Research Article

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GIS-based spatial modeling of landslide susceptibility using BWM-LSI: A case study – city of Smederevo (Serbia)

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Abstract: Landslides and slope processes constitute one of the most frequent natural hazards in valleys near major rivers and mountainous regions. The surface layer, characterized by its relatively loose composition, is prone to sliding due to a combination of distinct natural and human-related factors. Specific sections along the right bank of the Danube River in Smederevo city exhibit significant susceptibility to landslide activation, often leading to substantial material losses and posing a risk to the local population. The initial step in the provided research involves analyzing existing literature and mapping landslides within the study area. The initial analysis covers both natural conditions and anthropogenic activities. The second step includes establishing a geospatial database in the Geographic Information System and generating eight thematic maps. In the third step, different weight coefficients were assigned to the criteria, which facilitated the creation of the Landslide Susceptibility Index using the Best–Worst Method. Subsequently, in the fourth step, a composite map illustrating landslide susceptibility was produced. According to this research, about 4% of the territory of Smederevo, or 19.3 km^2, is highly or very highly susceptible to landslides. These localities are located on the right bank of the Danube River and around the Ralja River. Receiver operating characteristic-area under the curve value indicates very high predictive power (approximately 1), thus suggesting the reliability of the used methodology. This visualization of areas highly prone to such occurrences empowers policymakers to implement more effective environmental protection measures and institute sustainable management practices for agricultural parcels in this region. Also, the provided research represents the inaugural integration of advanced remote sensing techniques and interdisciplinary investigations, offering deeper insights into landslide activity in the study area and yielding more comprehensive results.

Keywords: landslides, susceptibility, mapping, city of Smederevo, natural and anthropogenic factors, environment, modeling, GIS, BWM, LSI

1 Introduction

Landslides represent a geological phenomenon that implies the transport of soil and rock formations down the slope under the influence of gravity [1,2]. The phenomenon of landslides is known as one of the most destructive natural disasters that endanger human lives, damage infrastructure, and cause changes in the appearance of the landscape [3–6]. According to available data, in the past 30 years, more than 3,800 landslides have been recorded worldwide, resulting in over 160,000 fatalities and material damages exceeding 11 billion dollars [7,8]. Landslides most often occur as a result of the interaction of specific natural conditions and anthropogenic activities [9–11]. The occurrence of landslides is influenced by geological characteristics (rock composition, faults), morphometric conditions, hydrological factors, and climatic elements among natural conditions [12,13]. On the other hand, anthropogenic activities contributing to the triggering of landslides include unsustainable land use, construction of roads and residential buildings on risky slopes, construction of water reservoirs, pronounced irrigation as well as the increasingly frequent problem of deforestation [14–17]. In landslide risk assessment, scientists, engineers, and decision-makers first assess the susceptibility of the territory to landslides [18]. Areas with recent and paleolandslides are mapped and identified.

In modern literature, four approaches to landslide modeling are distinguished: qualitative, semi-quantitative,

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quantitative, and modeling with machine learning. The qualitative method (heuristic approach) is based on historical data, landslide inventory, field research, knowledge and experience of a group of experts [19,20]. Semi-quantitative methods assign different weights to criteria and rank them based on logical tools like Analytic Hierarchy Process (AHP), Best–Worst Method (BWM), fuzzy logic, Weighted Linear Combination, etc. [21,22]. Quantitative methods provide a more objective view of the area's vulnerability [23]. To employ a quantitative approach effectively, a comprehensive database is essential, specifically a detailed inventory of landslides across the study area. Quantitative methods typically encompass both statistical and deterministic approaches. The statistical method analyzes the connection between the existing landslides and the factors that influence their occurrence, after which the hazard classes are obtained by mathematical calculation [24]. The deterministic approach involves studying the geotechnical properties of a certain slope using limit equilibrium methods or numerical analysis [25,26]. The latest studies connect the assessment of landslide occurrence with machine learning models: support vector machine, random forest, deep learning, logistic regression, neural networks, etc. [27–30]. Geographic Information System (GIS) and remote sensing play pivotal roles as tools for analyzing and visualizing the spatial distribution of potential landslides in all the aforementioned approaches [31]. The processing of geospatial data within a GIS environment, the analysis of satellite images, and the mapping of territories using drones constitute a widely applied technique that has been used to model natural hazards and address various environmental challenges [32–38]. High-resolution images, when combined with a digital elevation model (DEM), can yield pertinent results and visual representations of physical-geographical processes and phenomena on the Earth's surface [39,40].

In Serbia, landslides are among the most frequent natural disasters [41,42]. According to available estimates, about 25% of the territory of Serbia is susceptible to landslides [43,44]. The territory of the city of Smederevo is one of the most threatened areas in Serbia, where several landslides are activated every year, causing great material losses to the local population [45]. The objective of this preliminary investigation is to assess the geospatial susceptibility of Smederevo city to landslides. The study employs modern technologies such as GIS and drone imaging to calculate the Landslide Susceptibility Index (LSI) using a multi-criteria decision-making (MCDM) approach, specifically the semi-quantitative BWM. The methodology for calculating the LSI in this study is based on assigning different weight coefficients to all criteria and their processing in the BWM model. The results of this study can be useful to decision-makers and spatial planners for more effective management of natural disasters, future development of the City, infrastructure construction, and sustainable land use planning.

2 Material and methods

2.1 Study area and history of landslide occurrences

The city of Smederevo is located in the northeastern part of the Republic of Serbia and belongs to the Podunavlje Administrative District. It is situated on the right bank of the Danube River, and as per the 2022 census, the population of this territory is 98,677 inhabitants. The study area covers 484 km^2 (Figure 1). The territory of the City of Smederevo includes the gently undulating lowland area of the southern rim of the Pannonian Basin in the extreme north-eastern part of Šumadija. In the morpho-structural sense, the territory belongs to the lower part of the Velika Morava Valley, where the eastern part of the municipality covers the valley plain of the Velika Morava. Conversely, in the western part, the basins of the left tributaries of the Morava River are incised into the terrain at an elevation of 200 m. In geotectonic terms, this area is part of the larger Moravian-Banat basin structural unit. It comprises sediments from the middle and upper Miocene as well as the lower Pliocene. Additionally, it includes the post-basin structural unit of the Danube cover, consisting of the youngest sediments such as Pleistocene and Holocene aeolian, fluvial, and slope deposits. The basic structural feature consists of deep regional longitudinal neotectonically active faults running north-northwest-south-southeast. The largest and oldest structural forms are of the meridional direction and are represented by the positive morpho-structures of the Požarevac ridge and Krnjevo, between which the Velika Morava trench is located [46].

