LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN XANTHI AREA (THRACE – GREECE) BY FACTOR ANALYSIS, FUZZY MEMBERSHIP FUNCTIONS AND GIS.

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ABSTRACT

A methodology for identifying landslide prone areas and producing landslide susceptibility maps is presented, using factor analysis, fuzzy membership functions and Geographical Information Systems (GIS). Five conditioning factors were evaluated: slope angle, slope aspect, land use, geology, and topographical elevation. Fuzzy membership functions were defined for each factor using the landslide frequency data. Factor analysis provided importance weights for each one of the above conditioning factors. To obtain the final landslide susceptibility map, an overlay and index method was adopted.

1. INTRODUCTION

Landslides cause dramatic effects on human lives and economy worldwide. The evaluation of landslide susceptibility is perceived as the initial stage for mitigating landslide hazards. There is a growing interest worldwide in developing robust methods for landslide susceptibility and risk mapping, and hence provide planners with tools for selecting suitable areas for development scheme implementation. Much research is focused and published on the preparation of hazard maps based on statistical modeling or on ranking and weighting environmental factors according to their assumed or expected importance in causing slope failures [1-7]. New techniques have been successfully applied in the recent years such as fuzzy logic and neural networks in various other environmental problems and also in order to evaluate landslide susceptibility [8-11].

The purpose of the present study is to develop a methodology for evaluating landslide prone areas and produce a landslide susceptibility map for the northern Xanthi area (Thrace, Greece) (Fig. 1) based on factor analysis, fuzzy logic and GIS. For this purpose, the study includes five main stages: (1) the preparation of a landslide inventory of the study area based on field studies and data from previous works; (2) the determination of controlling parameters and the evaluation of landslide frequency for each of these; (3) the fuzzification of controlling parameters; (4) the application of multivariate statistical analysis (factor analysis) to determine the important weights of the parameters; (5) the use of geographical information systems to produce index maps representing the factors and a susceptibility map; and (6) the control of the reliability of the susceptibility map produced.

2. STUDY AREA DESCRIPTION

The methodology has been developed using data from shallow landslides of the mountainous part of Xanthi area (Thrace, Greece) (Fig. 1a). The geological and geomorphological characteristics of the area are described in previous works [12, 13]. The geological structure consists of rock formations attributed to the Paleozoic Rhodope massif that include the marble unit (marbles and schists) and the gneissic unit (migmatites, gneisses, marble-amphibolite intercalations and ultra mafic rocks), and to the Tertiary mollasic and igneous rocks (Fig. 1a). These rocks were reactivated during Tertiary times resulting to the uplifting of the area. Most of the landslides develop in the migmatite rocks. The topographical elevation values vary between 30 and 1800 m and the dominant drainage pattern is dendritic. From a climatic point of view this part of the Rhodope mountain chain receives a mean annual rainfall of about 1100mm, mainly concentrated during the winter [14]. The general physiographic trend is NW-SE following the main drainage system.

