Int. J. Environ. Res., 7(2):319-336, Spring 2013
ISSN: 1735-6865

Landslide Susceptibility Mapping for the Urmia Lake basin, Iran: A multi-Criteria Evaluation Approach using GIS

Feizizadeh , B.[1,2*], Blaschke, T.[2] , Nazmfar, H.[3] and Rezaei Moghaddam, M.H.[1]

[1]Department of Physical Geography Centre for Remote Sensing and GIS, University of Tabriz, Iran

[2] Department of Geography & Geology Centre for Geoinformatics , University of Salzburg, 5020, Austria

[3] Department of Geography and Urban Planning, University of Mohaghegh Ardabili, Ardabil, Iran

Received 17 March 2012; Revised 8 July 2012; Accepted 18 July 2012

ABSTRACT: Although typically small in terms of their spatial footprint, landslide hazards are relatively frequent in Northern Iran. We assess landslide susceptibility for the nearly 20.000 km2 large study area of the Urmia lake basin which is dominated by agricultural land use but includes the major settlements areas of the East Azerbaijan province, Iran. Landslide factors are established in form of GIS dataset layers including topography, geology, climatology and land use. After pre-processing all data layers are standardized based on a fuzzy logic model. An Analytical Hierarchical Process (AHP) delivers the weights for the GIS-analysis. Datasets are combined by GIS spatial analysis techniques and a landslide susceptibility map of the study area is created. An existing inventory of known landslides within the case study area was compared with the resulting susceptibility map. We found that high susceptible zones cover about 4.47% (944 km2) of the total area whereby geological outcrops of sedimentary and volcanic formations such as volcanic ash contribute most to the landslide susceptibility. Due to the dynamic growth of settlements especially in the vicinity of the city of Tabriz landslide hazards may cause even more damage in the future.The resulting information of this research is useful for a) a better understanding of existing landslides and their origins in North-Western Iran, b) supporting emergency decisions and c) prioritization of efforts for the reduction and mitigation of future landslide hazards.

Key words: Landslide, Susceptibility mapping,GIS- spatial analysis, MCDA,Urmia lake basin, Iran

INTRODUCTION

Disaster is defined as "a situation or an event which overwhelms local capacity, necessitating a request to a national or international level for external assistance; an unforeseen and often sudden event that causes great damage, destruction and human suffering" (Vos *et al.*, 2010; Akinci *et al.*, 2011; Afandizadeh *et al.*, 2012; Salehi *et al.*, 2012). Disasters are natural hazard events in which a natural phenomenon or a combination of natural phenomena, such as earthquakes, mass movements, floods, volcanic eruptions, tsunamis etc., can cause many loss of lives and damage to the property. It is almost impossible to prevent the occurrence of natural disasters and their damages. However, it is possible to reduce the impact of disasters on human lives, infrastructure and property by adopting suitable disaster mitigation strategies. The term of landslide describes "a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial hill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing" (U.S. Geological Survey, 2004). Landslide occurrences are attributable to the resisting strength of the soil or rock forming the slope against gravity, and a landslide results when the balance is tipped in favour of gravity. This balance can be changed by both natural and man-made circumstances. The elements that affect slope stability and landslides are numerous varied and interact in complex and often subtle ways (Varnes, 1984). Landslides can be caused by tectonic factors such as earthquakes or faults, but are often interrelated with climatic factors such as precipitation. Landslides have caused severe human and economic losses (Guzzetti, 2000). Individual slope failures are generally not so spectacular or as costly as earthquakes, major floods, or hurricanes but may cause more damage to properties than any other geological hazards (Varnes,

*Corresponding author E-mail:Bakhtiar.FeiziZadeh@stud.sbg.ac.at

1987). Landslides and slope instabilities are major hazards for human activities often causing economic losses, property damages and high maintenance costs, as well as injuries or fatalities (Das *et al.,* 2010). Damages and human casualties are predominantly attributed to main events. This leads to a substantial underestimation in the available statistical data on landslide impact (Castellanos Abella, 2008). In the North-West part of the Iran (Sahand Mountain), landslides occur frequently due to climatologic and geologic conditions with high tectonic activities (Feizizadeh and Blaschke, 2011). The Iranian plateau is a capable area for occurrence various kinds of landslides because of its mountainous feature, high tectonic activity, geological and climatologic variety (Jadda *et al.,* 2009).

The main objective of this research is to produce a detailed landslide susceptibility map for the Urmia lake basin in northwest Iran as needed by different authorities in the East Azerbaijan Province. Landslide susceptibility is defined as “the proneness of the terrain to produce slope failures and susceptibility is usually expressed in a cartographic way. Landslide susceptibility zoning involves a degree of interpretation and spatial distribution rate of the terrain units according to their propensity to produce landslides which is that dependent on topography, geology, geotechnical properties, climate vegetation and anthropogenic factors such as development and clearing of vegetation” (Fell *et al.,* 2008). A landslide susceptibility map depicts areas likely to have landslides in the future by correlating some of the principal factors that contribute to landslides with the past distribution of slope failures (Brabb, 1984; Yalcin, 2008). They provide important information to the prediction of future landslides hazards and could be based on the landslide hazard maps which are includes an indication of the time scale within which a particular landslides are likely to occur (Atkinson and Massari, 2011). Landslide susceptibility maps are basic tools for land-use planning, especially in mountain areas but also in areas with moderate terrain complexity but specific geological conditions such as outcrops. Landslide susceptibility mapping requires 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 the data available, the working scale and the selection of the appropriate analysis methodology. The process of creating these maps involves several qualitative or quantitative approaches. Early attempts defined susceptibility classes by qualitative overlaying of geological and morphological slope-attributes to landslide inventories (Nielsen *et al.,* 1979). Enormous progress has been made in the development of landslide inventories, landscape susceptibility mapping and hazard zoning, whereby much of this progress is based on the extensive use of GIS, GPS and remote sensing techniques (van Westen *et al.,* 2008).Today, practically all research on landslide susceptibility and hazard mapping makes use of digital tools for handling spatial data such as GIS, GPS and remote sensing. These tools also have deûned, to a large extent, the type of analysis that can be carried out. It can be stated that GIS has somehow determined the current state of the art in landslide hazard and risk assessment (van Westen *et al.,* 2005; 2008). These GIS-based techniques are increasingly viewed as a key to managing spatial and temporal data for natural hazards (Kimmance *et al.,* 1999; Parsons and Frost 2000; Lan *et al.,* 2009; 2004; Forte *et al.,* 2005; Kohler *et al.,* 2006). The main objectives of this research are a) to analysis landslide potential using GIS-multicriteria decision analysis and b) to explore the landside susceptibility parameters in Urmia lake basin, Iran.

The study area is the Urmia lake basin which is located in the East Azerbaijan province of Iran. This area with 35 cities and 1018 villages totalling in 3.2 million inhabitants is important in terms of housing, industrial and agricultural activities for the East Azerbaijan province (ICC, 2007; Ahmadi *et al.,* 2011; Farzin *et al.,* 2012). The study area is 19913 km^2 in size and covers 43.44 % of the East Azerbaijan province. It is located 36° 56' 36" N to 38° 21' 11" N and 45° 05' 33" E to 47° 55' 10" E as presented in Fig. 1. Urmia Lake as the largest water body in Iranian plateau is located northwest of Iran. More than 20 permanent and seasonal rivers as well as a few subterranean streams and springs feed the lake. As an ecological heritage Urmia Lake it a UN protected habitat (Ahadnejad Reveshty and Maruyama, 2010). The elevation of the Urmia lake basin ranges from 1260 at Urmia Lake to 3710 meters above sea level in the Sahand Mountains. The climate is semi-arid and annual precipitation is about 300 mm (Alijane, 2000). The area’s geology is very complex and the lithological units comprise several formations causing volcanic hazards, earthquakes and landslides. This geophysical setting makes slopes of this area potentially vulnerable to landslides and mass movements such as rock fall, creeps, flows, topples and landslides (Alaei Talganei, 2009). Landslides are common in Urmia lake basin and the complexity of the geological structure in the associated lithological units, comprised with several formations, cause volcanic hazards, earthquakes and landslides (Feizizadeh and Blaschke, 2011).

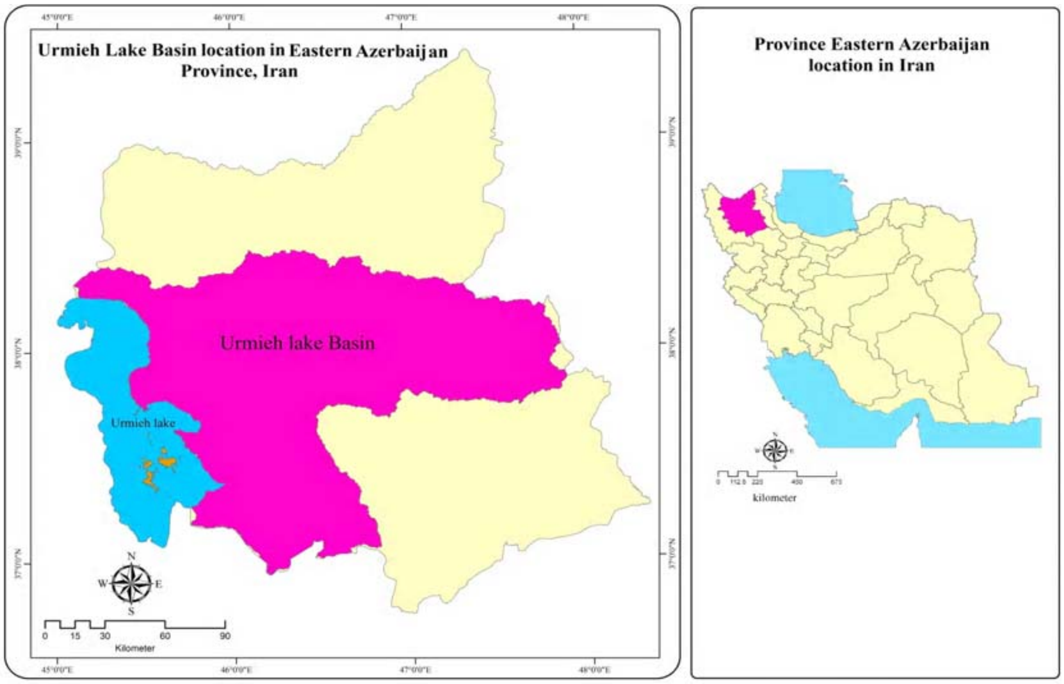

Fig. 1. location of case study area in the East Azerbaijan province (left) and Iran (right)