Within the relief of Smederevo, three distinct units can be identified [46]:

1. Valley plain of the Velika Morava;
2. Danube coast;
3. Ralja, Konjska River and its watershed.

The territory of the town of Smederevo lies in the down-stream part of the Velika Morava valley floor. Alluvial deposits primarily consist of fine-grained sands and silt-stones. On the alluvial plain of Velika Morava, there are alternating, loosely stratified alveritic clays and clayey sands that are poorly sorted. The sediments of the upper pontoon

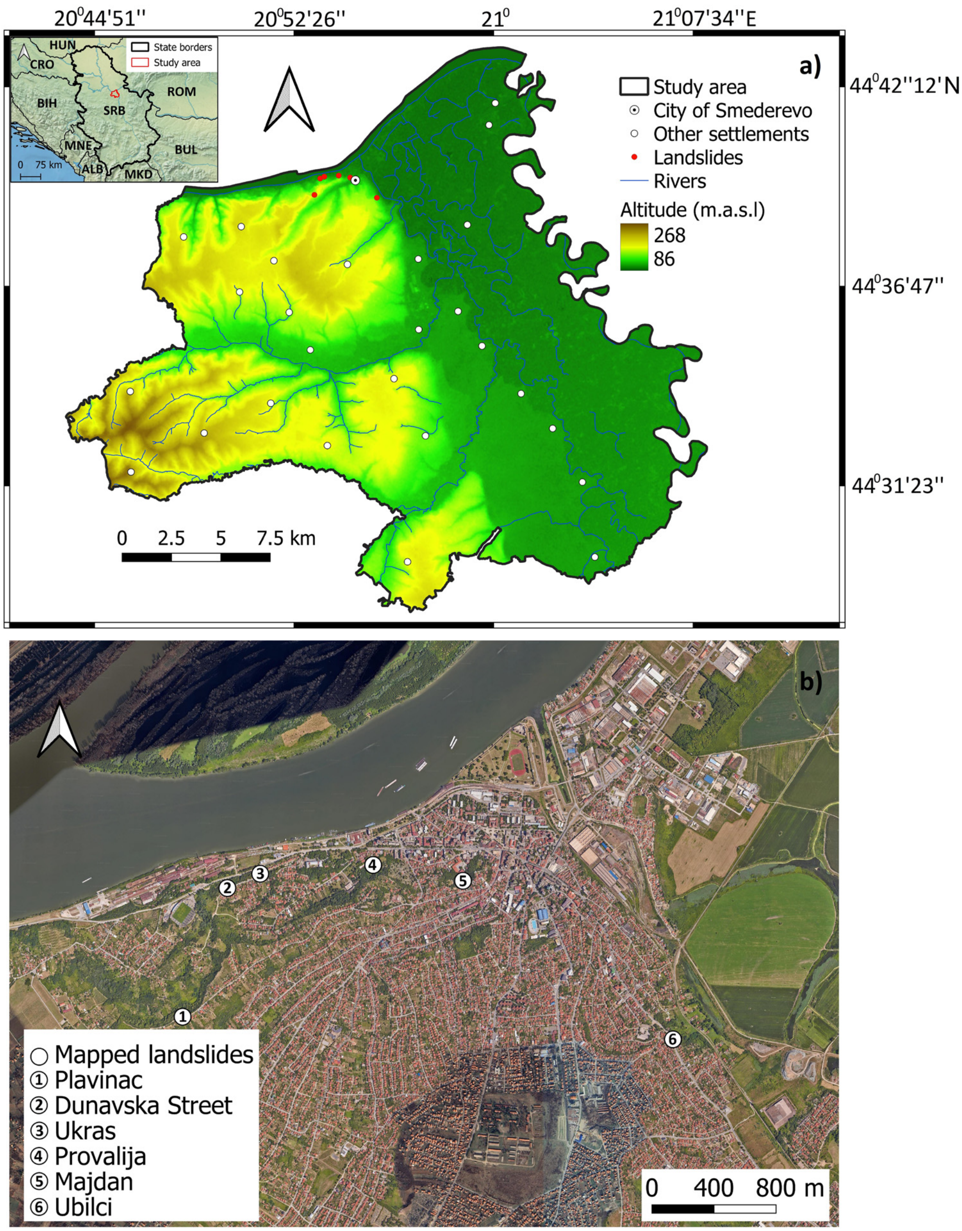

Figure 1: Geographical position of the study area (a) and mapped landslides (b).

form the Smederevo Podunavlje on the right bank of the Danube. They consist mainly of white quartz sands, sandy clays with clay intercalations, and clayey sands. The total thickness of the Pontic series near Smederevo is approximately 300 m. Ralja and Konjska River have relatively narrow valleys, with gentler slopes on the left side and steeper slopes on the right side. The oldest stratigraphic member, the Pannonian sediments, are exposed in the western part of the city, particularly on the right side of Ralja and in the Konjska River basin. This series is predominantly composed of white quartz sands with occasional interbeds of sandstone and sandy clay.

The city of Smederevo is renowned for its landslides, which originated from contemporary exodynamic processes occurring during the latest phase of hillside relief formation. The formation of landslides is influenced by various causal factors, including geological, hydrogeological, hydrological, and geomorphological conditions, as well as anthropogenic influences [45].

The specificity of this territory is reflected in the following characteristics [46]:

1. The geological foundation of the area is highly erodible, predominantly composed of unconsolidated sediments. Its structure allows for significant absorption of surface

waters to considerable depths and facilitates intense gravitational movement of the surface layer.
2. There is significant relief dissection in the central and western parts of the city, indicated by appropriate values of topographic slope, varying slope lengths, height above local erosive bases, horizontal dispersion, and a relatively dense drainage network in accordance with these features.
3. The substrate is inadequately protected due to extensive anthropogenic use, with a significant portion dedicated to agriculture, settlements, and roads, and a limited area covered by forests.

The following geomorphological processes were observed in the study area:
1. surface decomposition of marly sediments;
2. marsh processes;
3. process of terrain sliding.

The significance of landslides varies based on their scale and the volume of material displaced. Small landslides primarily hold morphological and scientific importance, while large-scale landslides adversely impact economic activities and overall human life. The most extensive landslide zone in the Pannonian Basin is situated between Belgrade and Smederevo. Within this zone, the area prone to landslides is most prominent along the Danube and is locally referred to as Rujište [47]. Nevertheless, in the territory of the city of Smederevo, landslides, although somewhat smaller in volume, have greater social significance because they directly affect the lives of people in the densely populated area of Smederevo. In the narrower urban area of Smederevo, there are a large number of landslides that were mainly activated by an anthropogenic factor because numerous buildings were built in their places. Due to the loose and non-resistant lake sediments, a typical example of large landslides occurs here, especially on the right bank of the Danube, where unbound sediments, tilting of layers, constant upheaval, and removal of accumulated material are the main factors of the constant sliding process [46]. In the city of Smederevo, there are a large number of landslides that differ from each other genetically and morphologically. Large landslides pose a problem for the functioning of the city because they threaten residential buildings, roads, sports facilities, water supply infrastructure, and sewerage.

