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Producing a Landslide Susceptibility Map through the Use of Analytic Hierarchical Process in Finikas Watershed, North Peloponnese, Greece

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Abstract The main goal of the present study was to produce a landslide susceptibility map for the Finikas watershed that is located in the Achaia County, North Peloponnese, Greece, following the Analytic Hierarchical Process. Six parameters were analyzed, namely: lithological units, elevation, slope angle, slope aspect, distance from faults and distance from river network. Each parameter was classified into different classes and weighted according to their susceptibility to slide by implementing the Analytical Hierarchical Process. The landslide susceptibility map was reclassified into five classes of varying landslide susceptibility. The high and very high susceptibility class was estimated to cover the 8.18% and 19.55% of the research area, respectively. The relative landslide density for the high and very high landslide susceptibility class was estimated to be 69.45%. The developed model could be considered as a useful tool for the national and local authorities as it could assist in managing landslide related variables in a much easier and automated manner, maximizing the functionality of GIS environment and producing quite accurate landslide susceptibility maps.

Keywords Landslide susceptibility mapping, Analytical hierarchical process, Finikas River, Greece

1. Introduction

Landslides are considered as geophysical and hydrological disasters that occur as unexpected and unpredictable movements, usually on unstable ground surface due to the force of gravity and the action of water [1]. They appear as one of the most frequent natural hazards with significant consequences to human life and the social - economic structure of a society [2].

As reviewed through the scientific literature, there is no agreement on the methods that one should use for landslide assessments [1-5]. However, according to [6], a landslide susceptibility analysis, an analysis that involves the determination of the spatial distribution of landslides, involves four processes: (a) the construction of a landslide inventory map, (b) the assessment of parameters that influence landslides, (c) the implementation of appropriate methods for determining the weights of each parameter and (d) the compilation of the landslide susceptibility map within a Geographic Information System (GIS) environment.

Several researchers have utilized multi criteria decision analysis (MCDA) techniques for landslide susceptibility and hazard assessments, since in most cases a mixture of qualitative and quantitative data are available [7]. In this context, data are processed using GIS and MCDA techniques to obtain information for making decisions. The most common approach involves obtaining expert opinion, through appropriate methods such as Analytical Hierarchical Process (AHP) to assigning weights to the landslide related parameters and then combining weights additively by weighted linear combination technique (WLC) to produce landslide susceptibility maps [8, 9].

Several studies have utilized AHP for landslide susceptibility mapping [10-12]. As referred by numerous researchers the main advantage of applying AHP as an expert based method in landslide susceptibility analysis are [9, 12]: all types of data concerning landslides can be included in the decision making process, expert's judgment is formulated so that all information is taken into account, decision rules are based on expert's knowledge and experiences, and finally inconsistencies in the decision process can be detected using consistency index values (Table 3). However, the main disadvantage of AHP is that subjective preference in the ranking of factors may differ from one expert to another [12].

The present study utilizes the Analytical Hierarchical Process (AHP) to produce a landslide susceptibility map, in Finikas watershed at North Peloponnesus, Greece.

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2. Methodology

2.1. Analytic Hierarchical Process

The AHP method was used in order to assign preferences among landslide related variables based on Saaty's proposal [13, 14]. When applying AHP a reduction in the complexity of a decision problem can be achieved. In particular, a complicated problem can be simplified into a sequence of pair-wise comparisons. The AHP method involves the construction of decision criteria, that are compared following a two-part query that investigates which criterion is more important, and how much more important, using a numerical relational scale [14] (Table 1). By this the relative importance of each criterion can be calculated.

Table 1. Scale of importance between two parameters in AHP

Scale	Intensity of importance	Definition
1	Equally	Two activities contribute equally to the Objective
3	Moderately	Experience and judgment slightly to moderately favour one activity over another
5	Strongly	Experience and judgment strongly or essentially favour one activity over another
7	Very strongly	An activity is strongly favoured over another and its dominance is showed in practice
9	Extremely	The evidence of favouring one activity over another is of the highest degree possible of an affirmation
2,4,6,8	Intermediate values	Used to represent compromises between the references in weights 1, 3, 5, 7 and 9

By applying AHP, it is possible to evaluate pair-wise rating inconsistency. The calculated eigenvalues are a consistency measure that is an indicator of the inconsistencies or intransitivities in a set of pair-wise ratings. According to [14] the largest eigenvalue λ_{max} is equal to the number of *n* comparisons. A measure of consistency, called consistency index *CI*, is defined as follows (Equation 1):

$$CI = (\lambda_{max} - n) / (n - 1) \quad (1)$$

Saaty [14] randomly generated reciprocal matrixes using scales 1/9, 1/7, 1/5, 1/3, 1, 3, 5, 7, 9 to evaluate a so called random consistency index *RI*. Saaty [13] also introduced a consistency ratio *CR*, which is a comparison between the consistency index and the random consistency index. Since human judgments can violate the transitivity rule and thus cause an inconsistency, the consistency ratio (*CR*) is calculated to check the consistency of the performed comparisons (Equation 2).

$$CR = CI / RI \quad (2)$$

If the value of the consistency ratio is smaller or equal to 10%, the inconsistency is acceptable, otherwise if the consistency ratio is greater than 10%, the subjective judgment needs to be revised [13].