MATERIALS & METHODS

GIS-multicriteria decision analyses (MCDA) provide a rich collection of techniques for landslide susceptibility mapping (Feizizadeh *et al.,* 2012). The MCDA framework is primarily concerned with how to combine the information from several criteria to form a single index of evaluation (Yu *et al.,* 2011; Feizizadeh and Blaschke, 2012). GIS-MCDA can be thought of as "a process that transforms and combines geographical data and value judgments (the decision-maker's preferences) to obtain information for decision making. It is in the context of the synergetic capabilities of GIS and MCDA that one can see the benefit for advancing theoretical and applied research on GIS-MCDA" (Malczewski, 2006). GIS-MCDA based landslide analysis allows to combine information derived from heterogeneous sources to support landslide monitoring. One of the multi-attribute techniques which have been incorporated into the GIS-based landslide analysis procedures is the Analytical Hierarchy Process (AHP) originally introduced by Saaty (1980). AHP builds a hierarchy of decision elements (factors) and renders comparisons possible between pairs of factors in form of a matrix. The results are weights for each factor and also a consistency ratio which quantifies the unambiguity of the pairwise weighting. It is based on three principles namely decomposition, comparative judgment and synthesis of priorities (Malczewski, 1999). AHP is a multiple criteria decision-making technique that allows subjective as well as objective factors to be considered in the decision-making process. It allows the active participation of decision-makers and gives managers a rational basis on which to make decisions. In MCDM the AHP method is widely used to obtain the required weightings for different criteria (Saaty, 1977; 1980; Saaty and Vargas, 1991; Wu 1998), AHP has been successfully employed in GIS-based MCDM since the early 1990s (Carver, 1991; Malczewski 1999; 2004; Makropoulos *et al.*, 2003). It calculates the required weights associated with criterion map layers with the help of a preference matrix in which all relevant criteria identified are compared against each other on the basis of preference factors. The weights can then be aggregated. GIS-based AHP has gained popularity because of its capacity to integrate a large quantity of heterogeneous data, and because obtaining the required weights can be relatively straightforward, even for a large number of criteria. It has been applied to a variety of decision making problems (Tiwari *et al.,* 1999; Nekhay *et al.,* 2008; Hossain and Das, 2009). Finally, AHP as a multi-objective, multi-criteria decision-making approach enables the user to specify preferences drawn from a set of alternatives. AHP gained wide application in site selection, suitability analysis and regional planning.

The set of criteria selected should adequately represent the decision-making environment and contribute towards the final goal (Prakash, 2003; Feizizadeh and Blaschke, 2011). There are no universal guidelines for selecting parameters that influence landslides in susceptibility mapping (Yalcin, 2008). In this study topography, geology, geotechnical properties, climate, vegetation and anthropogenic factors (Table 1) were selected using expert knowledge based on field studies related to active landslides. Despite the presence of spatial dependency between parameters, research results which consider many causal factors in a single analytical task are not uncommon in the literatures, apparently looking for greater detail. The result of the susceptibility map is determined by factors with high local representation such as lineaments and turned to have artifacts that reduce its reliability. There are also studies that used natural (lithology, lineament, etc.) and artificial (roads and other engineering structures), or causal (slope, lithology, etc.) and triggering (rain, seismicity, etc.) factors together (Ayalew and Yamagishi, 2005; Yalcin, 2008). The selection of the nine causal factors in this study is based on these four criteria, and also considers general literature inputs and data availability (Ayalew and Yamagishi, 2005). Lithology, DEM, slope, aspect, land cover, precipitation, distance to streams, distance to roads and faults are the factors that are most often used for susceptibility mapping by other researchers (Dai *et al.,* 2002; Lee and Min, 2001; Parise, 2001; Dai *et al.,* 2002; Cevik and Topal, 2003; Ercanoglu *et al.,* 2004; Lee *et al.,* 2004a,b; Lan *et al.,* 2004; Perotto-Baldiviezo *et al.,* 2004; Ayalew and Yamagishi, 2005; Komac, 2006; Pachauri and Pant, 1992; Yalcin, 2008; Thanh long, 2008; Feizizadeh *et al.,* 2011; Feizizadeh and Blaschke, 2011; Khezri, 2011; Joo Oh and Pradhan, 2011; Bai *et al.,* 2011; Padma *et al.,* 2011).

Table 1. Evaluation criteria

Topography	Elevation
	Slope
	Aspect
	distance to streams
Human factors	Land use/cover
	distance to roads
Geology	lithology
	distance to faults
Climate	precipitation

In landslide susceptibility studies, generally it is assumed that the future landslides must occur with the effects of the same factors as previous therefore the first step in landslide susceptibility assessments is to acquire information about the landslides that have occurred in the past (Akinci *et al.,* 2011) based on this idea, the first step in our study is to establish a spatial database for a spatially explicit analysis of the degree of susceptibility. GIS analytical techniques include: overlays, distance calculations, buffering etc. Major data sets include:

- Lithology and fault maps were derived from geological maps 1:100,000.
- Road and drainage maps were extracted from a topographical map of the area with a scale of 1:25000.
- Digital topographic maps with a scale of 1:25000 were used in order to create a TIN and DEM, as well as slope and aspect maps.
- Land use and land cover maps were derived from Landsat ETM+ satellite images through image processes techniques.
- Meteorological data, including precipitation data for a 30 year period was used to create a precipitation map.
- The Landslides inventory database for the province of East Azerbaijan.

In the preparation phase, all necessary geometric thematic editing was done on the original data sets and a topology was created. In the next step, all vector layers were converted into raster format with 20 m resolution and the spatial datasets were processed in ArcGIS. In doing so, a pairwise comparison technique was used to extraction standard weights, which is typically used for rating and standardizing the ordinal values (Malczewski, 2004). This technique is an extension of the classic binary logic, with the possibility of defining sets without sharp boundaries and allowing for partial assignation of elements to a particular set. A fuzzy set is essentially a set whose members may have degrees of membership between 0 and 1, as opposed to a classic binary set in which each element must have either 0 or 1 as the membership degree (Malczewski, 2004). In this particular landslide hazard analysis for the Urmia lake basin, the criteria used relate to topography, climate, geology, vegetation and anthropogenic factors all of which were represented by separate GIS dataset layers. The resulting memberships of different potential classes were subsequently standardized using the maximum eigenvectors approach on a 0 to 1 scale.

A main parameter of the slope stability is the slope angle which is directly related to landslides (Lee and Min 2001). It is frequently used in the calculation of landslide susceptibility maps (Clerici *et al.,* 2002; Saha *et al.,* 2002; Cevik and Topal, 2003; Ercanoglu *et al.,* 2004; Lee *et al.,* 2004a; Lee, 2005; Yalcin, 2005; 2008). The slope map of the study area was divided into five slope categories. ArcGIS software was used for this classification and for the calculation of the relationships to landslide susceptibility. The landslide susceptibility percentages for each slope class are presented in (Fig. 2a and Table 6).

Slope aspect strongly affects hydrologic processes via evapotranspiration and thus affects weathering processes and vegetation and root development, especially in drier environments (Sidle and Ochiai, 2006). Slope aspect characteristics which increase landslide occurrence were defined in previous studies (Churchill, 1982; Gao, 1993; Hylland and Lowe, 1997; Lan *et al.,* 2004). Together with slope, aspect is one of the important factors in landslide susceptibility mapping (Guzzetti *et al.,* 1999; Nagarajan *et al.,* 2000; Saha *et al.,* 2002; Cevik and Topal, 2003; Ercanoglu *et al.,* 2004; Lee *et al.,* 2004a; Lee, 2005). Aspect related parameters such as exposure to sunlight, drying winds, rainfall (degree of saturation), and discontinuities may control the occurrence of landslides (Dai *et al.,* 2001; Cevik and Topal, 2003; Suzen and Doyuran, 2004; Komac, 2006). Aspect regions are classified according to the aspect class as flat (⁻1°), north (315°–360°, 0°–45°), east (45°–135°), south (135°–225°) and west (225°–315°). The relationship between aspect and landslide susceptibility was analysed for aggregated aspect classes Fig. 2b) and Table 6.

