JGeope 4 (1), 2014, PP. 45-61

A GIS-based comparative study of the analytic hierarchy process, bivariate statistics and frequency ratio methods for landslide susceptibility mapping in part of the Tehran metropolis, Iran

Samad Moradi[1*], **Mohsen Rezaei**[2]
[1] *Department of Geology, Faculty of Basic Science, Shahid Chamran University,Ahvaz, Iran*
[2] *Department of Geology, Faculty of Basic Science, Kharazmi University, Iran*
**Corresponding author, e-mail: samadmoradi39@yahoo.com*

(*received: 24/02/2013 ; accepted: 06/07/2014*)

Abstract

The high hillsides of the Tehran metropolis are prone to landslides due to the climatic conditions and the geological, geomorphological characteristics of the region. Therefore, it is vitally important that a landslide susceptibility map of the region be prepared. For this purpose, thematic layers including landslide inventory, lithology, slope, aspect, curvature, distance to stream, distance to fault, elevation, land use, and precipitation were used. Next, weighted raster thematic maps with assigned values for their classes were multiplied by the corresponding weights and combined to yield a simple map where each cell has a certain landslide susceptibility index (LSI) value. After reclassification, this represents the final susceptibility map of the study area. Finally the three maps were compared to assess the strength of the corresponding methods. In this study area, 74% of landslides occurred in highly or completely shaly units. Lithology, slope, distance to fault and distance to stream data layers were found to be important factors in the study area. The outcome of this comparison was the conclusion that the active landslide zones do not completely fit into the high and very high susceptibility classes. However, 99.6% of these landslide zones fall into the high and very high susceptibility zones of the bivariate statistics (WI) method, or 74.5% in the case of the analytic hierarchy process (AHP) method and 97.2% with the frequency ratio (FR) method. The results showed the WI and FR methods to give a more realistic picture of the actual distribution of landslide susceptibility than the AHP method.

Keywords: *Landslide; Susceptibility; Analytic Hierarchy Process; WI; GIS; FR*

Introduction

Landslide susceptibility is defined as the proneness of terrain to yield slope failures and is usually expressed cartographically. A landslide susceptibility map depicts areas likely to experience landslides in the future by correlating some of the principal factors that contribute to landslides with the past distribution of slope failures (Brabb, 1984).

Landslide susceptibility mapping relies on a rather complex knowledge of slope movements and their controlling factors. The reliability of landslide susceptibility maps mostly depends on the amount and quality of available data, the working scale, and the selection of the appropriate analytical methodology. Early attempts defined susceptibility classes through qualitative overlaying of geological and morphological slope attributes to landslide inventories (Nielsen *et al*., 1979). More sophisticated assessments involved AHP, bivariate, multivariate, logistics regression, fuzzy logic and artificial neural network analysis (Carrara, 1983; van Westen, 1997; Dai *et al*., 2001; Lee & Min, 2001; Ercanoglu & Gokceoglu, 2004; Lee *et al*., 2004a; Komac, 2006).

Qualitative methods depend on expert opinions. The most common types of qualitative methods simply use landslide inventories to identify the sites of similar geological and geomorphological properties that are susceptible to failure. Some qualitative approaches, however, incorporate the concept of ranking and weighting, and may evolve to be semi-quantitative in nature (Ayalew & Yamagishi, 2005). Examples of this are the use of the analytic hierarchy process (AHP) by Saaty (1980) and Barredo *et al*. (2000), and the weighted linear combination (WLC) by Ayalew *et al*. (2005).

Quantitative methods are based on the numerical expressions of the relationship between controlling factors and landslides. There are two types of quantitative method: deterministic and statistical (Aleotti & Chowdhury, 1999). Deterministic quantitative methods depend on the engineering principles of slope instability expressed in terms of safety factors. Due to the need for exhaustive data from individual slopes these methods are only effective for mapping small areas.

In this study, Geographic Information Systems (GIS) software and ArcMap 9.3 were used as the basic analysis tools for spatial management and data manipulation. As the creation of thematic maps involves the interpolation of a large amount of data, the use of GIS has demonstrated its necessity. Similarly, as spatial decision problems involve a large set of conflicting evaluation criteria, a multi-criteria approach needs to be integrated with GIS. The development of GIS has enhanced the capabilities of the susceptibility assessment of large regions. The performance of neighbourhood operations with GIS allows the extraction of morphometric and hydrological parameters from digital elevation models (DEM). Parameters such as slope gradient, slope aspect, slope convexity, watershed area and drainage network can be easily included for susceptibility analysis. Complete overviews of the use of GIS for landslide susceptibility assessment can be found in van Westen (1994), Carrara *et al*. (1995), Aleotti and Chowdhury (1999), Dai *et al*. (2002), Cevik and Topal (2003), Ayalew and Yamagishi (2005) and Fall *et al*. (2006). The objective of this study was to use widely accepted models, a statistical method (frequency ratio model), a multi-criteria decision-making approach (AHP) and bivariate statistics (WI), and then evaluate their performances. The study area was selected because of the landslide-prone climatic conditions, geological features and geomorphological characteristics.

Description of the study area

The study area is located at 51° 4′ to 51° 27′ longitude and 35° 36′ to 35° 59′ latitude, and covers an area of 694 square kilometres in the central Alborz mountains where elevations range from 1166 m to 3840 m with a cold and dry climate. General stream direction is southward (Fig. 1). The Alborz range was created by the collision of the Turan and Iranian plates. This area is one of the most active seismo-tectonic provinces in Iran. The mountain belt is part of Alps-Himalayas mountain chain with similar seismic activity, which comes as a direct consequence of its tectonic setting. The Alborz mountain belt consists of different sedimentary, metamorphic and igneous rocks aging from the Precambrian to the Quaternary. The geomorphological features of the range are strictly related to its morpho-structural and selective erosion processes, which have led to a rugged topography. The slopes are near-vertical at the margin of strong rocks and main reverse faults. Inclined and undulating strata occur in outcrops of clay-rich weak rocks such as marl, shale and tuff. The mountains result in the northern part overlooking the Caspian Sea having a semi-Mediterranean climate with an average of precipitation from 700 mm in the mountains and up to 2000 mm in the coastal plain. In this area the slopes usually consist of debris deposits and residual soils. The outer Alborz terrain in the north has thick vegetative cover due to the soft sedimentary rocks present there.

Table 1: Units lithology in the study area

Unit label	Dominate lithology	Age	Unit label	Dominate lithology	Age
Ea1	Lava flows and rhyolitic tuff	LOWER-MIDDLE EOCENE	Est4	Sandstone	LOWER-MIDDLE EOCENE
Eab1	Lava flows and rhyolitic tuff		Et2	Shale	
Eb1	Tuff		Etb5	Tuff	
Eb3	Tuff		Etc3	Sandstone	
Ed	Dacite		Etd5	Lava flows and rhyolitic tuff	
Eda1	Andesite whit basalt		Ets2	Shale	
Edg	Andesite whit basalt		Ets5	Tuff	
Er1	Andesite whit basalt		Etsv1	Shale	
Er2	Shale		H	Lava flows and rhyolitic tuff	
Es6	Shale		PLQ	Sandstone	
Esc3	Sandstone		Q	Reccent alluvium	Quaternary
Esc4	Sandstone		Q1	Reccent alluvium	
Esh3	Shale		Q2	Reccent alluvium	
Esh5	Shale		Qal	Reccent alluvium	
Esht1	Shale		Qm	Reccent alluvium	
Ess3	Shale		Qsc	Scree	