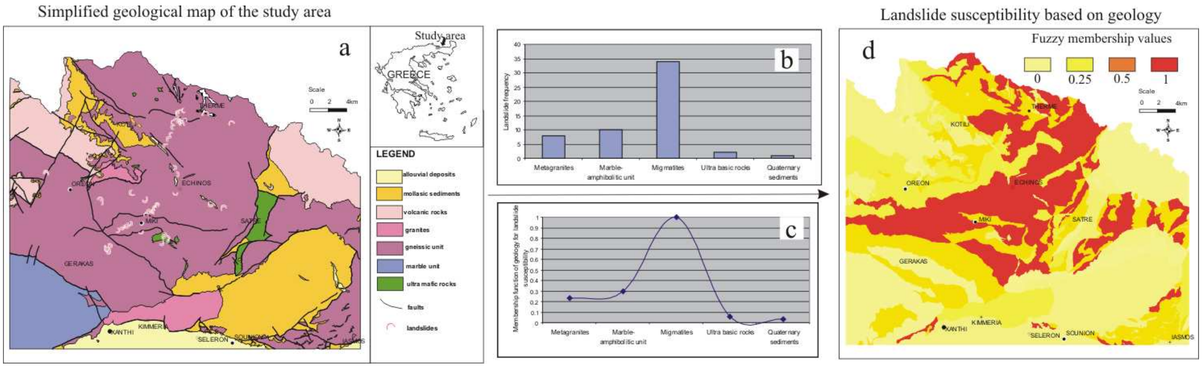

Figure 1: a) Geological map of the study area; b) landslide frequency histogram; c) fuzzy membership function; d) landslide susceptibility map based on geology.

3. CONTROLLING PARAMETERS

For a landslide susceptibility assessment, several parameters introduced in a GIS as spatial data layers are necessary to evaluate the zones susceptible to sliding. When applying any model to landslide susceptibility evaluation, it is very important to define criteria controlling the degrees of susceptibility. Although any parameter may be important with respect to the landslide occurrence in a region, the same parameter may not be important for another region. Hence, different parameters are used and ranked subjectively or objectively to produce a landslide susceptibility map [15] by various researchers according to the study area.

In the present study five controlling parameters were identified based on field work and on literature, i.e., slope angle, geology, topographical elevation, land use, slope aspect. A landslide inventory was created based on data from previous studies [14], thus 51 landslides were identified and the associated controlling parameters were determined for each landslide by field work. For each controlling parameter the landslide frequency diagram was created, i.e, a diagram showing the number of landslides observed in each of the various classes of every controlling factor. Subsequently, fuzzy membership functions were selected in order to quantify the controlling parameters to membership values of landslide susceptibility, ranging from 0 (nonmembership – low susceptibility) to 1 (complete membership – high susceptibility). The shape and control points of the fuzzy membership function for each parameter were selected based on the landslide frequency diagrams. For this purpose the GIS program Idrisi Andes [16] and its routine FUZZY was used. FUZZY evaluates the possibility that each pixel belongs to a fuzzy set by evaluating any of a series of fuzzy set membership functions. The software provides the possibility to use either Sigmoidal, J-shaped and Linear functions which are controlled by four points ordered from low to high on the measurement scale, or user defined membership functions. The first point (point a on Figure 2c) marks the location where the membership function begins to rise above 0. The second point (point b on Figure 2c) indicates where it reaches 1. The third point indicates the location where the membership grade begins to drop again below 1 (point c on Figure 2c), while the fourth point (point d on Figure 2c) marks where it returns to 0. Points may be duplicated to create monotonic or symmetric functions. The user-defined function requires the input of control points and their corresponding fuzzy set memberships. These pairs serve to define the shape of the fuzzy set membership curve [16]. Output is scaled from 0-1. In the present study the shape of the frequency diagrams indicates that a sigmoidal function may be applied for the parameters slope angle and topographical elevation. For categorical parameters such as land use and geology as well as for slope aspect, user defined membership functions were applied.

The parameter geology is related to the resistance to landslides. The most landslide sensitive formations are considered to be those with a flysch character, i.e., sandstone, siltstone, marl alterations. Formations resistant to landslides are considered to be limestones and quartzites. However, resistance to landsliding usually depends on tectonic events that occurred in the past, changing thus the initial character of each geological formation. As mentioned earlier, the study area consists of a marble unit and a gneissic unit (migmatites, gneisses, amphibolites and ultra mafic rocks) of Paleozoic, and of Tertiary mollasic and igneous rocks (Fig. 1a). The frequency diagram for geology (Fig. 1b) demonstrates that the majority of landslides occurred within the migmatite formation. A user defined fuzzy membership function was applied with the following control points: metagranites was assigned a membership value of 0.23, marbe amphibolitic unit a value of 0.3, migmatites a value of 1, ultra basic rocks were assigned a value of 0.06 and quaternary sediments a value of 0.03 (Fig. 1c). Thus the landslide susceptibility map based on geology was created (Fig. 1d)

For slope angle parameter, a symmetric sigmoidal fuzzy membership function was used with inflection points at 0º (point a), 20º (point b), 30º (point c) and 50º (point d).