Next to the absolute height differences surface topography controls many landslide relevant factors such as flow sources, flow direction and soil moisture concentration. Topography is an important factor in regard to the density and spatial extent of landslides (Ayalew and Yamagishi, 2005). Elevation and slope angle are considered to be the main topographic factors for landslide occurrence (Guzzetti *et al.,* 1999; Nagarajan *et al.,* 2000; Lee and Min, 2001; Clerici *et al.,* 2002; Cevik and Topal, 2003; Lee, 2005; Kelarestaghi and Ahmadi, 2009). The strong statistical relationships

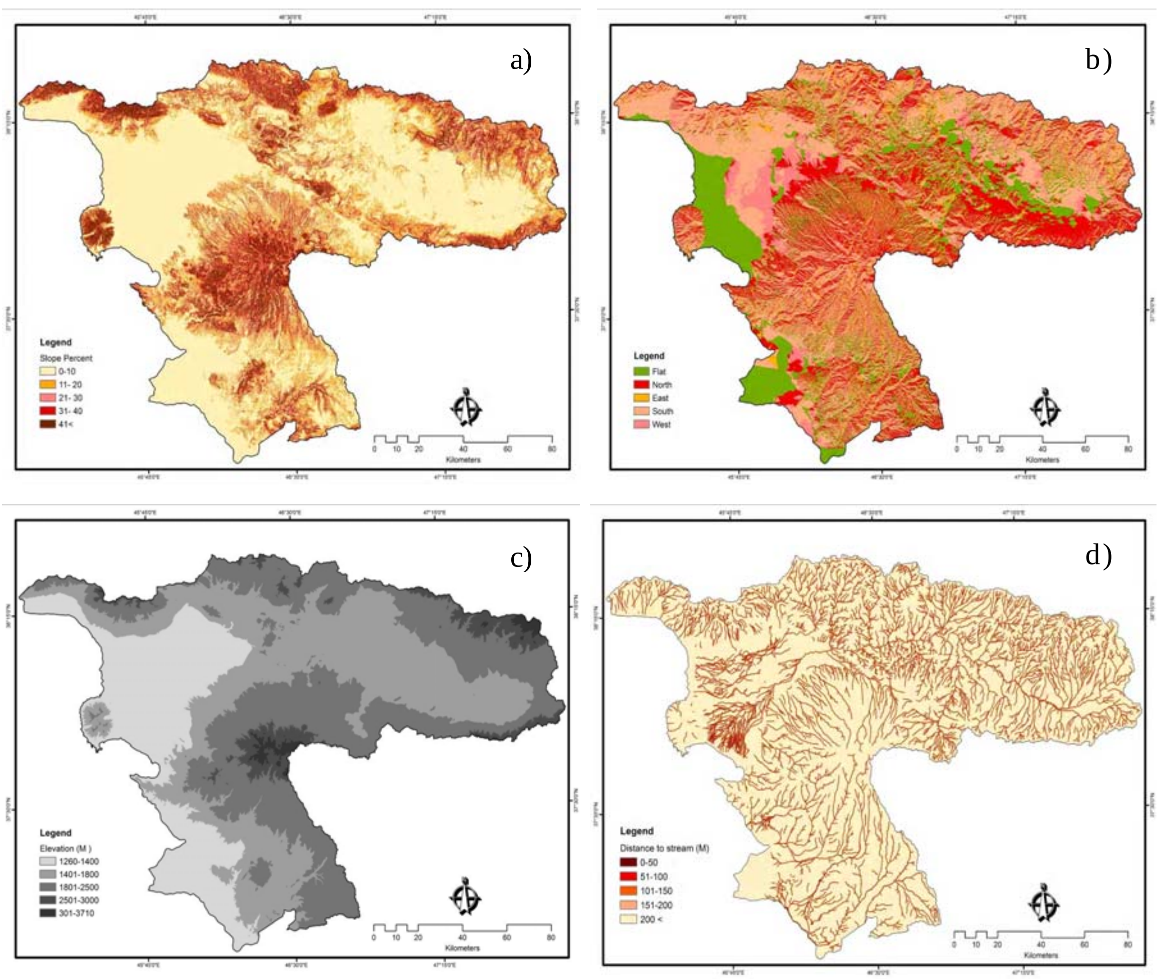

Fig. 2, a) Classification of slope map, b) Aspect map, c) Classification of digital elevation model, d) Distance to streams map

between elevation and landslide occurrence has been cited in many studies (e.g., Pachauri and Pant, 1992; Lineback Gritzner *et al.*, 2001; Dai and Lee, 2002). Fig. 2c) and Table 6 depict the classification of elevation to determine the distribution of landslide susceptibility. An important parameter that controls the stability of a slope is the saturation degree of the material on the slope. The closeness of the slope to drainage structures is another important factor in terms of stability. Streams may adversely affect stability by eroding the slopes or by saturating the lower part of material until resulting in water level increases (Gokceoglu and Aksoy, 1996; Dai *et al.*, 2001; Saha *et al.*, 2002; Cevik and Topal, 2003; Yalcin, 2005; 2008). Five different buffer areas were created to analyse the relationship between distance to streams and slopes. The results of this analysis of stream distances and landslides are shown in Fig. 2d) and Table 6.

Similar to the effect of the distance to streams, landslides may occur on the road and on the side of the slopes affected by roads (Pachauri and Pant, 1992; Pachauri *et al.*, 1998; Ayalew and Yamagishi, 2005; Yalcin, 2005). A road constructed beside slopes causes a decrease in the load on both the topography and on the heel of slope. As a result of increasing of the stress on the back of the slope because of changes in topography and decrease of load, some tension cracks may be created. On the slope of the hill that is balanced before the road is constructed, instability may be observed because of negative effects such as water ingress. In our study five different buffer zones (Fig. 3a) were created to determine the effect of the road on the stability of slope through comparing the buffer zones / distance to roads and the landslide susceptibility (Table 6).

One of the major factors in the triggering of landslides is seismicity. For the main part seismically generated landslides usually do not differ in their morphology and internal processes from those generated under non-seismic conditions (Thanh long, 2008). In this respect, faults are an important susceptibility factor. Highly faulted zones are areas of particularly high incidence of unstable slopes (Radbruch Hall, 1976) and the degree of fracturing and shearing plays an important role in determining slope stability (Varnes, 1984). Tectonics contributes to slope instability by fracturing, faulting, jointing and deforming foliation structures (Ibetsberger, 1996; Pachauri *et al.*, 1998). Distance from direct faults and the thrusts faults are known as main causative reasons for landslides: presence of these tectonic structures breaks the rock mass reducing its strength (Donati and Turrini, 2002). In this study five different buffer zones to existing faults (Fig. 3b) were created. The distribution of these buffer zones was then determined (Table 6).

Land use/cover is too often considered as a static factor in landslide hazard studies, and few researches involve constantly changing land use as a factor in the analysis (Van Beek and Van Asch, 2004; van Westen *et al.*, 2008). Land use/cover indicates indirectly that slopes are stabilized, barren, and sparsely vegetated areas exhibit faster erosion and greater instabilities than forests (Anbalagan, 1992; Turrini and Visintainer, 1998; Nagarajan *et al.*, 2000; Dai *et al.*, 2001; Cevik and Topal, 2003). Changes in land cover and land use resulting from human activities, such as deforestation, forest logging, road construction, ûre and cultivation on steep slopes can have an important impact on landslide activity (Cannon, 2000; Glade, 2003). Much work has been done to evaluate the effect of logging and deforestation on landslides (e.g. Furbish and Rice, 1983; Ziemer *et al.*, 1991). Vegetation effects on slope stability may be broadly classiûed as either hydrological or mechanical in nature. The mechanical factors consist of reinforcement of soil by roots, surcharge, wind-loading and surface protection (Greenway, 1987). The effects of vegetation cover on the hydrological processes of shallow landsliding can be subdivided into the loss of precipitation by interception, removal of soil moisture by evapotranspiration and the effects on hydraulic conductivity (Wilkinson *et al.*, 2002a, b). In this study five categories of land use/cover (Fig. 3c) were determined and compared to landslide susceptibility (Table 6).

Geology strongly influences slope stability (Sarkar *et al.*, 1995) and it is clear that there exists an association between slope instability and different types of regolith material (Sidle and Ochiai, 2006). However, this association may be strong or weak largely depending upon the type of regolith material. Examples of a strong association between landslide and different types of regolith material were given by many researchers (e.g., Yokota and Iwamatsu, 1999; Yalcin, 2008). Weathering alters the mechanical, mineralogical and hydrologic attributes of the regolith, and, hence, is an important factor of slope instability in many settings (Maharaj, 1995; Yokota and Iwamatsu, 1999; Chigira, 2002; Wakatsuki *et al.*, 2005). The geology of our study area is very complex and the lithology units comprise several formations (Table 5). The formations were therefore classified in nine categories in respect to landslide susceptibility (Fig. 3d). Table 6 reveals the resulting landslide susceptibility percentages per lithological category.