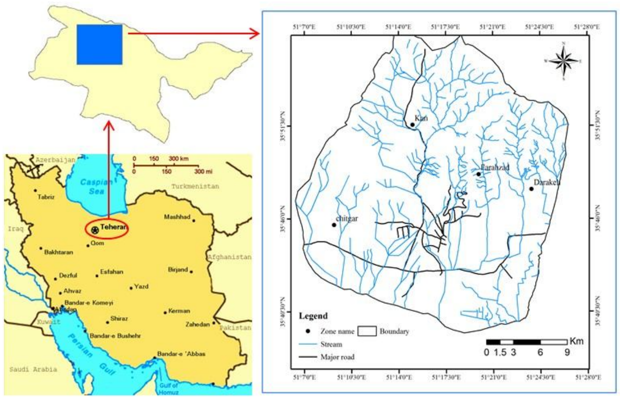

Figure 1: Location map of the study area

Materials and methods

The factors that are responsible for landslide occurrences could be distinguished into controlling (or causal) factors and triggering factors. The causal factors determine the initial favourable conditions for landslide occurrence while the triggering factors determine the timing of landsliding. Intensive rainfalls, earthquakes and human activities are the most common triggering mechanisms for slope failures in the study area. These triggering mechanisms are unpredictable as they vary in time, and it is therefore very difficult to use them in a hazard analysis. However, the controlling factors can be represented by relevant thematic maps generated using GIS techniques and so can be used in landslide susceptibility studies. In this study, Arc map v. 9.3, Excel v. 2007 and GIS software was used to produce thematic maps to assist in the production of landslide susceptibility maps. The first task in the preparation of the susceptibility map is the selection of the controlling factors. A common difficulty encountered in every multi-criteria analysis is the number of factors that must be taken into account. For the needs of our study nine parameters were selected as controlling factors: i) slope gradient, ii) slope curvature, iii) slope aspect, iv) lithology, v) land use, vi) mean annual precipitation, vii) proximity to major faults and thrusts, viii) distance from streams and ix) elevation of study area. The next step after the selection of the factors was the preparation of the thematic maps, in which the factors were classified into several classes. The data used for the preparation of these layers were obtained from topographical base maps, geological maps, satellite images, rainfall data, personal fieldwork and ortho-photography. The thematic maps corresponding to slope gradient, curvature, aspect and elevation were obtained directly in raster format from the produced DEM, while the others were produced by the vector format digitization transformed into the raster format. The next step was to assign weight values to the raster layers (representing factors), and to the classes of each layer, respectively. This step was realized with the use of the AHP developed by Saaty (1980), WI, and FR methods in order to achieve objectivity in the weight assignment. Next, the weighted raster thematic maps with the assigned values for their classes were multiplied by the corresponding weights and added up to yield a simple map, with each cell having a certain landslide susceptibility index (LSI) value. This map, after reclassification, represents the final susceptibility map of the study area. Finally the three maps were compared to assess the strength of the corresponding methods. To confirm the reliability of the results, the three maps were further matched against the landslide activity maps, which contained 54 landslide active zones (Fig. 2, 3).

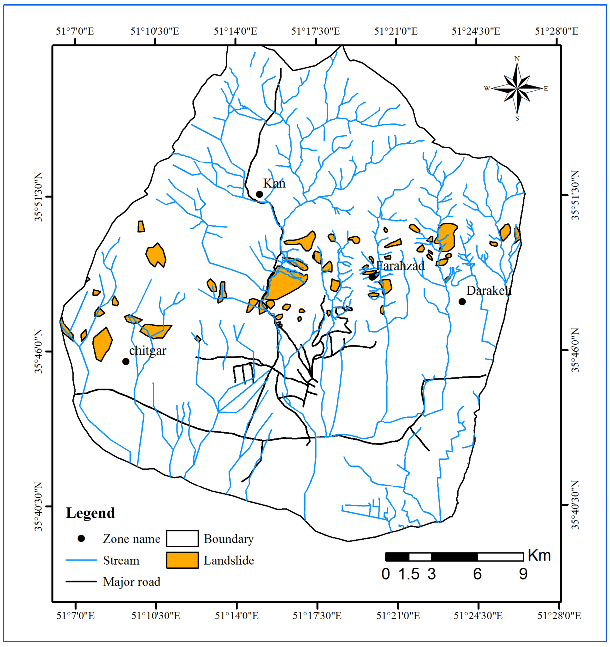

Figure 2: Landslide inventory map


Figure 3: Examples of mapped landslides in study area

Landslide-influencing data layers

Slope gradient

The main parameter of the slope stability analysis is the slope angle (Lee & Min, 2001). Because the slope angle is directly related to the landslides, it is frequently used when preparing landslide susceptibility maps (Clerici *et al*., 2002; Saha *et al*., 2002; Cevik & Topal, 2003; Ercanoglu *et al*., 2004; Lee *et al*., 2004a; Lee, 2005; Yalcin, 2007). Slope gradient controls the subsurface flow velocity after rainfall, the runoff rate, and the soil water content. As a slope increases, shear stress in unconsolidated soil cover generally increases as well.

The original raster format file was obtained directly from the DEM using Horn's method. It was processed in degrees, with slope values ranging from 0° to 89°. Slope values were subdivided into the following five classes: a) very gentle slopes, <6, b) gentle slopes, 6-16, c) moderately steep slopes, 16-25, d) steep slopes, 25-33 and e) escarpments, >33 (Fig. 4a). Generally, landslides are not expected to occur on gentle slopes due to lower sheer stress.

