

THE DETERMINATION OF THE LANDSLIDE OCCURRENCE PROBABILITY BY GIS SPATIAL ANALYSIS OF THE LAND MORPHOMETRIC CHARACTERISTICS (CASE STUDY: THE TRANSYLVANIAN PLATEAU)

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Abstract: The diagnosis and the prediction of landslides are essential problems in territorial planning from the efficient land-use perspective. In this context there were elaborated an amount of investigation methods, but there isn't any consensus yet. Even the methodology adopted by Romanian Governmental Decision no. 447/ 2003 is quite incomplete. The main goal of this study is to identify the probability of the damaged lands occurrence (affected by landslides) by introducing and using some variables and coefficients out of the record which will be integrated in a complex model of GIS spatial analysis. In this manner, the goal was to reduce the subjectivity level that occurs, in most of the methods, in the process of marking the variables. In the investigated territory, Transylvania Plateau, landslides are the most frequent process. These are the results of the favorable litology, hydro-climatic conditions, declivity and the fact that the landslides are still active is a result of not suitable land-use in the transition period from centralized agriculture (in communism) to a traditional agriculture, which means a considerable fragmentation of the properties. The implementation of the model in a relief unit characterized by a high morphological and morphometric variability, gives a high level of generality to the model. The value of the Relative Operating Characteristics curve (0,848) used to validate the model indicates the high predictability of the model and suggests its possibility to be used for other theories with similar morphological characteristics.

Key words: landslides, GIS data bases, GIS spatial analysis, probability, hazard coefficients

1. INTRODUCTION

It is well known that landslides, together with erosional processes and human activities generate useless of agricultural lands inducing major negative implications on the economic development in the affected areas. In Romania, landslides represent the natural hazards with the highest occurrence frequency and they have the widest manifestation area (Surdeanu, 1998).

The premise of the study is that the territorial morphometry represents the main factor which contributes to the occurrence, triggering and further evolution of the landslides. We believe that the quantitative assessment of each morphometric factor and the integrated analysis of all factors, based on

complex spatial analysis models, may lead to a true estimation of the probability that a certain territory be exposed to landslides.

The identification of the areas of susceptibility associated with the landslide occurrence probability, based on GIS models is a frequent subject in the specialized literature. For the moment there are two research directions: the heuristic one and the quantitative one (Van Westen, 2004; Thiery, 2007). The predictability model presented in this study is part of the second category and uses the statistical spatial analysis.

Statistical spatial analysis models are based on identifying the preparing factors and the probability of the occurrence and evolution of the studied phenomenon. Specialized literature emphasizes

many types of statistical approaches. First of all, one stresses the multi-varied statistical analysis, applied by Carrara et al., 1995, 1999, which is based on the analysis of the contribution of every factor in landslides occurrence, starting from their presence or absence in each uniform unit from a morphometric point of view.

Another type of approach is the bi-varied statistical analysis, which gives a statistical index to each factor implied in the model, being based on the presence of landslides in the analyzed territory. This type of approach is most frequently used and is based on identifying the relations between the preparing factors as independent variables and the existent landslides as dependent variables.

GIS spatial analysis models for the determination of the landslides occurrence probability, using the bi-varied statistical approach, were developed at the same time with the increase of possibilities for the storage and management of large amounts of databases. In this purpose, research was made by Bălteanu & Micu (2009), Bilaşco et al., (2011), Filip (2008), Onac et al., (2008), Armaş (2011), Arghiuş et al., (2013) for Romania. In the international specialized literature, similar approaches have been made by Chung et al., (1995), Nagrajan et al., (2000), Dhakal et al., (2000), Saha (2002), Sarkar & Kanguno (2004), Lee & Pradhman, (2007), Minucsér (2013).

The study of landslides is an old preoccupation of Romanian researchers: Tufescu (1966), Martiniuc (1961), Hârjoabă (1968), Băcăuanu (1980), Bălteanu (1983), Rădoane et al., (1995), Surdeanu (1998), and more recent: Micu & Bălteanu (2009), Manea & Surdeanu (2012), all using classical identification, inventory and mapping methodology.

Because of the bigger extension of the areas affected by landslides, the Government of Romania issued the Decree 447/2003 which settles the methodology for the elaboration and for the content of natural risk maps for landslides with application guidelines published in Monitorul Oficial 305 on the 7th of May 2003.

In some situations, this methodology allows some conclusive results, even though it is regarded as not so efficient by many specialists because the mark of some variables (lithological, climatic and hydrogeological) imposes an amount of subjectivity which derives not only from the different formation of the applicants but also from the deficient types, and scales of the maps and available data for different regions of the country.

Considering the necessity to respect the demands of the present methodology, but also

appreciating that this is based on elements which are difficult to quantify and do not have a spatial continuity (lithology, hydrogeology, seismicity), we consider that there is a possibility to validate the existing model with some unitary morphological and morphometric variables, derived from DEM. The main reason for the study is the fact that they are rigorously and objectively determined, independently from the interpretation that is given by the researcher to some data that can often be incomplete or inadequate from the point of view of scale. For increasing the accuracy of the results and for quantifying the predictability degree of the model we used a number of nine morphometric variables (hypsometry, slope, slope aspect, density of fragmentation, depth of fragmentation, wetness index, stream power index, plan curvature, profile curvature) which are considered to be essential in spatial analysis and planning studies.