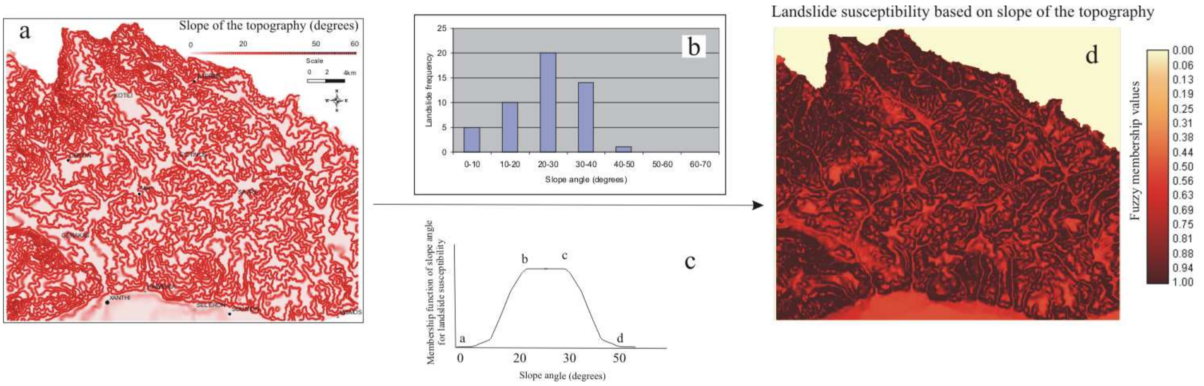

Figure 2: a) Slope of the topography; b) landslide frequency histogram; c) fuzzy membership function; d) landslide susceptibility map based on slope.

As the frequency diagram for this specified factor indicates, when slopes exceed 45º, a sharp decrease in the landslide frequency values was observed, which is determined by other researchers as well [11].

The frequency diagram for the parameter topographical elevation (Fig. 3) indicates that it may be fuzzified using a symmetric membership function (Fig. 3c) with inflection points at 200 m (point a), 300 m (point b), 700 m (point c), 900 m (point d). The frequency diagram for this factor shows (Fig. 3b), there is good agreement between landslide frequency and topographical elevations of 200–900 m, whereas for elevations above 900 m the landslide frequency diminishes. In contrast to what is mentioned by Pachauri and Pant [17], that the higher relief shows a greater susceptibility to sliding, Ercanoglu and Gokceoglu [11] found a good agreement between landslide frequency and topographical elevations of 100–500 m, which is in agreement to what is found in the present study.

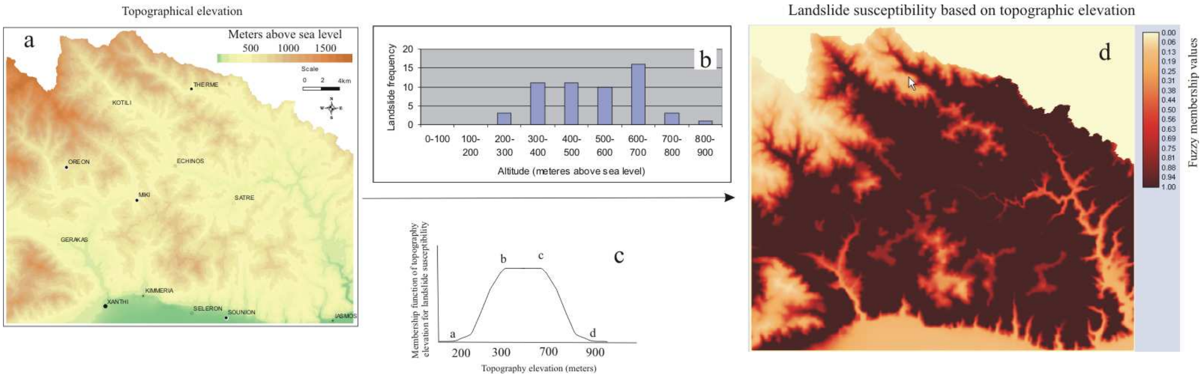

Figure 3: a) Topographical elevation; b) landslide frequency histogram; c) fuzzy membership function; d) landslide susceptibility map based on topographical elevation.