The "Provalija" and "Plavinac" landslides are located near the Old Steel mill and cover an area of approximately 250 ha (Figure 2). The amount of material released is believed to be more than 36 million cubic meters [45].

"Plavinac" is the largest landslide in Smederevo. It was activated in 1977 during springtime rains. During that season, ten additional smaller landslides occurred along the road leading to Udovice and Seone. In under a month, the Plavinac landslide destroyed 350 houses and directly caused 40 families to be displaced. Currently, another 130 buildings are at risk in the landslide zone, and the Smederevo–Belgrade regional road had to be partially moved from its original route. The extremely favorable lithological, hydrological, and geological conditions, as well as the Danube River, which cut and washed the foot of the slope on its right side, are responsible for the appearance of this landslide. Therefore, the static conditions changed and cracks were created in the sliding mass, which changed the hydrogeological regime and load [45]. Of course, it is also necessary to point out the anthropogenic factor, which can be seen mostly through the unplanned disposal of wastewater.

The "Ukras" landslide near the former textile industry factory is slightly smaller and covers an area of about two

Figure 2: "Provalija" landslide (2013) – left, and "Majdan' landslide (2015) – right.

hectares. It is very active with immediate danger of further spread. The appearance of this landslide was influenced by the physical and mechanical characteristics of the terrain and the large slope of the slope, which is also burdened by residential construction [45].

The “Majdan” landslide is located in the center of the city. It was reactivated by the collapse of the walls of the old shelter during the construction of the House of Culture. The height of the landslide is between 3 and 5 m (Figure 2). This landslide threatens the aforementioned Cultural Center as well as the elementary school [45].

The “Ubilci” landslide extends in the eastern part of the city, between the Smederevo-Požarevac road and the Smederevo–Mala Krsna railway. The occurrence of this landslide is conditioned by the unfavorable characteristics of the terrain, the discharge of surface water, as well as the load on the slopes of the newly constructed buildings. The construction of the Jezavski canal, asphalt road, and railway has reactivated the landslide, posing a continued threat to the aforementioned infrastructure facilities [45].

The “Sports Center slide” was activated again when the construction of the Smederevo Hall began, but in 2009, after the completion of the construction, it was completely repaired and no longer endangers nearby buildings.

The landslide on Dunavska Street is the most active and hazardous landslide in Smederevo (Figure 3). It is about 50 m long and between 25 and 35 m wide. Its area is 1,500 m^2. The landslide has a drop of 20 m, and four even smaller landslides can be seen around it. On the body of the landslide, there are smaller cracks, elevations, and depressions. The sliding surface cuts through the soil composed of sand and clay, and it is slightly wavy. Deluvial clays, marly clays, and sands are represented by the lithological members, and by man-made formations, the embankment is singled out. The body of the landslide in the area of Dunavska Street is formed by deluvial sediments, marly clays, and sands [45].

The causes of landslides in the Dunavska Street area are manifold and can be generally attributed to:

- lithological composition (alternation of sand and clay);
- steep terrain slope;
- accidental discharge of water from the water supply and sewage network into the body of the landslide;
- the movement of heavy vehicles along the Dunavska Street, which causes unfavorable vibrations, displacement, and the creation of depressions on the roadway;
- unfavorable characteristics of the embankment along Dunavska Street.

This landslide is still active. During the 21st century, it caused serious material damage several times. In April 2007, a landslide destroyed an asphalt road and displaced four thousand cubic meters of soil, along with telephone poles. As a result, several hundred citizens were without telephone service for several days. The landslide was reactivated in 2014 and 2015, when the landslide buried the road leading to the eastern stand of the Smederevo football club stadium, and again washed away the asphalt in Dunavska Street. Work on the complete rehabilitation of the landslide was carried out in 2015 and 2016, but this landslide is still considered a potential danger, especially in the event of heavy rainfall.

2.2 Data collection and GIS analysis

For the purposes of landslide mapping, historical data on locations where landslides occurred were used [45]. The locations were filmed with a “DJI Mini 2” drone. All

Figure 3: Dunavska Street: during the landslide (2007) – left, and landslide recovery (2023) – right.

geospatial data were processed in the open-source software QGIS 3.28 [48]. The DEM was downloaded from the Alaska Satellite Facility geoportal [49]. From there, the terrain slope and the aspect were derived. Geological features (rock types and faults) were digitized from the main Geological Map of Serbia, scale 1:100,000 [50] (Table 1).

River flows (permanent and periodic) were digitized from a topographic map on a scale of 1:50,000 [51]. Data on rainfall were obtained by linear regression of the values recorded for the Ralja River basin [52]. Land use (Corine Land Cover) was taken from the Copernicus – Land Monitoring Service geoportal [53], while roads and railways were digitized from the Open Street Map platform. All contents that were digitized were later converted to raster format [54]. The spatial resolution of the thematic maps and the synthetic map is 12.5 m.

2.3 Methodology

2.3.1 GIS analysis

All spatial data used for eight criteria were processed in GIS using QGIS software [48]. The terrain slope was obtained by processing the digital elevation model, and then the values were reclassified. Geological data were first digitized from geological maps and then rasterized. The rasterized data were reclassified into five classes. Data on faults were first obtained by digitizing all faults within the study area. After that, the data were rasterized and reclassified according to the level of vulnerability. Data on streams were obtained by digitizing all watercourses on the territory of the city of Smederevo. First, the topographic map was georeferenced in GIS, and then, the content was vectorized. These data were later rasterized and reclassified to create the final map. Data on rainfall were obtained based on formulas for estimating annual precipitation in the Ralja River basin [52]:

$$0.225\text{DEM} + 371, \tag{1}$$

where DEM is the digital elevation model.

The aspect was done based on DEM. First, the values for the azimuth exposure were obtained, and then the classification was performed in relation to the sides of the world. Depending on the level of susceptibility, values are assigned to each side of the world. Land use data were imported from the Copernicus geoportal and converted from vector to raster to access the reclassification. Finally, the roads and railways were digitized in GIS in order to reclassify the values into five classes. Data converted from vector to raster is of different scales [55]. However, the level of generalization of the rasterized content within the study area is acceptable because both the inputs, and the final data have a resolution of 12.5 m.