2. STUDY AREA

The Transylvanian Plateau is a complex physical geographical unit, not only from a tectonic, structural and lithological point of view, but also from morphometric and geomorphological point of view as a reflex of the varied conditions imposed by the bedrock and external modeling. In these conditions, on the territory of the Transylvanian Plateau one identifies a high frequency and variety of types and forms of landslides. The economic and territorial impact of these phenomena is higher due to the fact that the Transylvanian Plateau represents an important agricultural region of Romania, as about 70% of its area is agricultural land.

From regionally point of view the Transylvanian Plateau can be divided into three major units: Somesan Plateau, Transylvanian Plain and Tarnavelor Plateau, each with different morphometric characteristics, (Fig. 1).

The border area with the neighbouring mountains presents a very high morphometric variety, due to its different geological structures on which it is formed. Therefore three morphographic units can be identified: depressions, low plateaus, high transition hills near the mountains. The large spatial diversity of these morphometric units imposed their inclusion in this study, in the transition area of the Transylvanian Plateau to the neighboring mountain area and we analyzed them like a different structure with common characteristics.

Tarnavelor Plateau has the largest area of all the three units, 30%, followed by the Transylvanian Plain 18% and Somesan Plateau 12% of the entire

study area. The contact area of the Transylvanian Plateau with the mountains has a large extension (40%) compared to the regional units that compose the major unit. It is also the most complex from a morphometric point of view.

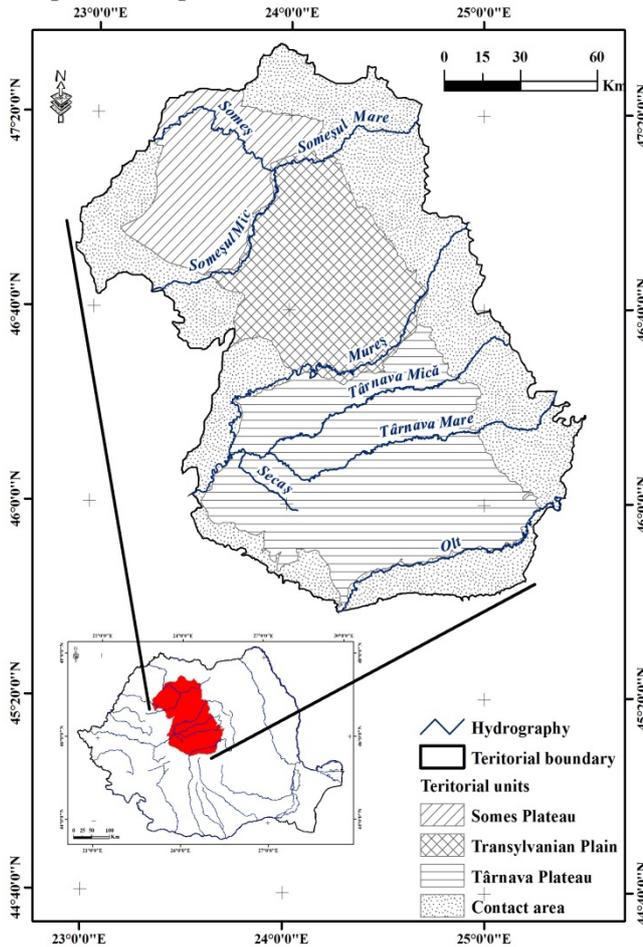


Figure 1. Geographical position of the study area

3. MATERIAL AND METHODS

The GIS spatial analysis models that analyze the probability of occurrence and the development of the landslides are divided in two major categories: quantitative or statistical models and semi-quantitative or deterministic models.

The achievement of a GIS spatial analysis model supposes the following of several steps: the creation of the database, the spatial modeling proper, the validation of the model to quantify its degree of predictability. Spatial analysis is based only on the morphometric characteristics of the territory, which are derived from the Digital Elevation Model (DEM).

The Digital Elevation Model, seen as a modeled database, represents the support for the parameters that compose the spatial analysis equation. Using the TopoGrid Function of the ArcGis software, which gives high accuracy results, we obtained a 20 m resolution DEM.

The spatial analysis model is developed using more database structures, starting from the primary morphometric database (contour lines obtained by vectorization of 1:25000 maps), modeled databases (the Digital Elevation Model, density of fragmentation, wetness index, stream power index, probability coefficient) and derived databases (slope angle, slope aspect, drainage density, plan curvature, profile curvature, hipsometry and depth of fragmentation).

Each element of the morphometric database is included in the spatial analysis model as a parameter for the identification of the landslide occurrence probability. The probability values of the parameters were obtained based on Decree 447/2003, taking into account the territorial extension for each characteristic interval, (Table 1).

