 4229–4239.

Gheshlaghi, H.A. & Feizizadeh, B. 2017. An integrated approach of analytic network process and fuzzy based spatial decision making systems applied to landslide risk mapping. *Journal of African earth sciences*, 133: 5–24.

Gökceoglu, C. & Aksoy, H. 1996. Landslide susceptibility mapping of the slopes in the residual soils of the Mengen region (Turkey) by deterministic stability analyses and image processing techniques. *Engineering Geology*, 44: 147–161.

Günter F., Reichanbach, P., Malet, J.P., van der Bechanaut, M., Hervis, J., Dashwood, C. & Guzzeti, F. 2013. Tier-based approaches for landslide susceptibility assessment in Europe. *Landslides*, 10: 529–564.

Guzzetti, F., Carrara, A., Cardinalli, M. & Reichenbach, P. 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. *Geomorphology*, 31: 181–216.

Guzzetti, F., Ardizzone, F., Cardinalli, M., Galli, M., Reichenbach, P. & Rossi, M. 2008. Distribution of landslides in the Upper Tiber River basin, central Italy. *Geomorphology*, 96: 105–122.

Huang, F., Cao, Z., Guo, J., Jiang, S.H., Li, S. & Guo, Z. 2020. Comparisons of heuristic, general statistical and machine learning models for landslide susceptibility prediction and mapping. *Catena*, 191: 104580.

Hung, L.Q., Van, N.T.H., Duc, D.M., Ha, L.T.C., Son, P.V., Khanh, N.H. & Binh, L.T. 2016. Landslide susceptibility mapping by combining the analytical hierarchy process and weighted linear combination methods: a case study in the upper Lo river catchment (Vietnam). *Landslides*, 13: 1285–1301.

Janjić, M. 1969. Inženjerskogeološke odlike terena NR Srbije [*Engineering geological characteristics of terrains of national republic of Serbia* – in Serbian]. Naučna knjiga, Belgrade, Serbia.

Janjić, M. 1979. Inženjerska geodinamika [*Engineering geodynamics* – in Serbian]. Rudarsko-geološki fakultet, Belgrade, Serbia.

Jazouli, A., Barakat, A. & Khellouk, R. 2019. GIS-multicriteria evaluation using AHP for landslide susceptibility mapping in Oum Er Rbia high basin (Morocco). *Geoenvironmental disasters*, 6: 3.

Komac, M. 2006. A landslide susceptibility model using the Analitical Hierarchy Process method and multivariate statistics in perialpine Slovenia. *Geomorphology,* 74: 17–28.

Kritikos, T. & Davies, T. 2015. Assessment of rainfall-generated shallow landslide/debris-flow susceptibility and runout using a GIS-based approach: application to western Southern Alps of New Zealand. *Landslides*, 12: 1051–1075.

Lee, S. & Min, K. 2001. Statistical analysis of landslide susceptibility at Yogin, Korea. *Environmental Geology*, 40: 1095–1113.

Leroueil, S. 2001. Natural slopes and cuts: movement and failure mechanisms. *Géotechnique*, 51: 197–243.

Marijanović, M., Abolmasov B. & Milenović, S. 2018. Procena rizika od klizišta na putnoj mreži opštine Krupanj [*Road network landslide risk assessment in the Krupanj municipality* – in Serbian, with an English abstract]. Put i životna sredina, Vršac, 491–500.

Myronidis, D., Papageorgiou, C. & Theophanous, S. 2016. Landslide susceptibility mapping based on landslide history and analytic hierarchy process (AHP). *Natural Hazards*, 81: 245–263.

Neaupane, K.M. & Piantanakulchai, M. 2006. Analytic network process model for landslide hazard zonation. *Engineering geology*, 85: 281–294.

Nefesiuglu, H., Duman, T. & Durmaz, S. 2008. Landslide susceptibility mapping for a part of tectonic Kelkit

Valley (Eastern Black Sea region of Turkey). *Geomorphology*, 94: 401–418.

Palau, R.M., Hürlimann, M., Berengeuer, M. & Sempre-Torres, D. 2020. Influence of the mapping unit for regional landslide early warning systems: comparison between pixels and polygons in Catalonia (NE Spain). *Landslides*, 17: 2067–2083.

Pourghasemi, H.R., Pradhan, B., Gokceoglu, C. & Moezzi, K.D. 2012. Landslide susceptibility mapping using a spatial multi criteria evaluation model at Haraz Watershed, Iran. *In*: Pradhan, B. & Buchroithner, M. (Eds.). *Terrigenous mass movement*s. Springer Berlin, Heidelberg, 23–49.

Saaty, T. 1980. Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, 1: 83–89.

Saaty, T. 1990. How to make decision: The analytic hierarchy process. *European Journal of Operational Research*, 48: 9–26.

Saaty, T. 2008. Decision making with the analytic hierarchy process. *International Journal of Services Sciences,* 1: 83–98.

Sarkar, S., Kanungo, D.P. & Mehrotra, G.S. 1995. Landslide hazard zonation: a case study in Garhwal Himalaya, India. *Mountain Research and Development Journal*, 15: 301–309.