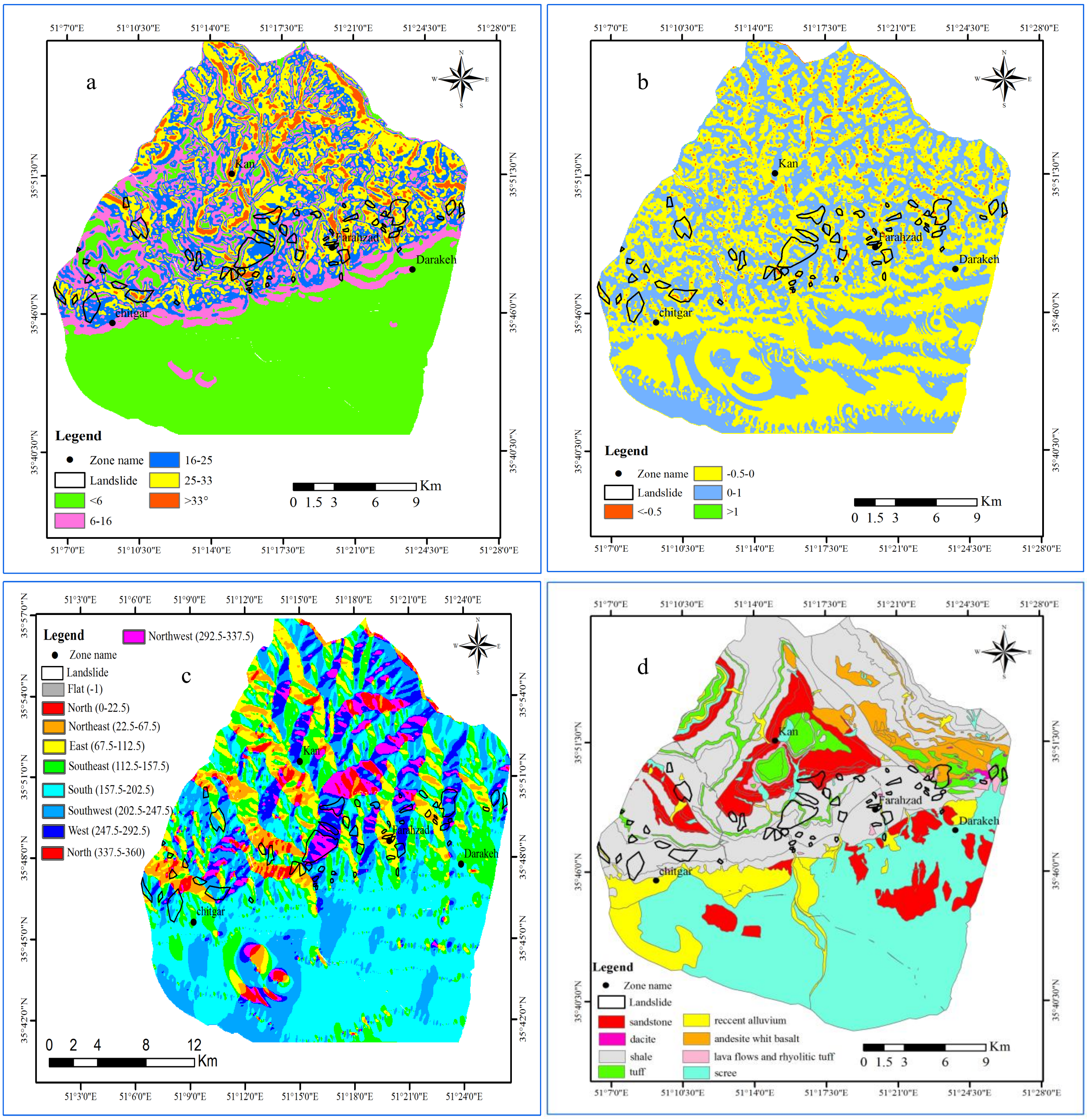

Figure 4: Continued on the next page

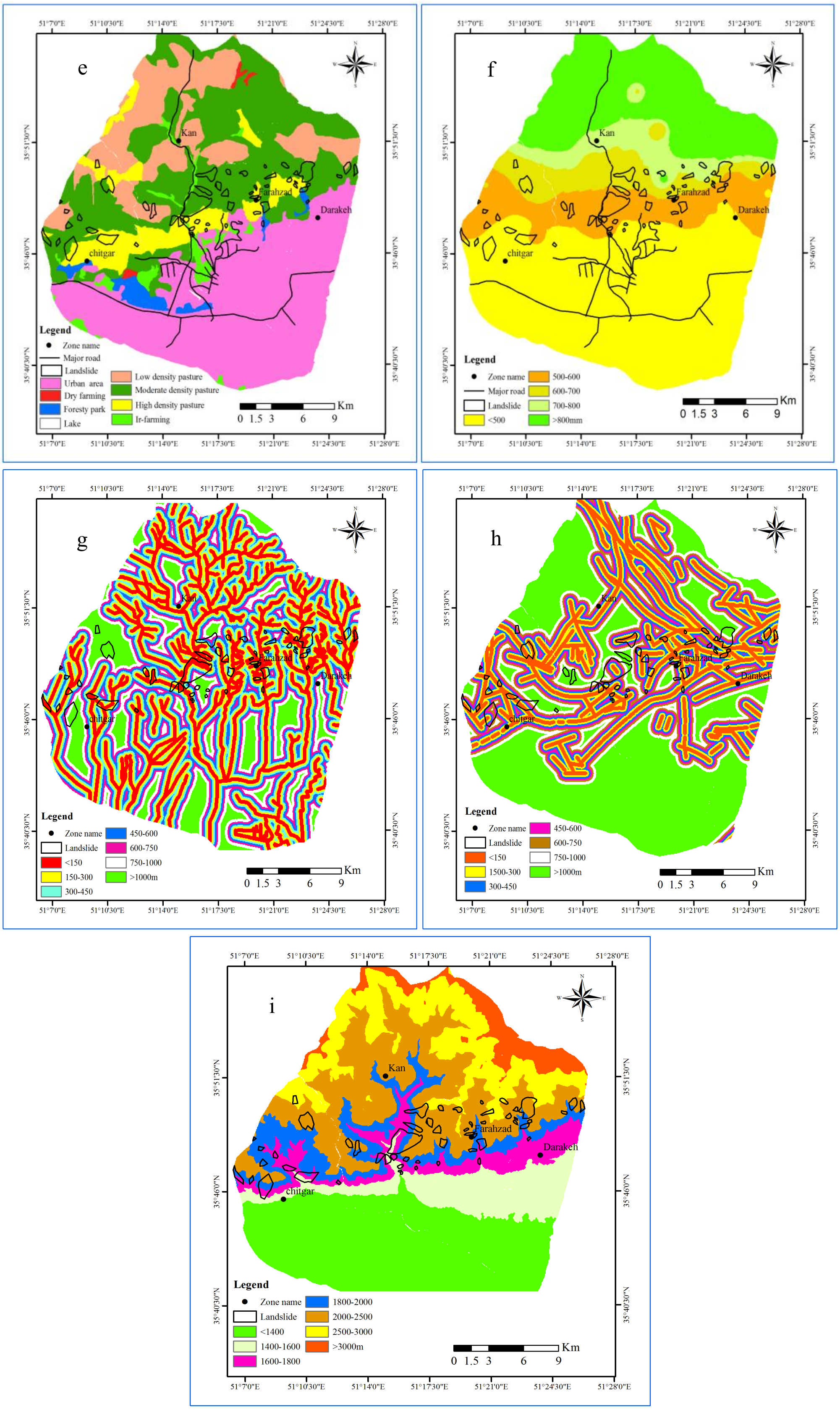

Figure 4: Maps of nine causal factors in landslide susceptibility

Curvature

Curvature values represent the morphology of slopes. Curvature was selected as the causal factor on the basis that it affects the hydrological condition of the soil cover. Potentially, after rainfall, the soil cover on a concave slope may contain more water and retain it for a longer period than a convex slope.

On the other hand, in many places convex slopes mark the outcrop of strong bedrock among looser rocks. Consequently, the concave slope profile areas have a higher probability of landslide occurrence than the convex areas. In the curvature raster file the positive curvature values indicate that the surface is convex at those cells. On the contrary, the negative values indicate that the surface is concave at those cells. A value of zero indicates that the surface is rectilinear. The more negative the value the higher the probability of landslide occurrence, and the more positive the value the lower the probability (Fig. 4b).

Slope aspect

Aspect is also considered an important factor in the preparation of landslide susceptibility maps (Guzzetti *et al*., 1999; Nagarajan *et al*., 2000; Saha *et al*., 2002; Cevik & Topal, 2003; Ercanoglu *et al*., 2004; Lee *et al*., 2004a; Lee, 2005; Yalcin, 2007). Aspect-associated parameters such as exposure to sunlight, drying winds, rainfall (degree of saturation), and discontinuities may affect the occurrence of landslides (Suzen & Doyuran, 2004; Komac, 2006). The association between aspect and landslide is shown using aspect maps. Aspect regions are classified in nine categories according to aspect class: flat (−1°), north (0°–22.5°; 337.5°–360°), northeast (22.5°–67.5°), east (67.5°–112.5°), southeast (112.5°–57.5°), south (157.5°–202.5°), southwest (202.5°–247.5°), west (247.5°–292.5°), and northwest (292.5°–337.5°) (Fig. 4c). Analyses were performed using aspect and landslide inventory maps to determine the distribution of landslides according to aspect class, and the percentage of landslides that occurred in each (Table 2).

Lithology

Lithology is one of the most important parameters in landslide studies because different lithological units have different degrees of susceptibility (Dai *et al*., 2001). In this study the basic data used to generate the original geological map in a vector format were obtained from existing geological maps published by an oil company (scale 1:100,000). In the geological map produced, formations were grouped into lithological units based on dominant lithology to the following five categories, which have different susceptibilities to landsliding: i) shale, ii) sandstone, iii) igneous and metamorphic rocks, iv) tuff, v) alluvial and scree (Fig. 4d). As a result of the landslide distribution analysis performed according to the lithological units, most landslides (73.5%) are located within shaly formations (Table 2).

Land use

The effect of land cover on slope stability can be clarified by a number of hydrological and mechanical effects. Land cover acts as a shelter and reduces susceptibility to soil erosion. Vegetation changes soil hydrology extensively by increasing rainfall interception, infiltration, and evapotranspiration. Interception and evapotranspiration decrease the volume of water that reaches the soil and is stored in it. They do not play a fundamental role during the short heavy rainfall events generally required to trigger shallow landslides, but can be important for the long-term evolution of water in soil, and thus for initial moisture conditions when an extreme event occurs.