Slope aspect (Fig. 4) measures the direction that each grid cell faces in three-dimensional space and is recorded in azimuth degrees relative to either true north. It is related to the general physiographic trend of the area and/or the main precipitation direction.

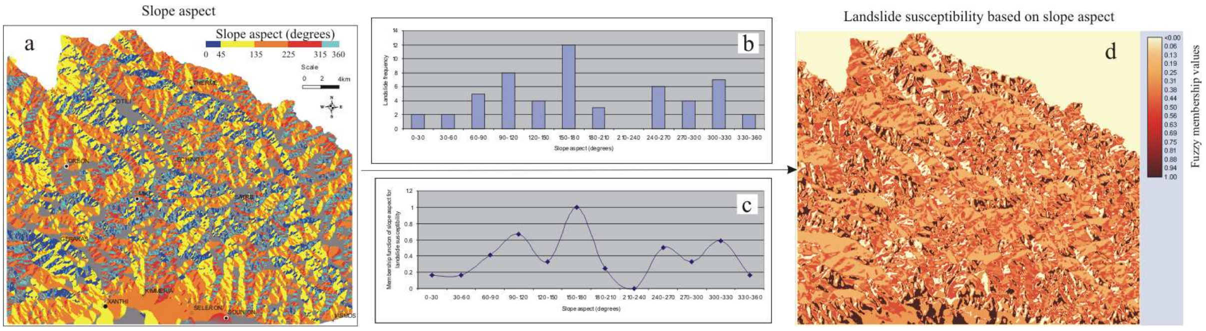

Figure 4: a) Slope aspect; b) landslide frequency histogram; c) fuzzy membership function; d) landslide susceptibility map based on slope aspect.

Although the relationship between landslide occurrence and slope aspect is still under investigation, some researchers [18, 19] introduce slope aspect in their computations, whereas others do not [20]. Ercanoglu and Gokceoglu [11] found that in their study area the relationship between the dip direction of movement identified in the area and the general physiographic trend of the area is roughly perpendicular. In the present study, however, and as the frequency diagram for slope aspect indicates, no such relationship can be extracted.

For this parameter a user defined fuzzy membership function was applied with appropriate control points to match the frequency diagram, whereas full membership, i.e. 1, is assigned to aspect values between 150° and 180°, and nonmembership, i.e. 0, is assigned to aspect values between 210° and 240°.

Land use (Fig. 5) is the factor related to the effects caused by human activities on landslide occurrence. The study area is covered mainly by dense and sparse forests. To a lower extent grasslands and residential areas (mainly in the form of small settlements) occupy the study area. Moreover, zones of 20 m around roads and rivers were delineated and incorporated in the land use layer. The frequency analysis (Fig. 5b) showed an indisputable negative effect of road construction on slope instability. A user defined fuzzy membership function (Fig. 5c) was applied this time as well, with the following control points: dense forest was assigned a membership value of 0.27, sparse forest a value of 0.36, grassland a value of 0.27, residential areas a value of 0.36, roads a value of 1 (complete membership) and water bodies a value of 0.23.