Schicker, R. & Moon, V. 2012. Comparison of bivariate and multivariate statistical approaches in landslide susceptibility mapping at a regional scale. *Geomorphology*, 161-162: 40–57.

Soeters, R. & van Westen, C. 1996. Slope instability recognition, analysis and zonation. *Landslides*, Special report, 247: 129–177.

Sharma, S. & Mahajan, A.K. 2019. A comparative assessment of information value, frequency ratio and analytical hierarchy process models for landslide susceptibility mapping of a Himalayan watershed, India. *Bulletin of Engineering Geology and Environmental*, 78: 2431–2448.

Sunarić, D., Jevremović, D. & Nedeljković, S. 2002. Analiza šteta izazvanih nekim savremenim geodinamičkim procesima u Srbiji [*Analysis of damage caused by some modern geodynamic processes in Serbia* – in Serbian]. *XIII simpozijum o hidrogeologiji i inženjerskoj geologiji.* Herceg Novi, 295–300.

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: 9–21.

van Westen, C., Rengers, N., Terlien, M. & Soeters, R. 1997. Prediction of the occurrence of slope instability phenomena through GIS based hazard zonation. *Geologische Rundschau*, 86: 404–414.

Varnes, D. 1984. Landslide hazard zonation: a review of principles and practice. Unesco.

Vessia, G., Di Curzio, D., Chiaudani, A. & Rusi, S. 2020. Regional rainfall threshold maps drawn through multivariate geostatistical techniques for shallow landslide hazard zonation. *Science of the total environment*, 705: 135815.

Wachal, D.J. & Hudak, P.F. 2000. Mapping landslide susceptibility in Travis County, Texas, USA. *GeoJournal*, 51: 245–253.

Wilson, J.P. & Gallant, J.C. 2000. *Terrain analysis principles and applications*. Wiley, New York.

Yalcin, A. 2007.Environmental impacts of landslides: a case study from East Black Sea region, Turkey. *Environmental Engineering Sciences*, 24: 821–833.

Резиме

Процена подложности на клижење помоћу методе аналитичког хијерархијског процеса и ГИС тежинског преклапања: студија случаја подручја општине Крупањ у западној Србији

Клижење је један од најчешћих и најзначајнијих савремених геолошких процеса (Јањић, 1969). Да би се умањио негативан утицај клизишта неопходно је познавати зоне склоне клижењу. Карте подложности на клижење (ЛСМ) дају важне информације планерима и инжењерима који осмишљавају или спроводе стратегију коришћења земљишта(Wachal & Hudak, 2000). Подложност на клижење, за општину Крупањ, одређена је помоћу метода аналитичког хијерархијског процеса (АХП) и тежинског преклапања (WO). Општина Крупањ је нарочито била погођена интезивним падавинама у мају 2014. које су покренуле бројна клизишта која су

изазвала велику материјалну штету. Због тога је велика пажња посвећена проблемима клизишта на овом простору. У периоду од 2014. до 2021. на овом подручју и зведена су инжењерскогеолошка истраживања у оквиру неколико различитих пројеката. Прикупљени подаци искоришћени су за процену подложности на клижење овог подручја. За процену подложности коришћено је девет фактора: нагиб, орјентација, закривљеност, надморска висина, удаљеност од раседа, удаљеност од река, удаљеност од граница, литолошки састав и коришћење земљишта. АХП је квантитативна експертска метода код које се значај фактора одређује помоћу бројева из Сатијеве скале а кроз матрицу поређења. Код примене ГИС алата за тежинско преклапање ради дефинисања значаја фактора коришћене су тежине добијене помоћу АХП методе. На основу матрице поређења у ГИС-у је добијена карта подложности за истражно подручје. На основу тежинских вредности можемо закључити да највећи значај имају литологија и нагиб падина. Затим следе коришћење земљишта, удаљеност од река, удаљеност од граница, удаљеност од раседа и надморска висина. Најмањег значаја за настанак клизишта на истражном подручју су оријентација и закривљеност. Добијена карта је класификована у четири класе (веома ниске, ниске, високе и веома високе подложности). Најзаступљенија је класа високе подложности на клижење која захвата површину од 206 km^2 или 55,70 % односно нешто више од половине истражног подручја. Класа веома високе подложности захвата 78 km^2 или 21,13 % истражног подручја, а класа ниске подложности 80 km^2 односно 21,73 % истражног подручја. Најмање је заступљена класа веома ниске подложности која захвата само 5 km^2 или 1,43 % истражног подручја. На крају, валидност карте подложности је проверена помоћу ROC криве и AUC вредности. За добијену карту подложности вредност AUC је 0,771 што значи да је њена тачност добра (77,1 %). Ове карте могу да се користе од стране експерата за потребе просторног планирања. Зоне које су дефинисане као осетљиве и веома осетљиве захтевају даља инжењерскогеолошка и геотехничка разматрања приликом изградње објеката. Модел осетљивости на клижење неког подручја зависи од избора фактора и података о клизиштима.

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