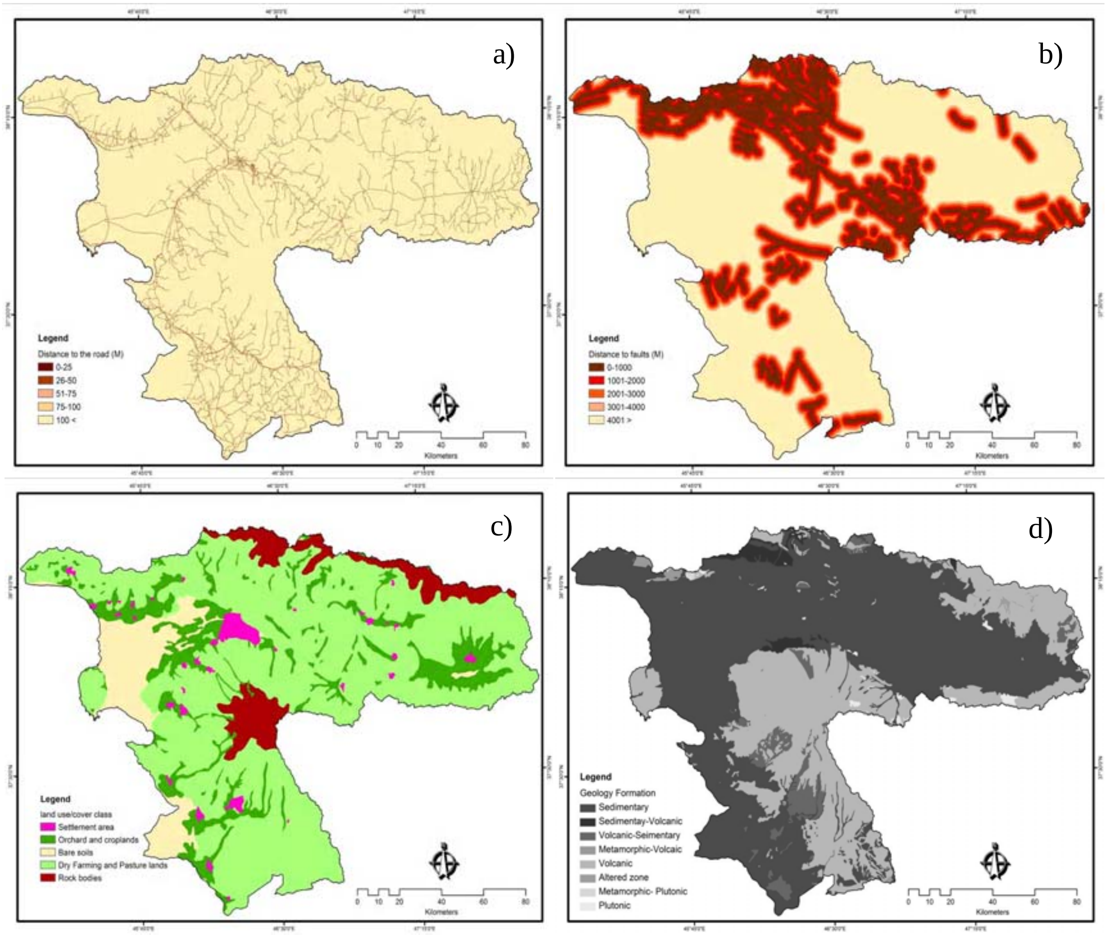

Fig. 3. a) Distance to roads, b) Distance to faults, c) Geology formation, d) Land use/cover classification

Spatial patterns of rainfall are closely associated with landslide initiation (Campbell, 1966; So, 1971, Starkel, 1976) by means of their influence to the generation of pore water pressure in unstable hill slopes (Sidle and Swanston, 1982; Iverson and Major, 1987; Tsukamoto and Ohta, 1988). Researchers usually refer to one of the four kinds of rainfall as factors of landslide initiation: (1) total rainfall, (2) short-term intensity, (3) antecedent storm precipitation, or (4) storm duration. However, it may depend on the region and on specificities what type of rainfall attributes may have the highest correlation with landslide occurrence. Some studies conclude that short-term rainfall intensity is the most important determinant (e.g., Sidle and Swanston, 1982; Keefer *et al.,* 1987). Others (Glade, 1998) found a correlation of long-term precipitation with landslide occurrences. In our methodology we use long-term precipitation for a 30 year period (1980-2010) and created a precipitation map (Fig. 4a). The landslide susceptibility percentages were calculated according to the category of precipitation by comparing the map of the precipitation and the landslide susceptibility (Table 6).

To apply the AHP approach described above, it is necessary to break a complex unstructured problem down into its component factors, arrange these factors in a hierarchic order, assign numerical values to subjective judgments on the relative importance of each factor and synthesize the judgments to determine the priorities to be assigned to these factors (Saaty and Vargas, 2001). The AHP requires the creation of a reciprocal pairwise comparison matrix. Entries into the matrix are found from comparison between each layer based on a 9-point rating scale as developed by Saaty (1977) (see Table 2), where a value of 1 is given to imply the criteria under comparison are of equal importance to the final solution and 9 expresses extreme importance of one criterion over another. Values in between are used for expressing moderate importance of one criterion over another (3), strong importance (5) and very strong importance (7). In case of the criteria being compared are deemed to be closer than indicated by this scale, one can use values in between (Robinson *et al.*, 2010). Comparisons are made by comparing the row criterion to the column criterion. If the row criterion is of less importance to the column criterion the reciprocal is used (e.g. very strongly less important would be expressed as 1/7). By definition the diagonal entries are all equal to 1 (criteria are equally important when compared to themselves) and the rating in any position i, j will be the reciprocal of that in position j, i (Robinson *et al.*, 2010). The principal eigenvector of this matrix yields the weights applicable to each layer (Malczewski, 1999; Robinson *et al.*, 2010). In this study we utilized the AHP's ability to incorporate different types of input data, and the pairwise comparison method for comparing two parameters at the same time. However, 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 susceptibility map. Consequently the weight values were determined accurately for the data sets used (Tables 3 and 4). One of the strengths of AHP is that it allows for inconsistent relationships while, at the same time, providing a consistency ratio (CR) as an indicator of the degree of consistency or inconsistency (Forman and Selly, 2001; Chen *et al.*, 2009). Therefore, we implemented the AHP in this study with an option to let the user define an acceptable CR threshold value. If the CR is greater than 0.10, it is important to be careful to accept the resulting weights without changing the inputs to the pairwise comparison matrix, and also to feel confident that the matrix really reflects the user's beliefs and does not contain errors (Bodin and Gass, 2003; Chen *et al.*, 2009; Feizizadeh and Blaschke, 2012). In our study the resulting CR for the pairwise comparison matrix for nine dataset layers was 0.053 (Table 3) indicating that the comparisons of characteristics were perfectly consistent and that the relative weights were appropriate to be subsequently used in the landslide susceptibility model. Lithology, land use/cover, slope, precipitation, distance to faults, distance to stream and aspect were found to be important parameters for the study area, whereas distance to road and elevation received a low degree of importance.

Table 2. Scales for pairwise comparisons (Saaty and Vargas 1991)

Intensity of importance	Description
1	Equal importance
3	Moderate importance
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Values for inverse comparison

Table 3. Pairwise comparison matrix, factor weights and consistency ratio of the data layers used

Factors	1	2	3	4	5	6	7	8	Eigen values
lithology									
(1) Altered zone	1								0.045
(2) Metamorphic- Plutonic	1	1							0.036
(3) Plutonic	3	3	1						0.020
(4) Volcanic	6	5	7	1					0.101
(5) Metamorphic-Volcanic	6	5	4	4	1				0.120
(6) Volcanic-Sedimentary	5	3	5	3	4	1			0.200
(7) Sedimentary-Volcanic	7	6	8	3	2	1	1		0.208
(8) Sedimentary	8	6	8	3	2	1	1	1	0.270
Consistency ratio: 0.061									
Precipitation (mm)									
(1)250 >	1								0.083
(2)251-300	3	1							0.098
(3)301-350	4	3	1						0.116
(4)350-400	7	4	1/3	1					0.301
(5)401-485	8	3	7	5	1				0.402
Consistency ratio: 0.075									

Table 3. Pairwise comparison matrix, factor weights and consistency ratio of the data layers used

Land use/cover						
(1)Settlement	1					0.053
(2)Orchard and croplands	3	1				0.067
(3)Dry-Farming & pasture lands	8	7	1			0.235
(4)Bare soil	9	8	3	1		0.320
(5) Rock bodies	9	8	3	3	1	0.325
Consistency ratio: 0.054						
Slope (°)						
(1)0-10	1					0.110
(2)10.1-20	3	1				0.173
(3)20.1-30	4	3	1			0.393
(4)30.1-40	3	3	1/3	1		0.062
(5)40.1 <	1/3	1/4	1/6	1/4	1	0.085
Consistency ratio: 0.083						
Distance to fault (m)						
(1)0-1000	1					0.514
(2)1001-2000	1/3	1				0.224
(3)2001-3000	1/5	1/3	1			0.126
(4)3001-4000	1/7	1/5	1/2	1		0.085
(5)4000 <	1/5	1/2	2	3	1	0.050
Consistency ratio: 0.024						
Distance to stream (m)						
(1)0-50	1					0.514
(2)51-100	1/3	1				0.224
(3)101-150	1/5	1/3	1			0.126
(4)151-200	1/7	1/5	1/2	1		0.085
(5)200 <	1/5	1/2	1/6	1/4	1	0.050
Consistency ratio: 0.024						
Distance to roads (m)						
(1)0-25	1					0.269
(2)26-50	4	1				0.255
(3)51-75	4	2	1			0.249
(4)76-100	4	2	1	1		0.135
(5)100 <	3	2	1	1	1	0.092
Consistency ratio: 0.002						
Aspect						
(1)Flat	1					0.036
(2)North	9	1				0.053
(3)East	1	1/8	1			0.104
(4)West	4	1/7	3	1		0.269
(5)South	9	7	7	7	1	0.511
Consistency ratio: 0.061						
Elevation (m)						
(1)1260-1400	1					0.076
(2)1401-1800	9	1				0.239
(3)1801-2500	9	8	1			0.393
(4)2501-3000	8	7	7	1		0.173
(5)3001-3710	7	1/7	1/6	1/5	1	0.119
Consistency ratio: 0.072						

Table 4. Pairwise comparison matrix for dataset layers of landslide analysis

Factors	1	2	3	4	5	6	7	8	9	Eigen values
(1) Aspect	1									0.025
(2) Distance to road	1/5	1								0.036
(3) DEM	1/2	1/3	1							0.020
(4) Distance to stream	1/3	1/3	1/3	1						0.112
(5) Distance to fault	1/3	1/5	1/5	1/3	1					0.124
(6) Slope	7	1/5	9	1/3	1/4	1				0.141
(7) Land use	8	6	1/5	1/5	1/3	1/3	1			0.160
(8) Precipitation	8	6	7	7	4	3	1/5	1		0.172
(9) lithology	9	7	1/3	8	7	4	1/5	8	1	0.210
Consistency ratio: 0.053										

