ΜΕΓΑΛΗΣ ΚΛΙΜΑΚΑΣ ΧΑΡΤΟΓΡΑΦΗΣΗ ΚΑΤΟΛΙΣΘΗΤΙΚΗΣ ΕΠΙΚΙΝΔΥΝΟΤΗΤΑΣ ΜΕ ΤΗ ΣΥΝΔΥΑΣΜΕΝΗ ΧΡΗΣΗ ΓΣΠ ΚΑΙ ΜΕΘΟΔΩΝ ΠΟΛΥΚΡΙΤΗΡΙΑΣ ΣΤΗΡΙΞΗΣ ΑΠΟΦΑΣΕΩΝ – ΕΝΑ ΠΑΡΑΔΕΙΓΜΑ ΣΤΗ ΒΟΡΕΙΑ ΜΕΣΣΗΝΙΑ (ΝΔ ΠΕΛΟΠΟΝΝΗΣΟΣ, ΕΛΛΑΔΑ)

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Περίληψη

Σκοπός της εργασίας είναι η εκτίμηση της επικινδυνότητας σε κατολισθήσεις του βόρειου τμήματος του Νομού Μεσσηνίας με τη συνδυασμένη χρήση Γεωγραφικών Συστημάτων Πληροφοριών και Πολυκριτηριακών Μεθόδων Στήριξης Αποφάσεων. Εφαρμόζοντας την Αναλυτική Ιεραρχική Διαδικασία και τη διαδικασία του Σταθμισμένου Γραμμικού Συνδυασμού κατασκευάστηκε ένας χάρτης κατολισθητικής επικινδυνότητας ο οποίος παρέχει χρήσιμες πληροφορίες για τις συνθήκες ευστάθειας της περιοχής και μπορεί να χρησιμεύσει σαν ένα πρώτο βήμα στο σχεδιασμό για την αντιμετώπιση των καταστροφών από κατολισθήσεις στο Νομό Μεσσηνίας. Ιδιαίτερα ο σκοπός μας είναι να μεταδώσουμε πληροφορίες σχετικά με την ευστάθεια των πρανών της περιοχής μελέτης σε μη-γεωλόγους οι οποίοι λαμβάνουν αποφάσεις για μεγάλα κατασκευαστικά έργα και μελλοντικές αλλαγές χρήσεων γης.

LARGE SCALE LANDSLIDE SUSCEPTIBILITY MAPPING USING GIS-BASED WEIGHTED LINEAR COMBINATION AND MULTICRITERIA DECISION ANALYSIS – A CASE STUDY IN NORTHERN MESSINIA (SW PELOPONNESUS, GREECE)

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Abstract

The purpose of this study is to assess the susceptibility of landslides at the northern part of Messinia prefecture using GIS and Multicriteria Decision Analysis. Analytic Hierarchy Process and Weighted Linear Combination method were used to create a landslide susceptibility map which provides valuable information concerning the stability conditions of the territory and may help towards the mitigation of natural landslide disasters in the study area. Particularly the intention is to transfer effectively information regarding slope stability to non-geologists who take decisions for future land use planning processes and major construction projects.

Λέξεις κλειδιά: Αναλυτική Ιεραρχική Διαδικασία, Σταθμισμένος Γραμμικός Συνδυασμός, Φυσικές καταστροφές, Μεσσηνία.

Key words: Natural disasters, Messinia,, Analytic Hierarchy Process, Weighted Linear Combination.

1. Introduction

The study area comprises the northern part of Messinia Prefecture covering a region of about 787 square kilometers at a tectonically active area where landslides are among the most common and hazardous occurring natural hazards. Tsakona landslide, (February 2003), at the boundary between Arcadia and Messinia, is a burning example that have caused the total destruction of a part of the new highway which connects the two prefectures (Fountoulis et al., 2004). After four years the highway is still under reconstruction and the economic losses due to this landslide alone are expected to reach millions of euros.