The vegetation cover also causes some mechanical changes through soil reinforcement and slope loading. The increase in soil strength due to root reinforcement has great potential to reduce the rate of landslide occurrence (Blijenberg, 1998; Cannon, 2000; Beguería, 2006). Several researchers (Ercanoglu & Gokceoglu, 2004; Tangestani, 2004; Yalcin, 2007) have emphasized the importance of land cover on slope stability. In this study, a single date image by Landsat ETM$^+$ was used to generate land cover types. The study area was divided into seven land cover classes (Table 1). Areas are covered with pastures of low, moderate and high density. Landslides are largely (65%) observed in pasture areas with moderate density (Fig. 4e).

Precipitation

The effect of precipitation on the risk of instability and slope movements was also studied. For this purpose, the 54-year (1951 to 2005) precipitation data were gathered from the stations within the study area and neighbouring areas and analysed. The effect of precipitation caused an increase in soil humidity and consequently heightened the potential for landslides, and as a starter factor for landslides in the case of heavy and long-term rainfall were studied.

Table 2: Distribution of landslides for various data layers and WI values of each attribute

Data layers	Classes	Landslide area%	WI
Lithology	Shale	73.56	0.71
	Igneous rocks	8.81	0.89
	Sandstone	7.99	-0.36
	Tuff	7.40	0.44
	Scree& alluvia	2.22	-2.70
Slope(°)			
	<6	4.06	-2.34
	6-16	16.75	0.03
	16-25	39.68	0.71
	25-33	31.54	0.56
	>33	7.98	0.62
Distance to fault(m)			
	<150	25.71	0.51
	150-300	18.55	0.44
	300-450	13.66	0.29
	450-600	12.50	0.44
	600-750	9.85	0.27
	750-1000	7.60	-0.14
	>1000	12.13	-1.14
Distance to stream(m)			
	<150	37.90	0.34
	150-300	17.27	-0.12
	300-450	13.26	-0.18
	450-600	8.43	-0.28
	600-750	4.34	-0.66
	750-1000	6.32	-0.34
	>1000	12.48	0.30
Curvature			
	<-0.5	3.38	0.86
	-0.5-0	51.89	-0.01
	0-1	44.71	-0.03
	>1	0.02	-0.94
Landuse			
	Low density pastures	25.05	1.05
	Ir-farming	1.60	-0.52
	Foresty park	1.43	-0.43
	High density pastures	6.21	-0.97
	Dry farming	-	-
	Moderate density pastures	65.46	0.71
	Urban area	0.26	-4.99
Rainfall(mm)			
	<500	18.08	-0.96
	500-600	48.29	1.22
	600-700	28.53	1.18
	700-800	4.84	-0.39
	>800	0.25	-4.51
Elevation(m)			
	<1400	-	-
	1400-1600	7.33	-0.78
	1600-1800	21.89	0.61
	1800-2000	22.81	0.46
	2000-2500	44.36	0.22
	2500-3000	3.61	-1.81
	>3000	-	
Aspect			
	S	15.19	-0.89
	SW	23.77	0.22
	SE	11.26	-0.30
	E	10.55	0.20
	W	19.34	0.83
	NW	12.96	1.16
	NE	5.20	0.065
	N	1.73	-0.56

Due to the lack of detailed data such as maximum daily rainfall only mean monthly precipitations were taken into consideration. Monthly rainfall data were collected from five stations in the study area. This value changes scientifically along with the elevation gradient reaching up to 800 mm at high mountainous areas. Taking this factor into account, the territory in the thematic map created was divided into five classes with different mean monthly rainfall rates: a) <500 mm, b) 500-600 mm, c) 600-700 mm, d) 700-800 mm and e) >800 mm (Fig. 4f). Potentially, the higher the rate, the more favourable the conditions for landslides.

Distance to streams

Distance from streams is one of the controlling factors for slope stability. The saturation degrees of the materials directly affect slope stability. The proximity of the slopes to drainage structures is also an important factor in terms of stability. Streams may negatively affect stability by eroding the slopes or by saturating the lower part of the material until the water level increases (Dai *et al*., 2001; Saha *et al*., 2002). In this respect, the relationship between streams and groundwater is also important.

Groundwater affects surface water by providing moisture for riparian vegetation and controlling the shear strength of slope material, thereby affecting slope stability and erosion processes. Low river flow during periods of no rain or melted snow input is called base flow, which represents the normal condition of rivers. Groundwater essentially provides the base flow for all rivers and has a major effect on the amount of water and the chemical composition of rivers. In smaller, low-order streams, groundwater also provides much of the increased discharge during, and immediately following, storms. The study area was divided into seven different buffer ranges. Classes were defined for 0-150 m, 150-300 m, 300-450 m, 450-600 m, 600-750 m, 750-1000 m and >1000 m (Fig. 4g). Consequently, as the distance from streams increases, the risk of a landslide decreases. Hence, the classes of the buffered map have been given rating values in a decreasing order based on the distance from the streams.

Distance to faults

It is observed that landslides are more abundant along minor and major faults. Fault zones increase landslide potential by creating steep slopes and sheared zones of weakened and fractured rocks. The major faults and thrusts included in the study area have been digitized from the geological maps and superimposed to form a vector layer. On this layer we applied a distance function to define buffer zones along the structural discontinuities. We created seven buffer zones, each 150 m wide. The territory included in these zones represents areas of different influence by tectonic features on landslide occurrence. As the distance from the tectonic lineaments increases, landslide frequency decreases (Fig. 4h). Thus the buffered regions were rated according to their distance from the faults.

Elevation

Elevation is one of the controlling factors in the stability of a slope. Elevation influences to landslides are often displayed as indirect relationships or by means of other factors. The thematic map of elevation was divided into seven classes with different ranges: a) <1400 m, b) 1400-1600 m, c) 1600-1800 m, d) 1800-2000 m, e) 2000-2500 m, f) 2500-3000 m and g) >3000 m (Fig. 4i).

Analytic hierarchy process (AHP)

The analytic hierarchy process is a theory of measurement for dealing with quantifiable and intangible criteria, and has been applied to numerous areas including decision theory and conflict resolution (Vargas, 1990). AHP is a multi-objective, multi-criteria decision-making approach that enables the user to arrive at a scale of preference drawn from a set of alternatives. AHP has gained wide application in site selection, suitability analysis, regional planning, and landslide susceptibility analysis (Ayalew *et al*., 2005). To apply this approach, it is necessary to break a complex unstructured problem down into its component factors, arrange these factors into an order hierarchy, assign numerical values to subjective judgements on the relative importance of each factor, and synthesize these judgements to determine the priorities to be assigned to these factors (Saaty & Vargas, 2001). In the construction of a pair-wise comparison matrix, each factor is rated against every other factor by assigning a relative dominant value between 1 and 9 to the intersecting cell (Table 2). When the factor on the vertical axis is more important than the factor on the horizontal axis, this value varies between 1 and 9. Conversely, the value varies between the reciprocals 1/2 and 1/9 (Table 3). In these techniques, firstly, the effects of each parameter to the susceptibility of landslides relative to each other were determined by dual evaluation in determining preferences as to the effects of the parameters to the landslide susceptibility maps. Normally, the determination of the values of the parameters relative to each other is a situation that depends on the choices of the decision-maker. However, in this study, both the comparison of the parameters relative to each other and the determination of the decision alternatives- namely the effect values of the sub-criteria of the parameters (weight)- were based on the comparison of landslide inventory maps constructed using aerial photos with the other data layers. Consequently the weight values were determined accurately for the real land data (Table 4 , Table 5). In this study, spatial databases were used, having been obtained through the field, laboratory and office studies carried out to create landslide susceptibility maps. The analysis of data layers converted to a raster data model was completed by determining their weights in terms of both data layers and sub-criteria, in consequence of the calculation made according to the AHP. As a result of these analyses, the landslide susceptibility map was produced for the study area (Fig. 5). For all the models, where AHP was used, the CR (consistency ratio) was calculated (see Saaty, 1977). Models with a CR greater than 0.1 were automatically rejected. The value of geospatial factors are determined by AHP method (Voogd, 1983) the acquired weights were used to calculate the landslide susceptibility models. In this method, lithology, slope gradient, distance to fault and distance to stream have been found to be important parameters for the study area, whereas aspect is of low importance.

