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# Landslide Susceptibility Mapping using Frequency Ratio and Analytic Hierarchy Process (AHP): Comparative study of two areas in Bulgaria

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## INTRODUCTION

Local governments in many countries would support the development of landslide prediction models, as landslides annually cause significant material and human losses. Various methods are used: empirical, heuristic, statistical, and physicallybased. The physically-based methods have a strong spatial restriction and require a large amount of hard-to-access information (*Ruette et al., 2011*). Therefore, increasing popularity acquire another type of predictive models – the so-called statistical (or probabilistic) models based on the assumption that future landslides may occur under conditions in which have already occurred and their properties are already known. They use the correlation between landslide occurrence and landslide causal factors – explanatory variables or parameters (*Ruette et al., 2011*). The development of GIS technologies allows easy implementation of these models for landslide prediction, while remote sensing provides many advantages in this respect. The most commonly used probabilistic models are Logistic Regression Analysis (*Süzen and Doyuran, 2004; Lee and Talib, 2005; Greco et al., 2007; Nefeslioglu et al., 2008; Pradhan, 2010; Pradhan and Lee, 2010; Ruette et al., 2011; Yalcin et al., 2011*), Frequencies Ratio Model (*Süzen and Doyuran, 2004; Lee and Talib, 2005; Yilmaz, 2009; Yalcin et al., 2011; Song et al., 2012*), Artificial Neural Networks (*Lee and Talib, 2005; Neaupane and Piantanakulchai, 2006; Nefeslioglu et al., 2008; Melchiorre et al., 2008; Mondino et al., 2009; Yilmaz, 2009; Pradhan and Lee, 2010; Song et al., 2012*), Analytic Hierarchy Process (*Yalcin et al., 2011; Pourghasemi and Pradhan, 2012)*, Fuzzy Logic (*Gorsevski and Jankowski, 2010*) and others. These methods of landslide hazard analysis are up to now not widely used in the region of the Balkan Peninsula. The Fuzzy Logic method was used in natural risk assessment in some areas of Southwest and Southeast Bulgaria (*Zlateva et al., 2011; Желев, 2013*). The disadvantage of most of those methods is that they require empirical data on past landslide events within the study area that are not always available.

This study has adopted the broader meaning of the term "landslide hazard" as a synonym of "landslide susceptibility", i.e. probability of landslide occurrence in a given area for a certain time interval. The purpose of this paper is to apply the Frequency Ratio Model for landslide susceptibility mapping for two relatively comparable territorial units – the Simitli and Satovcha municipalities. The results will then be used for creating a system of Multi-criteria Decision Analysis (MCDA) and calculating the weights of the landslide causal factors in the generation a model of Analytic Hierarchy Process (AHP), applicable to areas where landslide data is not available. The areas were selected on the basis of the administrative principle.

## STUDY AREA

Both areas are located on near latitude in the mountainous southwestern part of the territory of Bulgaria and are characterized by similar physical geographic conditions. The territory of Simitli Municipality lies between 41°45 'and 42°0' north latitude and between 22°54' and 23°21'36' east longitude and covers an area of 553 $km^2$. The area of Satovcha Municipality amounts 333 $km^2$ and lies between 41°27' and 41°43'47" north latitude and between 23°6'34" and 24°21'34" east longitude. Both areas are characterized by a wide variety of the relief. In such underlined boundaries the elevation changes from 194 to 2 590 meters in the municipality of Simitli and from 368 to 1 729 meters in the municipality of Satovcha calculated by satellite data from ASTER Global DEM 2012. The average altitudes are 948 meters for Simitli Municipality and 1 065 meters for Satovcha Municipality. These topographic features create tectonic and surface instabilities and a rapid changing of the climate elements in a vertical direction which combined with the variety of rocks predisposes to hazardous geomorphologic processes occurrence such as landslides. The geology of the researched areas includes magmatic rocks (granitoids), compact metamorphic rocks (limestone, marble, etc.), metamorphic rocks with layer texture (gneisses, schists) and clastic (unconsolidated) sedimentary rocks in proportion respectively 31.6%, 2.3%, 42.8% and 23.4% for Simitli Municipality and 20.3%, 9.2% , 65.3% and 4.9% for Satovcha Municipality. Gneisses, shales and clastic rocks occupy a large territory of both areas and are a basis of more than 86% of the landslides occurrences. The average annual precipitation changes from 540 mm in the low part of the relief to about 900 to 1100 mm in the mountainous areas of both territories and the average air temperature changes respectively from 13,1°C to -1,4°C calculated by the method of linear regression for the whole area of Southwestern Bulgaria. Furthermore a large part of both areas is an open space with little or no vegetation and represents urban area, arable lands and shrub and/or herbaceous vegetation association – 46.6% in municipality of Simitli and 68.4% in municipality of Satovcha.