Table 5. Lithology units of Urmia lake basin

Period	Rock Type	Main rock	Describ
Cambrian	Sedimentary	Dolomite	Massive cherty, recrystallized dol
Cambrian	Sedimentary	Sandstone	sandstone
Eocene	Plutonic	Gabbro	Gabbro
Lower Cretaceous	Sedimentary	Shale and other	Shale, quartzite sandstone, limestone
Lower Cretaceous	Volcanic	Volcanic rocks	Basic volcanic rocks
Lower-Middle Eocene	Volcanic	Undifferentiated lava	Undifferentiated lava flows
Lower-Middle Pliocene	Sedimentary	Clastic sediment	Fine clastic sediments with dolomite and fish beds
Lower Pliocene	Volcanic	Dacite	Sahnd dasitic dome and cone
Middle Eocene	Volcanic-Metamorphic	Latite	Metamorphic lalite
Middle Miocene	Sedimentary	Marl and other	Marl and siltstone
Miocene-Pliocene	Volcanic-Sedimentary	Tuff and other	Tuff, sandstone, siltstone, conglomerate
Oligocene	Volcanic	Andesite and other	Basaltic andesite and trachyandesite
Oligocene	Plutonic	Aplite	Aplite
Oligocene-Miocene	Plutonic	Syenite	Nepheline syenite
Paleocene	Sub-volcanic	Sub-volcanic	Dykes, sills, sub-volcanic intrusions
Paleocene-Lower Eocene	Volcanic	Submarine volcanic and other	Submarine volcanic, pyroxene andesite, analcime tephrite and trachyte
Pliocene	Volcanic	Ignimbrite	Ignimbrite
Pliocene	Volcanic-Sedimentary	Volcano-sedimentary Conglomerate	Volcano sedimentary conglomerate
Pliocene-Quaternary	Sedimentary	Lacustrine deposits	Lacustrine deposits
Pliocene-Quaternary	Volcanic	Trachyandesite and other	Trachyandesite, dacite, rhyodacite flows and volcanic dome
Poorly consolidated conglomerate	Sedimentary	Conglomerate	Poorly consolidated conglomerate
Precambrian	Metamorphic-Volcanic	Schist and other	Chlorite sericite - schist and crystal tuff
Quaternary	Sedimentary	Alluvium	Recent alluvium and Young terraces and alluvial fan
Quaternary	Sedimentary	Gravel fan	Old terraces
Quaternary	Sedimentary	Lahar and other	Lahar and conglomerate
Quaternary	Sedimentary	Limestone	Young terraces, fresh water limestone
Quaternary	Metamorphic	Mica schist	Andalusite and cordierite mica schist, amphibolite, marble and metadiabase
Quaternary	Sedimentary	Moraine	Moraine deposit
Quaternary	Sedimentary	Salt flat	Salt flat
Quaternary	Sedimentary	Siltstone and other	Silt, conglomerate and travertine
Quaternary	Sedimentary	Terraces	High level terraces
Quaternary	Sedimentary	Travertine	Travertine

Table 6. calculations landslide susceptibility classes and comparison with landslide evolution factors

Factors	Class	Area per factor class	Area per Land slide susceptibility class (%)			
		%	High	Moderate	Low	No
lithology	Altered zone	0.130	0.42	0.21	0.11	0
	Metamorphic- Plutonic	0.135	0.85	0.065	0.004	0
	Plutonic	0.45	1.76	0.875	0.246	0
	Volcanic	25.55	26.48	34.94	23.87	1.40
	Metamorphic-Volcanic	0.65	3.84	0.37	1.13	0
	Volcanic-Sedimentary	3.21	0.72	4.25	3.70	1.14
	Sedimentary-Volcanic	2.5	4.91	1.99	0.85	0
	Sedimentary	67.375	61.02	57.30	70.65	97.46
	Sum	100	100	100	100	100
Distance to fault (m)	0-1000	29.70	55.15	22.91	3.80	0
	1001-2000	17.36	18.13	14.06	5.05	0
	2001-3000	10.51	6.60	10.24	5.51	0
	3001-4000	7.95	4.7	7.76	6.42	0
	4000 <	34.48	15.42	45.03	79.22	100
	Sum	100	100	100	100	100
Land use/ cover	Settlement	1.97	0.001	1.09	4.08	0.79
	Orchard and croplands	14.67	1.14	11.05	24.68	8.45
	Dry-Farming and pasture lands	66.5	78.52	75.35	54.59	0.21
	Bare soil	8.92	0	0	13.16	90.52
	Rock bodies	7.94	20.339	12.41	3.49	0.03
	Sum	100	100	100	100	100
Precipitation (mm)	250 >	35.16	0.68	22.2	64.621	98.27
	251-300	40.37	33.93	45.71	34.27	1.73
	301-350	16.27	47.35	20.69	0	0
	350-400	6.32	10.10	8.97	1.10	0
	401-485	1.87	7.94	2.43	0.009	0
	Sum	100	100	100	100	100
Distance to roads (m)	0-25	1.64	2.28	0	0.91	0
	26-50	1.52	1.70	4.44	1.07	0.086
	51-75	1.52	1.28	51.02	1.24	0.11
	76-100	1.46	0.96	4.44	1.43	0.13
	100 <	93.86	93.78	40.1	95.35	99.674
	sum	100	100	100	100	100
Distance to stream (m)	0-50	15.47	19.34	16.62	11.80	0.087
	51-100	14.42	23.66	14.53	11.26	0.23
	101-150	12.67	17.89	12.47	10.54	0.68
	151-200	10.72	11.15	10.23	10.09	0.93
	200 <	46.71	27.96	46.15	56.31	98.073
		100	100	100	100	100
Slope (°)	0-10	58.36	4.80	48.15	82.12	99.95
	10.1-20	14.02	8.23	17.05	10.19	0.37
	20.1-30	10.58	14.16	13.73	4.8	0.004
	30.1-40	7.54	21.76	9.70	1.81	0.07
	40.1 <	9.50	51.05	11.37	1.08	0.006
	Sum	100	100	100	100	100
Aspect	Flat	22.04	0.75	12.64	38.16	78.07
	North	25.06	18.5	26.57	24.42	1.23
	East	6.89	10.76	7.98	4.43	0.57
	West	12.83	12.05	39.07	13.31	19.71
	South	33.18	57.94	13.74	19.68	0.42
	Sum	100	100	100	100	100
Elevation (m)	1260-1400	22.36	0.24	15.91	31.76	97.29
	1401-1800	36	15.87	31.79	50.30	1.81
	1801-2500	35.42	73.10	45.36	13.30	0.51
	2501-3000	4.09	10.53	5.47	3.44	0.26
	3001-3710	2.13	0.26	1.47	1.2	0.13
	Sum	100	100	100	100	100

RESULTS & DISCUSSION

In this study the AHP method was applied to develop a landslide susceptibility map for the Urmia lake basin which is located in north-western Iran. Nine landslide causal factors were taken into consideration, which include aspect, slope, elevation, distance from streams, lithology, distance from roads, distance to fault, precipitation and land use/land cover. These parameters were extracted and calculated from their associated database. The factors were evaluated, and then factor weight and class weight were assigned to each of the associated factors finally datasets are combined by weighted overlay techniques and a landslide susceptibility map of the study area is created (See Fig. 4b and c). The influences of factors on the landslide susceptibility map were evaluated qualitatively to selection of positive factors and improve the prediction accuracy of the landslide susceptibility map (Table 6). Based on the result of the obtained susceptibility map, high susceptible zones cover about 4.47% (944 km^2) of the total area while about 61.25 % (12197.29 km^2) were classified as being the moderately susceptible and 31.25 % of case study area (6224.71 km^2) were classified as a low susceptible. Remarkably, only 2.72% of case study area (541.85 km^2) was classified to having no susceptibility for landslide. In respect to the causative forces this study revealed that the most sensitive classes to landslides in the Urmia lake basin are the factors geology formation and seismicity. In particular, those Quaternary deposits, sedimentary and volcanic formations that are located within less than 1000m meter distance to existing faults and which are at the same time located on slopes steeper than 10° are potentially were highly susceptible for landslides.

The landslide susceptibility map was tested based on the known landslide locations within the study area. The landslide inventory map of the Urmia Lake Basin comprises 132 landslide events (MNR, 2010), which are used for the validation of the results of this research. The comparison reveals that about 21.2 % of known landslides in the case study area fall into the high susceptibility category, while about 75.7 % of the current (known) landslides fall into the moderately susceptible category and about 3.1% of all landslides are covered by the low susceptibility class. However, no single landslide event occurs in an area classified to have no susceptibility. Particularly the extreme values for high susceptibility and no susceptibility prove the capability of GIS-MCDA for landslide susceptibility mapping.

Landslides are natural phenomena which often have detrimental consequences. Existing landslides and landslide susceptibility can be systematically assessed using different factors and methods. For this study - and for many other studies cited herein - the major underlying assumption is that movements and landslide predisposing factors in the future will be similar to those verified in the past. From the large body of literature in this field - only a fraction could be referenced in this paper - we may conclude that predictions of future landslides are possible in a spatially differentiated although not in terms of time. This is one of the reasons that the term 'susceptibility' is increasingly used.