Table 3: Nine-point scale of preference between two parameters in AHP (Saaty, 1980)

Scales	Degree of preferences	Explanation
1	Equally	Two activities contribute equally to the objective.
3	Moderately	Experience and judgment slightly to moderately favor one activity over another.
5	Strongly	Experience and judgment strongly or essentially favor one activity over another.
7	V. strongly	An activity is strongly favored over another and its dominance is showed in practice.
9	Extremely	The evidence of favoring 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 preferences in weights 1, 3, 5, 7 and 9.
Reciprocals	Opposites	Used for inverse comparison.

Table 4: Pair-wise comparison matrix, factor weights and consistency ratio of the data Layers
(Continued on the next page)

Factors	1	2	3	4	5	6	7	8	weights
Lithology									
(1)Shale	1								0.590
(2) Igneous rocks	1/5	1							0.179
(3) Sandstone	1/6	1/2	1						0.113
(4) Tuff	1/7	1/5	1/2	1					0.070
(5)alluvia &Scree	1/8	1/4	1/3	1/2	1				0.046
Consistency ratio:0.034									
Slope(°)									
(1)<6	1								0.066
(2) 6-16	3	1							0.162
(3) 16-25	5	3	1						0.420
(4) 25-33	3	2	1/2	1					0.252
(5)>33	2	1/2	1/4	1/3	1				0.098
Consistency ratio:0.021									
Distance to fault(m)									
(1)<150	1								0.354
(2) 150-300	1/2	1							0.239
(3) 300-450	1/3	1/2	1						0.158
(4) 450-600	1/4	1/3	1/2	1					0.103
(5)600-750	1/5	1/4	1/3	1/2	1				0.067
(6)750-1000	1/6	1/5	1/4	1/3	1/2	1			0.044
(7)>1000	1/7	1/6	1/5	1/4	1/3	1/2	1		0.031

Consistency ratio: 0.032									
Distance to stream(m)									
(1)<150	1								0.354
(2) 150-300	1/2	1							0.239
(3) 300-450	1/3	1/2	1						0.158
(4) 450-600	1/4	1/3	1/2	1					0.103
(5)600-750	1/5	1/4	1/3	1/2	1				0.067
(6)750-1000	1/6	1/5	1/4	1/3	1/2	1			0.044
(7)>1000	1/7	1/6	1/5	1/4	1/3	1/2	1		0.031
Consistency ratio:0.032									
Curvature									
(1)<-0.5	1								0.581
(2) -0.5-0	1/3	1							0.231
(3)0-1	1/5	1/2	1						0.120
(4) >1	1/7	1/4	1/2	1					0.066
Consistency ratio:0.009									
Landuse									
(1) R2	1								0.524
(2) R3	1/5	1							0.159
(3) R1	1/7	1/2	1						0.127
(4) IF	1/8	1/3	1/3	1					0.058
(5) PF	1/8	1/3	1/3	1	1				0.058
(6) URB	1/9	1/4	1/4	1/2	1/2	1			0.035
(7) DF	1/9	1/4	1/4	1/2	1/2	1	1		0.035
Consistency ratio:0.039									
Rainfall(mm)									
(1)<500	1								0.061
(2)500-600	2	1							0.097
(3)600-700	3	2	1						0.159
(4)700-800	4	3	2	1					0.262
(5)>800	5	4	3	2	1				0.418
Consistency ratio:0.017									
Elevation(m)									
(1)<1400	1								0.041
(2)1400-1600	2	1							0.062
(3)1600-1800	3	2	1						0.100
(4)1800-2000	4	3	2	1					0.154
(5)2000-2500	7	6	4	3	1				0.362
(6)2500-3000	6	5	3	2	1/2	1			0.248
(7)>3000	1/2	1/3	1/4	1/5	1/7	1/6	1		0.030
Consistency ratio:0.032									
Aspect									
(1)S	1								0.464
(2)SW	1/5	1							0.165
(3)SE	1/6	1/2	1						0.109
(4)E	1/7	1/3	1/2	1					0.088
(5)W	1/7	1/3	1/2	1/2	1				0.062
(6)NW	1/8	1/4	1/3	1/3	1/2	1			0.046
(7)NE	1/8	1/4	1/3	1/3	1/2	1/2	1		0.036
(8)N	1/9	1/5	1/4	1/4	1/3	1/3	1/2	1	0.025
Consistency ratio:0.058									

Table 5: Matrix of factors weights evaluation

	(a)	**(b)**	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**	**(h)**	**(i)**	**Weights**
Lithology(a)	1	3	4	5	5	5	6	7	8	0.338
Slope(b)	1/3	1	3	4	3	3	5	6	6	0.208
Dist from fault(c)	1/4	1/3	1	3	3	3	4	5	6	0.144
Dist from stream (d)	1/5	1/4	1/3	1	2	2	3	3	5	0.086
Curvature(e)	1/5	1/3	1/3	1/2	1	2	2	3	5	0.072
Landuse(f)	1/5	1/3	1/3	1/2	1/2	1	2	3	5	0.061
Rainfall(g)	1/6	1/5	1/4	1/3	1/2	1/2	1	2	3	0.040
Elevation(h)	1/7	1/6	1/5	1/3	1/3	1/3	1/2	1	2	0.028
Aspect(i)	1/8	1/6	1/6	1/5	1/5	1/5	1/3	1/2	1	0.020
										CI=0.07

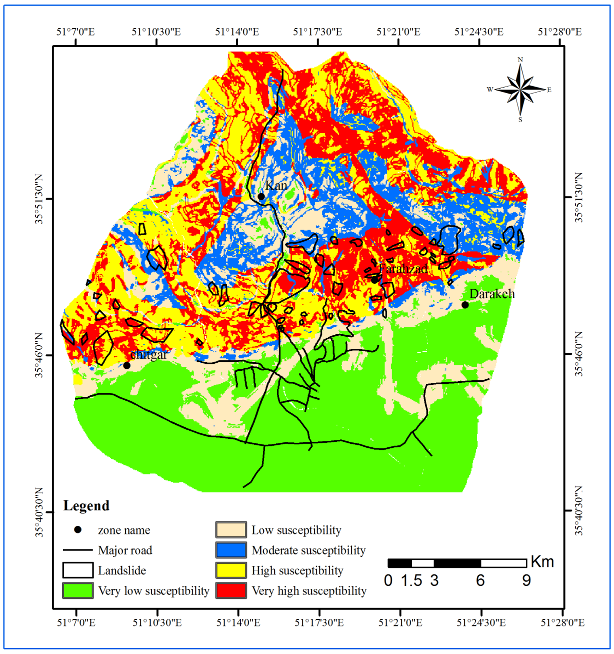

Figure 5: The landslide susceptibility map produced by the AHP.

Bivariate statistics

In bivariate statistical analysis each individual factor is compared to the landslide inventory map. The weighted value of the classes used to categorize every parameter is determined on the basis of landslide density in each individual class. This method requires the selection and mapping of significant parameters and their categorization into a number of relevant classes, landslide inventory mapping, overlay mapping of the landslide inventory map with each parameter map, determination of the density of landslide in each parameter class and definition of weighted values, assignment of weighting values to the various parameter maps, finally, the degree of vulnerability of each land unit is determined and calculated after overlay mapping(Aleotti & Chowdhury, 1999).

Although bivariate statistical analysis is considered to be a quantitative approach to landslide susceptibility assessment, a certain degree of subjectivity exists, particularly in the assignment of weighting values to the various parameter maps. In addition, it must be noted that in many situations the analysed factors are not independent and may show either a high or low correlation (Leroi, 1996; Aleotti & Chowdhury, 1999). In this section, landslide susceptibility analysis was performed using a statistical bivariate method-namely the statistical index (WI) method (van Westen, 1997).