The intervals chosen for each coefficient were selected on the basis of the studies mentioned in references via expert knowledge-based approach. In the spatial analysis model, we use the determinist quantitative analysis based on mathematic indexes integrated into a formula that takes into consideration all the parameters identified spatially before:

$$KM = \sqrt{\frac{Fs \cdot Fa}{7}} \cdot Fh \cdot Fdd \cdot Fda \cdot Fwi \cdot Fspi \cdot Fcpl \cdot Fcpr$$

KM- Probability coefficient

Fs- slope factor

Fa- aspect (slope aspect) factor

Fh- hipsometry factor

Fdd- density of fragmentation factor

Fda- depth of fragmentation factor

Fwi- wetness index factor

Fspi- stream power index factor

Fcpl- plan curvature factor

Fcpr- profile curvature factor

All these factors are analyzed as GIS databases to be integrated in the spatial analysis model. The hypsometric factor has a double role: first as a database shaped on the basis of contour lines and the drainage network which is the base for deriving other factors; and second as a derived database and active component of the spatial analysis equation which will finalize the final model for the identification of the landslide occurrence probability. To implement the equation by means of the above-mentioned factors, it was necessary to set up two additional GIS spatial analysis sub-models to identify the spatial extension and the influence of the SPI and WPI factors in the final result of the modeling.

4. RESULTS

The execution of the spatial analysis model was based on the creation and analysis of the

databases and the thematic maps specific for every parameter. For each parameter, we identified the characteristic intervals and the probability class where

they belong according to the weight of the area of that class out of the total area of the analysed territory.

Table 1. Computed statistical values for the GIS model variables

Code	Parameter	Value	P	Intervals	Explanation
Fh	Hipsometry	< 0.1	Low	165-400 m	<ul style="list-style-type: none"> - there are considered to be surfaces with low probability the altitude extended surfaces until 400 meters which are, in general, not affected by slope processes and which are influenced by river bed processes; - the surfaces with 400-700 m, specific to terraces fronts are partially affected by slope processes; - More than 900 m altitude relief, characteristic to mountain contact areas, presents an accentuated morphodynamic potential.
		0.1-0.3	Average	401-500 m	
		0.31-0.5	Average-High	501-700 m	
		0.51-0.8	High	901-1800 m	
		>0.8	Very high	701 – 900 m	
Fs	Slope angle	< 0.1	Low	0-5°	<ul style="list-style-type: none"> - Low slope surfaces (<5°) characteristic for major river beds of the main rivers, terraces plain and extended slopes are, in general, not affected by landslides; - moderately inclined surfaces (5.1-15°) are preferable for mass movements - highly inclined surfaces (>25°) presents high and very high susceptibility for landslides and gravity processes.
		0.1-0.3	Average	5.1-15°	
		0.31-0.5	Average-high	15.1-25°	
		0.51-0.8	High	25.1-30°, >35°	
		>0.8	Very high	30.1-35°	
Fa	Aspect (slope aspect)	< 0.1	Low	PLAIN	<ul style="list-style-type: none"> - plane surfaces, specific to valley corridors, terraces plain and extended watersheds are, in general, not affected by landslides; - slopes with N, NE, E and NW exposure are shadow and half shadow slopes with low susceptibility for landslides. - SE, S, SW, W slopes (sunny and semi-sunny) are highly susceptible to landslides because of the high amount of precipitation and high sunny degree which is favourable to frost and defrost processes.
		0.1-0.3	Average	N, NE	
		0.31-0.5	Average-high	E, NW	
		0.51-0.8	High	SE, S	
		>0.8	Very high	SW, W	
Fdd	Drainage density	< 0.1	Low	0-1 m/kmp	<ul style="list-style-type: none"> - low values of drainage density, identified in slope area induce low probability to occur landslides because the river network is almost absent. - average values of drainage density, specific to average section of the slope, impose a high susceptibility due to regressive erosion of the 1 and 2 river flows; - high values characterise the confluence areas and the surfaces with a lack of vegetation with the presence of linear erosion.
		0.1-0.3	Average	1-1.5 m/kmp	
		0.31-0.5	Average-high	1.5-2 m/kmp	
		0.51-0.8	High	2-2.5 m/kmp	
		>0.8	Very high	>2.5 m/kmp	
Fda	Depth of fragmentation	< 0.1	Low	0-100 m	<ul style="list-style-type: none"> - low values of the depth emphasizes a low potential for landslides; - high values of the depth induce a high potential for landslides to occur due to high altitude gauge (arear overlaid on high slope surfaces).
		0.1-0.3	Average	100.1-200 m	
		0.31-0.5	Average-high	200.1-300 m	
		0.51-0.8	High	300.1-400	
		>0.8	Very high	>400 m	
Fwi	Wetness Index	< 0.1	Low	0-14	<ul style="list-style-type: none"> - low values emphasise low saturation in water index surfaces identified with watershed area and low hills. -high values of the parameter indicate surfaces characterized by a high saturation index regarding the water from the soil, identified mainly, in the
		0.1-0.3	Average	14-16	
		0.31-0.5	Average-high	16-18	
		0.51-0.8	high	18-20	

