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GIS-Based Landslide Susceptibility Mapping by AHP Method, A Case Study, Dena City, Iran

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ABSTRACT

Slope instability research and susceptibility mapping is a fundamental component of hazard management in decreasing the risk of living with landslides. Landslide susceptibility is defined as the proneness of the terrain to produce slope failures and susceptibility is usually expressed in a cartographic way. The Dena city in Iran is a landslide prone zone because of its own characteristics including the mountainous topography, climate conditions, seismic potential, geology and geomorphology. Landslides have been resulting in damage to roads and villages of this region therefore landslide susceptibility map for this area can save lives and prevent sever damages.

In this study, the analytical hierarchy process (AHP) is employed to produce susceptibility maps. For this purpose, eight layers including landslide inventory, raining, lithology-weathering, earthquake, slope, land cover, distance to stream, and distance to road will be considered. Using this method each layer is broken into smaller factors, then these factors are weighted based on their importance, and finally the last prepared layers are assembled and the final map is generated. Commercial software ArcGis is used to produce the layer maps which are used in the production of the landslide susceptibility maps. Based on the scale of the available topographic maps used in this research, the scale of final susceptibility maps is chosen to be 1:50000.

KEY WORDS: Landslide; Susceptibility map; GIS; Analytical hierarchy process

1. INTRODUCTION

Landslides and man-made slopes have always involved some form of risk assessment and management. This is often done by the use of “engineering judgment” by the Geotechnical Engineers or Engineering Geologists in consultation with owners [1]. Slope instability research and susceptibility mapping is a substantial component of hazard management in decreasing the risk of living with landslides.

Landslide susceptibility is defined as the potential of the zone to produce slope failures and susceptibility is usually expressed in a cartographic way [2]. Landslide susceptibility zoning involves a degree of uncertainty and interpretation. Susceptibility zoning involves the spatial distribution and rating of the terrain units according to their potential to produce landslides [3]. Considering that landslides will occur in the future because of the same conditions that produced them in the past, we can use susceptibility assessments to predict the geographical location of future landslides [4, 5, 6]. Landslide occurrence is related to many factors including climate, hydrology, lithology, structure and geomorphic history; nevertheless, it is not always possible to include all aspects of these parameters in susceptibility assessment [7]. Depending on the region conditions, different factors such as lithology-geology, seismic potential, slope and land cover which are considered as layers affect landslide susceptibility zoning.

In order to provide landslide susceptibility maps various methods such as fuzzy logic, statistic methods and Analytic Hierarchy Process (AHP) can be used. One of these methods is the AHP that was used in [8] and [9]. The AHP is a theory of measurement for dealing with quantifiable and intangible criteria has been applied to numerous areas, such as decision theory and conflict resolution [10]. Using this method, each layer used in landslide susceptibility zoning is broken into smaller factors, then these factors are weighted based on their importance, and eventually the prepared layers are assembled and the final map is produced. It is based on three principles: decomposition, comparative judgment and synthesis of priorities [11]. In this method, weight of each layer depends on the judgment of expert, so that the more precise is the judgment, the more compatible is the produced map with reality.

The Dena city in Iran is a landslide prone area because of the following characteristics: the mountainous topography, climate conditions, situating on earthquake prone zone, its geology and geomorphology. As in the previous years, the landslides were resulting in damages to roads and villages of this region; the main objective of this study is to identify the zones with high landslide potential. Doing so, the housing and road authorities can come up with strategic plans to reduce the amount of damages to lives and properties. The study area is covered 2500 km^2 and is between 51˚00´and 51˚45´ longitude and 30˚20´ and 31˚12´ latitudes (Figure 1). The climate condition is mountainous and average rain precipitation is high. Precipitation is measured from 18 stations. The annual maximum precipitation is for Tangaab station with 1333 mm raining. According to 20 years data obtained in this region, the minimum temperature and the maximum temperature was -19°C and 44°C, respectively.

In this study for preparing the susceptibility maps, eight layers including landslide inventory, raining, lithology-geology, seismic potential, slope, land cover, distance to stream, and distance to road are selected.

ArcGis software is used to produce the layer maps which are used in the production of the landslide susceptibility map. It is strongly recommended that landslide zoning be carried out in a GIS-based system so that the zoning can be readily applied for land use planning and can be up-dated as more information is used [12].

The most important factor in determining the scale of susceptibility map is scale of topographic map and initial data. Another effective factor is the purpose of susceptibility map and the area of study region. According to the area of the region to be investigated, the scale of susceptibility map will be between 1:25000 and 1:100000. In this study the scale of output map is 1:50000.