2.3.2 BWM

BWM represents a relatively new method of MCDM that is increasingly applied in natural hazards [56,57]. For the purposes of the study, linear BWM was used, which has certain advantages compared to the most commonly applied methods of MCDM (such as AHP): (1) BWM needs less pairwise assessment; (2) due to higher consistency percentage, the results obtained using BWM are more reliable; (3) BWM uses only integers in its matrix and at the same time provides the possibility of checking the consistency of given pairwise comparisons [58].

The procedure for obtaining weight coefficients using BWM can be explained in the following steps [59,60]:

Step 1. Based on existing studies and literature, decision-makers determine a set of relevant criteria $\{c_1, c_2, c_3, \ldots, c_n\}$. Based on expert experience, the criteria are prioritized from

Table 1: Data collection and sources

Criteria	Format	Spatial resolution (m)	Source of data	Year
Terrain slope	Raster	12.5	[42]	2006
Geology	Vector to raster		[43]	1979
Distance from faults	Vector to raster		[43]	1979
Distance from streams	Vector to raster		[44]	1970
Rainfall	Raster		[45]	2009
Aspect	Raster		[42]	2006
Land use	Vector to raster		[46]	2018
Distance from roads and railways	Vector to raster		[47]	2023

most to least significant. In the case of landslides, eight criteria were chosen. The criteria are outlined in the following section.

Step 2. The best (most significant) criterion and the worst (least significant) criterion are identified according to their preferences. For landslide hazard analysis, slope was determined as the best criterion, while aspect was designated as the worst criterion.

Step 3. Decision-makers compare the best criterion with all other criteria using a scale between 1 and 8 (number 1 represents equal importance, whereas number 8 means that the best criterion is rated extremely more important than other criteria). This results in the following Best-to-Others vector:

$$A_B = (a_{B1}, a_{B2}, \ldots., a_{Bn}), \tag{2}$$

where a_{Bj} stands for to what extent the best criterion B is more preferred to criterion j. Therefore, it is evident that $a_{BB} = 1$.

Step 4. Experts assign values between 1 and 8 to compare all other criteria with the worst criterion (1: j is equally important to worst; 8: j is extremely more important than worst). The resulting Others-to-Worst vector would be:

$$A_W = (a_{1W}, \ldots., a_{2W}, \ldots., a_{nW}), \tag{3}$$

where the preference of criterion j over the worst criterion is expressed as a_{jW}, while $a_{WW} = 1$.

Step 5. The calculation of optimal weights of various criteria is approached. By minimizing the maximum value of the set of $\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}$ for all j, the problem can be translated into the following as highlighted by [58]:

$$\{|w_B - a_{Bj}w_j|, |w_j - a_{jW}w_W|\}, \tag{4}$$

$$\text{subject to} \sum_{j=1}^{n} w_j = 1, w_j \geq 0, \quad \text{for all } j \tag{5}$$

This problem can be written as a linear programming model, as shown below:

min ξ, such that

$$|w_B - a_{Bj}w_j| \leq \xi, \quad \text{for all } j, \tag{6}$$

$$|w_j - a_{jW}w_W| \leq \xi, \quad \text{for all } j, \tag{7}$$

$$\sum_{j=1}^{n} w_j = 1, \tag{8}$$

$$w_j \geq 0\ , \quad \text{for all } j. \tag{9}$$

The consistency ratio (CR) and associated threshold are calculated by making use of the following formulas for input-based BWM [61]:

$$\text{CR} = \max\ \text{CR}_j, \text{where} \tag{10}$$

$$\text{CR}_j = \begin{cases} \dfrac{|a_{Bj} \times a_{jW} - a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}} & a_{BW} > 1, \\ 0, & a_{BW} = 1. \end{cases} \tag{11}$$

The calculated CR is then compared to the threshold values presented in Table 2 [61].

The values in the matrix were assigned to calculate and obtain the weighting coefficients. The terrain slope was determined as the best and most important criterion, while the exposure was marked as the worst criterion (Table 3).

All the comparisons were consistent. Two primary drawbacks of the BWM method can be outlined regarding its limitations. First, BWM does not systematically identify the most optimal solution, which leads to non-unique weight coefficients. Second, the calculation process is complex if there are more than nine criteria. Such an endeavor would require grouping multiple criteria into clusters. The weight coefficients were included in the thematic maps and processed in the QGIS 3.28. software [42,62,63].

All approaches and procedures used for the purpose of this research are presented in the flowchart (Figure 4).

3 Results and discussion

The main goal of creating a map of the susceptibility of a certain area to landslides is the identification of areas that are potentially threatened by this phenomenon, prediction, preventive action, and rehabilitation. Since landslides occur due to the activation of many factors, it is necessary to include as many appropriate natural and anthropogenic conditions as possible when analyzing the area, so that the data are as reliable as possible. The factors mainly relate to the geological, geomorphological, climatological, and hydrological characteristics of the terrain and infrastructure. In this study, a total of eight factors were considered: terrain

Table 2: Thresholds for different combinations using input-based consistency measurement [61]

	Number of criteria					
Scales	**3**	**4**	**5**	**6**	**7**	**8**
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1989	0.2206	0.2527	0.2577
5	0.1354	0.1994	0.2306	0.2546	0.2716	0.2844
6	0.1330	0.1990	0.2643	0.3044	0.3144	0.3221
7	0.1294	0.2457	0.2819	0.3029	0.3144	0.3251
8	0.1309	0.2521	0.2958	0.3154	0.3408	0.3620

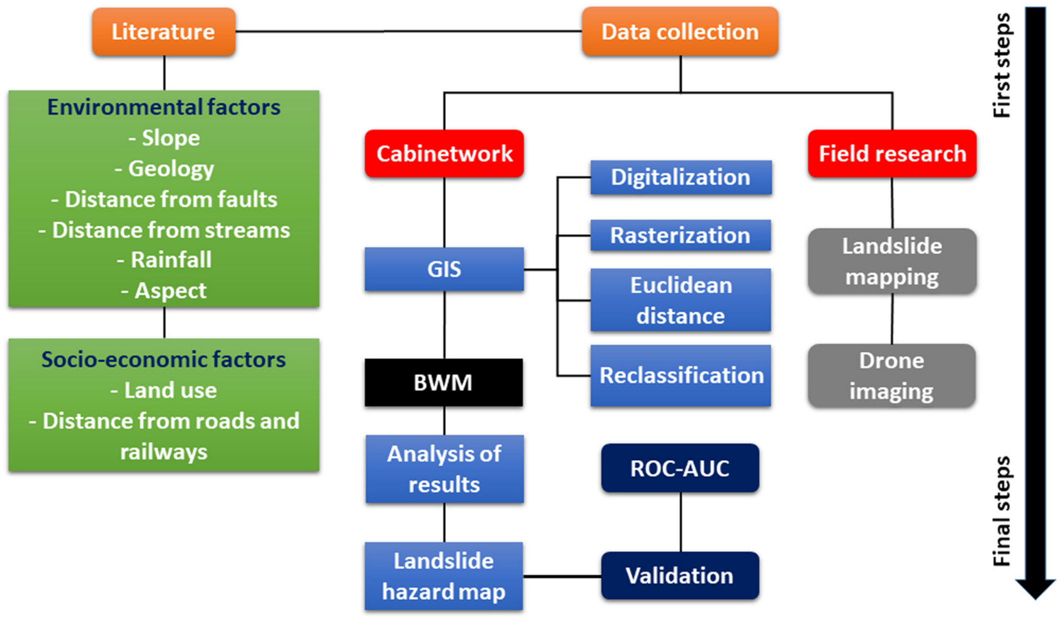

Figure 4: Flowchart of the proposed methodology and procedures used in this study.