The main drainage networks in Northern Messinia are constituted by the rivers Neda, Sellas, Amfitas and Maurozoumena. The Neda drainage network flows in the Kyparissiakos gulf having a general stream direction from east to west. At the northern part of Kyparissia Mt. Sellas river forms an orthogonal drainage network where the branches have an initial E-W direction which abruptly changes to N-S, (following the alpine fold axes) and thrusts trending and again to E-W where the main branch discharges in the Kyparissiakos gulf controlled by the Kyparissia fault zone. On the other hand Amfitas and Maurozoumena are the main fluvial systems that drains the hydrological basin of Ano Messinia joining together to form a main stream that flows out south in the lower Messinia basin.

The largest settlements (Kyparissia, Dorio, Meligalas) are arranged along the plain areas of Kyparissia, Dorio and Ano Messinia basins but there are many small villages scattered throughout the majority of the territory.

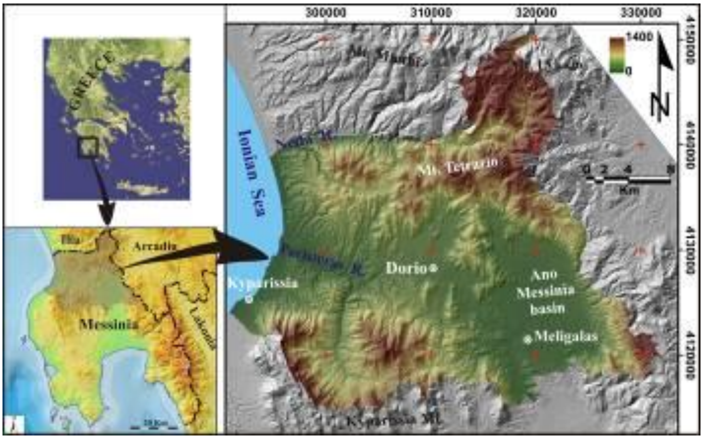

Figure 1. Location map and shaded relief image showing morphology of the study area.

2. Geological and structural setting

At the Northern Messinia area, two alpine geotectonic units of the external Hellenides are present, namely (i) the Tripolis unit (shallow-water cabonates, Triassic–L. Eocene and flysch, L. Eocene–E. Miocene), and (ii) the Pindos unit (pelagic limestones, radiolarites, the so-called "first flysch", thin-bedded limestones, L. Cretaceous and flysch, Danian–Eocene). Pindos unit overthrusts Tripolis unit forming successive thrusts with movement direction from east to west.

The post alpine deposits outcropping in the study area can be distinguished into marine and terrestrial formations. The marine deposits occur only in the Kyparissia - Kalo Nero graben and consist of marls, sandstones and conglomerates of Late Pliocene – Lower Pliocene and Early Pleistocene age (Fountoulis 1994). The terrestrial deposits mainly represent red-colored siliceous sands and conglomerates alternating with clay occurring in all basins.

The neotectonic macrostructure of the broader area (SW Peloponnesus) is characterized by the presence of large grabens and horsts bounded by wide fault zones, striking N-S and E-W. The main 1st order macro-structures in the study area, as illustrated in fig. 2, are: (a) the Kalamata-Kyparissia megagraben, (b) the Megalopolis-Lykaeon-Minthi-Tetrazio composite tectonic graben and (c) the Kyparissia Mts morphotectonic unit, (Fountoulis 1994). The kinematic evolution of these neotectonic units is complicated since block rotation differentiates the uplift and subsidence rates throughout the margins of the neotectonic blocks.

Within these 1st order neotectonic macrostructures a great number of smaller structures are present, as shown in fig. 2. These neotectonic structures of minor order are dynamically related, as they have resulted from the same stress field but they have a different kinematic evolution. This differentiation has initiated either during the first stages of their creation, or later, during their evolution (Mariolakos et al. 1995).

3. Methodology

In our study we implemented Multicriteria Decision Analysis (MCDA) and GIS for the preparation of a landslide susceptibility map at the northern part of Messinia prefecture as shown in the flow chart in fig. 3. Several qualitative and quantitative methods were proposed for landslide susceptibility evaluation, reviews of which are given by various researchers (Aleotti & Chowdhury 1999, Guzzeti et al. 1999, Huabin et al. 2005). In our study we apply the weighted linear combination method (WLC) for the creation of the susceptibility map constructing several thematic maps. Each map represents a landslide factor and for each factor we must identify a number of classes. As a result the territory in each thematic map is divided into homogenous areas according to the factor's classes. In WLC method the classes of the factors are standardized to a common numeric range and then combined by means of a weighted average.