In the WI method a weight value for a parameter class is defined as the natural logarithm of the landslide density class, divided by the landslide density over the entire map (van Westen, 1997; Rautela & Lakhera, 2000). The following formula forms the basis of this approach:

$$WI = \ln \frac{Densclass}{Densmap} = \ln \frac{\frac{Npix(Si)}{Npix(Ni)}}{\frac{SNpix(Si)}{SNpix(Ni)}}$$

where

WI = The weight given to a certain parameter class

Densclass = Landslide density within the parameter class

Densmap = Landslide density within the entire map

Npix(Si) = Number of pixels that contain a landslide in a certain parameter class

Npix(Ni) = Total number of pixels in certain parameter class.

SNpix(Si) = Number of pixels all landslide

SNpix(Ni) = Total number of all pixels

The WI method is based on statistical correlation (map crossing) of the landslide inventory map with attributes of different parameter maps. In this study, every parameter map was crossed with the landslide inventory map, and the density of the landslide in each class was calculated. Correlation results were stored in resultant rasters and the density of the landslide per parameter class was calculated. Then the WI value of each attribute was calculated (Table 2). Finally, all layers were overlaid and a resultant susceptibility map was obtained (Fig. 6). The final susceptibility map was divided into equal classes according to the total number of elements. The classes were: very low, low, moderate, high, and very high susceptibility. To check the reliability of the landslide susceptibility map produced by the WI method, the landslide activity map and susceptibility map were statistically compared. In this comparison, the area in the landslide activity map that shows where the landslides occurred is matched with the WI map.

The assigning of weighting factors for various attributes is a method that is frequently used. The weighting factor values may be selected either arbitrarily- mainly on the basis of expert opinion (Anbalagan, 1992; Turrini & Visintainer, 1998)- or through intermediate processes (Dai *et al*., 2001; Lee & Min, 2001; Lee *et al*., 2004a,b).

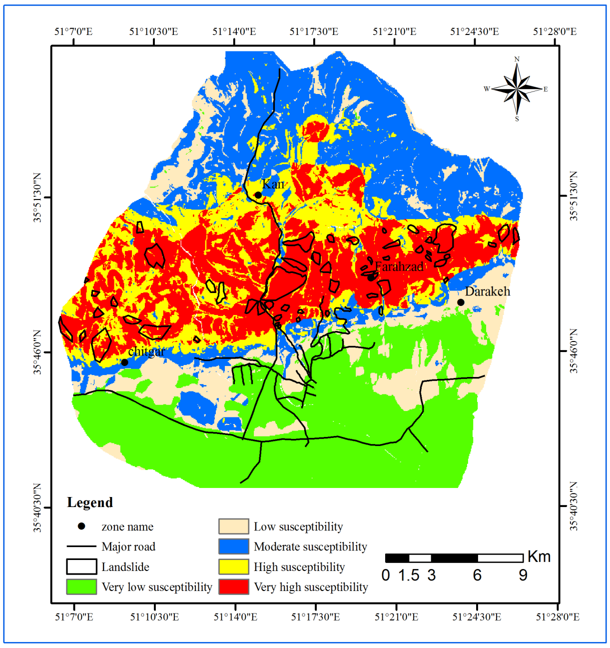

Figure 6: The landslide susceptibility map developed using the WI method.

Frequency ratio method

When evaluating the probability of land sliding within a specific period of time and within a certain area, it is of major importance to recognize the conditions that can cause the landslide and the process that could trigger the movement. The correlation between landslide areas and associated factors that cause landslides can be allocated from the connections between areas without past landslides and landslide-related parameters.

In order to prepare the landslide susceptibility map quantitatively, the frequency ratio method was implemented using GIS techniques. Frequency ratio methods are based on the observed associations between distribution of landslides and each landslide-related factor to expose the correlation between landslide locations and the factors in the study area. Using the frequency ratio model, the spatial associations between landslide location and each of the factors contributing to landslide occurrence were derived. The frequency is calculated from the analysis of the relationship between landslides and the attributed factors. Therefore, the frequency ratios of each factor's type or range were calculated from their relationship with landslide events as shown in Table 6. The frequency ratio was calculated for the sub-criteria of parameter, and then the frequency ratios were summed to calculate the LSI (Eq. 1) (Lee & Talib, 2005).

$$LSI = Fr_1 + Fr_2 + Fr_3 + \ldots\ldots + Fr_n \qquad (1)$$

where FR is the rating of each factor's type or range. According to the frequency ratio method, the ratio is that of the area where the landslide occurred, to the total area, so that a value of 1 is an average value. If the value is >1, it means the percentage of the landslide is higher than the area and refers to a higher correlation, whereas values lower than 1 mean a lower correlation (Akgun *et al*., 2008). The geological characteristics of the study area are very important factors in susceptibility analysis. There are five classes of lithological units in the study area: shale units, igneous rocks units, sandstone units, tuff units and scree and alluvial units. Shale units were found to be a more susceptible lithology. Shale units and igneous rocks include 2.04, 1.72 of the higher frequency ratio, respectively. Slope angle is one of the most important factors controlling slope stability, and landslides mostly occur at certain critical slope angles. Mild slopes are estimated to have a low frequency for shallow domiciled landslides because of the minor shear stresses commonly associated with low slopes. Frequency ratio analysis showed that a slope angle in the range of 16-25 and >33 shows a high probability of landslide occurrence. As expected, a low gradient indicated a low frequency ratio- in the range of 0-6- giving a 0.09 ratio (Table 6). Like slope, aspect is another important parameter when preparing landslide susceptibility maps. In the study area, landslides generally occurred on slopes facing east-southeast and west-northwest-southwest.

The assessment of the aspect factor on northwest-facing slopes shows a high probability (3.21) of landslide occurrence (Table 6). Elevation-landslide analysis showed that landslides mostly occurred from 1400m to 3000 m; in particular, the frequency ratio is very high in the elevation range of 1600-1800 m (Table 6). The results are related to geological characteristics because the areas in the elevation range of 1600-1800m are generally overlaid to the shale units. Land cover type is very important for landslide studies, especially the areas that are covered with various kinds of vegetation. Land cover analysis showed that landslides commonly occurred in the low-density and moderate density pasture areas, the frequency ratios being 2.87 and 2.03, respectively (Table 6).

Table 6: Frequency ratio values of the landslide-conditioning parameters.

Data layers	Classes	% of landslide area(a)	% of total area(b)	FR(a/b)
Lithology	Shale	73.56	36.07	2.04
	Igneous rocks	8.81	5.13	1.72
	Sandstone	7.99	11.49	0.70
	Tuff	7.40	4.74	1.56
	Scree& alluvia	2.22	42.58	0.16
Slope(°)				
	<6	4.06	42.19	0.09
	6-16	16.75	16.14	1.03
	16-25	39.68	19.47	2.03
	25-33	31.54	17.93	1.75
	>33	7.98	4.25	1.87
Distance to fault(m)				
	<150	25.71	15.50	1.65
	150-300	18.55	11.91	1.55
	300-450	13.66	10.24	1.33
	450-600	12.50	8.05	1.55
	600-750	9.85	7.53	1.30
	750-1000	7.60	8.71	0.87
	>1000	12.13	38.03	0.31
Distance to stream(m)				
	<150	37.90	26.87	1.41
	150-300	17.27	19.56	0.88
	300-450	13.26	15.81	0.84
	450-600	8.43	11.19	0.75
	600-750	4.34	8.41	0.52
	750-1000	6.32	8.90	0.71
	>1000	12.48	9.25	1.35
Curvature				
	<-0.5	3.38	1.42	2.37
	-0.5-0	51.89	52.22	0.99
	0-1	44.71	46.29	0.97
	>1	0.02	0.06	0.39
Landuse				
	Low density pasture	25.05	8.74	2.87
	Ir-farming	1.60	2.68	0.60
	Foresty park	1.43	2.20	0.65
	High density pasture	6.21	16.38	0.38
	Dry farming	0	0.37	0
	Moderate density pasture	65.46	32.17	2.03
	Urban area	0.26	37.82	0.01
Rainfall(mm)				
	<500	18.08	47.43	0.38
	500-600	48.29	14.26	3.39
	600-700	28.53	8.79	3.25
	700-800	4.84	7.14	0.68
	>800	0.25	22.38	0.01
Elevation(m)				
	<1400	0	29.05	0
	1400-1600	7.33	16.03	0.46
	1600-1800	21.89	11.85	1.85
	1800-2000	22.81	14.39	1.58
	2000-2500	44.36	35.54	1.25
	2500-3000	3.61	22.19	0.16
	>3000	0	5.08	0
Aspect				
	S	15.19	36.86	0.41
	SW	23.77	19.14	1.24
	SE	11.26	15.20	0.74
	E	10.55	8.61	1.23
	W	19.34	8.43	2.29
	NW	12.96	4.04	3.21
	NE	5.20	4.88	1.07
	N	1.73	2.85	1.19