In this study a landslide susceptibility map has been constructed using a GIS-based MCDA approach (AHP). Results indicate that geological formations are a major controlling factor for landslides in the Urmia lake basin. The lithological units comprise several formations as presented in Table 5. From the resulting landslide susceptibility classes and from comparisons with landslide evaluation factors (Table 6), it can be concluded that the most susceptible groups for landslide occurrence fall into areas of particular geological formations. Geological outcrops have a very high susceptibility. Particularly dangerous are combinations of sedimentary layers (61.02 % of high susceptibility) and volcanic formations such as volcanic ash (26.48 % of high susceptibility). The seismicity factor can only be approximated. In this study, it was evaluated based on distances to faults. Nevertheless, also this second geological factor revealed a strong relationship with landslide susceptibility. The first category of distance to fault (0-1000m) covers about 55.15 % of all high susceptibility area.

Next to the geological factors, precipitation also turned out to have a strong relationship with landslide occurrence: areas with more than 300 mm precipitation cover about 65.39% of the total high susceptibility area. Areas with precipitation less than 300 mm cover only 24.46% of the case study area. The combination of the resulting susceptibility map and the land use indicates that the most hazardous categories were in dry-farming, pasture lands as well as rock bodies (78.52% and 20.34% high susceptibility, respectively). The relationship between landslide occurrence and slope showed that gentle slopes had a low susceptibility of landslide because of the generally lower shear stresses. At slope of 10° or less, the high susceptibility ratio was 4.80%, indicating a low probability of landslide susceptibility. For slopes above 10.1°-20°, the ratio 8.23% which indicated higher probability of landslide susceptibility however the highest rate of landslide susceptibility was in slope greater than 40° (51.05% of high susceptibility). The areas with slope steepness greater than 40° covered less than 9.50% of the area and are mostly covered by bedrocks including volcanic formation such as Tuff, sandstone, siltstone and conglomerate. South slopes also indicate a relationship with landslide susceptibility; this category covered 57.94 % of high susceptibility area of aspect criterion. Elevation also has a high relationship with landslide susceptibility. In this study area elevations from 1800 to 2500 cover 73.10% of the high susceptibility area. Elevation is certainly correlated with climate conditions which also influence mass movement and landslide. This research shows that both high precipitation and high elevation are important factors for landslide susceptibility in the Sahand Mountains. Meso-and microclimates are dominated by topography and, specific to the Sahand Mountains, by the impact of westerly winds. These winds are the most important source of precipitation in northern Iran, originating from the Mediterranean Sea. The Sahand Mountains act as a climatic barrier and cause convectional processes on the previously mentioned slopes. They also cause the Edafiki processes that result in high precipitation (Alijanei, 2000) which makes these unstable slopes very susceptible to landslides.

The only anthropogenic factor - except for land use/cover - we could use in the AHP was the road network. Distance to roads also turned out to have a strong relationship with landslide occurrence. According to literature and to local experts, this could be mainly being the result of cutting slopes during road construction and subsequent erosion processes. It turned out that the closer the distance to the road was, the greater the landslide probability was. It can be seen from table 6 that distance classes of 0-25 and 25-50 meter together account for about 3% of the total study area but for about 8% of the classes high and moderate landslide susceptibility. Drainage networks (distance to stream) also show a strong relationship with landslide occurrence. The distances classes 0-50m and 50-100m together account for 39.9% of the study area but for about 78% of the categories high and moderate susceptibility.

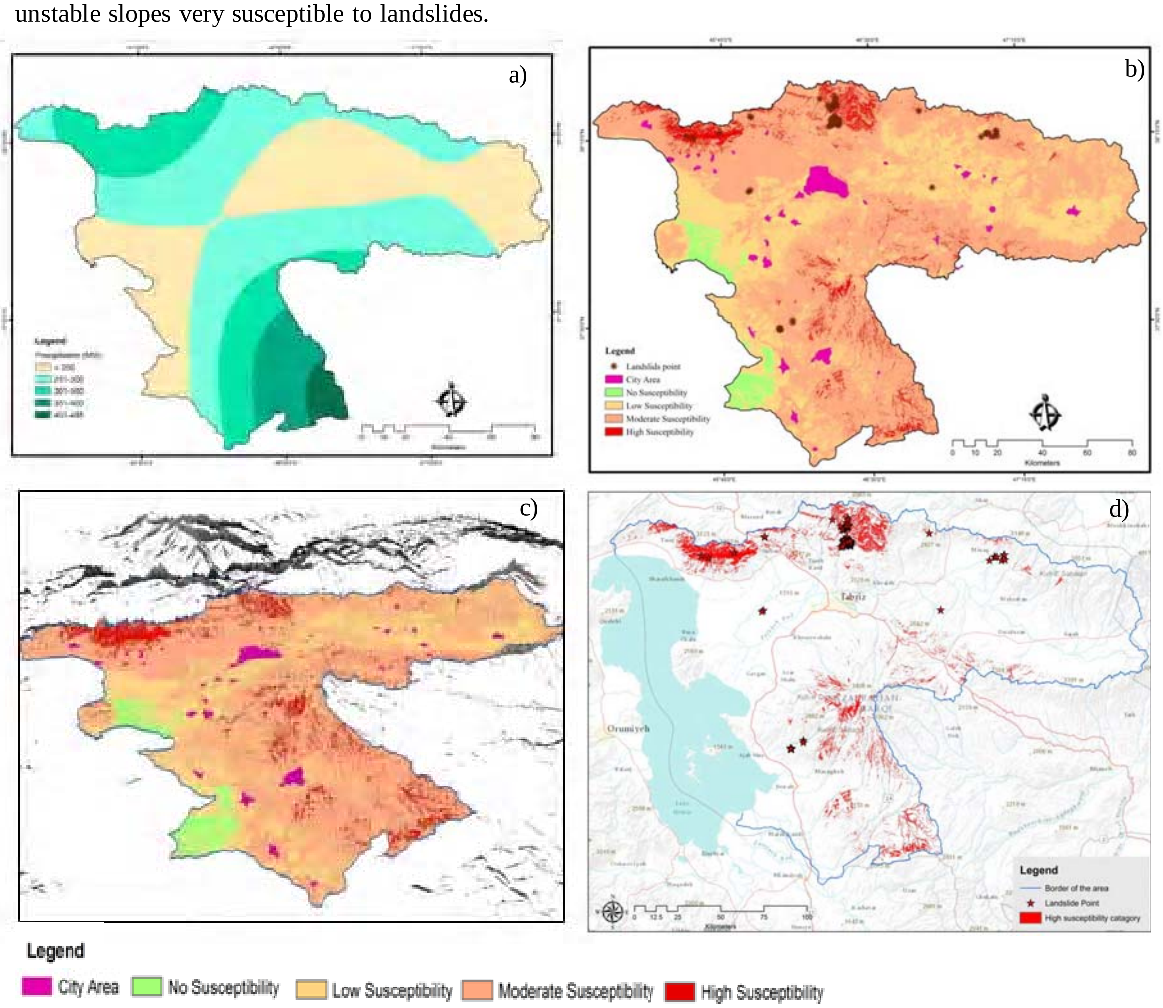

Fig. 4, a) Annual average precipitation map, b) landslide susceptibility map, c) 3D landslide susceptibility map, d) Landslide hazard and settlements in case study area

CONCLUSION

Based on landslide susceptibility map, high susceptible zones were covering most of the landslides that occurred in the unstable slopes over the last several years have been induced by precipitation (MNR, 2010). It is known that the role of precipitation as triggering mechanisms of landslides is strongly influenced by the landscape dynamic and geology. In Urmia lake basin landscapes are common, and rainfall and snowmelt (especially snow melting of Sahand glacier) often have the potential for initiating slope failures. Susceptible stratigraphy as well as weathering, contribute much for the occurrence of landslides in this area. With conditions conducive to the development of slope instability being in place in several areas, there was a demand to conduct landslide susceptibility mapping. Prepared landslide prediction map could be the basis for decisions making. The information provided by this map could help citizens, planners and engineers to reduce losses caused by existing and future landslides by means of prevention, mitigation and avoidance. If the factors relevant to the tectonic activity, vulnerability of buildings and other property were available, a hazard and risk analysis could also be done. Results of this research could be useful for explaining the known existing landslide, making emergency decisions and relieving the efforts on the avoidance and mitigation of future landslide hazards (Fig. 4d). So far, in Iran as presumably in many other parts of the world, hazard maps and risk maps usually incorporate estimated frequencies of landslides and are not based on quantitative measures and models which utilize the knowledge about existing landslides for susceptibility maps. Landslide hazard zoning have mainly been used to manage landslide hazard risk in urban areas by either limiting development in some known hazard-prone areas, and/or to requiring geotechnical engineering assessment of slope stability. It was – and still is – difficult to develop accurate maps for larger areas and particularly for areas which are less inhabited and the pressure on the planning authorities is not so high. In the future, this type of model-based susceptibility maps will be more and more accepted by local experts as we see already from this study. Future development will also include actions to explicitly designate areas in agricultural land use planning. However, in cultural landscapes the "ecological and socio-economic realms are intricately linked" (Blaschke, 2006, 201). This requires to taking more data sets into account beyond the physio-geographical, geological and infrastructure data layers. If the calculations will not get too complex so that they can still be understood by local planners and decision makers as in this study, such maps should ultimately enable: a) a better understanding of existing landslides and their origins, b) supporting emergency decisions and c) prioritization of efforts for the reduction and mitigation of future landslide hazards.

ACKNOWLEDGEMENT

The authors would like to thank the anonymous reviewers for their constructive comments on an earlier version of this paper.

REFERENCES

Afandizadeh, Sh., Kalantari, N. and Rezaeestakhruie, H. (2012). A Partial Linearization Method for Multi-Objective Continuous Network Design Problem with Environmental Considerations. Int. J. Environ. Res., **6 (2)**, 381-390.

Ahmadi, R., Mohebbi, F., Hagigi, P., Esmailly, L. and Salmanzadeh, R. (2011). Macro-invertebrates in the Wetlands of the Zarrineh estuary at the south of Urmia Lake (Iran). Int. J. Environ. Res., **5 (4)**, 1047-1052.