2.2. Landslide Susceptibility Mapping

The next phase of the analysis was to combine all the weighted parameters by using the WLC method [15]. By applying the WLC method, the weighted values assigned for each parameter was numerically added resulting in the production of a landslide susceptibility map (Equation 3):

$$LS_i = \Sigma\ (Vw_j\ x\ cv_j) \quad (3)$$

where Vw_j the weight of the j^{th} variable and cv_j the standardized ratings of class k^{th} of the j^{th} variable.

To provide an easily to interpret map the produced landslide susceptibility map was classified into five categories of susceptibility, namely; very high susceptibility, high susceptibility, moderate susceptibility, low susceptibility and very low susceptibility [16]. ArcGIS 10.3 was used for compiling and analysing the data and also for producing the landslide susceptibility maps.

2.3. Validation

The final phase of the analysis is to validate the outcome of the AHP methodology. The approach followed in the present study was the one introduced by [17, 18]. The authors report that an ideal landslide susceptibility map must have an increasing landslide density ratio when moving from low susceptible classes to high susceptible classes and the high susceptibility class to cover small extent areas.

3. Study Area and Data

The study area is located at the northern part of Peloponnesus, Greece, covering an area of approximately 92 km^2. The area lays between longitudes 312,000 and 327,000 and latitudes 4,224,000 and 4,242,000 (coordinates based on the Greek Coordinate system, EGSA'87). It involves the Finikas water sub-basin, with altitude ranging between 0 to 1900 m above sea level (Figure 1). A strong influence in shaping the terrain of the wider research area had the presence of Finikas River, the length of which reaches 22.5 km. The climate of the area is characterized as Mediterranean type (Csa) with mild winters and dry and hot summers. December appears to be the rainiest month, with mean precipitation reaching 128.9 mm followed by November (124.7 mm), while the driest month appears to be August (7.0 mm) followed by July (8.8 mm).

The geological formations that cover the wider area of research belong to the Olonos - Pindos tectonic zone, in which Upper Cretaceous – Eocene sedimentary sequences outcrop [19, 20]. According to the geological maps compiled by the Greek Institute of Geological and Mineral Exploration the geological formations that are present and cover the wider area are [21, 22]: Quaternary formations, Plio-Pleistocene deposits, flysch formations, limestones and dolomites and shale and cherts formations (Figure 2).