The degree of soil saturation is one of the controlling factors for slope stability. Streams increase the level of water in soil around slopes. There is a reverse relationship between the occurrence of landslides and distance of streams. Typically, the occurrence of landslide will decrease with increasing distance from streams. In this study, the occurrence of landslide has decreased with increasing distance from the stream (Table 6). The distance from faults increases the landslide constituting declines in the study, which is compatible with what would be expected. The analysis of distance to faults showed that landslides to usually occur at the distance range of 0-150 m (Table 6). Curvature is a causal factor on the basis that it affects the hydrological conditions of the soil cover. Potentially, after rainfall the soil cover on a concave slope can contain more water and retain it for a longer period than a convex slope. Curvature analysis showed that landslides to usually occur at curvatures of <-0.5 (Table 6). The effect of precipitation both in regard to increased soil humidity by increased precipitation and consequently increased potential for landslide, and as a starter factor for landslide in the case of heavy and long-term rainfall, were studied. The precipitation-landslide analysis showed landslides to mostly occur at the range of 500 mm to 600 mm. The results are related to geological characteristics because the areas in the range of 500-600 mm precipitation are generally overlaid to shale units. On completion of the analysis the frequency ratio of each layer's classes was determined, and a landslide susceptibility map (Fig. 7) was produced by the LSI map using Eq. (1).

Results and testing of landslide susceptibility analysis

To test the reliability of the landslide susceptibility maps produced by the AHP, WI, and FR methods, a comparison between a landslide activity map of 54 active zones of recent landslides and the susceptibility maps was made. In these comparisons, the area in the landslide activity map showing where the landslides occurred was matched with the landslide susceptibility maps. The confirmation process has begun in such a way that the three susceptibility maps were first divided into five classes based on standard deviations of the corresponding histograms (Ayalew *et al.*, 2005) (Fig. 8).

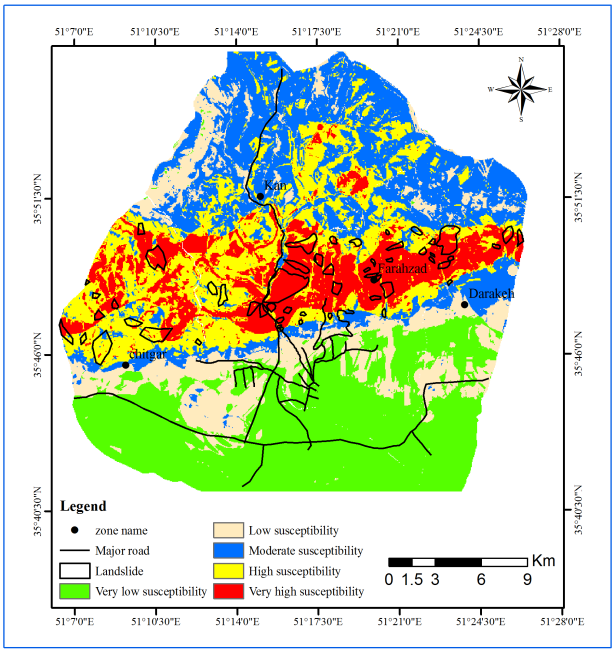

Figure 7: The landslide susceptibility map produced by FR.

Next they were crossed with the landslide activity map. Fig. 9 presents a histogram that summarizes the result of the entire process. The high and very high susceptibility zones (4 and 5) found by the AHP, WI and FR methods contain 74.5%, 99.6% and 97.2% of the active landslide zones, respectively. Approximately 23.6% of the active landslide zones coincide with the moderate susceptibility (3) class of the three maps. The other zones contain less than 4.82% of the active landslide zones. No active landslide zones appear in the very low susceptibility (1) class of the three maps (AHP, WI and FR). Fig. 8 indicates that the extent of the active landslide zones located in the very high susceptibility class to be higher in the maps produced by the WI than the AHP and FR maps. 81.7% of the active landslide zones fall into the very high susceptibility class of the WI map. This is reduced to 40.04% in the case of the susceptibility map produced by the AHP map. As expected, only 4.8% of the landslide zones fall into the low susceptibility (2) class of the AHP map, and there are no active landslide zones in the WI and FR maps. The very low susceptibility (1) class has no active landslide zones in the AHP, WI and FR maps. Looking at Fig. 9 it is easy to conclude that the very high and high susceptibility classes of the WI and FR maps together captured the locations of the active landslide zones (99.6%) and 97.2% better than the corresponding counterparts of the AHP map, with 74.5%. This might be due to the WI's and FR's approach determined on the basis of objective judgments.

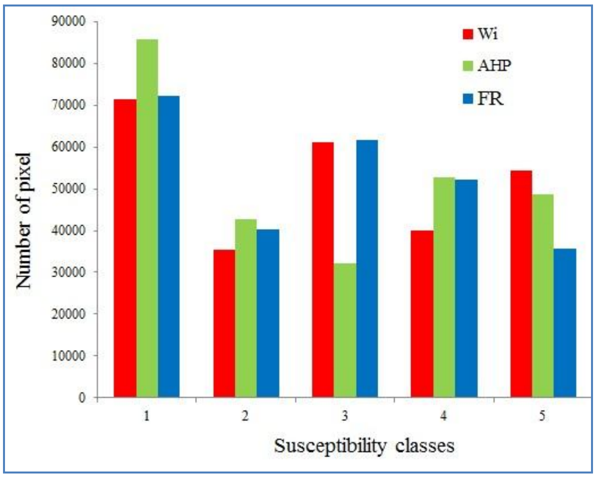

Figure 8: Bar graphs showing the relative distribution of susceptibility levels when the susceptibility maps are classified on the basis of Standard deviations.

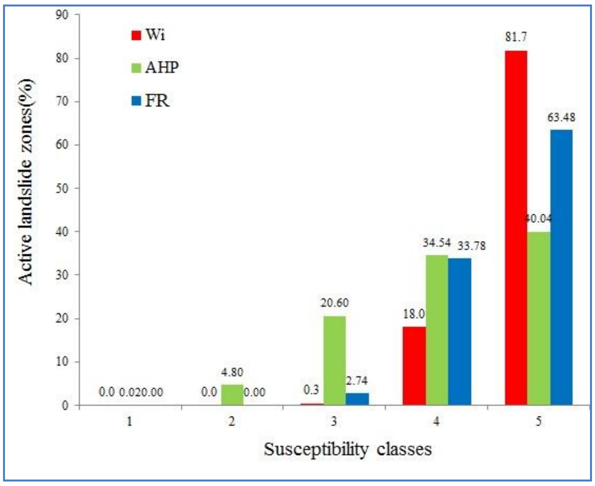

Figure 9: A histogram showing the amount of active landslide zones that fall into the various classes of the AHP, WI and FR susceptibility maps.

Discussion and conclusion

Understanding the processes that lead to landsliding and the effort for subsequent susceptibility mapping provides fundamental knowledge about the evolution of landscapes, and lays the foundation for hazard management and the development of safety measures. Based on this awareness, this study has presented the results of comprehensive research comprising slope stability assessment and landslide susceptibility mapping in part of the Tehran metropolis in Iran. In this region, landslides frequently occur after precipitation. This is because the topography and lithological materials are eminently suitable for the creation of landslides.