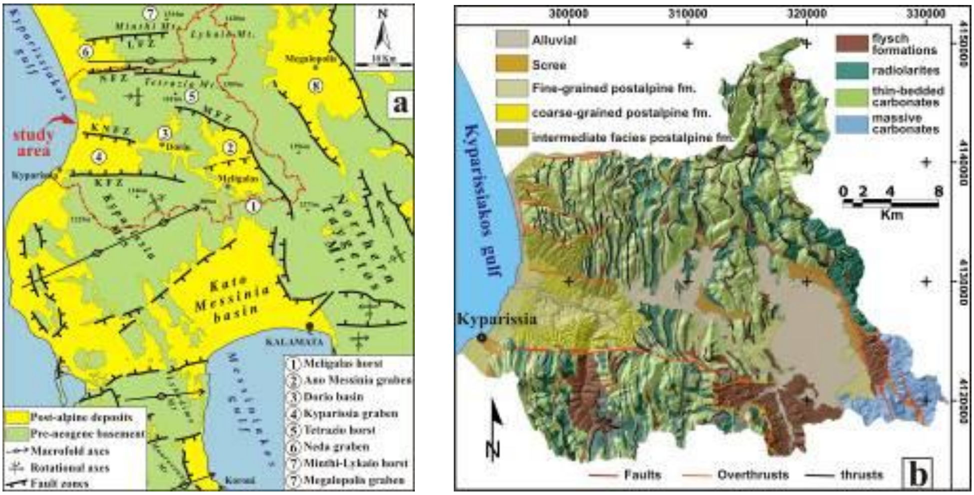

Figure 2. (a) Tectonic sketch map showing the main neotectonic macrostructures of the study area, (b) Reclassified geological map based on the geotechnical behavior of the main lithologies occurring in the study area.

In our study area ten (10) parameters were selected as controlling factors for landslide occurrence and each factor was classified into several classes. These factors are (i) slope gradient, (ii) slope curvature, (iii) slope aspect, (iv) lithology, (v) land use, (vi) soil thickness, (vii) mean annual precipitations, (viii) proximity to major faults and thrusts, (ix) distance from streams and (x) distance from main roads. The selection of these factors was based on their affinity with landslide occurrence in the study area. The influence that each factor has on the landslide occurrence is described in details in a previous study of ours (Ladas et al. 2007).

The following step was the production of the thematic maps as illustrated in fig. 3. The data used for the preparation of these layers were obtained from the Hellenic Military Geographical Service topographical sheets (scale 1/50.00), IGME geological maps (Kyparissia, Kato Figaleia, Megalopolis, Filiatra, Meligalas & Kalamata sheets, scale 1/50.000), Filiatra neotectonic map (scale 1/100.000), CORINE 2000 program land use map, Ministry of Agriculture land resource maps (Kyparissia, Kato Figaleia, Megalopolis, Filiatra, Meligalas & Kalamata sheets, scale 1/50.000), rainfall data (10 rainfall stations), personal fieldwork and ortho-photography (scale 1/5.000). The thematic maps corresponding to (a) slope gradient, (b) curvature and (c) aspect, were obtained directly in raster format from the produced DEM while the others were produced by vector format digitization that was transformed in raster format.

The next step was to assign weights and rank values to the raster layers (representing factors) and to the classes of each layer respectively. This was realized with the use of the Analytic Hierarchy Process, developed by Saaty (1980). Finally the weighted raster thematic maps with the assigned ranking values for their classes were multiplied by the corresponding weights and added up to yield a simple map where each cell has a certain landslide susceptibility index (LSI) value. This map after reclassification represents the final susceptibility map of the study area.