The outline of the paper is as follows. In Section 2 the main factors affecting the susceptibility mappings are stated. Section 3 deals with analytical hierarchy process and providing the susceptibility maps. Conclusions are addressed in Section 4.

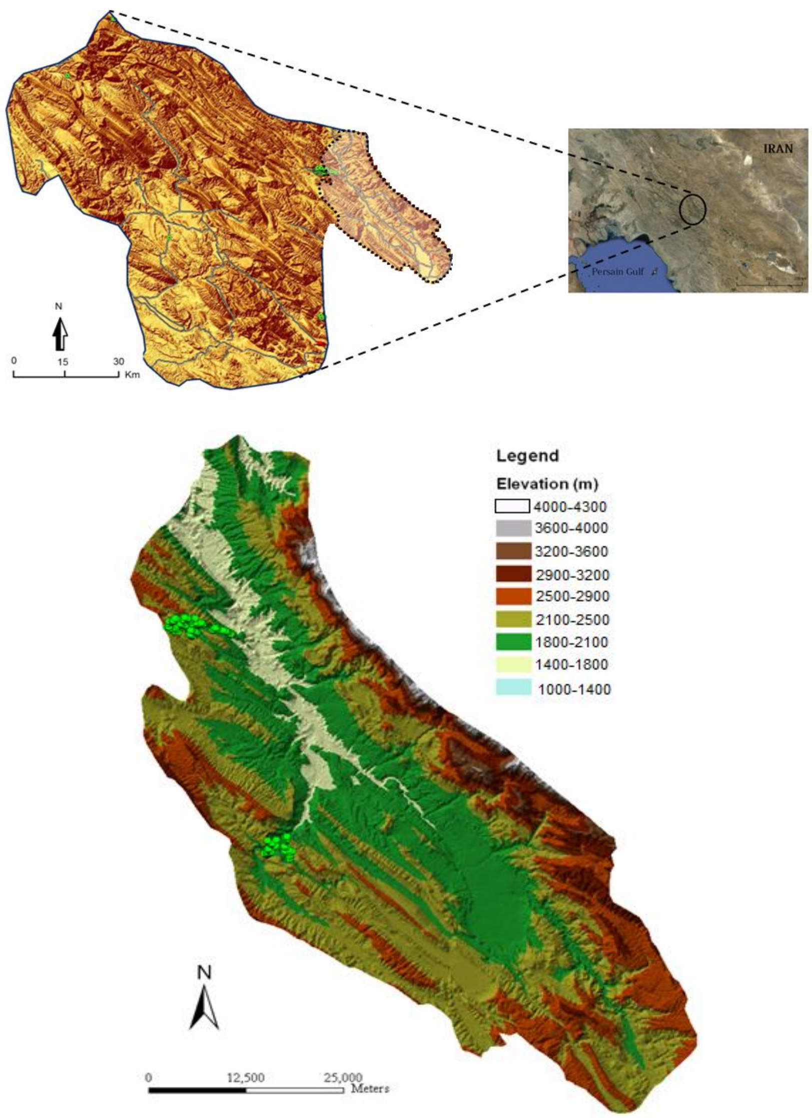

Fig. 1. The location of study area and occurring landslides

2. Layers influencing susceptibility mapping

The main factors affect the susceptibility mappings are: landslide inventory, raining, lithology-geology, seismic potential, slope, land cover, distance to stream, and distance to road.

They are shown in the first column of Table 1. In this section these factors are detailed.

2.1. **Landslide inventory**

It is very important to determine the location and area of the landslide correctly when preparing the landslide susceptibility maps [25]. Landslide inventory is an essential part and basic information for any landslide zoning such as susceptibility, risk and hazard zonings. It involves the location, classification, volume, travel distance, state of activity and date of occurrence of land sliding in an area [12].

There are different methods to identify landslides. They include aerial photos, literature survey for historical landslide records and field observations. Land cover of region, weathering conditions at the time of taking aerial photos and topography conditions can influence the quality of infrared aerial images and as a result determination of landslides from maps. Determining landslides from field records is the most accurate method. In this study, the field record has been used to determine 150 landslides.