## METODOLOGY

The Frequency Ratio Method for landslide susceptibility mapping, proposed by *Lee and Talib (2005),* is based on the relationship between the areas where a landslide has occurred and the landslide-related factors. This relationship is expressed quantitatively by the ratio of landslide frequency in each class of each factor and the area of the respective class compared to the total area of the studied territory. As *Lee and Talib (2005)* state, a higher ratio shows stronger relationship between the landslide occurrence and the class of the given factor. Finally, the frequency ratios of each factor are summed to obtain the Landslide Susceptibility Index (LSI) of the researched area using equation (1)

(1) $$LSI_{(FRM)} = \sum_{i=1}^{n} FR_i$$

Wherein $FR_i$ is the frequency ratio of factor ***i***, and ***n*** is the number of the selected landslide-related factors.

Analytic Hierarchy Process (AHP) is a model developed *by Saaty (1980)* and represents a multi-criteria decision-making approach to the base of which stands a method for converting subjective assessments of the relative importance of a range of factors (criteria) in a network of digital values (or weights) by pairs comparisons. The criteria and the alternatives are assumed to be independent in this approach. The importance of each factor is compared with the others on a scale from 1 to 9 in the matrix constructed. The obtained weights are appreciated by the proposed by Saaty (1980) Consistency Index – *CI* (2).

(2) $$CI = \frac{\lambda_{\max} - n}{n-1}$$

The weighted linear combination is calculated using equation (3):

(3) $$LSI_{(AHP)} = \sum_{i=1}^{n} w_i w_{ij} \qquad (j=1 \text{ to } m_i)$$

Where $w_i$ is the calculated weight of factor ***i***, $w_{ij}$ is the calculated weight of class ***j*** in factor ***i***, ***n*** is the number of factors, and $m_i$ is the number of classes in factor ***i***.
The landslide susceptibility indexes (LSI) obtained for the territories of the two municipalities, by the proposed methods, are normalized in the interval from 0 to 1 in order to facilitate the comparison of the results.

## DATA COLLECTION AND MATERIALS

Data collection was carried out based on specialized cartographic sources, reference materials and publications. Civilian topographic maps at scale 1:50 000, geological maps at scale 1: 100 000 for the period between 1989 and 1995 and digital elevation model based on satellite data ASTER Global DEM, modified version 2012 were used, as well as satellite images from Landsat ETM+ with spatial resolution of 30 meters. The vegetation cover data were obtained from the CLC 2006. The data for the landslide locations in the territories of both municipalities were collected from the registers of state institutions in Bulgaria for the period from 1984 to 2013. The total number of the registered landslides is 29 (10 in Simitli municipality and 19 in Satovcha municipality). A significantly larger number of landslides was identified by deciphering and interpretation of satellite images from Landsat ETM+ and images from Ikonos and QuickBird, available in Google Earth services. However, the recorded landslides were used in this study for the performance of both models and landslide susceptibility mapping, which although insufficient for an accurate statistical sample are correct in terms of accuracy of information. The data were georeferenced in UTM WGS-84 Zone 34T and then were jointed in a common geo-database in GIS environment.