slope, geology, land use, distance from roads, distance from faults, distance from river flows, amount of precipitation, and exposure. Following the existing literature, the mentioned eight criteria were selected. Any additional inclusion of new criteria would require significant changes in weighting coefficients and increased subjectivity when creating matrices and obtaining results.

The BWM was used to analyze the factors and their individual impact on the occurrence of landslides, and the criteria were evaluated using a rating scale from 1 to 5, where the values have the following meaning: 1 – very low vulnerability; 2 – low vulnerability; 3 – moderate vulnerability; 4 – high vulnerability; 5 – very high vulnerability.

The slope of the terrain (weight 0.332) is one of the main factors determining the occurrence of landslides. The division of terrain according to slope was made into five classes, with the highest value (5) assigned to terrains with a slope of 10–25°. Terrains with slopes above 25° occupy a small area and a negligible relative share of the research area (about 0.01%), which is why they were assigned values 3 and 4. On the other hand, gentle slopes and flat terrains (0–5°) are characterized by very low potential for the occurrence of landslides, which is why they were assigned the lowest value (Table 4).

The geology of the terrain (weight 0.199) also plays a key role, because geological units differ significantly according to their susceptibility to geomorphological processes [64]. River terraces built of sand and other alluvial soil, loess formations, clastites, and pelites with coal seams are the most susceptible to landslides, which is why these units are assigned the highest values. The 10–15 m terraces likely have the lowest susceptibility class because they are composed of geological materials that are less prone to landslides compared to other terraces. This lower susceptibility aligns with their engineering geological properties and the frequency of landslides, as indicated by Đokanović, respectively [65]. The other classes have lower values, and the smallest units are built of sand and peat, which are spread on the rim of the basin. Land use (weight 0.133) in the area of the city of Smederevo is diverse. Zones of non-irrigated arable land and other complexes of agricultural plots are most suitable for the activation of landslides, which have the highest value in the ranking, whereas the lowest values are characterized by water surfaces, wetlands, landfills, and green urban zones.

Distance from roads and railways (weight 0.1) is one of the most important anthropogenic factors contributing to discontinuities in the soil. This is especially pronounced in hilly terrains, where hill cutting with slopes greater than

Table 3: Matrix with assigned values

Besto to others	S	G	LU	DFR	DFF	DFS	RF	A
S	1	2	3	4	5	6	7	8
Other to the worst	S	G	LU	DFR	DFF	DFS	RF	A
A	8	7	6	5	4	3	2	1

Note: S, terrain slope; G, geology; LU, land use; DFR, distance from roads and railways; DFF, distance from faults; DFS, distance from streams; RF, rainfall; A, aspect.

Table 4: Reclassification of natural and anthropogenic values

Factor and weight coefficient	Parameter	Rank	Area (km^2)	Percentage (%)
Terrain slope (°) – 0.332	0–5	1	405.29	83.61
	5–10	2	67.27	13.88
	10–25	3	12.09	2.50
	25–30	4	0.06	0.01
	>30	5	0.01	0.002
Geology – 0.199	Alluvial deposit	2	10.29	2.13
	Gravel and sandstone	2	139.47	28.81
	Terrace 20–30 m, sand and allevrite	5	0.20	0.04
	Eolian-deluvial sediments	4	15.73	3.25
	Clastic, pelites, and carbonates	2	14.93	3.09
	Terrace 90–110 m, gravel and sand	4	51.70	10.68
	Clastic and pelites with coal	5	9.59	1.98
	Loess over the terrace 20–30 m	5	42.91	8.86
	Proluvial–deluvial sediments	4	3.43	0.71
	Allevrite, sand and clay	3	27.99	5.78
	Glay, sand and peat	1	32.48	6.71
	Terrace 3–5 m, allevrite and sand	4	72.88	15.06
	Terrace 10–15 m, gravel and sand	3	62.46	12.90
Land use – 0.133	Discontinuous urban fabric	4	44.00	9.09
	Industrial or commercial units	4	5.10	1.05
	Mineral extraction sites	3	1.25	0.26
	Dump sites	2	0.89	0.18
	Green urban areas	2	0.51	0.10
	Sport and leisure facilities	4	0.36	0.07
	Non-irrigated arable land	5	171.41	35.41
	Vineyards	4	7.90	1.63
	Fruit trees and berry plantations	4	45.05	9.31
	Pastures	4	3.36	0.69
	Complex cultivation patterns	5	73.04	15.09
	Agricult. land with a share of nat. vegetation	4	96.19	19.87
	Broad-leaved forest	3	16.22	1.25
	Transitional woodland-shrub	3	6.07	0.46
	Inland marshes	2	2.25	2.16
	Water bodies	1	10.46	9.09
Distance from roads and railways (m) – 0.1	0–50	5	109.46	22.62
	50–100	4	72.81	15.05
	100–200	3	98.83	20.42
	200–300	2	65.26	13.48
	>300	1	137.57	28.43
Distance from faults (m) – 0.08	0–100	5	30.01	6.20
	100–200	4	28.21	5.83
	200–400	3	52.42	10.83
	400–800	2	85.01	17.57
	>800	1	288.28	59.57
Distance from streams (m) – 0.066	0–150	5	93.14	19.25
	150–300	4	78.89	16.30
	300–400	3	44.87	9.27
	400–500	2	38.77	8.01
	>500	1	228.26	47.17
Rainfall (mm) – 0.057	<390	1	0.03	0.01
	390–400	2	274.21	56.66
	400–410	3	98.68	20.39
	410–420	4	94.65	19.56
	>420	5	16.38	3.38
Aspect – 0.033	N, NE, NW	5	159.80	33.02
	E, W	4	95.16	19.66

(Continued)

Table 4: *Continued*

Factor and weight coefficient	Parameter	Rank	Area (km^2)	Percentage (%)
	SE, SW	3	103.90	21.47
	S	2	45.94	9.49
	Flat	1	79.12	16.35

10° leads to slope instability and results in the occurrence of landslides [2,64,66]. In accordance with this, the classification of the distance zones from traffic roads was carried out, whereby the assigned value decreases with distance. The most sensitive areas are in the immediate vicinity of roads, up to 50 m away (steep slopes, unstable, bare, erodible rocks, and weak vegetation), while in the zone >300 m away, the impact is negligible. Distance from faults (weight 0.08) are characterized by cracks, which allow longer retention of moisture, thus creating favorable conditions for the activation of landslides. Therefore, zones were classified according to the distance from the fault lines. The highest values have terrains up to 100 m from the fault lines.