		>0.8	Very high	>20	slope area, at the contact between slopes and major river beds, generating a high susceptibility for landslides.
Fspi	Stream Power Index	< 0.1	Low	>0	- low values for the SPI emphasise a low erosional power of the drainage and, of course, a low probability for the occurrence of the landslides. - high values of the SPI characterise the areas where the erosional power is high, this fact determines a high probability and very high that the landslides to occur.
		0.1-0.3	Average	0-1	
		0.31-0.5	Average high	1.1-1.2	
		0.51-0.8	High	1.21-1.4	
		>0.8	Very high	>1.4	
Fcpl	Plan Curvature	< 0.1	Low	< - 0.1	- negative values represents concave surfaces overlaid over the accumulation zones with a low probability. - the values closed to 0 are given to the linear surfaces, in general to the low declivity slopes with a average to high probability. - maximum positive values indicates convexe surfaces for forming the elementar hydrographical network which acts to the level of the slope by depth and regressive giving a high and very high probability.
		0.1-0.3	Average	-0.09 – 0	
		0.31-0.5	Average-high	0-0.1	
		0.51-0.8	High	0.1-0.2	
		>0.8	Very high	>0.2	
Fcpr	Profile Curvature	< 0.1	Low	<0	- negative values characterise convexe slopes with high flow and low infiltration level, generating a low probability; - the values closed to 0 are for the bent linear surfaces with a average to high probability; - high values characterise concave slopes with high flow and high level of infiltration of the water into the soil, a high dynamics due to their shape, aspects that induce a very high probability to occur landslides.
		0.1-0.3	Average	0-0.1	
		0.31-0.5	Average-high	0.1-0.2	
		0.51-0.8	High	0.2-0.5	
		>0.8	Very high	>0.5	

4.1. The analysis and creation of the databases

The methodology for the determination of the probability value proposed in the Government Decree 447/2003 is based on the quantitative and qualitative analysis of the landslides for every probability interval. Because the area of implementation is very large, the qualitative assessment of every probability interval for each parameter was not possible. In order to determine the probability value, we proposed an analytical procedure which takes into account the area of every probability interval out of the total studied area.

The proposed analytical procedure considers that the probability for a landslide to occur on a territory is directly proportional to its spatial extension. Therefore, if the spatial extension of the high probability interval is very high on the entire study area, the probability of landslide occurrence is high and that interval receives a high value in the value interval.

The calculation of the probability value according to the proposed procedure is based on a two-equation system: the equation calculating the

value of the probability coefficient specific for the extension area of the probability interval (2 and 3) and the equation calculating the value of the interval probability coefficient (4).

$$(x * y) / 100 = z \quad (2)$$

$$x = vp_{\max} - vp_{\min} \quad (3) \quad \text{where:}$$

- x – the value of the probability interval;
- y – the interval area of spatial extension, as percentage;
- z – the value of the probability coefficient depending on the area;
- vp_{\max} , vp_{\min} – the maximal value of the probability interval, the minimal value of the probability interval.

$$vp = a + z \quad (4) \quad \text{where:}$$

- vp – the probability value;
- a – the basic value of the probability interval;
- z – the value of the probability coefficient depending on the area.

To illustrate the analytical method proposed in this paper, we will give an example of the calculation of the probability value for the intervals of the slope angle factor (Table 2).

For low probability

$$(0.1 * 35) / 100 = 0.03$$

$$0 + 0.035 = 0.03$$

For average probability

$$(0.20 * 57) / 100 = 0.11$$

$$0.10 + 0.11 = 0.21$$

For average-high probability

$$(0.19 * 7) / 100 = 0.01$$

$$0.31 + 0.01 = 0.32$$

For high probability

$$(0.29 * 1) / 100 = 0.002$$

$$0.51 + 0.002 = 0.51$$

For very high probability

$$(0.20 * 0.01) / 100 = 0.00002$$

$$0.80 + 0.000002 = 0.80$$

Based on these equations, we computed the probability value for each interval of the morphometric factors taken into account for the assessment of the landslide occurrence probability.

4.2. The analysis of the probability factors

4.2.1 Slope angle

The slope angle is a parameter absolutely necessary to be quantified, both quantitatively, as a factor that enables slope processes, and qualitatively, as a factor that generates landforms emerged as a consequence of those processes.

The database corresponding to the slope factor has been created taking into account the grid type raster database, derived from DEM, and the indications from table 2.

Table 2. Values and probability classes (slope)

Probability	Intervals	Probability Value	Area (km ²)
Low	0-2°	0.03	8898.71
	2.1° - 5°		
Medium	5.1 – 15	0.21	14421.21
Medium High	15.1° – 20°	0.32	1792.00
	20.1° – 25°		
High	25.1° -30°	0.51	81.66
	>35°		
Very High	30.1° – 35°	0.80	11.38

The quantitative analysis of the probability values specific for the slope angle factor, performed at the level of the entire study area, reveals the large spatial extension of low probability (35% of all areas) followed by the average probability (57%). The average-high, high and very high probability intervals have a reduced territorial extension, of 7%,

1% and 0.01% respectively. This indicates a good stability of the slopes in the analysed territory.

4.2.2 Slope aspect

The slope exposure to the sun influences the development of geomorphological slope processes by means of climatic parameters that are unequally distributed on the surface: solar radiation, insolation, precipitation (Dragotă et al., 2008) and temperature.

The analysis of the probability indices has been performed according to the probability values presented in table 3. By reclassification, a grid type raster database has been obtained, showing the very high weight (27.53%) of the average probability interval, followed by average-high, high and very high probability with weights of 24.41%, 23.84% and 23.68% respectively. One remarks that the areas characterized by low probability are very small, covering only 0.54% of the total area of the Transylvanian Plateau.