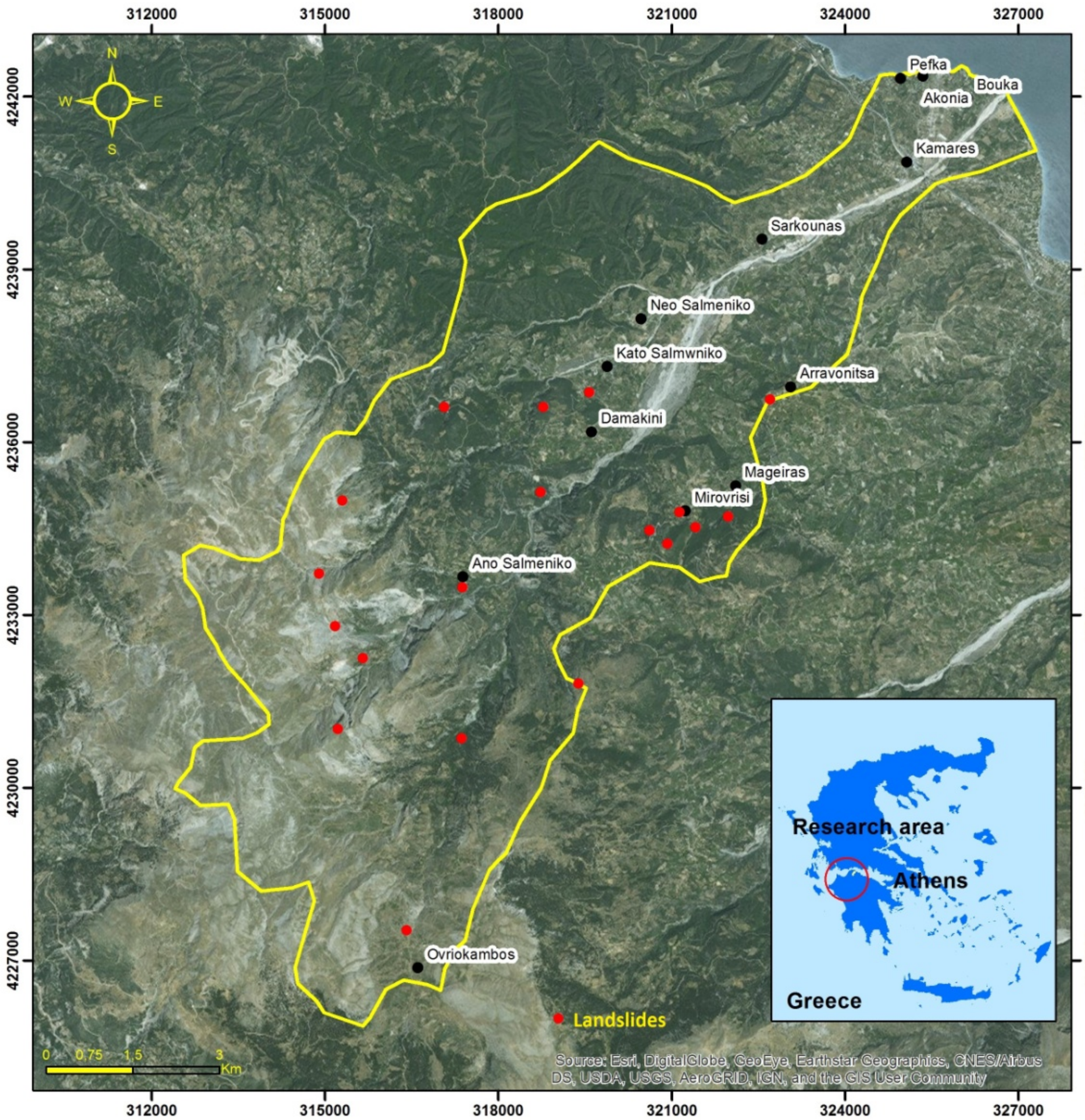

Figure 1. Study area

Landslide phenomena that have been recorded in the area are mainly caused due to the physical conditions and the general geotechnical behavior of the geological formation that cover the area. According to several researchers that have studied landslide phenomena in the wider area of research, in most cases, the main triggering variables were the combined action of intense rainfall events, seismic activity, while human activity played a much less important role [23-25]. Within the Finikas watershed most of the reported landslides were located along the road network and within the residential complexes, classified according to the Varnes Classification System [26], as rotational and translational slides, creep and also rockfalls (Figure 1).

Six landslide related variables were analyzed: lithological units, elevation, slope angle, slope aspect, distance from faults and distance from river network. In the following paragraphs a brief description, of the landslide related variables would be presented.

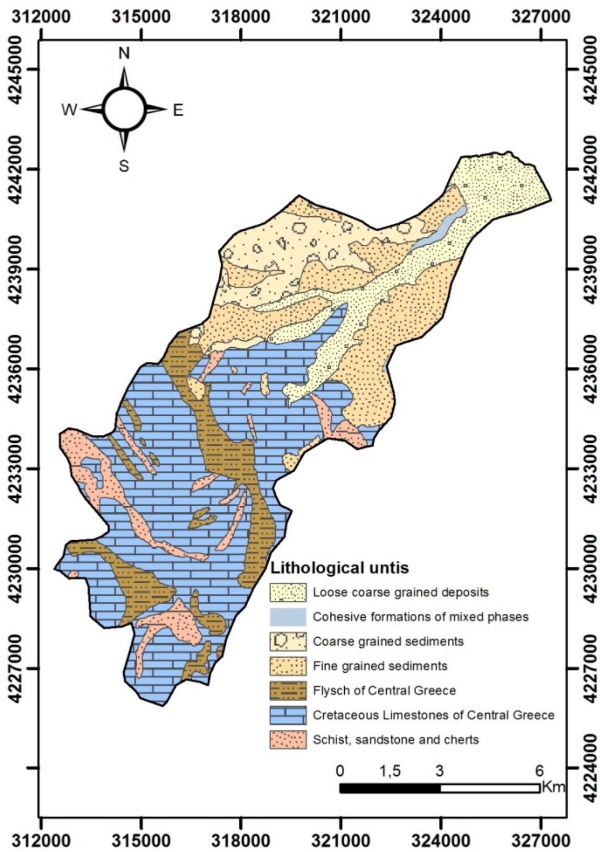

Figure 2. Lithological units

The elevation plays an important role in landslide susceptibility assessments [4, 27]. The mean elevation of the basin is 780 m, with the quarter of the study area (approximately 24%) showing elevation values less than 300 m (Figure 3).

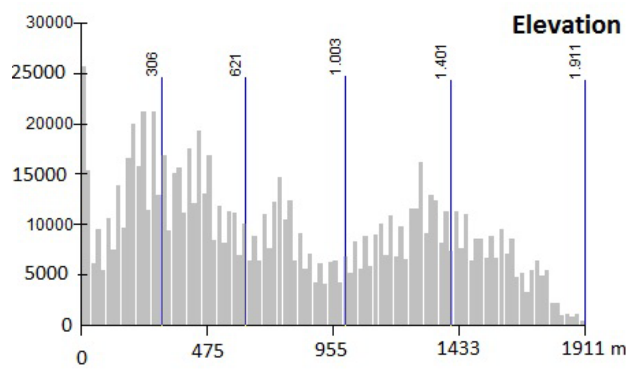

Figure 3. Classification statistics of elevation

The elevation was classified into five classes (< 300 m, 301 – 620 m, 621 – 1000 m, 1001 – 1400 m, > 1401 m) (Figure 4).