Table 1. Main layers, weighting and consistency ratio

Data layers	a	b	c	d	e	f	g	weighting
(a) Lithology & Geology	1	3	2	4	6	3	7	0.339
(b) Land cover		1	0.5	3	4	1	5	0.136
(c) Slope			1	5	6	1	6	0.210
(d) Distance to stream				1	1	0	3	0.031
(e) Distance to road					1	0	3	0.056
(f)Raining						1	6	0.198
(g) Earthquake							1	0.030
Consistency Ratio (CR) = 0.0043								

The majority of landslides identified in this region have been occurred in river banks and roads. The landslides in river banks are often due to loss of land cover, steep slope topographic, and erosions. Unsystematic and non-technical road construction has been cause of many landslides in this region as well (Fig. 2).

Fig. 2. A rotational slide along the road of Yasouj-Esfahan due to unsystematic road construction

2.2. **Lithology-geology**

The main source of data related to the geomorphology of an area of land is determined by the lithology properties of that land [13]. The landslide phenomenon, a part of the geologic studies and research, is related to the lithology and weathering properties of the material of the land [2]. In the most of recent studies, such as references [14] and [2], this parameter has been considered as the most important factor in landslide susceptibility mapping. Geological maps showing geological structures in the study area, has made of deferent types of soil and rock. The most important formations in this region having high potential for occurring landslide are Papde and Gurpi. These formations are commonly composed of marl rocks. The main compositions of marl are clay and calcium carbonate. Marl has high cohesion and is very sensitive in neighborhood of water. In these formations, landslide occurs when water infiltrates in internal layers and external layers are exposed to weathering. In this region, the rocks are exposed to physical and chemical factors. As is show in Table 2, in order to consider the effect of lithology and geology, this region has been divided into 9 parts.

2.3. **Slope**

The slope is one of the main parameters in the slope stability analysis. The slope angle directly affects landslide, thus it is used in preparing landslide susceptibility maps [15, 16, 17, 18, 19, 20, 2]. In some of the recent studies, such as by Yao [21] and Nandi [22], this parameter has been considered as the most important factors in landslide susceptibility mapping. For preparing landslide susceptibility map, the slope map was divided into four slope categories (See Table. 2). According to the landslide inventory map, most landslides had occurred in 30-50 degree of slope ranges.

2.4**. Land cover**

The effect of land cover on slope stability has been studied since 1960s. Generally, land cover has effect on strength of slope materials against sliding and control of water content of slope. In addition, plant roots reinforce the slope and normally are considered as reinforcements [23]. Land cover absorbs the water of soil and decreases the potential of landslide. This is an important issue in marl soils. In studies performed by Komac [24] and Leventhal [25], this parameter has been considered as one of the most important factors in preparing landslide susceptibility maps. Land cover is determined from Arial photo and field investigations. In this study, land cover map is divided into 9 land cover categories. According to the identified landslides, most landslides occur in sparse forest with 5-25% land cover density (Table2).

2.4. **Distance to road**

The distance to road is one of the main parameters in preparing landslide susceptibility maps. Roads can be one of the reasons of occurring landslides [14, 26, 2]. Roads change the nature of topography and decrease the shear strength of toe of slope and cause the tensile stress. Naturally, slope may be stable, but after road construction, road can have undesirable effect on slope. The road causes infiltrating of water in slopes and enforces extra stresses due to traffic loads. In this region, many landslides have occurred because of unsystematic road construction in marl sediment alluvials. In this study, main roads are investigated, and this factor is divided into 5 distances to road categories (Table2).

2.5. **Distance to stream**

Similar to the effect of the distance to road, landslides may occur on the side of the slopes affected by stream. The closeness of the slope to streams may adversely affect stability of slopes [15, 13, 27, 20, 2]. Stream increases the potential of landslide by erosion of the slope and increasing the degree of saturation of materials of slope. In this region, proximity to stream is one of the most important factors affecting the occurrence of landslides. The map of distance to the streams was created using a 700-meter buffer zone around the major stream canals (Table2).

2.6**. Raining**

Rainfalls produce sudden floods which cause shallow landslides. Most of the landslides occur after the heavy rain falls, thus the rainfall is one of the main parameters in producing landslide maps. Water infiltrates rapidly upon heavy rainfall and increases the degree of saturation and potential of landslide occurrence. The study area is commonly mountainous with cool weather. In this study 20 precipitation stations were used to consider this parameter. The precipitation directly is related to height. For this region, the equation of precipitation-height is expressed as:

$$Y=0.565X-324 \qquad (1)$$

where,Y is precipitation (mm) and X is height (m).

Using this equation, the amount of precipitation in each point can be determined. Having determined the amount of precipitation at each point, this amount is divided into 5 ranges of raining categories (Table2).