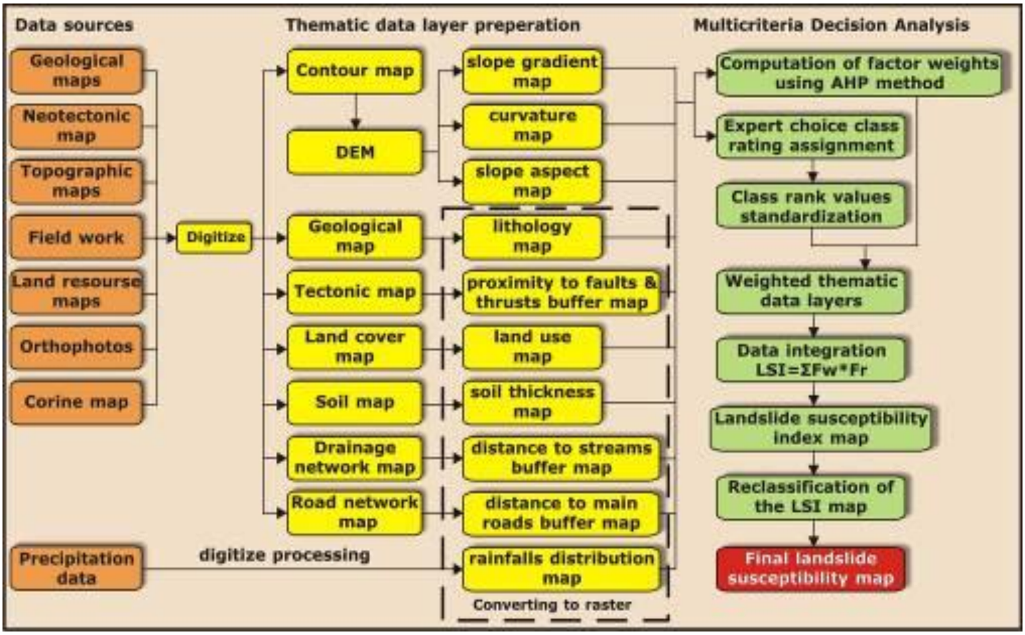

Figure 3. Flow chart showing methodology of the landslide susceptibility analysis.

4. Factor Analysis

All the primary vector thematic map-layers, representing landslides controlling factors, were converted into raster format for future analysis through a vector to raster conversion procedure using a pixel size of 15x15m in order to match the spatial resolution of the DEM and to confirm to the detail and resolution of the original maps (scale 1:50.000).

As slope failures represent the interplay results of various factors the influence of each factor on the occurrence of landslides is different and must be weighted. For this study, the Analytic Hierarchy Process (AHP), developed by Saaty (1980), was selected as the decision analysis tool for the evaluation of the relative weight of each factor in order to introduce objectivity in weight assignment (Barredo et al. 2000, Ayalew et al. 2005, Akgun et al. 2006). In AHP all factors are compared pairwise in terms of the intensity of their importance using a continuous 1 to 9 point scale shown in Table 1. The scale, used for the comparisons, enables the decision-maker to incorporate experience and knowledge intuitively and is insensitive to small changes minimizing the effect of uncertainty in evaluations.

Using Expert Choice 11 software (trial version) we build the pairwise comparison matrix needed to calculate factor weights in AHP as shown in table 1. After the pairwise score rating the consistency used to build the matrix is checked by the consistency ratio (CR). Saaty (1980) prescribes that the CR must be less than 0.1 to accept the computed weights otherworld the ratings should be re-evaluated. In Table 1 the CR is 0.07 indicating the adequate degree of consistency of the comparison matrix.

After the development of the weights, all factors were combined using the Weighted Linear Combination (WLC) method which is one of the best known and most commonly used multicriteria-GIS based methods (Malczewski 2000, Ayalew et al. 2004). In the procedure for multi-criteria analysis using WLC it is necessary not only for the weights of the factors to have a sum of 1 but also that the classes of the factors are standardized to a common numeric range. The ratings of the classes within each factor shown in Table 2 were based on the relative importance of each class obtained from field knowledge according to the obvious relationship between each conditioning factor and the distribution of the landslides in the broader area.

In our case in order to approve a uniform standardized susceptibility rating scale we use the formula in Equation 1 dividing each rank value by the maximum value for the specific given factor and afterwards multiply it by 100 in order to achieve integer numbers and get values between 0 and 100. In this way the ranked values of the classes were standardized according to the relative distance between the original and the maximum rank value and the maximum rank value for the classes of each factor is always equal to 100. The produced integer numbers ranking from 0 to 100 were assigned as relative values for each class of all the factors as shown in Table 2.