## RESULTS

Nine factors with the strongest influence on landslide occurrence were selected for landslide susceptibility assessment of the territories of both municipalities. These are lithology, verage slope gradient, slope exposition, land cover, distance from rivers, roads and faults. Two indexes which characterize the spatial differentiation of hydrological conditions and the distribution of soil moisture are used, which represent two of the most important conditions for the landslide occurrence. These are Topographic Wetness Index – *TWI (4)*, proposed by *Beven (1979)* which describes hydrological conditions and Stream Power Index – *SPI (5)*, proposed by *Moore (1993)* which describes the potential erosive power of ground flow.

(4) $$TWI = \ln\left(\frac{A_s}{\tan\beta}\right)$$

(5) $$SPI = A_s * \tan\beta$$

$A_s$ is the area of each grid cell and $\beta$ is the slope angle in a given sell in degrees.
These indexes, as well the slope gradients and slope expositions were derived from the Digital Elevation Models of both territories.
As a first step, Frequency Ratio Model was applied to both municipalities (Tab. 1 and Fig. 1). The geological base is the most important factor for landslide occurrences. Digital geological maps of both territories were created for the purpose of this study. The rock types were grouped into four classes – magmatic rocks, compact metamorphic rocks, metamorphic rocks with layer texture and clastic sedimentary rocks. A strong correlation between landslide occurrence and rock types was found.