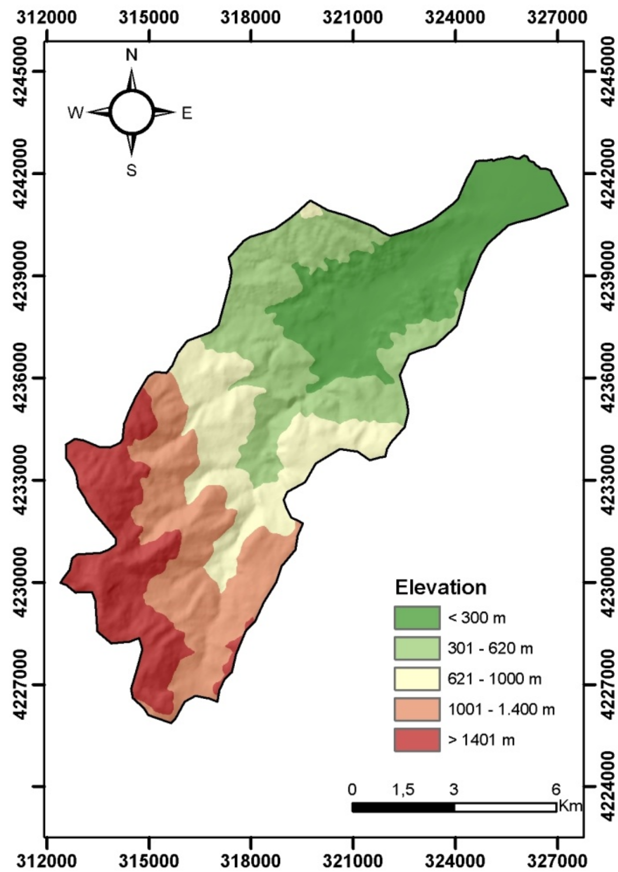

Figure 4. Elevation

Slope is also considered as one of the most influencing factors to landslide occurrences [4]. In most cases, gentle slopes usually have a low frequency of landslide occurrences than steep slopes [4]. The mean slope within the basin is 16°. About 21% of the area has slope angle less than 7° and at least 6% slope angle higher than 33° (Figure 5).

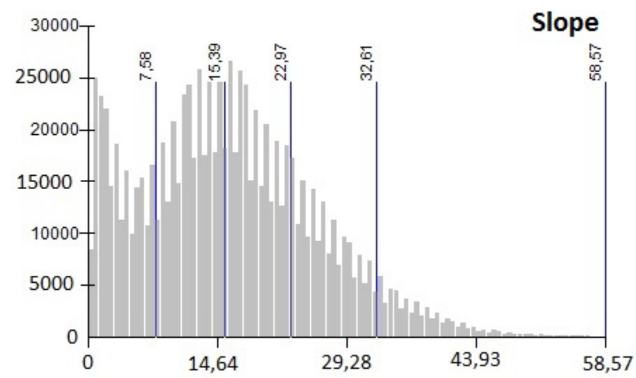

Figure 5. Classification statistics of slope

As for the slope layer it was classified into five classes according to the local geological and geotechnical conditions (<7°, 8°-15°, 16°-23°, 24°-32°, >33°) (Figure 6).

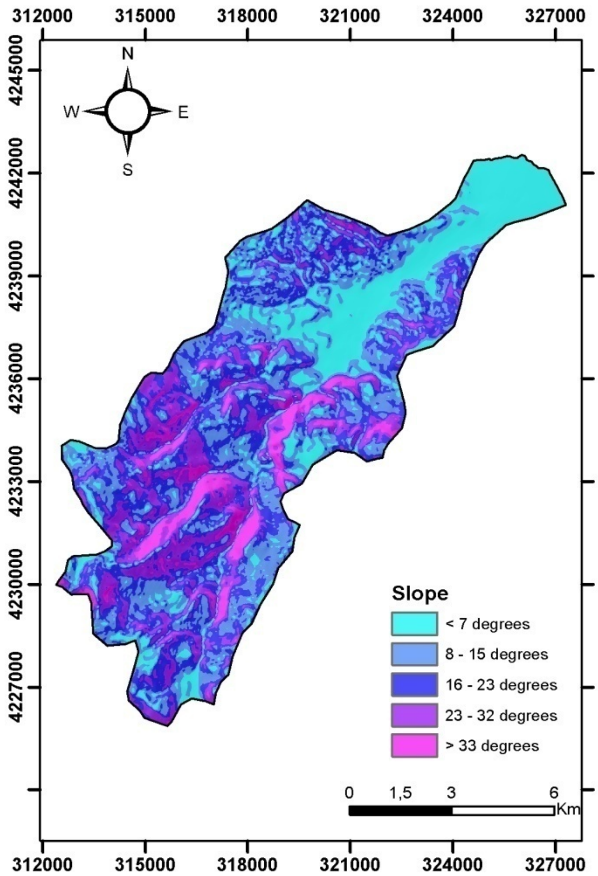

Figure 6. Slope

Concerning aspect the mean orientation of slope was estimate to be 147°, with approximately half of the study area showing orientation from NW to NE (Figure 7).