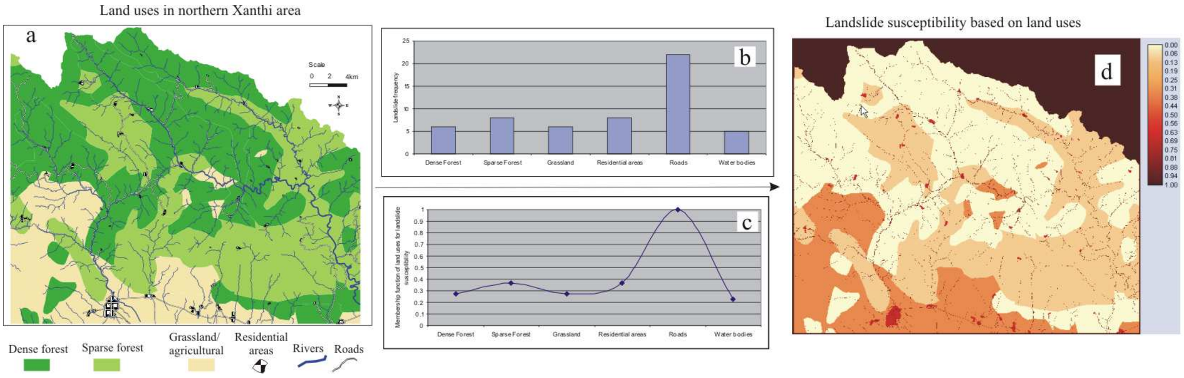

Figure 5: a) Land uses; b) landslide frequency histogram; c) fuzzy membership function; d) landslide susceptibility map based on land uses.

4. FACTOR ANALYSIS

The general purpose of factor analysis is to interpret the structure within the variance-covariance matrix of a multivariate data collection. The technique used is extraction of the eigenvalues and eigenvectors from the matrix of correlations or covariances [11, 21]. All calculations were performed using the GIS software Idrisi Andes [16]. The results of factor analysis are presented in Table 1.

TABLE 1. Factor analysis results

COMPONENT	**1**	**2**	**3**	**4**	**5**
%VARIANCE	70.9	16.6	8.1	2.9	1.5
LOADING	**1**	**2**	**3**	**4**	**5**
Slope	0.95	-0.19	-0.15	0.23	-0.14
Aspect	0.93	-0.20	-0.10	0.06	0.22
Elevation	0.82	0.12	0.56	-0.01	-0.02
Land use	-0.92	0.18	0.15	0.29	0.07
Geology	0.517	0.84	-0.17	0.01	0.01

According to the above results, the importance weight for slope angle is the highest, and corresponds to 70.9% of the input variance. Geology is the second most important parameter, corresponding to 16.6% of the input variance. Furthermore, elevation of the topography, land use and slope aspect are the third, fourth and fifth important parameters corresponding to 8.1%, 2.9% and 1.5%, respectively, of the input variance. Based on the determined importance weights the final landslide susceptibility map for the study area was created (Fig. 6), with index values ranging from 0 (non susceptible areas) to 1 (very high susceptibility to landsliding). The results are shown in tabular form in Table 2.