2.**7. Earthquake**

Similar to raining, most of the landslides occur after earthquakes. Debris flow and rock fall occurrence is related to summer storms and earthquakes [28]. Occurrence of earthquake is directly related to activity of faults.

Table 2. Internal layers, weighting and consistency ratio.

Data layers		a	b	c	d	e	f	g	weighting
	(a) Lithology & Geology	1	3	2	4	6	3	7	0.339
	(b) Land cover		1	0.5	3	4	1	5	0.136
	(c) Slope			1	5	6	1	6	0.210
	(d) Distance to stream				1	1	0	3	0.031
	(e) Distance to road					1	0	3	0.056
	(f)Raining						1	6	0.198
	(g) Earthquake							1	0.030
	consistency ratio (CR) = 0.0043								

Factors		1	2	3	4	5	6	7	9	weighting
Lithology & Geology										
	(1) Pabdeh	1	1	2	2	4	5	6	9	0.253
	(2) Limestone and shale		1	2	2	3	4	5	9	0.235
	(3) Asmari			1	2	2	3	3	6	0.149
	(4) Gurpi				1	2	3	4	5	0.133
	(5) Sachun					1	1	2	3	0.069
	(6) Gachsaran						1	2	3	0.064
	(7) Bakhteyari							1	2	0.039
	(8) Aghajari								2	0.034
	(9) Jahrom								1	0.023
	Consistency Ratio (CR) = 0.0140									
Land cover										
	(1) Forest with 5-25% density	1	2	3	4	5	6	7	9	0.313
	(2) Grassland with 5-25% density		1	2	2	3	3	4	6	0.173
	(3) Forest with 25-50% density			1	2	3	4	6	8	0.170
	(4) Dry farming				1	2	4	6	8	0.138
	(5) Grassland with 25-50% density					1	2	2	4	0.068
	(6) Shrubland						1	2	2	0.045
	(7) Grassland with >50% density							1	2	0.037
	(8) Backwood								2	0.033
	(9) Forest with >50% density								1	0.022
	Consistency Ratio (CR) = 0.0359									
Slope(°)										
	(1) 0-15	1	0.33	0.11	0.2					0.050
	(2) 15-30		1	0.2	0.33					0.116
	(3) 30-50			1	4					0.600
	(6) >50				1					0.235
	Consistency Ratio (CR) = 0.0477									
Distance to stream (m)										
	(1) 0-100	1	2	4	6	8				0.468
	(2) 100-200		1	2	4	6				0.268
	(3) 200-300			1	2	4				0.144
	(4) 300-500				1	2				0.076
	(5) 500-700					1				0.044
	Consistency Ratio (CR) = 0.0103									
Distance to road (m)										
	(1) 0-100	1	2	4	6	8				0.468
	(2) 100-200		1	2	4	6				0.268
	(3) 200-300			1	2	4				0.144
	(4) 300-500				1	2				0.076
	(5) 500-700					1				0.044
	Consistency Ratio (CR) = 0.0103									
Raining (mm)										
	(1) 500-750	1	0.5	0.25	0.13					0.068
	(2) 750-1000		1	0.5	0.25					0.137
	(3) 1000-1250			1	0.75					0.303
	(4) 1250-1500				1					0.492
	Consistency Ratio (CR) = 0.0254									
earthquake (PHA)(g)										
	(1) 0-0.2	1	0.33	0.11						0.002
	(2) 0.2-0.4		1	0.2						0.005
	(3) 0.40-0.6			1						0.022
	Consistency Ratio (CR) = 0.0252									

Fault rupture length has often been used to estimate earthquake magnitude. This approach is called the deterministic method while the probabilistic method is also used to perform a seismic risk analysis. The Frequency of seismically induced land sliding is related to the peak ground acceleration at the site, and the magnitude of the earthquake [3].

The study region is located in a seismically active region and earthquakes are common in this region. There is a critical magnitude and peak ground acceleration (or distance from the earthquake epicenter) above which land sliding will occur. This varies for different classes of landslide [29]. In the literature various attenuation relationships can be found to be used for seismic risk analysis in earthquake geotechnical engineering. For this investigation, the attenuation relationship presented by Campbell [30] for the mean peak horizontal acceleration (PHA) is employed. This equation is expressed as

$$\ln PHA(g) = -4.141 + 0.868M - 1.09 \ln[R + 0.0606 \exp(0.7M)] \qquad (2)$$

where M is the local magnitude or surface wave magnitude and R is the closest distance to fault rupture in kilometers. For all fault movement, M is defined as

$$M = 5.08 + 1.16 \log L \qquad (3)$$

where, L is the surface rupture length of fault. In this study area, there are 2 major reverse faults; Dena fault and Kazeron fault, with the length of 95 and 69km, respectively.
To consider the effect of earthquake in landslide susceptibility mapping, the region was divided into smaller zones (500×500 m) and the PHA of each part was determined. Doing so, the PHA was divided into five categories as observed in Table2.