Equation 1 - Formula for rank values standardization

$X'_{ij} = X_{ij}/X_j^{max} * \text{standardized range}.$

where X'ij is the standardized rank value for the ith class for the jth factor, Xij is the primary rank value, Xjmax is the maximum rank value for the jth factor and standardized range=100.

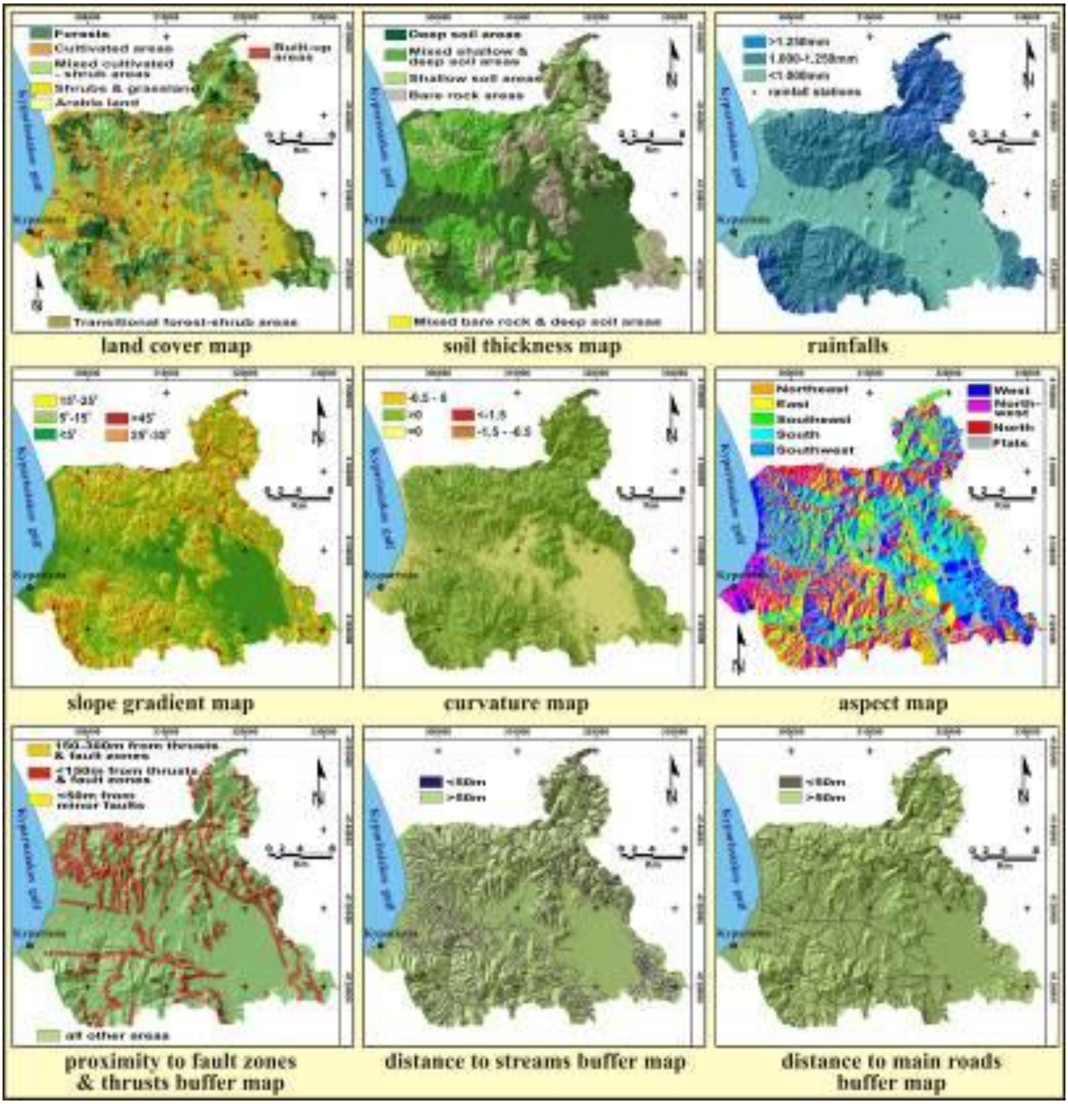

Figure 4. Thematic maps of the controlling factors used for the creation of the susceptibility map. By applying the WLC method, the weight value assigned for each factor was multiplied by the standardized rank values given to the classes and numerically added according to Equation 2 in order to produce a Landslide Susceptibility Index (LSI) map.