*Table 1. Frequency ratio and class weights*

| Class | Simitli Municipality | | | Satovcha Municipality | | | $W_{ij}$ |
|---|---|---|---|---|---|---|---|
| | Landslide % | Grid domain % | FR | Landslide % | Grid domain % | FR | |
| **Slope (degree)** | | | | | | | |
| 0 - 10 | 0 | 2,7 | 0,00 | 5,3 | 4,5 | 1,17 | 0,04 |
| 10 - 20 | 10 | 7,5 | 1,33 | 5,3 | 13,9 | 0,38 | 0,07 |
| 20 - 30 | 30 | 13,7 | 2,18 | 10,5 | 22,7 | 0,46 | 0,13 |
| 30 - 40 | 40 | 21,3 | 1,88 | 47,4 | 26,0 | 1,82 | 0,46 |
| 40 - 45 | 10 | 12,8 | 0,78 | 10,5 | 11,2 | 0,94 | 0,08 |
| 45 - 50 | 10 | 13,3 | 0,75 | 10,5 | 8,9 | 1,19 | 0,08 |
| 50 - 55 | 0 | 12,3 | 0,00 | 0,0 | 6,3 | 0,00 | 0,04 |
| 55 - 60 | 0 | 10,0 | 0,00 | 5,3 | 3,9 | 1,33 | 0,04 |
| 60 - 65 | 0 | 5,2 | 0,00 | 5,3 | 1,9 | 2,73 | 0,04 |
| Over 65 | 0 | 1,1 | 0,00 | 0,0 | 0,6 | 0,00 | 0 |
| **Aspects** | | | | | | | |
| North (N) | 0 | 13,4 | 0,00 | 10,5 | 6,2 | 1,71 | 0 |
| Northeast (NE) | 30 | 10,5 | 2,86 | 0,0 | 8,3 | 0,00 | 0,04 |
| East (E) | 10 | 10,6 | 0,94 | 10,5 | 12,7 | 0,83 | 0,07 |
| Southeast (SE) | 0 | 10,9 | 0,00 | 5,3 | 15,6 | 0,34 | 0,07 |
| South (S) | 10 | 12,9 | 0,78 | 15,8 | 17,0 | 0,93 | 0,03 |
| Southwest (SW) | 10 | 15,0 | 0,67 | 42,1 | 17,3 | 2,44 | 0,11 |
| West (W) | 30 | 13,3 | 2,26 | 10,5 | 14,0 | 0,75 | 0,46 |
| Northwest (NW) | 10 | 13,4 | 0,75 | 5,3 | 8,9 | 0,59 | 0,17 |
| **TWI** | | | | | | | |
| -6,57 to -3,38 | 0 | 0,7 | 0,00 | 5,3 | 22,3 | 0,24 | 0,03 |
| -3,38 to -1,57 | 0 | 3,3 | 0,00 | 0,0 | 0,2 | 0,00 | 0,03 |
| -1,57 to -0,25 | 0 | 8,3 | 0,00 | 0,0 | 0,0 | 0,00 | 0,03 |
| -0,25 to 0,65 | 20 | 10,9 | 1,83 | 0,0 | 1,6 | 0,00 | 0,07 |
| 0,65 to 1,56 | 10 | 10,7 | 0,94 | 21,1 | 18,7 | 1,13 | 0,10 |
| 1,56 to 2,39 | 20 | 15,2 | 1,32 | 31,6 | 21,3 | 1,48 | 0,41 |
| 2,39 to 3,14 | 40 | 19,1 | 2,10 | 21,1 | 14,9 | 1,42 | 0,19 |
| 3,14 to 3,95 | 10 | 16,7 | 0,60 | 15,8 | 8,7 | 1,81 | 0,10 |
| 3,95 to 5,01 | 0 | 10,7 | 0,00 | 5,3 | 5,6 | 0,95 | 0,03 |
| 5,01 to 13 | 0 | 4,3 | 0,00 | 0,0 | 6,7 | 0,00 | 0 |
| **SPI** | | | | | | | |
| -13,06 to -6,84 | 0 | 0,9 | 0,00 | 5,3 | 22,5 | 0,23 | 0,03 |
| -6,84 to -4,84 | 0 | 2,3 | 0,00 | 0,0 | 0,0 | 0,00 | 0,03 |
| -4,84 to -3,35 | 0 | 3,8 | 0,00 | 0,0 | 0,0 | 0,00 | 0,03 |
| -3,35 to - 2,15 | 0 | 6,2 | 0,00 | 5,3 | 0,4 | 14,11 | 0,07 |
| -2,15 to -1,14 | 20 | 11,7 | 1,71 | 15,8 | 7,2 | 2,18 | 0,10 |
| -1,14 to -0,15 | 20 | 11,1 | 1,80 | 15,8 | 21,5 | 0,73 | 0,18 |
| -0,15 to 0,75 | 40 | 15,1 | 2,65 | 26,3 | 22,9 | 1,15 | 0,37 |
| 0,75 to 1,58 | 20 | 20,9 | 0,96 | 5,3 | 13,2 | 0,40 | 0,10 |
| 1,58 to 2,49 | 0 | 19,1 | 0,00 | 21,1 | 6,3 | 3,36 | 0,06 |
| 2,49 to 8 | 0 | 9,0 | 0,00 | 5,3 | 6,0 | 0,87 | 0,04 |
| **Distance from faults (m)** | | | | | | | |