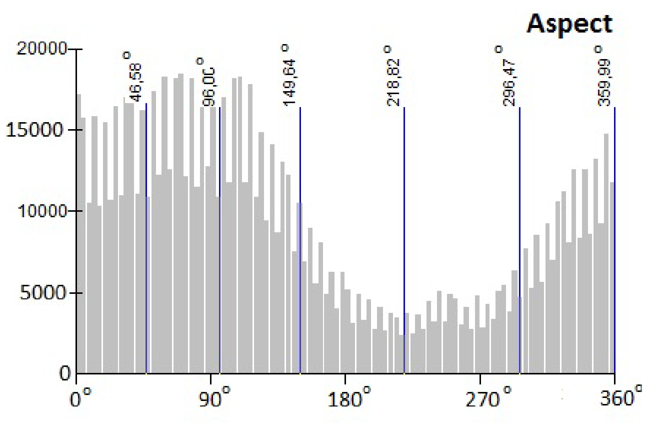

Figure 7. Classification statistics of aspect

The aspect layer was classified into eight classes, namely: North (337.5-22.5), Northeast (22.5-67.5), East (67.5-112.5), Southeast (112.5-157.5), South (157.5-202.5), Southwest (202.5-247.5), West (247.5-292.5), Northwest (292.5-337.5) (Figure 8).

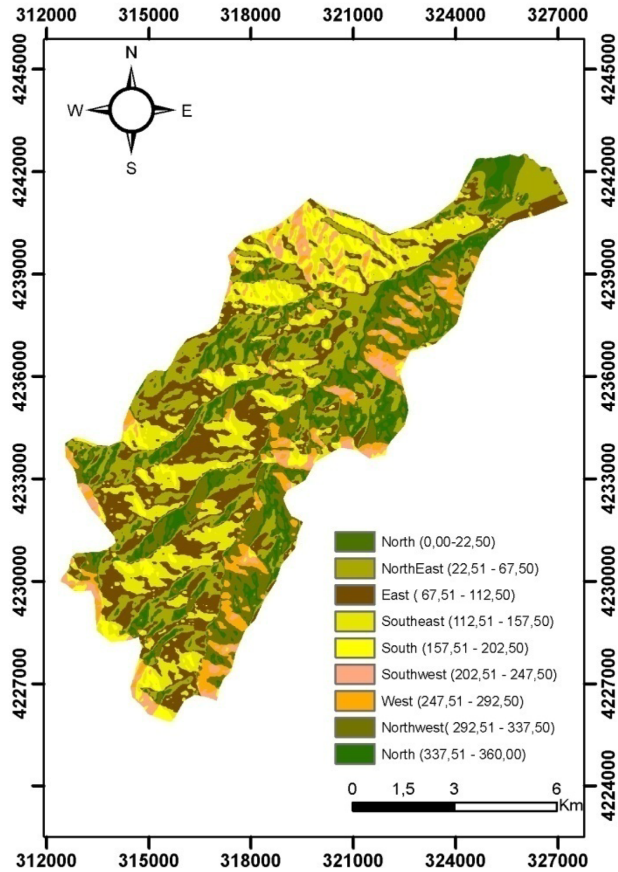

Figure 8. Aspect

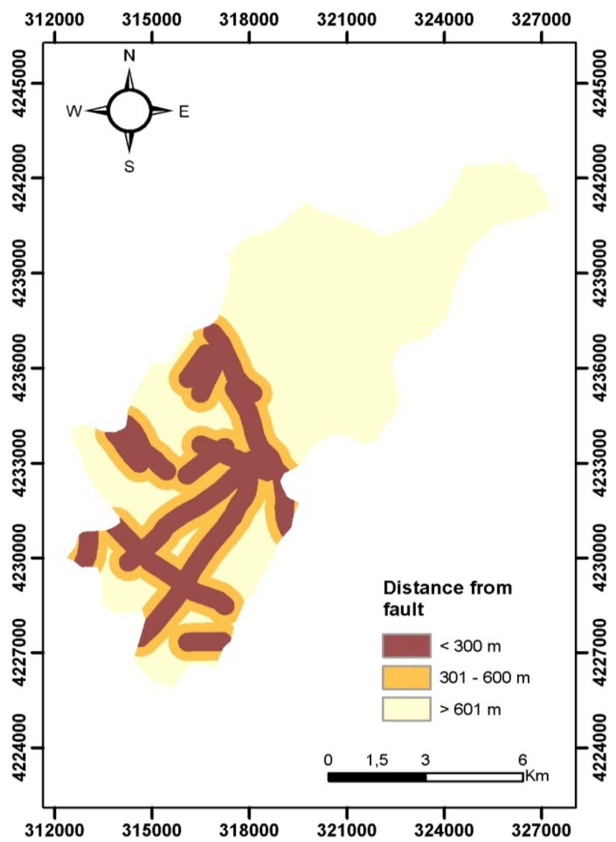

Figure 9. Distance from faults

The tectonic characteristics, mainly faults were digitized from existing geological map, scale 1:50.000 [21, 22]. The research area was classified into a three class layer, areas that cover zones that have distance less than 300 m from faults, areas that cover zones that have distance between 301 and 600 m, and areas with distance greater than 601 m (Figure 9).

Finally, the distance to the river network was classified into a four class layer (< 50 m, 51 – 100 m, 101 - 200 m, > 201 m) (Figure 10).