In Tehran, rough landscapes and susceptible stratigraphy are common, and often have the potential for initiating slope failures. Susceptible stratigraphy and weathering also contribute greatly to the occurrence of landslides in the region. There were some differences between the AHP, FR and WI methods: derived susceptibility maps with the WI and FR give better results than the AHP map. To confirm the feasibility of the results, the three susceptibility maps were compared with 54 active landslide zones. The result was that the active landslide zones had a high correlation to the high and very high susceptibility class of the three maps: 99.6% of these landslide zones fall into the high and very high susceptibility classes of the WI map. The AHP and FR maps show 74.5% and 97.2% of the landslide zones, respectively. The probable reason for the differences between the AHP, FR and WI maps are related to the objective nature of the WI and FR methods. Based on these findings, it can be noted that the high and very high susceptibility zones identified by the WI and FR methods predict a higher percentage of landslides in the area. This study shows that when field conditions and characteristics are correctly determined by good expertise, the WI and FR approaches give better results. The landslide-prone areas delineated by susceptibility map represent an important basis for the assessment of landslide risk in the study area. Thus, the susceptibility map produced through this research can be very useful for decision-makers when choosing suitable locations for future planning in large-scale regions.

References

Akgun, A., Dag, S., Bulut, F., 2008. Landslide susceptibility mapping for a landslide-prone area (Findikli, NE of Turkey) by likelihood-frequency ratio and weighted linear combination models. Environmental Geology, 54: 1127-1143.

Aleotti, P., Chowdhury, R., 1999. Landslide hazard assessment: summary review and new perspectives Bulletin of Engineering Geology and the Environment, 58: 21-44.

Anbalagan, R., 1992. Landslide hazard evaluation and zonation mapping in mountainous terrain. Engineering Geology 32: 269-277.

Ayalew, L., Yamagishi, H., 2005. The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda–Yahiko Mountains, Central Japan. Geomorphology, 65: 15-31

Ayalew, L., Yamagishi, H., Marui, H. & Kanno, T., 2005. Landslides in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparisons of results from two methods and verifications. Engineering Geology, 81: 432-445.

Barredo, J.I., Benavides, A., Hervas, J., van Westen, C.J., 2000. Comparing heuristic landslide hazard assessment techniques using GIS in the Tirajana basin, Gran Canaria Island, Spain. International Journal of Applied Earth Observation and Geoinformation, 2: 9-23.

Brabb, E.E., 1984. Innovative approaches to landslide hazard and risk mapping. Proc., Fourth International Symposium on Landslides, Canadian Geotechnical Society, Toronto, Canada, 1: 307-324.

Carrara, A., 1983. A multivariate model for landslide hazard evaluation. Mathematical Geology, 15: 403-426.

Carrara, A., Cardinalli, M., Guzzetti, F., Reichenbach, P., 1995. GIS technology in mapping landslide hazard. In: Carrara, A., Guzzetti, F. (Eds.), Geographical Information Systems in Assessing Natural Hazard. Kluwer Academic Publisher, p. 173-175.

Cevik, E., Topal, T., 2003. GIS-based landslide susceptibility mapping for a problematic segment of the natural gas pipeline, Hendek (Turkey). Environmental Geology, 44: 949-962.

Clerici, A., Perego, S., Tellini, C., Vescovi, P., 2002. A procedure for landslide susceptibility zonation by the conditional analysis method. Geomorphology, 48: 349-364.

Dai, F.C., Lee, C.F., Li, J., Xu, Z.W., 2001. Assessment of landslide susceptibility on the natural terrain of Lantau Island, Hong Kong. Environmental Geology, 43 (3): 381-391.

Dai, F.C., Lee, C.F., Ngai, Y.Y., 2002. Landslide risk assessment and management: an overview. Engineering Geology 64 (1): 65-87.

Ercanoglu, M., Gokceoglu, C., 2004. Use of fuzzy relations to produce landslide susceptibility map of a landslide prone area (West Black Sea Region, Turkey). Engineering Geology, 75 (3–4): 229–250.

Ercanoglu, M., Gokceoglu, C., Van Asch, TH.W.J., 2004. Landslide susceptibility zoning north of Yenice (NW Turkey) by multivariate statistical techniques. Natural Hazards, 32: 1-23.

Fall, M., Azam, R., Noubactep, C., 2006. A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping. Engineering Geology, 82 (4): 241-263.

Guzzetti, F., Carrara, A., Cardinalli, M., Reichenbach, P., 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology, 31: 181-216.

Komac, M., 2006. A landslide susceptibility model using the analytical hierarchy process method and multivariate statistics in perialpine Slovenia. Geomorphology 74 (1–4), 17–28. Engineering Geology, 76 (1–2): 109-128.

Lee, S., 2005. Application of logistic regression model and its validation for landslide susceptibility mapping using GIS and remote sensing data. International Journal of Remote Sensing, 26 (7): 1477-1491.

Lee, S., Talib, J.A., 2005. Probabilistic landslide susceptibility and factor effect analysis. . Environmental Geology, 47: 982-990.

Lee, S., Min, K., 2001. Statistical analysis of landslide susceptibility at Yongin, Korea. Environmental Geology, 40: 1095-1113.

Lee, S., Choi, J., Min, K., 2004a. Probabilistic landslide hazard mapping using GIS and remote sensing data at Boun, Korea. International Journal of Remote Sensing, 25 (11): 2037-2052.

Lee, S., Ryu, J., Won, J., Park, H., 2004b. Determination and application of the weight for landslide susceptibility mapping using an artificial neural network. Engineering Geology, 71: 289-302.

Leroi, E., 1996. Landslide hazard-risk maps at different scales: objectives, tools and
development. Proc VII Int Symp Landslides, Trondheim, 1: 35-52.

Nagarajan, R., Roy, A., Vinod Kumar, R., Mukherjee, A., Khire, M.V., 2000. Landslide hazard susceptibility mapping based on terrain and climatic factors for tropical monsoon regions. Bulletin of Engineering Geology and the Environment, 58: 275-287.

Nielsen, T.H., Wrigth, R.h., Vlasic, T.C., Spangle, W.E., 1979. Relative slope stability and land-use planning in the San Francisco Bay region, California. US Geological Survey Professional Paper 944.

Rautela, P., Lakhera, R.C., 2000. Landslide risk analysis between Giri and Ton Rivers in Himalaya (India). International Journal of Applied Earth Observation and eoinformation, 2: 153-160.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15: 234- 281.

Saaty, T.L., 1980. The Analytical Hierarchy Process. McGraw Hill, New York.

Saaty, T.L., Vargas, G.L., 2001. Models, Methods, Concepts, and Applications of the Analytic Hierarchy Process. Kluwer Academic Publisher, Boston.

Saha, A.K., Gupta, R.P., Arora, M.K., 2002. GIS-based landslide hazard zonation in the Bhagirathi (Ganga) valley, Himalayas. International Journal of Remote Sensing, 23 (2): 357-369.

Suzen, M.L., Doyuran, V., 2004. Data driven bivariate landslide susceptibility assessment using geographical information systems: a method and application to Asarsuyu catchment, Turkey. Engineering Geology, 71: 303-321.

Turrini, M.C., Visintainer, P., 1998. Proposal of a method to define areas of landslide hazard and application to an area of the Dolomites, Italy. Engineering Geology, 50: 255-265.

Vargas, L.G., 1990. An overview of the analytic hierarchy process and its applications. European Journal of Operational Research, 48: 2-8.

vanWesten, C.J., 1994. GIS in landslide hazard zonation: a review with example from the Colombian Andes. In: Price, M.F., Heywood, D.I. (Eds.), Taylor and Francis, London.

van Westen, C.J., 1997. Statistical landslide hazard analysis. ILWIS 2.1 for Windows application guide. ITC Publication, Enschede, p. 73- 84.

Voogd, H., 1983. Multicriteria Evaluation for Urban and Regional Planning. Pion Ltd., London.

Yalcin, A., 2008. GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariate statistics in Ardesen (Turkey):comparisons of results and confirmations. Catena, 72: 1-12.