| 0 - 200 | 30 | 22,9 | 1,31 | 52,6 | 24,0 | 2,19 | 0,54 |
| 200 - 400 | 0 | 15,4 | 0,00 | 10,5 | 17,8 | 0,59 | 0,05 |
| 400 - 600 | 10 | 12,1 | 0,83 | 21,1 | 14,4 | 1,46 | 0,17 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 600 - 800 | 30 | 9,1 | 3,29 | 0,0 | 11,2 | 0,00 | 0,11 |
| 800 - 1000 | 20 | 6,8 | 2,95 | 0,0 | 8,6 | 0,00 | 0,08 |
| 1000 - 1200 | 10 | 5,2 | 1,92 | 5,3 | 6,1 | 0,87 | 0,06 |
| 1200 - 1400 | 0 | 4,3 | 0,00 | 5,3 | 4,8 | 1,09 | 0 |
| 1400 - 1600 | 0 | 3,4 | 0,00 | 5,3 | 3,4 | 1,53 | 0 |
| 1600 - 1800 | 0 | 2,8 | 0,00 | 0,0 | 2,8 | 0,00 | 0 |
| Over 1800 | 0 | 18,0 | 0,00 | 0,0 | 7,0 | 0,00 | 0 |
| **Distance from rivers (m)** | | | | | | | |
| 0 - 150 | 50 | 45,5 | 1,10 | 63,2 | 36,3 | 1,74 | 0,65 |
| 150 - 300 | 30 | 29,3 | 1,02 | 26,3 | 26,6 | 0,99 | 0,23 |
| 300 - 450 | 10 | 15,2 | 0,66 | 5,3 | 17,9 | 0,29 | 0,06 |
| 450 - 600 | 10 | 6,6 | 1,51 | 5,3 | 9,5 | 0,56 | 0,06 |
| 600 - 750 | 0 | 2,4 | 0,00 | 0,0 | 5,0 | 0,00 | 0 |
| 750 - 900 | 0 | 0,8 | 0,00 | 0,0 | 2,5 | 0,00 | 0 |
| 900 - 1050 | 0 | 0,1 | 0,00 | 0,0 | 1,1 | 0,00 | 0 |
| 1050 - 1200 | 0 | 0,0 | 0,00 | 0,0 | 0,6 | 0,00 | 0 |
| Over 1200 | | | | 0,0 | 0,5 | 0,00 | 0 |
| **Distance from roads (m)** | | | | | | | |
| 0 - 200 | 50 | 18,4 | 2,71 | 63,2 | 17,8 | 3,56 | 0,61 |
| 200 - 400 | 30 | 14,1 | 2,13 | 21,1 | 13,7 | 1,53 | 0,09 |
| 400 - 600 | 0 | 11,8 | 0,00 | 5,3 | 11,7 | 0,45 | 0,09 |
| 600 - 800 | 0 | 10,0 | 0,00 | 5,3 | 10,3 | 0,51 | 0,09 |
| 800 - 1000 | 0 | 8,7 | 0,00 | 0,0 | 8,9 | 0,00 | 0,05 |
| 1000 - 1200 | 0 | 7,3 | 0,00 | 5,3 | 7,6 | 0,69 | 0,05 |
| 1200 - 1400 | 0 | 6,0 | 0,00 | 0,0 | 6,1 | 0,00 | 0 |
| 1400 - 1600 | 10 | 4,9 | 2,03 | 0,0 | 5,1 | 0,00 | 0 |
| 1600 - 1800 | 0 | 4,1 | 0,00 | 0,0 | 4,3 | 0,00 | 0 |
| Over 1800 | 10 | 14,7 | 0,68 | 0,0 | 14,5 | 0,00 | 0 |
| **Geology** | | | | | | | |
| Magmatic rocks | 0 | 31,6 | 0,00 | 0,0 | 20,6 | 0,00 | 0 |
| Metamorphic rocks with massive texture | 0 | 2,3 | 0,00 | 21,1 | 9,2 | 2,28 | 0,09 |
| Gneisses, schists | 20 | 42,8 | 0,47 | 78,9 | 65,3 | 1,21 | 0,29 |
| Clastic sedimentary rocks | 80 | 23,4 | 3,42 | 0,0 | 4,9 | 0,00 | 0,62 |
| **Land cover** | | | | | | | |
| Forests | 0 | 53,4 | 0,00 | 15,8 | 31,6 | 0,50 | 0,05 |
| Mines, dumps and constructions sites | 0 | 0,5 | 0,00 | 0,0 | 2,3 | 0,00 | 0 |
| Arable land | 0 | 1,5 | 0,00 | 0,0 | 0,4 | 0,00 | 0 |
| Open spaces with little or no vegetation | 0 | 0,6 | 0,00 | 0,0 | 19,5 | 0,00 | 0 |
| Heterogeneous agricultural areas | 60 | 11,0 | 5,44 | 15,8 | 1,2 | 13,38 | 0,27 |
| Urban fabrics | 20 | 1,1 | 18,55 | 52,6 | 13,3 | 3,95 | 0,59 |
| Shrub and/or herbaceous vegetation association | 20 | 31,9 | 0,63 | 15,8 | 31,6 | 0,50 | 0,10 |