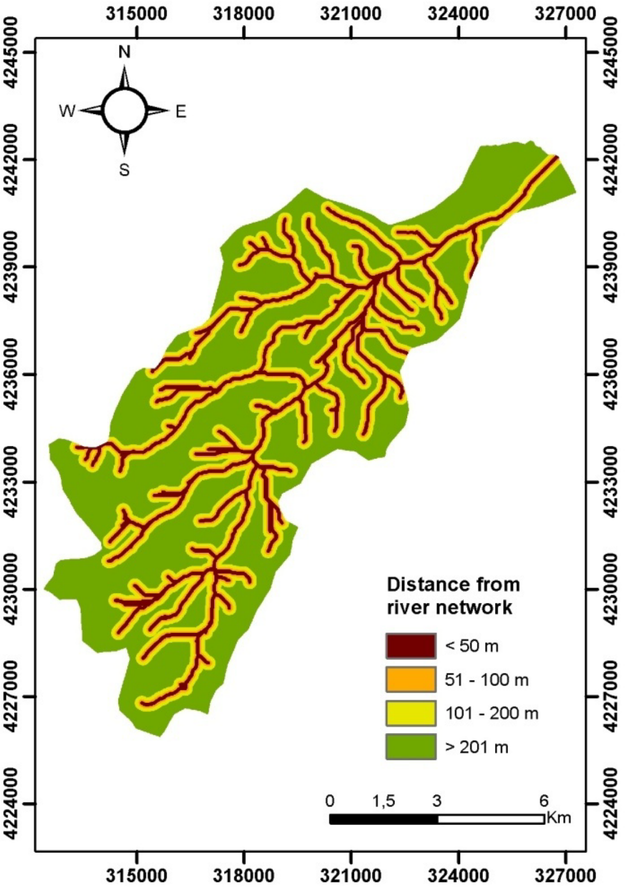

Figure 10. Distance from river network

4. Results and Discussion

The outcomes of the implementation of AHP concerning the weighting of the landslide related variables and each variables class are presented in Tables 2, 3, 4, 5, 6, 7 and 8. As it can be seen the most important variables according to the performed weighing process are lithological units and slope, (both having values of 0.3118), followed by distance from river network (0.1401) and elevation (0.1214). The least important appears to be aspect (0.0457) followed by distance from faults (0.0691). The consistency index was estimated to be 0.021 a value that indicates that no inconsistency in the decision process has been detected.

The outcomes are persistent with related studies that impose the significance of lithology and slope in landslide susceptibility assessments [28, 29].

Table 3 illustrates the results of the implementation of AHP concerning the lithological unit variable. The 7th class, schist, sand and chert formations showed the highest coefficient (0.2962), followed by limestone (0.1851), flysch formations (0.1783) and fine grained sediments (0.1555). The consistency index for the lithological unit variable was estimated 0.028 indicating none inconsistency.

Table 2. Weight coefficient of each landslide related variable

	V1	V2	V3	V4	V5	V6	Vw
V1	1	3	1	5	3	4	0.3118
V2	1/3	1	1/3	3	1	2	0.1214
V3	1	3	1	5	3	4	0.3118
V4	1/5	1/3	1/5	1	1/4	1/2	0.0457
V5	1/3	1	1/3	4	1	3	0.1401
V6	1/4	1/2	1/4	2	1/3	1	0.0691

V1: lithological units, V2: elevation, V3: slope, V4: aspect, V5: distance from river network, V6: distance to faults, Vw: weight variable.

Table 3. Weight coefficient of lithological unit

	L1	L2	L3	L4	L5	L6	L7	cv1
L1	1	1/2	1/6	1/7	1/6	1/6	1/8	0.0251
L2	2	1	1/5	1/5	1/7	1/8	1/9	0.0303
L3	6	5	1	1	1/2	1/2	1/4	0.1294
L4	7	5	1	1	1/2	1	1	0.1555
L5	6	7	2	1	1	1	1	0.1783
L6	6	8	1	1	1	1	1	0.1851
L7	8	9	4	2	2	2	1	0.2962

L1: Loose coarse grained deposits, L2: Cohesive formations of mixed phase, L3: Coarse grained sediments, L4: Fine grained sediments, L5: Flysch formations, L6: Cretaceous limestone, L7: Schist, sandstone, cherts, cv1: weight of lithological units.

High percentage of landslide occurrence has been observed in Plio-Pleistocene sediments, flysch formations, and Cretaceous limestone, findings that are in agreement with previous studies [23, 23]. According to [24] the Plio-Pleistocene sediments are more susceptible in rotational slides, movements that are influenced by the heterogeneous structure and the degree of looseness. In areas covered by flysch formations, rotational and translational slides, is attributed to the anisotropic geotechnical behavior of the formation. Finally, the Cretaceous limestone, appear susceptible to rockfalls, that are influenced by the degree of weathering and fragmentation, the orientation of the discontinuities surfaces and the intense morphological relief.

Table 4 illustrates the results of the implementation of AHP concerning the elevation variable. The 5th class (>1401 m) showed the highest coefficient (0.4550). The consistency index for the variable was estimated 0.046 indicating none inconsistency.