Table 3. Values and probability classes (slope aspect)

Probability	Intervals	Probability Value	Area (km ²)
Low	plan	0.05	137.00
Medium	N	0.15	6938.98
	NE		
Medium High	E	0.35	6153.47
	NV		
High	SE	0.57	6008.03
	S		
Very High	SV	0.84	5967.48
	V		

4.2.3. Hypsometry

The hypsometric analysis of the Transylvanian Plateau reveals the considerable extension of low altitude areas, largely distributed in the Transylvanian Plain, Someșan Plateau, as well as in the contact basins and corridors. Higher altitudes are specific for Târnavă Plateau and the Transylvanian Subcarpathian Hills (the transition sector to the mountain unit).

Table 4. Hypsometric values and probability classes

Probability	Intervals	Probability Value	Area (km ²)
Low	165-400 m	0.03	9732.77
Medium	401-500 m	0.16	8475.38
Medium High	501-700 m	0.35	6333.49
High	901-1800 m	0.51	58.53
Very High	701 – 900 m	0.80	604.79

Taking into account the above-mentioned facts, the probability values for every altitudinal interval have been chosen (Table 4) according to

which the database representing the hypsometric probability factor has been finalized. The areas with low and average landslide occurrence probability have the highest weight (38.68% and 33.63% respectively).

They are identified mainly in Someşan Plateau and the Transylvanian Plain. The average-high, high and very high probability covers small areas, with weights of 25.13%, 0.23% and 2.40%. These three probability categories are located in the Transylvanian Subcarpathian Hills, the high area of Târnavă Plateau and the contact area with the Western Carpathians.

4.2.4. Density of fragmentation

The landform density of fragmentation represents an important indicator in the calculation and determination of the landslide occurrence probability. It is part of the category of preparing factors. At high values, calculated at the basis or on the slope, it determines a high instability of the slope. A high value of the drainage network density means a high fragmentation of the slope, which is favourable for the development of geomorphological slope processes.

Table 5. Values and probability classes (density of fragmentation)

Probability	Intervals	Probability Value	Area (km ²)
Low	0 - 0.5 m/km ²	0.05	13655.49
	0.5 - 1 m/km ²		
Medium	1 - 1.5 m/km ²	0.14	5647.52
Medium High	1.5-2 m/km ²	0.33	2627.40
High	2 - 2.5 m/km ²	0.53	1826.28
Very High	>2.5 m/km ²	0.81	1449.10

These processes, in their turn, due to the nature of their mechanisms of development and manifestation, favor a higher degree of water infiltration. The minimal values of the density of fragmentation are associated to stable and relatively stable slopes and landforms as regards the effects of linear erosion exerted by the drainage network. They present a low landslide occurrence probability (Table 5). Concerning the weight of each probability interval on the total area of the analysed territory, one remarks the very high extension of the low probability interval (54%), followed by the average and average-high intervals, with 22% and 11% respectively, indicating a relative stability of the slopes in the study area.

The high and very high probability intervals cover small areas of 7% and 6% respectively, out of the total area of study.

4.2.5. The depth of fragmentation

The landform vertical fragmentation, as a probability factor for the emergence of landslides, highlights territorial discrepancies regarding the difference in height on a certain calculation area. Having in mind the purpose of the analysis, in this study we opted for the hectare size quadrat as calculation units for the depth of fragmentation. This option is based on the fact that the development and further evolution of landslides take place on very small areas, so the analysis of the depth of fragmentation according to the classical methodology (by km²) does not meet the modeling objectives. The high value of the difference in height indicates unstable ground, usually with high slopes, favourable for the emergence of landslides. The low values of the depth of fragmentation are usually characteristic of the large watershed areas, lowlands and river floodplains. Of course, they define area with low landslide occurrence probability.

The calculation of the probability coefficient value (Table 6) is based, according to the methodology proposed in this study, on the extension areas of each interval. Therefore, for the depth of land fragmentation factor, 51.72% of the area is included in the average probability class, 48.09% in the low probability class, 0.19% in the average-high probability and only 0.01% in the very high probability category. One may notice that the high probability interval has not been given a numerical probability value in the created database. This is due to the fact that this difference in height does not exist in the study area.

Table 6. Values and probability classes (depth of fragmentation)

Probability	Intervals	Probability Value	Area (km ²)
Low	0 - 100 m	0.04	12123.56
Medium	101 - 200 m	0.20	13038.99
	201 - 300 m		
Medium High	301 - 400 m	0.31	48.04
High	401 - 500 m	-	-
Very High	>501 m	0.80	1.83

4.2.5/4.2.6. Wetness index (WI) and stream power index (SPI)

These two factors can be associated because they are part of the same category of factors that take into consideration the topography of the terrain

and highlight the degree of water accumulation on certain areas (WI) or the power of water erosion in a stream within a certain catchment area (SPI). The spatial modeling of these two factors has been performed according to the equations derived by Beven & Kirkby (1979) for WI and Moore et al., (1991) for SPI, implemented in ArcGIS as:

$$\ln\left(\frac{\text{accumulation} * 400}{\tan(\text{slope})}\right), [WI]$$

$$\ln\left(\frac{\text{accumulation} + 0.001}{\text{slope} / 100 + 0.001}\right), [SPI]$$

where:

- Ln, Tan* – mathematical identifiers
- accumulation* – flow accumulation
- 400* – area in m² of the DEM cell
- slope* – slope in radians

The calculated values of the wetness index are between 12.43 and 25.29 and are directly proportional to the landslide occurrence probability. The low values correspond to lands with low degree of water saturation which involves a low landslide probability. The high values are characteristic for areas with relatively high water saturation, therefore having a direct impact on the landslide trigger mechanisms and a high probability of landslide emergence.