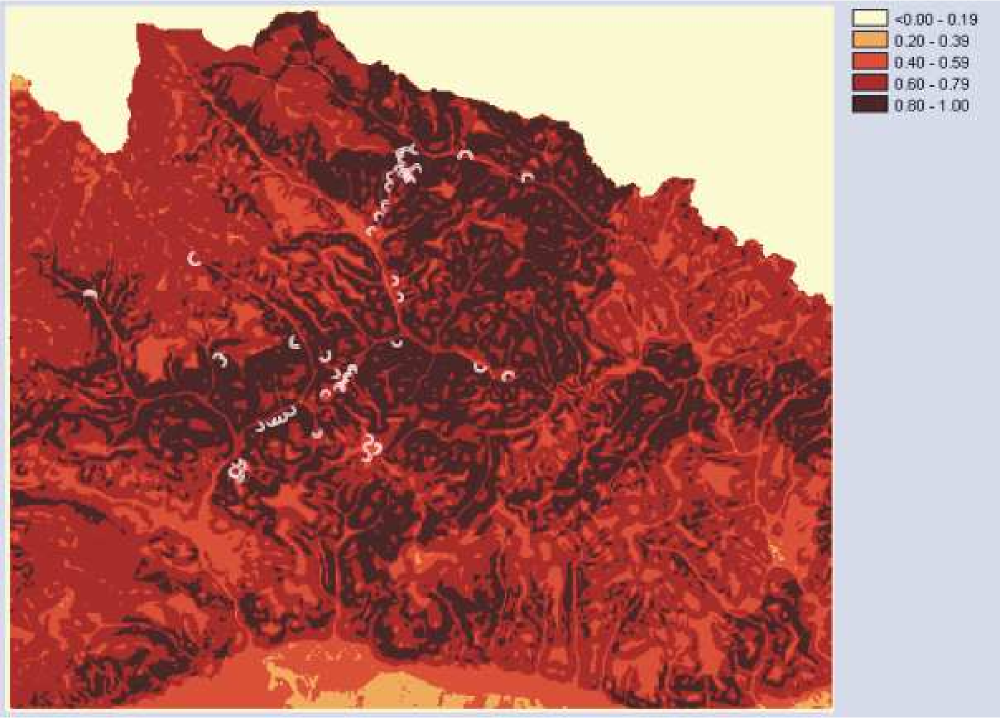

Figure 6: Landslide susceptibility map

TABLE 2. Landslide susceptibility results

Susceptibility Class	**Index value**	**Landslides observed**	**% of the study area**
Non-susceptible	0-0.19	0	5
Low susceptibility	0.20-0.39	0	13
Moderate susceptibility	0.40-0.59	2	27.5
High susceptibility	0.60-0.79	20	30.25
Very high susceptibility	0.80-1	29	24.25

5. DISCUSSION AND CONCLUSIONS

Landslide susceptibility was assessed using fuzzy membership functions and factor analysis. For this purpose, data obtained from previous surveys were combined with those obtained by extensive field work carried in the present study. As a result, a landslide inventory was created for the study area, which comprised 51 landslides. Then, conditioning parameters were determined and for each parameter a landslide frequency diagram was created. Based on these frequency diagrams, fuzzy membership functions were determined, each parameter was fuzzified, and landslide susceptibility maps were constructed for each individual parameter. In order to determine the importance weight of each controlling parameter, factor analysis was applied in the form of the correlation matrix. Accordingly, the fuzzified index maps were aggregated in order to produce the final landslide susceptibility map for the northern Xanthi area. To control the performance of the produced susceptibility map, a comparison between the landslide susceptibility class zones on the map and the number of landslides observed in each class was carried out (Table 2). Forty nine landslides, i.e., 96% of the landslides, were observed in the very high and high susceptibility zones and only two were located in the ones of moderate susceptibility. This high accuracy percentage indicates that the presented herein methodology offers a reliable approach for landslide susceptibility mapping.

According to the produced results, the landslides in the study area are merely controlled by slope angle, which is in agreement with what is found by other researchers elsewhere [11]. On the contrary, no dominant physigraphic direction was found to favour landslides, in contrast to what was previously mentioned by other researchers. In fact, factor analysis determined an importance weight of 1.5% for slope aspect, indicating that this parameter does not contribute significantly to the occurrence of landslides in the area.

Another interesting conclusion reached by the present study is the role of geology in the landslide occurrence. In contrast to the general belief that flysch type formations favour landslides, the present work shows that in the study area the majority of landslides occurred within migmatite formations, whereas only a negligible percentage of landslides occurred within the molassic and flysch type sediments. This indicates that although the type of geological formation might be an important controlling parameter, the tectonic history of each formation is responsible for its behaviour to landsliding.

Moreover, the present work demonstrated the influence of human activities in the landslide occurrence. The majority of landslides in the study area occurred on road sides or in residential areas, indicating thus that they might have been prevented if proper design and construction methods were employed.

As a concluding remark, it should be stated that the presented methodology seems to be a reliable approach for landslide susceptibility mapping, providing a mathematical basis for expressing each controlling parameter, and combining numerical and categorical data in the computational procedure.

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