Distance from rivers (weight 0.066) is an important hydrological factor. The susceptibility of the area to the formation of landslides is affected by the river system, primarily due to river erosion. Therefore, zones up to 150 m along river courses were assigned the highest values. Regarding the role of rainfall (weight 0.057), the highest value was obtained by the areas that recorded the highest average amount of precipitation, and the areas with the lowest amount of rainfall obtained the lowest value. However, there were no significant differences in the amount of rainfall excreted in the studied area. The role of aspect (weight, 0.033) as a factor in the occurrence of landslides is related to precipitation and evaporation. Terrains with cold exposures (north, northwest, and northeast) were assigned the highest value, because they are less exposed to evaporation and contain more moisture than terrains with other exposures, especially southern and unexposed surfaces.

Based on the applied values, eight-factor maps were created, each with five classes according to the susceptibility of the factor to the formation of landslides [very low susceptibility – VL, low susceptibility – L, medium susceptibility – M, high susceptibility – H, and very high susceptibility – VH (Figure 5)].

On the basis of field research and database analysis through GIS and BWM (GIS-BWM), a synthetic map of the predisposition of the study area to landslides was generated (Figure 6). The landslide hazard map shows significant differences in the vulnerability of the western and eastern parts of the study area. The western half of the city of Smederevo is significantly more susceptible to landslides than the eastern half. The landslide susceptibility map reveals significant differences in the vulnerability to landslide hazards between the western and eastern parts of the study area. The western half of the city of Smederevo is significantly more susceptible to landslides than the eastern half. Due to different geological and morphometric characteristics, the east side is considerably safer from landslide activation.

Landslide susceptibility zones are classified into five categories: very low susceptibility, low susceptibility, medium susceptibility, high susceptibility, and very high susceptibility.

Zones of very high and high susceptibility to landslides cover an area of 19.3 km^2, that is, only 4% of the territory of the city of Smederevo (Table 5). They are present almost exclusively in the western half of the studied area (with the exception of surface exploitation of gravel in the northeast). They mostly spread in the form of elongated lots along the right valley sides of the Danube and Ralja, but they also occur in the smaller valleys of their tributaries. It is dominantly steeper terrains, with cold exposures, in which slope angles from 10° to 25° are recorded. The geological structure of the terrain, represented by a set of fault lines and the corresponding geological substrate (Neogene lake sediments, with a high concentration of sand, gravel, and loess), also corresponds to the category of terrain characterized by a high degree of risk of triggering landslides. The purpose of the land was not of decisive importance in defining the zone due to the heterogeneous composition and different uses of the surfaces. The high predisposition of these terrains to the occurrence of landslides is additionally conditioned by the proximity of roads and river courses. In addition to river erosion of the Danube, the intensification of denudation processes in the north of the studied area encouraged the routing of the old road Smederevo–Belgrade, while on the valley side of Ralja and Velika Morava, the highway Belgrade–Niš (corridor X) played this role. The sublimation of the mentioned factors makes this zone optimal for the occurrence of landslides.