Equation 2 – Evaluation of LSI

$LSI = \Sigma Fw * Fr$ – (where Fw=weight of each factor and Fr=standardized rank value of each factor class).

Table 1. *Nine-point continuous rating scale for pair-wise comparisons in AHP and matrix of factors weights evaluation.*

Less important				**Equally important**	**More important**			
Extrem	Very Strongl	Strongly	Moderate		Moderately	Strongly	Very. Strongly	Extremel
1/9	1/7	1/5	1/3	1	3	5	7	9
					1/8, 1/6, 1/4, 1/2, 2, 4, 6, 8, Intermediate values			

	(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**	**(i)**	**(j)**	**Weights**
Lithology (a)	1	2	3	4	5	5	5	5	5	6	0.269
Slope gradient (b)	1/2	1	3	3	4	3	5	5	5	5	0.209
Proximity to thrusts (c)	1/3	1/3	1	3	3	3	3	3	3	5	0.137
Land use (d)	1/4	1/3	1/3	1	3	3	3	3	3	5	0.107
Soil thickness (e)	1/5	1/4	1/3	1/3	1	2	2	2	3	5	0.070
Curvature (f)	1/5	1/3	1/3	1/3	1/2	1	2	2	2	2	0.055
Distance from streams (g)	1/5	1/5	1/3	1/3	1/2	1/2	1	1	3	5	0.050
Distance from roads (h)	1/5	1/5	1/3	1/3	1/2	1/2	1	1	3	5	0.050
Rainfalls (i)	1/5	1/5	1/3	1/3	1/3	1/2	1/3	1/3	1	3	0.033
Aspect (j)	1/6	1/5	1/5	1/5	1/5	1/2	1/5	1/5	1/3	1	0.021
											CR=0.07

Table 2. *The weights and rank values given to the factosr and their classes respectively.*

Factors	**weights**	**Classes**	**Rank values**	**Standardized ratings**
Lithology	0.2690	Scree	6	100
		Flysch formations & radiolarites	5	83
		Fine-grained post-alpine formations	4	67
		Intermediate post-alpine facies	3	50
		Coarse-grained post-alpine formations.	2	33
		Thin-bedded carbonates	1	17
		Massive carbonates & alluvial	0	0
Land use	0.107	Shrubs & grassland	6	100
		Transitional forest-shrub areas	5	83
		Mixed cultivated-shrub areas	4	67
		Forests	3	50
		Cultivated areas	2	33
		Built-up areas	1	17
		Arable land	0	0
Slope gradient	0.209	Escarpments, $>35^0$	5	100
		Steep slopes, 25^0-35^0	4	80
		Moderately steep slopes, 15^0-25^0	3	60
		Gentle slopes, 5^0-15^0	2	40
		Very gentle slopes, $<5^0$	1	20
Curvature	0.,055	<-1.5	4	100
		-1.5 - -0.5	3	75
		-0.5 - 0	2	50
		>0	1	25
		=0	0	0
Aspect	0.021	N & NW facing slopes	3	100
		W & SW facing slopes	2	67
		all other directions	1	33

Factors	weights	Classes	Rank values	Standardized ratings
		flats	0	0
Soil thickness	0.070	Deep soil areas	4	100
		Mixed shallow & deep soil areas	3	75
		Mixed bare rock & deep soil areas	2	50
		Shallow soil areas	1	25
		Bare rock	0	0
Rainfalls	0.033	>1.250mm	3	100
		1.000-1.250m	2	67
		<1.000mm	1	33
Proximity to thrusts/faults	0.137	<150m from thrusts & fault zones	3	100
		150-300m from thrusts & fault zones	2	67
		<50m from minor faults	1	33
		All other areas	0	0
Distance to roads	0.050	<50m	1	100
		>50m	0	0
Distance to streams	0.050	<50m	1	100
		>50m	0	0