3. Analytical hierarchy process (AHP)

In order to prepare the landslide susceptibility maps, various methods such as fuzzy logic, statistic methods and AHP can be used. The Analytical Hierarchy Process is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution [10]. The AHP method was used to define the factors that govern landslide occurrence more transparently and to derive their weights [21].

AHP is a multi-objective, multi-criteria decision-making approach which enables the user to arrive at a scale of preference drawn from a set of alternatives [2]. AHP method includes a matrix-based pair-wise comparison of the effect of each factor for land sliding. AHP is a semi-qualitative method and frequently used with most of researchers. An extensive description about AHP is explained by Saaty [8] and Saaty and Vargas [31].

AHP has gained wide application in site selection, suitability analysis, regional planning, and landslide susceptibility analysis [14]. Using this method, each layer is broken into smaller factors, and then these factors are compared based on their importance. For comparison of importance of factors relative to each other, each factor is rated against every other factor by assigning a relative dominant value between 1 and 9. This value and its description are shown in Table ”3”.

Table 3. Fundamental scale for pair-wise comparisons (after Saaty and Vargas [31])

Description	Dominant value
Equal importance	1
Moderate prevalence of one over another	3
Strong or essential prevalence	5
Very strong or demonstrated prevalence	7
Extremely high prevalence	9
Intermediate values	2,4,6,8

In order to establish a pair-wise comparison matrix (A), factors of each level and their weights are shown as: A_1, A_2, … , A_n and w_1,w_2, … , w_n. The relative importance of a_i and a_j is shown as a_{ij}. The pair-wise comparison matrix of factors A_1, A_2, … , A_n as $A=[a_{ij}]$ is expressed as:

$$A = \{a_{ij}\}_{n\times n} = \begin{bmatrix} 1 & a_{12} \cdots & a_{1n} \\ a_{21} & 1 \quad \cdots & a_{2n} \\ \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \frac{w_1}{w_2} \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 \quad \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & 1 \end{bmatrix} (4)$$

In this matrix, the element, $a_{ij} = 1/a_{ji}$ and thus, when i=j, $a_{ij}=1$. A matrix is normalized using Eq. 5 as

$$a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad i,j = 1,2,\ldots\ldots,n \qquad (5)$$

And finally, weights of factors are computed using Eq. 6 as:

$$w_i = \left(\frac{1}{n}\right) \sum_{j=1}^{n} a'_{ij} \quad i = 1,2,\ldots\ldots,n \qquad (6)$$

In matrix-based pair-wise comparison, if the factor on the horizontal axis is more important than the factor on the vertical axis, this value varies between 1 and 9. Conversely, the value varies between the reciprocals 1/2 and 1/9 (Table 1, 2). In AHP, for checking consistency of matrix, consistency ratio is used, which depends on the number of parameters. The consistency ratio (CR) is obtained by comparing the consistency index (CI) with average random consistency index (RI).The consistency ratio is defined as

$$\mathrm{CR} = \frac{\mathrm{CR}}{\mathrm{RI}} \tag{7}$$

The consistency index of a matrix of comparisons is given by

$$\text{Consistency Index (CI)} = \frac{\lambda_{\max} - n}{n-1} \tag{8}$$

And the average random consistency index (R.I.) is derived from a sample of randomly generated reciprocal matrices using the scales 1/9, 1/8,…., 8 and 9 (see Table 4).

Table 4: Average random consistency index (RI)

N (number of factors)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	**0.00**	**0.00**	**0.52**	**0.89**	**1.11**	**1.25**	**1.35**	**1.40**	**1.45**	**1.49**

For these matrices, the consistency ratio (CR) must be less than 0.1 [32] (Table 1, 2). After preparing layers, the last prepared layers are assembled and the final map is generated (Figure 3). The most important internal layers and their weightings are shown in table 5.