The extension of areas with different degrees of probability varies between 4% for very high probability, 7% for high probability, 20% for low and average-high probability and 49% for average probability (Table 7).

Table 7. Values and probability classes (WI)

Probability	Intervals	Probability Value	Area (km ²)
Low	0 - 14	0.02	5128.61
Medium	14 - 16	0.19	10377.66
Medium High	16 - 18	0.34	5030.30
High	18 - 20	0.53	2574.76
Very High	>20	0.80	2168.58

The analysis of the SPI calculated values, ranging between -2.8 and 1.45, highlights the areas with potentially high erosion exerted by water streams. The negative values of the SPI indicate the flat areas of watersheds and plateaus, with an incipient drainage network and low landslide occurrence probability. Positive values are characteristic for moderate and steep slopes, terrace risers and steep banks, where there is a high landslide occurrence probability (Table 8). The areas with the largest extension (73.54%) are part of the average probability class, followed by areas presenting a low probability, with a weight of 26.45%, due to the incipient development of a permanent drainage network in those sectors. The other probability intervals have very low weights,

covering extremely small areas at the contact between the plateau and the mountains.

Table 8. Values and probability classes (SPI)

Probability	Intervals	Probability Value	Area (km ²)
Low	< 0	0.02	6667.64
Medium	0 - 1	0.24	18535.10
Medium High	1.1 – 1.2	0.31	0.32
High	1.21 – 1.4	0.51	0.02
Very High	>1.4	0.80	0.003

4.2.7. Plan and profile curvature

The areas with a prominent slope and exposure change are identified with the help of the topographical surface curvature. According to the method of curvature analysis, two indicators may be obtained: *the plan curvature and the profile curvature*.

The profile curvature provides information about the areas with moderate and high flow on the topographical surface, taking into consideration the shape of the slope (linear, convex or concave). The negative values define convex slopes, with low (almost null) landslide occurrence probability.

The zero value is associated to linear slopes, which present an average or average-high landslide occurrence probability. Positive values highlight the slope pronounced concavity and therefore there is a very high landslide occurrence probability.

As for the territorial extension of the probability intervals according to the profile curvature, the GIS analysis shows the very large extension of the average and average-high probability, with weights of 48.7% and 51.60% respectively. The other three intervals present lower weights, 0.14% for the low probability class, 0.19% for the high probability class while the weight of the very high probability interval is almost null as compared to the entire area of the study unit (Table 9).

Table 9. Values and probability classes (profile curvature)

Probability	Intervals	Probability Value	Area (km ²)
Low	< - 0.1	0.01	35.64
Medium	-0.09 - 0	0.19	12115.00
Medium High	0 – 0.1	0.40	13004.81
High	0.1 – 0.2	0.51	49.07
Very High	>0.2	0.80	0.44

The plan curvature represents the perpendicular direction on the maximum slope orientation. The positive values highlight the convex slopes, with convergent flow and a high landslide occurrence probability. The negative values are characteristic for concave slopes with divergent flow and a low to average landslide occurrence probability. Values close

to 0 are associated to linear flow slopes which present an average to high landslide probability.

Regarding the territorial extension of the probability intervals, defined according to the terrain plan curvature, one remarks the very large extension of average-high (32.07%) and high (46.91%) probability intervals and the small extension of the other three intervals: 9.17% for the low probability interval, 11.70% for the average probability and 0.15% for the very high probability (Table 10). All the factors analysed above constitute raster databases and represent defining elements of the probability calculation equation implemented in the process of spatial analysis and identification of areas with different degrees of landslide occurrence probability.

Table 10: Values and probability classes (plan curvature)

Probability	Intervals	Probability Value	Area (km ²)
Low	< 0	0.01	2310.25
Medium	0 - 0.1	0.12	2947.98
Medium High	0.1 – 0.2	0.37	8083.69
High	0.2 – 0.5	0.64	11824.28
Very High	>0.5	0.80	38.79

4.3. Spatial analysis

The spatial modeling of the landslide occurrence probability demands the use of several spatial analysis techniques. In their turn, these techniques suppose the use of specialized software

and the processing of thematic databases by means of mathematical equations transposed into GIS spatial analysis functions. The main purpose is to generate new attributes, stored in different database structures.

Starting from the spatial databases, by means of modeling techniques, GIS spatial analysis and reclassification of databases, intermediate models have been conceived and later integrated in the final structure of the probability model (Fig. 2). In order to derive and represent the probability coefficients defining the analyzed factors, spatial analysis techniques have been used by database reclassification.

The probability coefficients derived from each factor are represented by raster format databases. These represent, in their turn, the main entry elements in the spatial analysis equations meant to determine the landslide occurrence probability.

The first one was to calculate the coefficients representing WI and SPI according to the functions included in ArcGIS programme. The second and most important one was to create, by means of spatial analysis, the complex model based on the probability equation and on the entry modeled and derived databases.