An important factor for the landslide occurrence is the average slope gradient. The average slopes, derived from DEM, were classified into ten classes in accordance with the objectives

of the models. The frequency of landslide occurrence is highest on slopes ranging between 20 and 50 degrees. The slope aspects influence indirectly on the landslides through the soil moisture conditions. They are classified into eight classes. Both Indexes TWI and SPI, generated from DEM, are also classified into ten classes. The frequency of the landslide events is higher in positive values of TWI and negative values of SPI. The distance from rivers controlling the movement of groundwater is also an important factor that was taken into account in the modeling. The class numbers of this factor in both areas depends on the characteristics of their river networks. The roads, like the rivers, affect the groundwater movement but they also create conditions for mass sliding. High dependence was established between the vegetation cover and the landslide occurrence. The land cover classes from CLC2006 model were grouped into seven classes for the purposes of the study. Urban structures and heterogeneous agricultural areas are characterized with the highest values of frequency ratio. This result reflects the influence of the anthropogenic activity on the landslide occurrence.
The results of the Frequency Ratio Model were used in creating of a decision making system and computing the weights of the landslide causal factors (Table 3), as well as the weights of the classes in each factor (Table 1) under generating of the AHP model. The standard deviation in the landslide frequency in each class of the selected nine factors was calculated for this purpose so that it provides a statistical estimation of the variation or dispersion from the average value. The lower the standard deviation is, the more equivalent the significance of the classes is. Therefore, the high standard deviation indicates a major importance of the factor. The factor "geology" holds the highest value of the standard deviation followed by the factor "distance from the rivers." Land coverage, distance from the roads and slopes factors are also characterized with a high standard deviation. The least significant is the importance of the aspects. Pairs comparisons of the nine selected factors was made on the base of those criteria using the nine-point scale proposed by Saaty (1980) and a pairwise comparison matrix was composed (Table 2).

*Table 2. The pairwise comparison matrix for assigning weight values*

| | Slope | TWI | SPI | Aspects | Distance from faults | Distance from rivers | Distance from roads | Geology | Land cover |
|---|---|---|---|---|---|---|---|---|---|
| Slope | 1 | 2 | 3 | 3 | 1 | 1/5 | 1/2 | 1/7 | 1/2 |
| TWI | 1/2 | 1 | 1 | 2 | 1/2 | 1/6 | 1/3 | 1/7 | 1/3 |
| SPI | 1/3 | 1 | 1 | 2 | 1/3 | 1/6 | 1/3 | 1/9 | 1/4 |
| Aspects | 1/3 | 1/2 | 1/2 | 1 | 1/3 | 1/7 | 1/5 | 1/9 | 1/5 |
| Distance from faults | 1 | 2 | 3 | 3 | 1 | 1/5 | 1/2 | 1/7 | 1/2 |
| Distance from rivers | 5 | 6 | 6 | 7 | 5 | 1 | 3 | 1/3 | 3 |
| Distance from roads | 2 | 3 | 3 | 5 | 2 | 1/3 | 1 | 1/5 | 1 |
| Geology | 7 | 7 | 9 | 9 | 7 | 3 | 5 | 1 | 5 |
| Land cover | 2 | 3 | 4 | 5 | 2 | 1/3 | 1 | 1/5 | 1 |

In the same way the importance of the ranges in each one of the selected nine factors was estimated. The criteria used in this case was the frequency of landslide occurrence.

The values of pairwise comparison matrix were normalized by columns to calculate both weights of selected nine factors and weights of their classes.