The elevation could be considered as a variable that indirectly contributes to the slope failure. The descriptive analysis performed in the study showed that, areas with elevations higher than 600 m, experience considerable higher chance of landslide occurrence.

Table 5 illustrates the results of the implementation of

AHP concerning the slope variable. The 5th class (> 33°) showed the highest coefficient (0.5088), followed by the 3rd class (0.2301). The consistency index for the slope variable was estimated 0.008 indicating none inconsistency.

Table 4. Weight coefficient of elevation

	elev1	elev2	elev3	elev4	elev5	cv2
elev1	1	1/3	1/4	1/5	1/7	0.0474
elev2	3	1	1/3	1/4	1/5	0.0881
elev3	4	3	1	1/2	1/3	0.1807
elev4	5	4	2	1	1/2	0.2288
elev5	7	5	3	2	1	0.4550

elev1: < 300 m, elev2: 301-620 m, elev3: 621 – 1000m, elev4: 1001 – 1400 m, elev5: > 1401 m, cv2: weight of elevation.

Table 5. Weight coefficient of slope

	slp1	slp2	slp3	slp4	slp5	cv3
slp1	1	1/3	1/5	1/2	1/7	0.0502
slp2	3	1	1/1	3	1/4	0.1504
slp3	5	2	1	3	1/3	0.2301
slp4	2	1/3	1/3	1	1/6	0.0605
slp5	7	4	3	6	1	0.5088

slp1: < 7°, slp2: 8°-15°, slp3: 16° – 22°, slp4: 23° – 32°, slp5: > 33°, cv3: weight of slope.

Table 6 illustrates the results of the implementation of AHP concerning the aspect variable. The 8th class (Northwest) showed the highest coefficient (0.3660), followed by the 2nd class (Northeast), with coefficient value 0.2868. The consistency index for the variable was estimated 0.077 indicating none inconsistency.

Table 6. Weight coefficient of aspect

	N	NE	E	SE	S	SW	W	NW	cv4
N	1	1/7	1	1/4	1/3	5	5	1/8	0.0494
NE	7	1	8	5	4	9	9	1/2	0.2868
E	1	1/8	1	1/2	1/3	5	5	1/8	0.0489
SE	4	1/5	4	1	1/2	7	7	1/5	0.1239
S	3	1/4	3	1/2	1	5	5	1/6	0.0873
SW	1/5	1/9	1/5	1/7	1/5	1	1	1/9	0.0188
W	1/5	1/9	1/5	1/7	1/5	1	1	1/9	0.0188
NW	8	2	8	5	6	9	9	1	0.3660

cv4: weight of aspect.

In Greece certain slope orientations are associated with increased snow concentrations and consequently longer periods of freeze and thaw action processes. These slopes can favor higher erosion and weathering processes as the climatic conditions facilitate the cyclic alternation of dry and wet periods. The SE–SW (135°– 225°) oriented slopes are mostly affected by rainfalls and the NW–NE (315° – 45°) oriented slopes are mostly sunless, affected by the increased snow concentrations [28-30].

Table 7 illustrates the results of the implementation of AHP concerning the distance from faults variable. The 1st class (< 300 m) illustrated the highest coefficient (0.6491), whereas the consistency index for the variable was estimated 0.077, indicating none inconsistency.

Table 7. Weight coefficient of distance from faults

	flt1	flt2	flt3	cv5
flt1	1	3	7	0.6491
flt2	1/3	1	5	0.2790
flt3	1/7	1/5	1	0.0719

flt1: < 300 m, flt2: 301-600 m, flt3: > 601 m, cv5: weight of distance from faults.

Finally, table 8 illustrates the results of the implementation of AHP concerning the distance from river variable. The 1st class (> 50 m) has been assigned with the highest coefficient (0.5783), with the calculated consistency index equal to 0.028, indicating also none inconsistency.

Table 8. Weight coefficient of distance from river

	riv1	riv2	riv3	riv4	cv6
riv1	1	3	5	7	0.5738
riv2	1/3	1	2	5	0.2388
riv3	1/5	1/2	1	3	0.1310
riv4	1/7	1/5	1/3	1	0.0563

riv1: < 50 m, riv2: 51-100 m, riv3: 101 – 200m, riv4: > 201 m, cv6: weight of distance from river.