The model has been executed using the equation (1) implemented in a GIS environment using the Raster Calculator function shaped as:

$$\text{SquareRoot} ((\text{"Fs"} * \text{"Fa"}) / 7 * \text{"Fh"} * \text{"Fdd"} * \text{"Fda"} * \text{"Fwi"} * \text{"Fspi"} * \text{"Fcpl"} * \text{"Fcpr"})$$

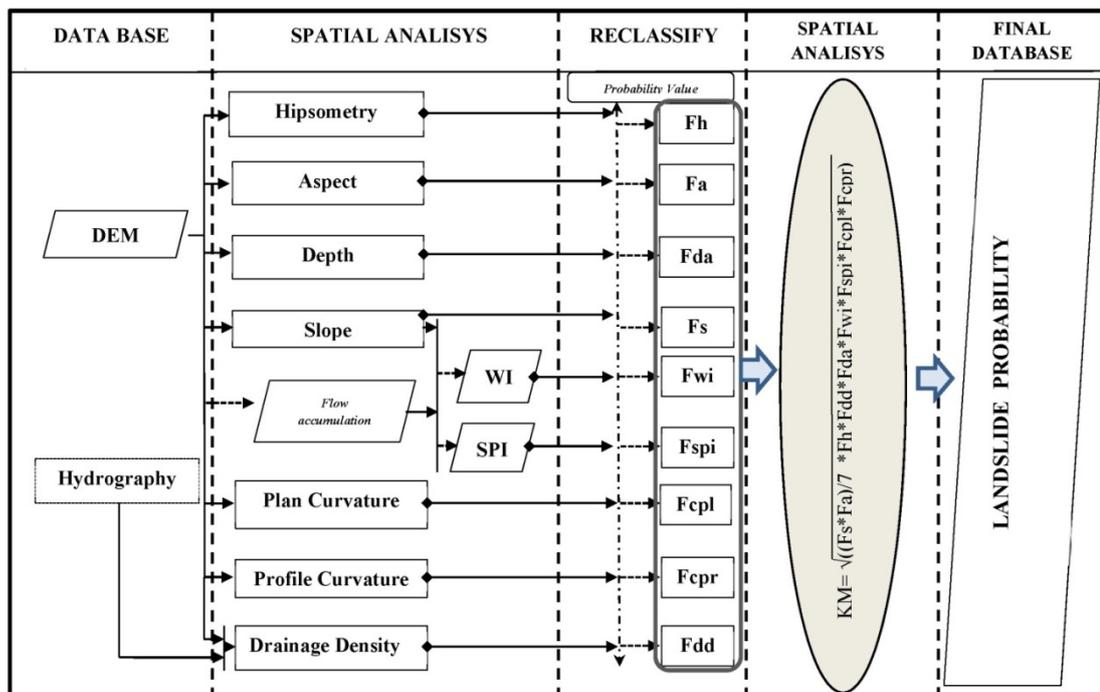


Figure 2: GIS spatial analysis model of the landslide occurrence probability

The result of the model is materialized in a raster database which highlights the landslide occurrence probability for every pixel of the analysed area (Fig. 3).

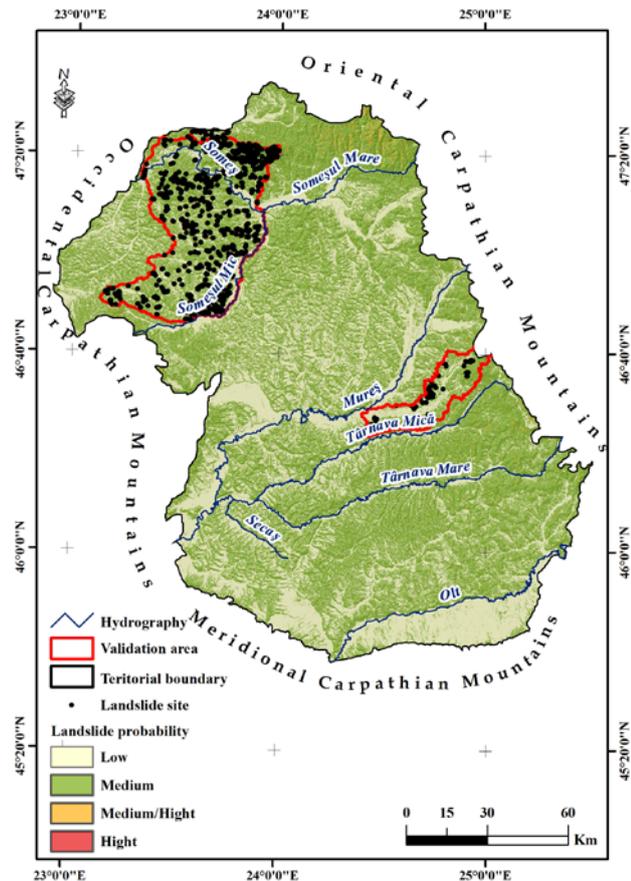


Figure 3. Morphometry based landslide probability map of the study area

On the whole, most of the territory belonging to the Transylvanian Plateau is included in the average category of landslide occurrence probability, which defines an area with a weight of 59.07%. Lands comprised in this probability category cover larger areas of Târnavă Plateau, Someșan Plateau and the Transylvanian Subcarpathians.

The low probability category represents 40.30% of the total area of the analysed unit. Lands corresponding to it are mainly located along the large valleys of Someș and Mureș (mostly), Arieș and Olt (in fewer cases), as well as in the Transylvanian Plain, on larger areas.