5. The Susceptibility map

As a result of the adopted weighting-ranking system the landslide susceptibility index (LSI) values for each cell in the resulting susceptibility map are varying within the range of 0 and 100. Reclassification of the original susceptibility map was needed, as it contained many micro-facets, which make its interpretation difficult. The final map showing the spatial distribution of the LSI values was classified into five categories namely, "very low", "low", "moderate", "high" and "very high" as shown in Fig. 5. This classification, which divides the study area into five susceptibility zones, was based on natural breaks in the cumulative frequency histogram of LSI values. The higher the LSI is, the more susceptible the area is to landsliding. The "very low" category has LSI values below 25, the "low" from 25 to 38, the "moderate" from 38 to 49, the "high" from 49 to 61 and the "very high" above 61. Surfaces classified as being of "high" and "very high" susceptibility constitute 32,2% of the study area, surfaces of "very low" and "low" susceptibility account for 40,9% and surfaces of "moderate" susceptibility covers 26,9% of the total area.

The susceptibility map shows that the high susceptible zones were located mainly in areas where flysch formations and radiolarites outcrop on steep slopes near major fault zones and thrust surfaces. Those areas have a combination of factors that lead to a relative high landslide potential. In order to examine the potential landslide risk in respect to villages, the settlements of the study area were overlaid on the susceptibility map. This correlation suggests that 35 settlements are entirely or partly located within high and/or very high landslide potential zones.

In order to test the performance of the produced susceptibility map we compare it with the distribution of the major landslide events occurred in the study area and the predicted map showed satisfactory results. The occurrence of landslides in the moderate or low susceptibility zones is attributed to human activities or local effects i.e. the orientation of the local discontinuities surfaces, which couldn’t be incorporated in our analysis due to the extensive study area and the map scale used (1:50.000).

As the produced susceptibility map represent an important basis for the assessment of landslide hazard over the study area it can be very useful to decision-makers for choosing suitable locations for future planning in large-scale regions. For example still undeveloped landslide prone areas can be restricted to compatible land uses. Additionally planers and developers could use the susceptibility map to identify roads and settlements subject to damage by future landslides and take drastic measures for preventing the landslide events. Moreover it can be used as planning guide of new roads constructions steering the decision makers away from areas prone to landslides or indicating that special design considerations have to be applied in road constructions through hazardous areas.

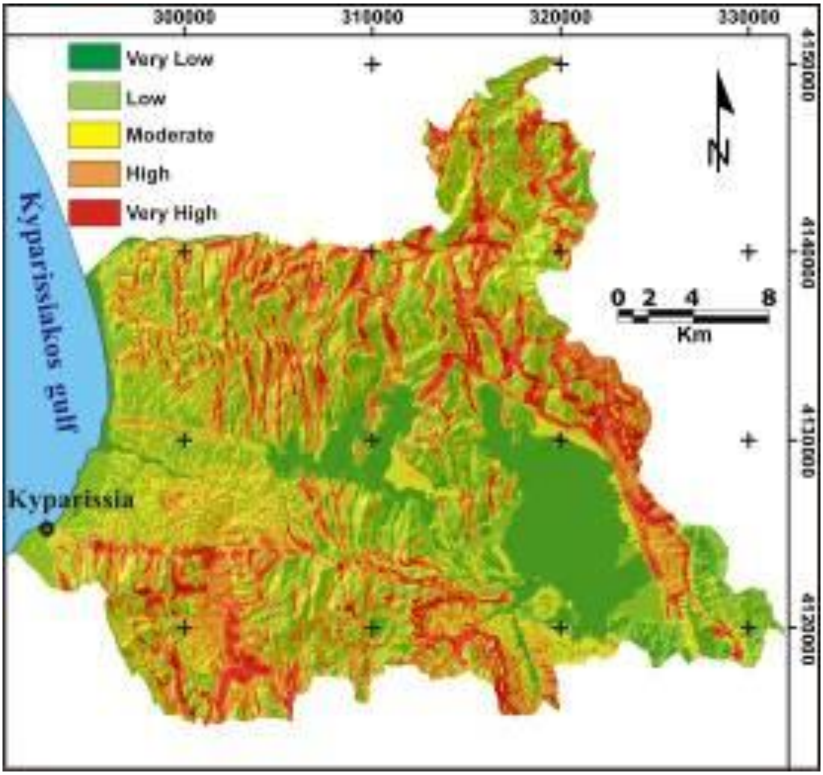

Figure 5. Reclassified landslide susceptibility map of the study area.

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