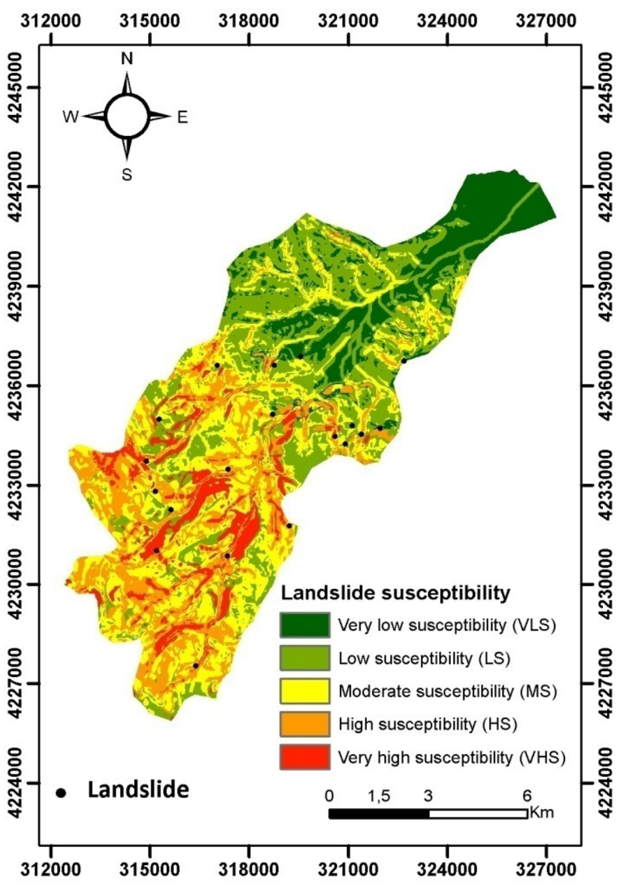

Figure 11. Landslide susceptibility map

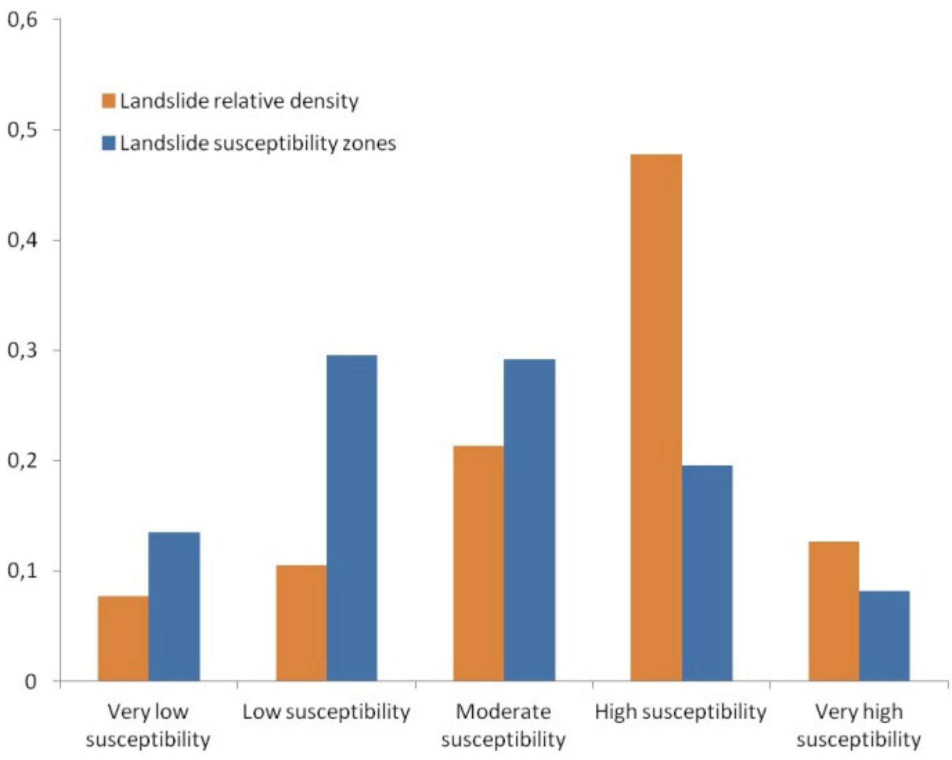

Figure 12. Validation

Based on the weighting coefficients estimated by the AHP the landslide susceptibility values were obtained and produced the landslide susceptibility map (Figure 11). The high and very high susceptible zones are located at the southern region of the research area, in areas with altitude higher than 600 m, following the spatial distribution of the river network.

Concerning the produced landslide susceptibility map, the very high and high susceptibility class was estimated to cover 8.18% and 19.55% respectively. The relative landslide density for the high and very high landslide susceptibility class was estimated to be 69.45% (Figure 12). The findings of the analysis were partly persistent with the notion that an ideal landslide susceptibility map should have an increasing landslide density ratio when moving from low susceptible classes to high susceptible classes and that the higher susceptibility class cover small extent areas. Although the very high susceptibility area covers small extent, it also exhibits relative low landslide density. This may be justified by the fact that the very high susceptibility area covers mainly areas that are remote and difficult to reach and thus several landslide incidences that may have occurred have not been documented.

5. Conclusions

The presented study applied Analytical Hierarchical Process in order to produce a landslide susceptibility map in Finikas watershed basin, North Peloponnesus, Greece. Six landslide variables were analysed and included in the study, namely lithological units, elevation, slope, aspect, distance from faults and distance from river network.

According to the findings of the AHP implementation, lithological unit and slope were among the most significant variables that contribute to landslide susceptibility. The predictive power of the AHP model was estimated to be relative good since 69.45% of the recorded landslides fall in the high and very high landslide susceptibility zone.

Because of its simplicity and robustness in obtaining weights and integrating heterogeneous data, the AHP can be considered as an ideal tool for assisting in managing landslide related variables in a much easier and automated manner, maximizing the functionality of GIS environment and producing quite accurate landslide susceptibility maps.

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