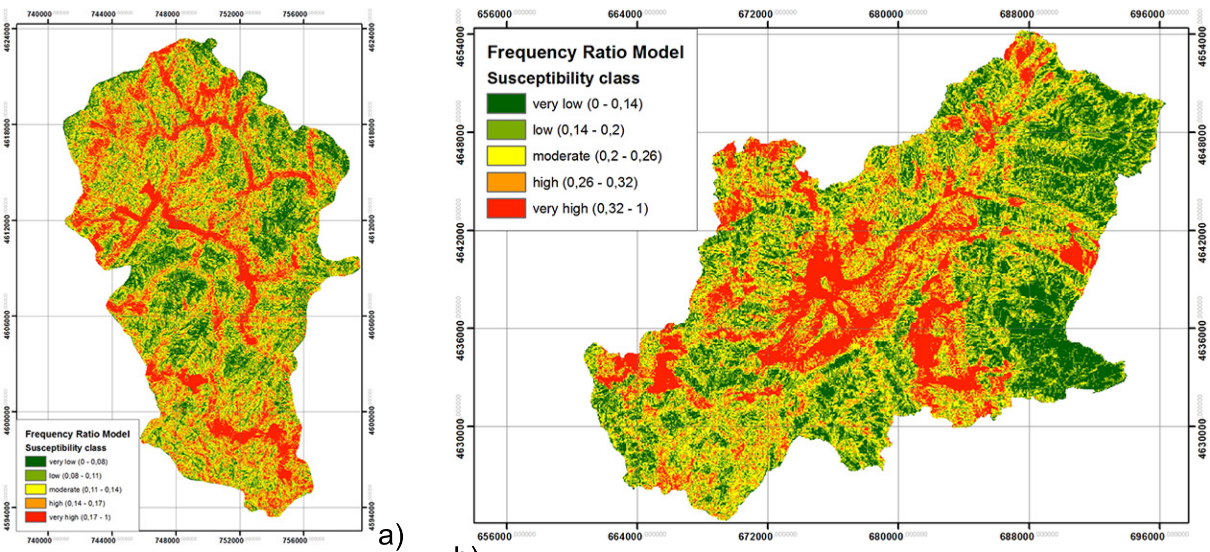
*Table 3. Factor weights*

| ***Factor names*** | ***$w_i$*** |
|---|---|
| *Slope* | *0,06* |
| *TWI* | *0,04* |
| *SPI* | *0,03* |
| *Aspects* | *0,02* |
| *Distance from faults* | *0,06* |
| *Distance from rivers* | *0,22* |
| *Distance from roads* | *0,10* |
| *Rock classes* | *0,37* |
| *Land cover classes* | *0,10* |

Then, the priority vector (weight) of each factor ($w_i$) as well as the weight of each class from the factor "i" ($w_{ij}$) were found by calculating the average value of the row. After the calculation of the Consistency Index the obtained values were considered relevant and ware assigned to the respective classes. AHP model was then applied using an equation (3) to the territory of both municipalities and the landslide susceptibility maps were drawn (Fig. 2). The results from both models were compared and verified by the existing empirical landslide data. In order to compare the results obtained by both models the values of landslide susceptibility index were normalized using an equation (6):

(6) $$A'_{ij} = \frac{A_{ij} - \min}{\max}$$

Where $A_{ij}$ is the value of a grid cell and $A'_{ij}$ is the normalized value.
Landslide susceptibility maps were first divided into five landslide susceptibility zones in GIS based on standard deviations of the corresponding histograms. Next, they were crossed with the landslide inventory maps containing information about the registered landslide occurrences in both areas.
The results show that 60% of landslides in the Simitli Municipality and 53% of the landslides in Municipality of Satovcha fall into the range of the maximum of the landslide susceptibility index in the AHP model. The rest of the landslides fall in the mean (10%) and the high (30-40%) values of the index. Around 48-56% of the landslide locations in both areas in the FRM fall within the extreme values of the index and the rest – under the mean and high values (Fig. 3).



a) b)

*Fig. 1. Landslide susceptibility map produced from the frequency ratio model: a) Satovcha Municipality; b) Simitli Municipality*