The average-high and high probability categories are almost unsizeable in the graphical representation and in the quantitative spatial analysis. They have a weight of only 0.63% of the total area of the plateau, covering very small areas at the contact with the mountains. It is important to stress the fact that, once the spatial analysis model

has been finished, no areas with very high landslide occurrence probability included in the category > 0.8 have been identified at the level of the entire Transylvanian Plateau.

4.4. Model validation

In order to establish the model degree of predictability, we opted for its validation by means of ROC curve determined at the level of two distinctive areas, considered to be representative for the Transylvanian Plateau: Niraj drainage basin, remarkable because its high landform diversity makes it a true “synthesis” of the whole Transylvanian Plateau, and Someșan Plateau which is, in its turn, a morphometrically complex landform unit. The ROC method allows the evaluation of the predictability rate of the methods applied comparing the obtained probability map with the map of the existing landslides.

The landslide inventory was based on SPOT imagery, topographical maps and field inventory. In the Niraj drainage basin, 126 landslides have been detected and mapped covering a total area of 984 ha. In Someșan Plateau, a number of 322 landslides have been identified, covering a total area of 5510 ha (Fig. 3).

The ROC curve is calculated for the 10 percent threshold which represents the percentage of the analyzed area for which the false positive and the true positive values are determined. The values of the OX represent areas in which the model has calculated a very high probability but where there are no landslides (false positive). The values represented on the OY correspond to areas in which the model has determined a high probability, validated by the existence of landslides (true positive). (Fig. 4). The best validation was obtained for the high probability class (0.977), followed by the average class (0.806) and the very high class (0.761).

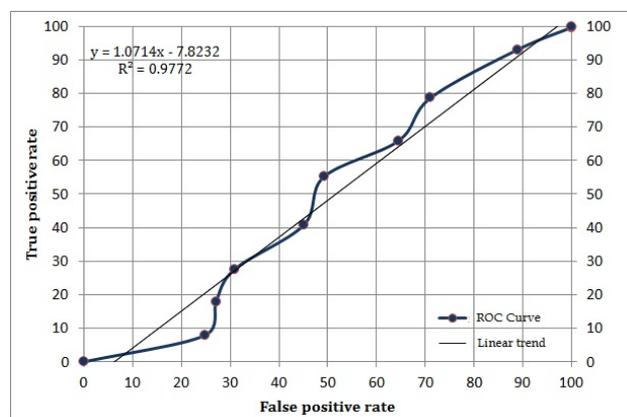


Figure 4: ROC curve for the high landslide occurrence probability

5. CONCLUSION

The results of this study allow us to state that the analysis of the land morphometric characteristics and their integration as key factors in a methodological approach meant to determine the landslide occurrence probability is fully justified scientifically and very useful because of its practical implications.

The scientific relevance of the model proposed in this study starts from the premise that morphometry, as a defining factor of the terrain dynamic state, has a double function, playing a part both in the preparation and triggering the landslides. The fundament of the model lays on our firm conviction that morphometry represents a very sensitive and true “geindicator” of the terrain states of stability or instability.

These states are in fact prefigured by means of the two above-mentioned functions, which (extremely important) may be interpreted in a relatively constant (homogeneous) metrics according to the spatial attributes of the landforms.

We consider that a major advantage of this model is that, compared to other models (like the one proposed by means of law), it has a higher degree of objectivity because all the parameters may be analysed according to the same criteria, at a higher degree of resolution. More than that, it excludes the subjectivity of the analyst in assessing the importance of certain factorial characteristics.

As shown above, most methods (including the one derived from Decree 447/2003) take into account factors which frequently cannot be properly calibrated due to the inadequate scale of the existing maps, the deficient character of the available data or the researcher’s subjectivity in the procedures of assessment regarding the importance of that factor.

Unlike these methods, the GIS-assisted spatial analysis of the terrain morphometric features ensures a high resolution and a systematic, objective and unitary interpretation of the landform defining characteristics.

The proposed model is based on the analysis and integration of factors as databases in a GIS spatial analysis model, based on statistical and deterministic analysis. This methodology allows the determination of the spatial extension of areas which present different landslide occurrence probabilities. The model is materialized in hectare size raster database structures that may prove to be extremely useful in the development of other spatial analysis models.

The accuracy of the final results of the model has been tested by its validation using the ROC

curve on very large areas, considered to be representative for the morphometric variety of the Transylvanian Plateau, which proves the viability and veracity of this method.

It can be concluded that the applied model has a very good correlation with the probability classes and active landslides and the causative factors selected are relevant for the models applied.

The results show a good predictability of the model and prove its usefulness for the practical research.

All these facts allow us to state that the model proposed in this approach may be applied with good results in the investigation of other territories with similar features (in the sense that there is a lack of landform morphometric homogeneity).

More importantly, the model may be adopted as a working alternative for the methodologies that are inherently exposed, in a more or less obvious manner, to cartographic or statistical deficiencies. In conclusion, it is our opinion that this model constitutes an original approach which significantly contributes to the improvement of the methodology regarding the prediction of landslide processes.

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Received at: 08. 11. 2013

Revised at: 10. 02. 2014

Accepted for publication at: 20. 02. 2014

Published online at: 25. 02. 2014