Akinci, H., Dogan, S., Kiliçoglu, C. and Serhan Temiz, M. (2011). Production of landslide susceptibility map of Samsun (Turkey) City Center by using frequency ratio method, International Journal of the Physical Sciences, **6 (5)**, 1015-1025.

Alaei Talganei, M. (2009). Geomorphology of Iran, edit fifth, published by Gumes, Tehran, Iran.

Atkinson, P. M. and Massari, R. (2011). Autologistic modelling of susceptibility to landsliding in the Central Apennines, Italy. Geomorphology, **130**, 55–64.

Ahadnejad Reveshty, M. and Maruyama, Y. (2010). Study of Uremia Lake Level Fluctuations and Predict Probable Changes Using Multi-Temporal Satellite Images and Ground Truth Data Period (1976-2010) New Challenge about Climate Change or Human Impact, international conference of Map Asia, Kuala Lumpur Malaysia, 26-28 July 2010.

Ayalew, L. and 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. and 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.

Ayalew, L. and Yamagishi, H. (2004). Slope movements in the Blue Nile basin, as seen from landscape evolution perspective. Geomorphology, **57 (1-2)**, 95-116.

Alijane, B. (2000). Climatology of Iran, University of Paym-E-Noor, Tehran.

Anbalagan, R. (1992). Landslide hazard evaluation and zonation mapping in mountainous terrain. Eng. Geol., **32**, 269–277.

Bai, S., Lu, G., Wang, J., Zhou, P. and Ding, L. (2011). GIS-based rare events logistic regression for landslide-susceptibility mapping of Lianyungang, China, Environ. Earth Sci., **62**, 139–149.

Bodin, L. and Gass, S. (2003). On teaching the analytic hierarchy process. Computer and Operations Research, **30**, 1487-1497.

Brimicombe, A. (2003). GIS, environmental modelling and engineering, London, New York, Taylor and Francis, 312.

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

Blaschke, T. (2006). The role of the spatial dimension within the framework of sustainable landscapes and natural capital. Landscape and Urban Planning **75(3-4),** 198-226.

Campbell, A. P. (1966). Measurement of movement of an earth flow. Soil Water, **2 (3)**, 23-24.

Chen, Y., Khan S. and Paydar, Z. (2009). To retire or expand. A fuzzy GIS-based spatial multi-criteria evaluation framework for irrigated agriculture. Irrigation and Drainage, **59 (2)**, 174–188.

Chigira, M., Nakamoto, M. and Nakata, E. (2002). Weathering mechanisms and their effects on the landsliding of ignimbrite subject to vapor-phase crystallization in the Shirakawa pyroclastic flow, northern Japan. Engineering Geology, **66 (1-2)**, 111-125.

Churchill, R. R. (1982). Aspect-induced differences in hillslope processes. Earth Surface Processes and Landforms, **7 (2)**, 171-182.

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

Cannon, S. H. (2000). Debris ûow response of southern California watersheds burned by wildûre. In: Wieczorec, G.F., Naeser, N.D. (Eds.), Debris Flow Hazards Mitigation: Mechanics, Prediction and Assessment. A.A. Balkema Publishers, Rotterdam, 45–52.

Clerici, A., Perego, S., Tellini, C. and Vescovi, P. (2002). A procedure for landslide susceptibility zonation by the conditional analysis method. Geomorphology, **48**, 349–364.

Castellanos Abella, E. A. (2008). Multi-Scale landslide risk assessment in Cuba, PhD thesis, ITC. Netherlands.

Das, I., Sahoo, S., van Westen, C., Stein, A. and Hack, R. (2010) . Landslide susceptibility assessment using logistic regression and its comparisonwith a rockmass classiûcation system, along a road section in the northern Himalayas (India). Geomorphology **114,** 627–637.

Dai, F. C., Lee, C. F., Li, J. and Xu, Z. W. (2001). Assessment of landslide susceptibility on the natural terrain of Lantau Island, Hong Kong. Environ. Geol., **43 (3)**, 381–391.

Dai, F. C. and Lee, C. F. (2002). Landslide characteristics and slope instability modelling using GIS, Lantau Island, Hong Kong. Geomorphology, **42**, 213-228.

Donati, L. and Turrini, M. C. (2002). An objective method to rank the importance of the factors predisposing to landslides with the GIS methodology: application to an area of the Apennines (Valnerina; Perugia, Italy). Engineering Geology, **63 (3-4)**, 277-289.

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

Farzin, S., Ifaei, P., Farzin. N., Hassanzadeh, Y. and Aalami, M. T. (2012). An Investigation on Changes and Prediction of Urmia Lake water Surface Evaporation by Chaos Theory. Int. J. Environ. Res., **6 (3)**, 815-824.

Feizizadeh, B., Blaschke, T. and Rafiq, L. (2011). GIS based landslide susceptibility mapping: a case study Bostan Abad County, Iran, G4DM - International Conference of Geoinformatics for Disaster Management, Antalya, Turkey.

Feizizadeh, B. and Blaschke, T. (2011). Landslide Risk Assessment Based on GIS Multi-Criteria Evaluation: A case Study Bostan Abad County, Iran. Journal of Earth Science and Engineering, **1**, 66-71.

Feizizadeh, B. and Blaschke, T. (2012). Land suitability analysis for Tabriz County, Iran: a multi-criteria evaluation approach using GIS, Journal of Environmental Planning and Management, DOI:10.1080/09640568.2011.646964.

Feizizadeh, B., Blaschke, T. and Nazmfar, H. (2012). GIS-based Ordered Weighted Averaging and Dempster Shafer Methods for Landslide Susceptibility Mapping in Urmia lake Basin, Iran, International Journal of Digital Earth (*in press*).

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E. Z. and Savage, W. (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. Engineering Geology, **102**, 99–111.

Forte, F., Pennetta, L. and Strobl, R. O. (2005). Historic records and GIS applications for ûood risk analysis in the Salento peninsula (southern Italy). Nat. Hazards Earth Syst. Sci., **5**, 833–844.

Forman, E. H. and Selly, M. A. (2001). Decision by Objective, How to Convince Others That You are Right. World Scientific Publishing Co. Pte. Ltd, Singapore.

Furbish, D. J. and Rice, R. M. (1983). Predicting landslides related to clearcut logging, Northwestern California, USA. Mountain Research and Development, **3**, 253–259.

Kohler, P., Müller, M., Sanders, M. and Wächter, J. (2006) .Data management and GIS in the Center for Disaster Management and Risk Reduction Technology (CEDIM): from integrated spatial data to the mapping of risk. Nat. Hazards Earth Syst. Sci., **6**, 621–628.

Kelarestaghi, A., Ahmadi, H. (2009). Landslide susceptibility analysis with a bivariate approach and GIS in Northern Iran, Arab J. Geosci., **2**, 95-101.

Kimmance, J. P., Bradshaw, M. P. and Seetoh, H. H. (1999). Geographical Information System (GIS) Application to Construction and Geotechnical Data Management on MRT Construction Projects in Singapore, Tunnelling Underground Space Tech., **14 (4)**, 469–479.

Keefer, D. K., Wilson, R. C., Mark, R. K., Brabb, E. E., Brown, W. M., Ellen, S. D., Harp, E. L., Wieczorek, G. F., Alger, C. S. and Zatkin, R. S. (1987) .Real-time landslide warning during heavy rainfall. Science, **238**, 921-925.

Hossain, M. S. and Das, N. G. (2009). GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (*Macrobrachium rosenbergii*) farming in Companigonj Upazila of Noakhali, Bangladesh. Computers and Electronics in Agriculture, **70**, 172–186.

Hylland, M. D. and Lowe, M. (1997). Regional landslide-hazard evaluation using landslide slopes, western Wasatch Country, Utah. Environment and Engineering Geoscience, **3 (1)**, 31-43.

ICC, (2007). Iranian Census Centre. From http://www.amar.org.ir.

Ibetsberger, H. J. (1996). The Tsergo Ri landslide: an uncommon area of high morphological activity in the Langthang valley, Nepal. Tectonophysics, **260**, 85-93.

Iverson, R. M. and Major, J. J. (1987). Rainfall, ground-water flow, and seasonal movement at Minor Creek landslide, northwestern California: physical interpretation of empirical relation. Geological survey. America Bulletin, **99**, 579-594.

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.

Khezri, S. (2011). Landslide susceptibility in the Zab Basin, northwest of Iran. Procedia Social and Behavioral Sciences, **19**, 726–731.

Lan, H. X., Zhou C. H., Wang, L. J., Zhang, H.Y. and Li R. H. (2004). Landslide hazard spatial analysis and prediction using GIS in the Xiaojiang watershed, Yunnan, China. Engineering Geology, **76 (1–2)**, 109–128.

Lan, H. X., Martin, C. D., Froese, C. R., Kim, T. H., Morgn. A. J., Chao, D. and Chowdhury, S. (2009). A web-based GIS for managing and assessing landslide data for the town of Peace River, Canada, Nat. Hazards Earth Syst. Sci., **9**, 1433–1443.

Lee, S., Choi, J. and 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. and Park, H. (2004b). Determination and application of the weight for landslide susceptibility mapping using an artificial neural network. Engineering Geology, **71**, 289–302.

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. and Min, K. (2001). Statistical analysis of landslide susceptibility at Yongin, Korea. Environment Geology, **40**, 1095–1113.

Lineback Gritzner, M., Marcus, W. A., Aspinall, R. and Custer, S. G. (2001). Assessing landslide potential using GIS, soil wetness modeling and topographic attributes, Payette River, Idaho. Geomorphology, **37**, 149-165.