Table 5. The most important internal layers and their weightings

Layers	**The most important internal layers**	**Weighting**
Lithology & Geology	Pabdeh	0.253
Land cover	Forest with 5-25% density	0.313
Slope (°)	30-50	0.600
Distance to stream (m)	0-100	0.468
Distance to road (m)	0-100	0.468
Raining (mm)	1250-1500	0.492
Earthquake(g)	0.4-0.6	0.022

RESULTS AND DISCUSSION

Slope instability research and susceptibility mapping is an essential component of hazard management in decreasing the risk of living with landslides. Comprehending the processes of occurring landslide and the subsequent effort for preparing susceptibility mapping provides fundamental knowledge about the evolution of

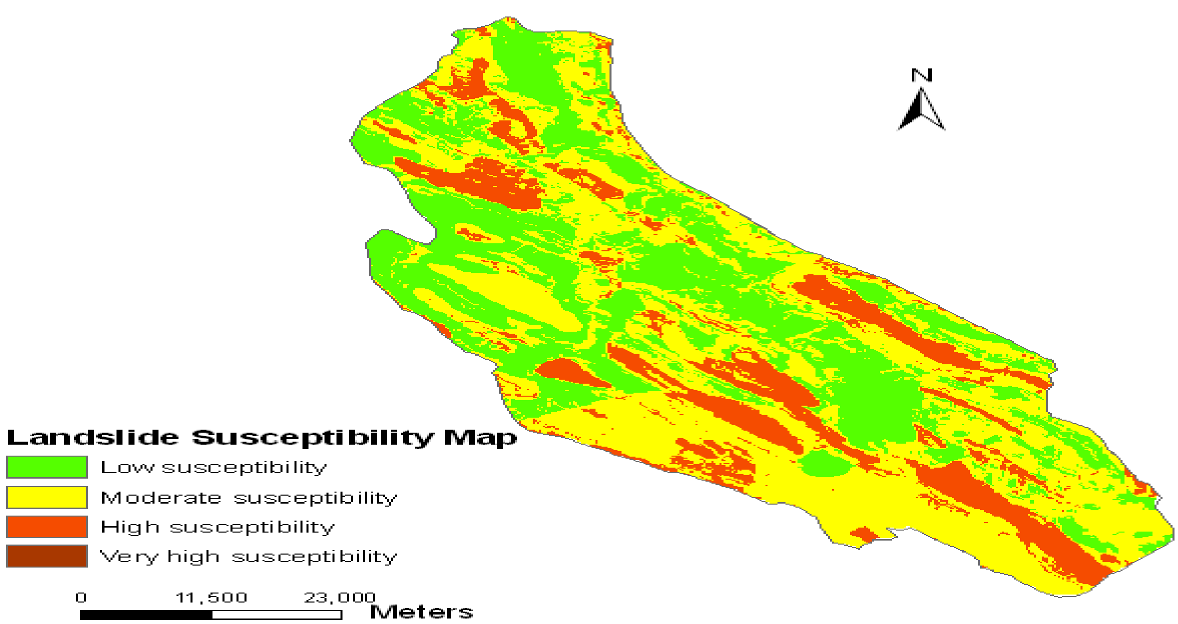

Fig. 3. The landslide susceptibility map produced by AHP

landscapes and decreasing the risk due to landslides. There are various methods for landslide susceptibility mapping. In this study, AHP method was used to prepare landslide susceptibility maps in Dena city in Iran.

This region is a landslide prone zone because of its own characteristics including the mountainous, topography, climate conditions, located on earthquake zone, geology and geomorphology. In this study area, using field records, 150 landslides have been determined. Majority of these landslides occurred because of losses of land cover, steep slope topographic, erosion due to river, and unsystematic road construction in marl sediment alluvial.

After preparing landslide inventory map, eight layers including landslide inventory, raining, lithology-weathering, earthquake, slope, land cover, distance to stream, and distance to road have been considered. To confirm the practicality of the results, the susceptibility map was compared with 150 active landslides. The results demonstrated that the active landslide zones had a high correlation to the high and very high susceptibility class of map. The AHP map shows 82% of the active landslide zones located at high and very high susceptibility zones of map. High and very high susceptibility zones are commonly matched in Papde and Gurpi formations. These formations are composed of marl rocks that are very sensitive in the neighborhood of water. The low susceptibility zones are correlated in Jahrom formation with forest land cover with more than 50% density. In this region, land cover significantly decreases the potential of land sliding. Based on this study, it can be stated that the high and very high susceptibility landslide zones identified by the AHP method, can predict potential landslide areas in the reality. The result of this study shows, that when field conditions are properly determined by good proficiency, the AHP method can give more truly results.

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