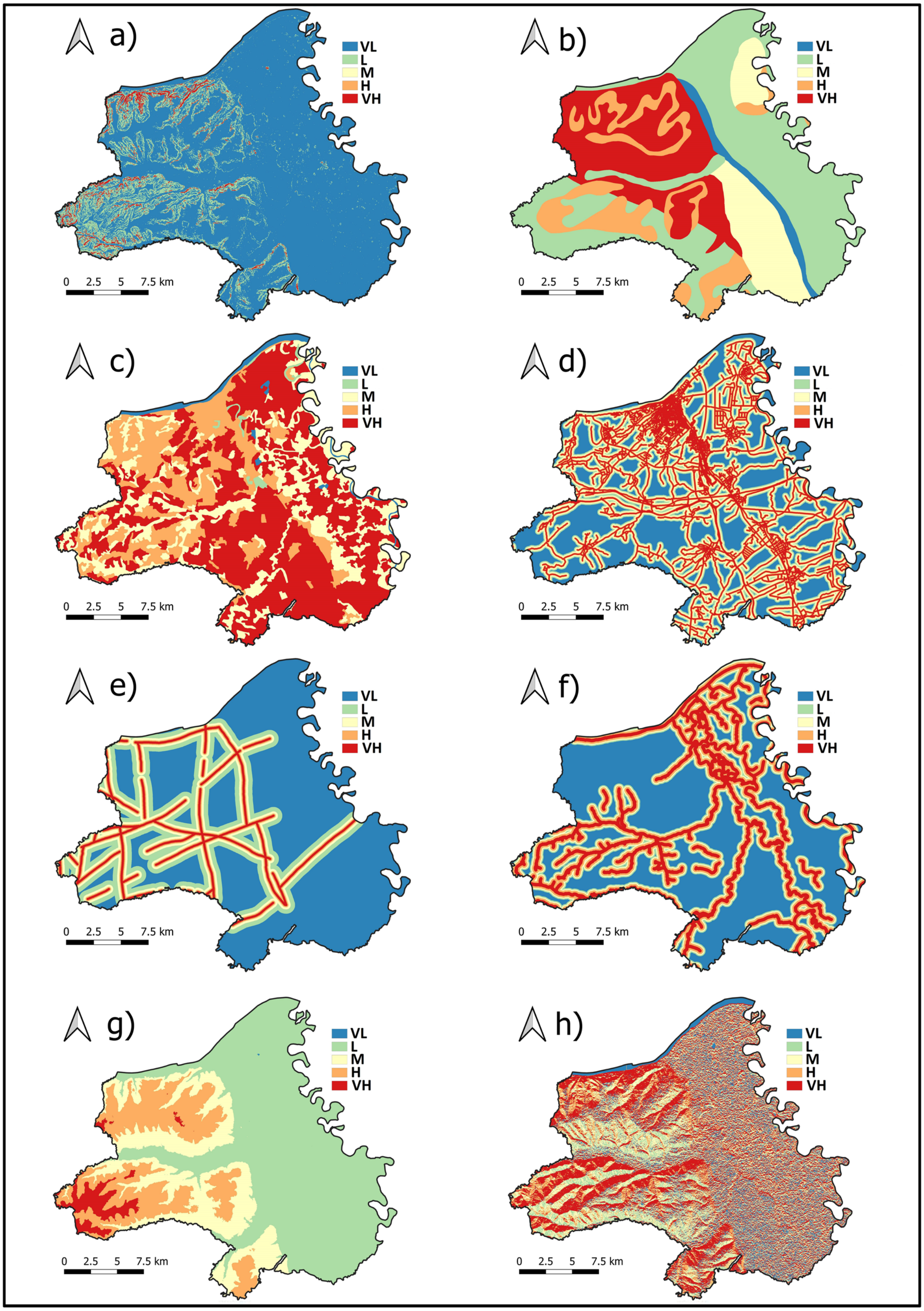

Figure 5: Suitability reclassified maps: (a) Terrain slope; (b) Geology; (c) Land use; (d) Distance from roads and railways; (e) Distance from faults; (f) Distance from streams; (g) Rainfall; and (h) Aspect.

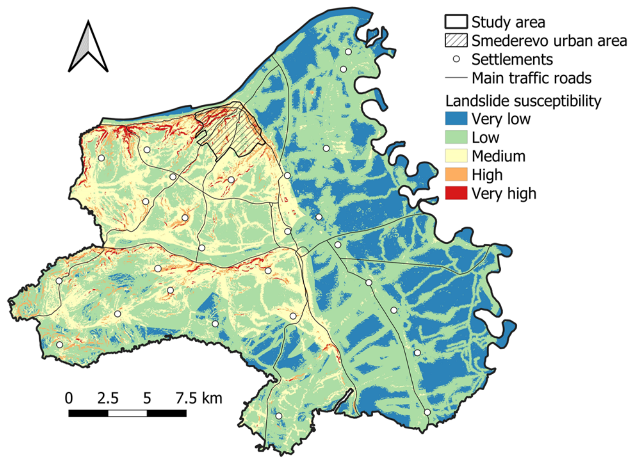

Figure 6: Landslide susceptibility map of the study area.

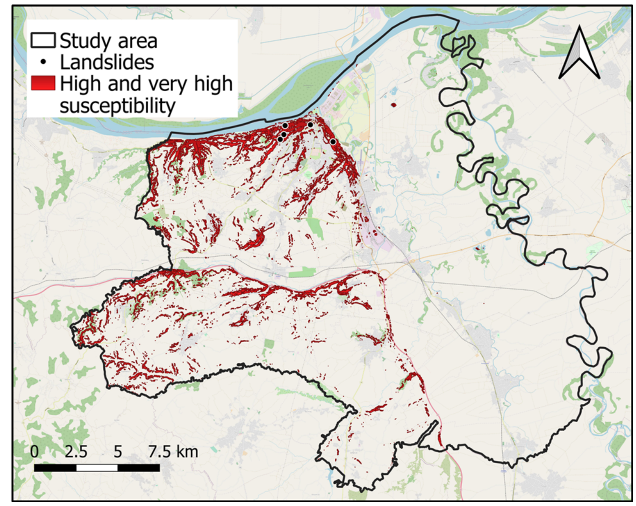

Figure 7: Zones of high and very high susceptibility to landslides within the study area.

Table 5: Area and share of landslide susceptibility zones in the city of Smederevo

Susceptibility	Area (km^2)	Percent (%)
Very low	107.49	22.21
Low	249.63	51.58
Medium	107.51	22.22
High	14.29	2.95
Very high	5.01	1.04
Total	483.93	100.00

Considering the relatively small area and the low relative proportion of the very high susceptibility zone (1.04%) and the high susceptibility zone (2.95%), one might get the impression that this is a negligible phenomenon for the city of Smederevo (Figure 7).

However, in this vulnerable part of the study area, there is the highest concentration of population, settlements, and economic entities. Highly susceptible and very highly susceptible landslide zones were identified in 13 out of 28 settlements within the study area. The settlements that are partially or completely threatened are Landol, Mihajlovac, Vrbovac, Suvodol, Drugovac, Malo Orašje, Binovac, Vodanj, Seone, Vučak, Petrijevo, Radinac, and the city of Smederevo. High and very high vulnerability is observed along the E75 highway and at the Vodanj–Kolari toll stations. A very high susceptibility is also evident along most of the Smederevo–Grocka road. According to the 2022 census, approximately 80% of the population resides in these areas.

It is worth noting that approximately 30% of the urban core of Smederevo falls within areas with a very high or high susceptibility to landslide activation. This natural hazard significantly impacts the living conditions and quality of life of the local population. The consequences so far have been manifested in the form of destruction or endangerment of residential and auxiliary buildings, streets, highway approaches to the city, industrial and other economic facilities, and infrastructure facilities. The anthropogenic factor was key to the activation of many landslides in the city (due to the construction of large infrastructure facilities, roads, water supply, etc.).

The zone of moderate susceptibility to landslides extends over 107.51 km^2 of the studied territory. Terrains characterized by medium susceptibility to landslides are also predominantly located in the western hilly area, including zones of very high and high susceptibility. Apart from its predominant occurrence in this section of the study area, smaller occurrences can be found scattered throughout the eastern part of the administrative unit (the city of Smederevo) within the Velika Morava valley. This moderate, "transitional" zone does not show regularity of appearance in relation to certain defined factors and their classes, but is characterized by terrains of diverse natural conditions. Zones of medium susceptibility to landslides occur in terrains with gentle slopes (0–5° and 5–10°) of different exposures.

The remaining area of the city of Smederevo includes the zone of low (51.58%) and very low susceptibility to the activation of landslides (22.21%). The probability of landslide occurrence in both zones is negligible, but there are certain differences between them. The zone of low susceptibility is present in all parts of the studied area with a slope of up to 5°, often near roads and above various geological formations. On the other hand, the zone of very low susceptibility mainly occurs in the alluvial plain of Velika Morava (Veliko Pomoravlje). In this zone, the slope angle does not exceed 5°, and the geology includes fine gravel, sand, clay, and peat that are not subject to denudation.

Figure 8: Unstable terrain within the study area (dashed lines represent areas of active landslides).

Although the spatial distribution of compact arable land is pronounced in Veliko Pomoravlje, the denudation is insignificant due to the lowland relief.