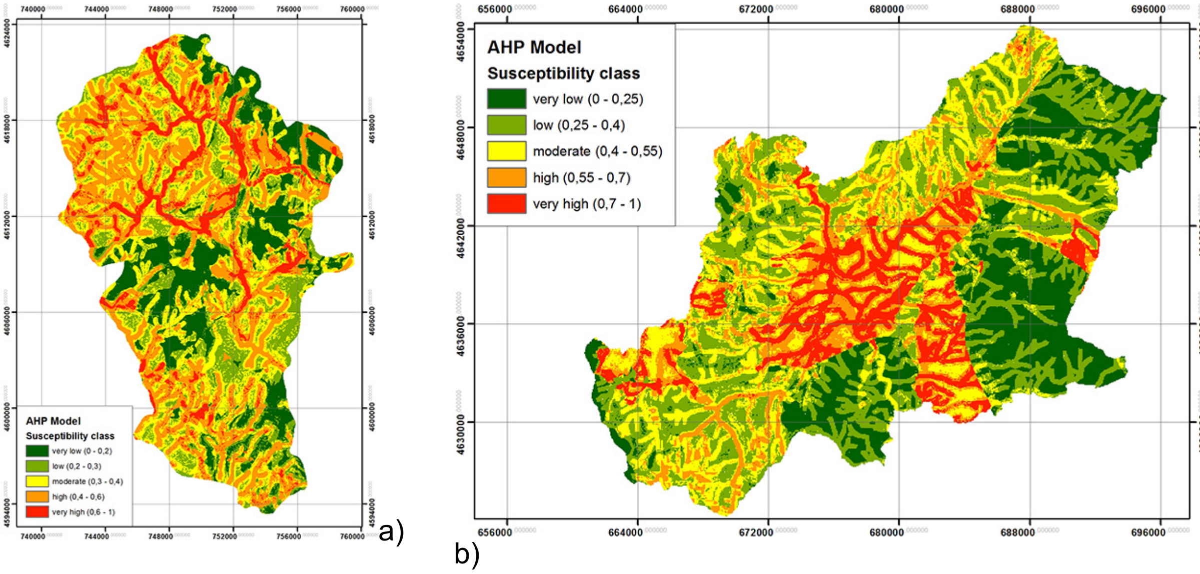



*Fig. 2. Landslide susceptibility map produced from the analytic hierarchy process: a) Satovcha Municipality; b) Simitli Municipality*

## DISCUTION

Landslide susceptibility maps for the areas of municipalities Satovcha and Simitly, where the empirical data on landslide locations are insufficient, were created using the modeling of Frequency Ratio and Analytic Hierarchy Process. Both areas are characterized by relatively comparable environmental conditions and land use. Nine landslide-controlling factors were selected for the purpose of the study.

The geology (rock types) is the factor with the highest weight in the proposed AHP model, followed by the distance from rivers and land cover factors. Area under the curve (AUC) was calculated for verification and evaluation of the results on the basis of the available landslide data in both municipalities. Despite the large margin of error due to the subjective assessment, the results show that proposed AHP model may be used successfully when empirical data on landslide locations is missing. Furthermore, the landslide susceptibility maps, generated on the basis of the proposed AHP model, might serve in future field research to achieve higher accuracy of the empirical models, as well as for risk assessment.

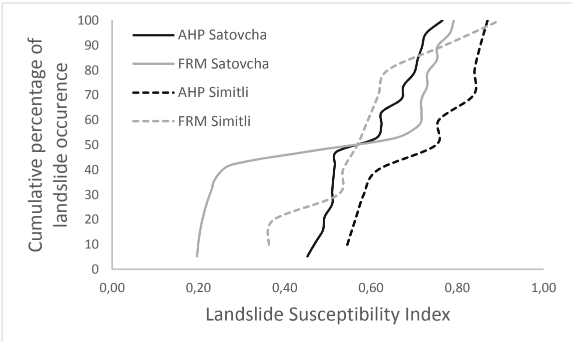



*Fig. 3. Verification the results of the of the applied models*

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