Malczewski, J. (2004) GIS-based land-use suitability analysis: a critical overview. Progress in Planning, **62 (1)**, 3-65.

MNR, (2010). Ministry of Natural Resources, East Azerbaijan Province, Landslide event report, Tabriz, Iran.

Malczewski, J. (2006). GIS-based multicriteria decision analysis: a survey of the literature. International Journal of Geographical Information Science, **20 (7)**, 703–726.

Malczewski, J. (1999). GIS and Multicriteria Decision Analysis, Wiley, Toronto.

Maharaj, R. (1995). Engineering-geological mapping of tropical soils for land-use planning and geotechnical purposes: a case study from Jamaica, West Indies. Engineering Geology, **40**, 243-286.

Nagarajan, R., Roy, A., Vinod Kumar, R., Mukherjee, A. and Khire, M. V. (2000). Landslide hazard susceptibility mapping based on terrain and climatic factors for tropical monsoon regions. Bull. Eng. Geol. Environ., **58**, 275–287.

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

Nekhay, O., Arriaza, M., Guzmán-Álvarez, J. R. (2008). Spatial analysis of the suitability of olive plantations for wildlife habitat restoration. Computers and Electronics in Agriculture, **65**, 49-64.

Robinson, T. P., van Klinken, D. R. and Metternicht, G. (2010). Comparison of alternative strategies for invasive species distribution modelling. Ecological Modelling, **221**, 2261–2269.

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

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, **15**, 231-281.

Saaty, T. L, Vargas, L. G. (1991). Prediction, Projection and Forecasting. Kluwer Academic Publisher, Dordrecht, 251.

Sarkar, S., Kanungo, D. P., Mehrotra, G. S. (1995). Landslide hazard zoning: a case study in Garhwal Himalaya, India. Mountain Research and Development, **15 (4)**, 301-309.

So, C. L. (1971). Mass movements associated with the rainstorm of June 1966 in Hong Kong. Inst. British Geographers Trans, **53**, 55-65.

Starkel, L. (1976). The role of extreme (catastrophic) meteorological events in the contemporary evolution of slopes. In: Derbyshire, E. (ed), Geomorphology and Climate, John Wiley and Sons, New York. 203-246.

Sidle. R. C. and Swanston, D. N. (1982). Analysis of a small debris slide in coastal Alaska. Canadian geotechnical journal, **19**, 167-174.

Sidle, R. C. and Ochiai, H. (2006). Landslides: processes, prediction, and landuse. American Geophysical Union, Water Resources Monograph. Washington, D.C.

Suzen, M. L. and 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.

Pachauri, A. K. and Pant, M. (1992). Landslide hazard mapping based on geological attributes. Engineering geology, **32**, 81-100.

Pachauri, A. K., Gupta, P. V. and Chander, R. (1998). Landslide zoning in a part of the Garhwal Himalayas. Environmental Geology, **36**, 325–334.

Parsons, R. L., Frost, J. D. (2000). Interactive analysis of spatial sub-surface data using GIS-Based tool, J. Comput. Civ. Eng., **14 (4)**, 215–222.

Parise, M. (2001). Landslide mapping techniques and their use in the assessment of the landslide hazard. Physics and Chemistry of the Earth, **26**, 697–703.

Perotto-Baldiviezo, H. L., Fisher, R. F., Wu, X. B., Thurow, T. L., Smith, C. T. (2004). GIS-based spatial analysis and modeling for landslide hazard assessment in steeplands, Southern Honduras. Agriculture, Ecosystems and Environment, **103 (1)**, 165–176.

Padma, S., Shanmuga, Priyaa, S., Saravanan, K. and Sanjeevi, S. (2011). Landslide susceptibility mapping of the Munnar region of southern India using remote sensing and grass GIS, Disaster, Risk and Vulnerablity Conference 2011, School of Environmental Sciences, in association with Mahatma Gandhi University, India, Applied Geoinformatics for Society and Environment, Germany.

Prakash, T. N. (2003). Land Suitability Analysis for Agricultural Crops: A Fuzzy Multicriteria Decision Making Approach. MSc thesis in ITC, http://www.ITC.com.

Radbruch Hall, D. H. (1976). Map showing areal slope stability in part of the northern Coast Ranges, California. U.S. Geol. Survey Map 1-982.

Salehi, E., Zebardast, L. and Yavri, A. R. (2012). Detecting Forest Fragmentation with Morphological Image Processing in Golestan National Park in northeast of Iran. Int. J. Environ. Res., **6 (2)**, 531-536.

Tsukamoto, Y. and Ohta, T. (1988). Runoff processes on a steep forested slope. Journal of Hydrology, **102**, 165-178.

Turrini, M. C. and Visintainer, P. (1998). Proposal of a method to deûne areas of landslide hazard and application to an area of the Dolomites, Italy. Eng. Geol., **50**, 255–265.

Tiwari, D. N., Loof, R. and Paudyal, G. N. (1999). Environmental-economic decision-making in lowland irrigated agriculture using multi-criteria analysis techniques. Agricultural Systems, **60**, 99-112.

Thanh long, N. (2008). Landslide susceptibility mapping of the mountainous area in a Luoi District, thua thien hue province, Vietnam, PhD Thesis, Department of Hydrology & Hydraulic Engineering, University of Brussels.

Van Westen, C. J., Van Asch, T. W. J. and Soeters, R. (2005). Landslide hazard and risk zonation; why is it still so difûcult? Bulletin of Engineering geology and the Environment, **65 (2)**, 167–184.

Van Westen, C. J., Castellanos, E. and Kuriakose, S. L. (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview, Engineering Geology, **102 (3–4)**, 112–131.

Varnes, D. J. (1987). Slope movement types and processes. National Academy of Sciences, Washington, D.D, 11-33.

Varnes, D. J. (1984). Intern. Assoc. of Engineering Geology Comm. on Landslides and Other Mass Movements on Slopes: Landslide hazard zonation: a review of principles and practice, UNESCO Band 63, Paris.

Van Beek, L. P. H. and Van Asch, T. W. J. (2004) Regional assessment of the effects of land-use change and landslide hazard by means of physically based modeling. Natural Hazards, **30 (3)**, 289–304.

Vos, F., Rodriguez, J., Below, R. and Guha-Sapir, D. (2010). Annual Disaster Statistical Review 2009: The Numbers and Trends, Centre for Research on the Epidemiology of Disasters (CRED), Université catholique de Louvain, Brussels, Belgium.

Wakatsuki, T., Tanaka, Y. and Matsukura, Y. (2005) .Soil slips on weathering-limited slopes underlain by coarse-grained granite or fine- grained gneiss near Seoul, Republic of Korea. Catena, **60 (2)**, 181-203.

Wilkinson, P. L., Anderson, M. G., Lloyd, D. M. and Renaud, J. P. (2002a). Landslide hazard and bioengineering: towards providing improved decision support through integrated numerical model development. Environmental Modelling & Software, **17 (4)**, 333–344.

Wilkinson, P. L., Anderson, M. G. and Lloyd, D. M. (2002b). An integrated hydrological model for rain-induced landslide prediction. Earth Surface Processes and Landforms, **27**, 1285–1297.

Jadda, M., Shafri, H. M. Z., Mansor, S. B., Sharifikia, M. and Pirasteh, P. (2009). Landslide Susceptibility Evaluation and Factor Effect Analysis Using Probabilistic-Frequency Ratio Model. European Journal of Scientific Research, **33 (4)**, 654-668.

Joo Oh, H. and Pradhan, P. (2011). Application of a neuro-fuzzy model to landslide-susceptibility mapping for shallow landslides in a tropical hilly area, Computers & Geosciences, **37**, 1264–1276.

Goetz, J. N., Guthrie R. H. and Brenning, A. (2011). Integrating physical and empirical landslide susceptibility models using generalized additive models. Geomorphology, **129**, 376–386.

Gao, J. (1993). Identification of topographic settings conductive to landsliding from DEM in Nelson County. Earth Surface Process and Landforms, **18**, 579-591.

Glade, T. (2003). Landslide occurrence as a response to land use change: a review of evidence from New Zealand. CATENA, **51 (3–4)**, 297–314.

Glade, T. (1998). Establishing the frequency and magnitude of landslide- triggering rainstorm events in New Zealand. Environmental Geology, **35 (2-3)**, 160-174.

Greenway, D. R. (1987). Vegetation and slope stability. In: Anderson, M.G., Richards, K.S. (Eds.), Slope Stability. John Wiley and Sons Ltd., West Sussex, England.

Guzzetti, F., Carrara, A., Cardinali, M. and 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.

Guzzetti, F. (2000) Landslide fatalities and the evaluation of landslide risk in Italy. Slop Engineering Geology, **58 (2)**, 89-170.

Yokota, S. I. and Wamatsu, A. (1999). Weathering distribution in a steep slope of soft pyroclastic rocks as an indicator of slope instability. Engineering Geology, **55**, 57-68.

Yalcin, A. (2005). An investigation on Ardesen (Rize) region on the basis of landslide susceptibility. PhD Thesis, Karadeniz Technical University, Trabzon, Turkey.

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.

Yu, J., Chen, Y. and Wu, J. (2011). Cellular automata based spatial multi-criteria l and suitability simulation for irrigated agriculture. International Journal of Geographical Information Science, **25 (1)**, 131–148.

Ziemer, R. R., Lewis, J., Rice, R. M. and Lisle, T. E. (1991). Modelling the cumulative effects of forest management strategies. Journal of Environmental Quality, **20 (1)**, 36–42.

Zillman, J. (1999). The physical impact of disaster. In. J. Ingleton (Editor), Natural disaster management. Tudor Rose Holding Ltd., Leicester, 320.