The overall geomorphological conditions in the study area facilitating the activation and movement of landslide masses are observed in the central and western parts of the city of Smederevo. This is characterized by steep topographic slopes, varied gradient slopes, elevated positions relative to local erosive bases, horizontal fragmentation, and a relatively dense drainage network. Furthermore, insufficient protection of the substrate results from inefficient anthropogenic use of geospace, with extensive areas dedicated to agriculture, substantial urban and infrastructure development, and limited forest cover. Therefore, anthropogenic geomorphological processes are pronounced in the investigated area. Numerous linear elements have been created, including cuttings, roads, canals, breakwaters, embanked terraces along local roads, highways, and railways. There are numerous indirect impacts of anthropogenic activities on geomorphological and hydrological processes: changes in hydrological dynamics due to the construction of water supply networks; regulation and alteration of river courses by cutting new channels and backfilling old riverbeds; surface and groundwater pollution from industrial waste and sewer networks; intensified gravitational processes on slopes prone to sliding due to construction activities; increased susceptibility to landslides from infrastructure development; and vibrations from heavy vehicles on unstable slopes. This corresponds with findings provided by Miljković et al. [45].

The use of the BWM-LSI method and consistency ratio to assess landslide-prone areas at a regional scale is a complex task influenced by various natural and anthropogenic factors, as demonstrated in this study. The consistent outputs obtained from the BWM-LSI method proved valuable, facilitating accurate mapping of landslide occurrences in the study area and providing insights into the relationship between landslide distribution and causative factors. This approach allows for the evaluation of landslide susceptibility, providing a comprehensive assessment of disaster risk and the existing characteristics of landslides. It focuses on basic conditions without considering dynamic predisposing factors such as extreme climatic events and human engineering activities, or predicting landslide occurrence times. The rationale for adopting the BWM-LSI methodology lies in its use of integer values for pairwise comparisons of criteria, contrasting with other MCDM methods like AHP that involve fractional numbers. This methodological choice aligns with previous studies and guidelines outlined by Gigović et al. [67].

Mapping and evaluating the susceptibility of the studied area to landslides, obtained through the BWM, enabled the identification of potential high-risk zones. Field research and literature review align with the obtained results, affirming the suitability and reliability of the applied model in investigating this issue (Figure 8). Further investigation should focus on an in-depth examination of the causal factors (and their interplay) that influence landslide occurrences within the study area [9]. It is crucial to emphasize the necessity for additional research, particularly regarding the validation of results using precise LIDAR measurements and other advanced technologies. Validation of the results is carried out to avoid errors during the processing of input data or the analysis of final values. One widely used statistical method is the receiver operating characteristic (ROC)–area under the curve (AUC) approach [68]. The ROC curve is a graph that is generated from the true positive value (sensitivity) on the *X*-axis and the false positive on the *Y*-axis at different thresholds (or cut-off points) [63].

The ROC-AUC measures the classifier's ability to distinguish between positive and negative examples and ranges from 0 to 1, with a value of 1 indicating a perfect classifier, while a value less than 0.5 indicates a random acceptance [69,70]. For the example of Smederevo, the predictive power is 1 (Figure 9), which shows a perfect connection between the mapped avalanches and the final landslide susceptibility map. By doing so, decision-makers could gain a more comprehensive understanding, aiding in the implementation of appropriate mitigation measures within the investigated area.

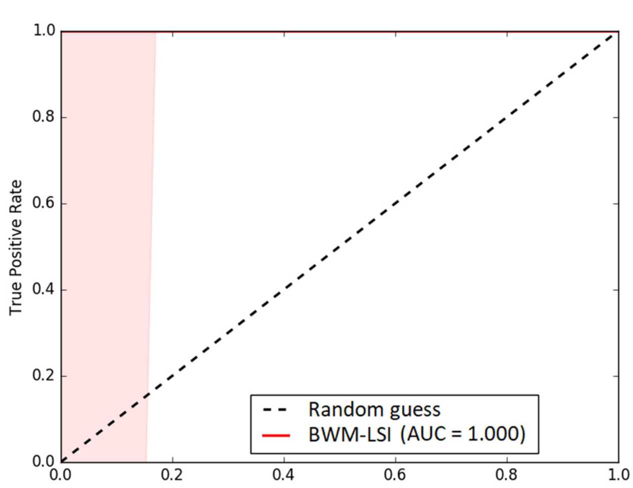

Figure 9: Validation of BWM-LSI approach using ROC-AUC.

4 Conclusion

Landslides are considered among the most destructive natural disasters in unstable terrains. Due to specific natural conditions and human activities, areas prone to landslides can occur at significantly lower altitudes, not limited to mountainous regions. This initial study represents the inaugural integration of remote sensing techniques and interdisciplinary investigations, offering deeper insights into landslide activity in the study area and yielding more comprehensive results. The consistent results derived from the BWM-LSI method proved instrumental, enabling precise mapping of landslide occurrences in the study area and offering insights into the correlation between landslide distribution and causal factors. This approach facilitated the assessment of landslide susceptibility in the city of Smederevo, providing a thorough evaluation of disaster risk and the current characteristics of landslides. In the city of Smederevo, the interplay of geological, geomorphological, hydrological, climatological, and anthropogenic conditions largely determine landslide occurrence locations. The first step in developing suitable guidelines for landslide risk management involves the creation of landslide susceptibility maps. In the Smederevo area, using GIS and the BWM-LSI method, it was observed that about 4% of the total territory (i.e., 19.3 km^2) is in the zone of high and very high susceptibility to landslides. Using a drone to survey the terrain enables the identification of vulnerable areas, such as heavily dissected hills with sparse vegetation or exposed soil. To prevent future damage, it is essential to apply the derived hazard maps in the overall mitigation process properly. In future analyses, two additional criteria should be considered: population density and number of building structures per 1 km^2. This will underscore the critical necessity for proactive measures to mitigate the impact of landslide hazards on the local environment and community.

Some European countries primarily allocate national funds for mitigating damage caused by landslides and significantly less for prevention (creating hazard maps). From that perspective, this initial study can serve decision-makers as one of the most important preventive measures tool in landslide risk management. Based on the results and detailed field research, zones in the city area and other settlements threatened by landslides can be identified. Thus, future catastrophes, i.e., human and material losses, can be prevented or significantly reduced.

On the other hand, spatial planners, based on the final map showing the landslide hazard distribution and terrain susceptibility to landslides, can choose geoecologically safer locations for the adequate economic and social infrastructure development of the city of Smederevo. Further research and field studies are recommended to deepen our understanding and address the intricate interplay of factors influencing vulnerability to landslide hazards in the city of Smederevo. This is necessary to identify specific measures or management actions for future implementation contributing to a satisfactory level of sustainable development. The first step involves applying the presented methodology in urban practices to mitigate landslides effectively.

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