Assessment of landslide susceptibility for a landslide-prone area (north of Yenice, NW Turkey) by fuzzy approach

Murat Ercanoglu · Candan Gokceoglu

Abstract Regional landslide susceptibility assessments pose complex problems. To solve these problems, numerous approaches, such as statistical analysis, geotechnical engineering approach, geomorphologic approach and fuzzy logic, have been employed. However, all the available methods for regional landslide susceptibility assessments have some uncertainties due to a lack of knowledge and variability. Minimizing these uncertainties provides realistic approaches. Use of the fuzzy logic approach to produce a landslide susceptibility map of a landslide-prone area in NW Turkey is the main purpose of the present study. For this purpose, the study includes five main stages, these being the preparation of a landslide inventory of the study area, the application of factor analysis, the extraction of fuzzy if-then rules, the use of a geographical information system, and the control of the reliability of the resulting landslide susceptibility map. Slope angle, slope aspect, land use, weathering depth, water conditions and topographical elevation were considered as landslide conditioning factors for the study area. A total of 23 if-then rules was extracted from the field data. Employing these rules, fuzzified index maps representing each parameter were obtained. Finally, combining these maps, the landslide susceptibility map of the area was prepared. When compared with the landslide susceptibility map, the landslides identified in the area were found to be located in the very high- and high-susceptibility zones. As far as the performance of the fuzzy approach for processing is concerned, the images appear to be quite satisfactory, the zones determined on the map being zones of relative susceptibility.

Keywords Fuzzy sets · Landslide inventory · Landslide susceptibility map · Yenice (NW Turkey)

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Introduction

Particularly in the last two decades, the assessments of landslide susceptibility, hazard and risk have became an important subject for engineers, earth scientists, planners and decision makers, because landslide susceptibility, hazard and risk maps are of great help to planners for selecting suitable areas to implement development schemes in any area. In addition, the other reasons for the international interest in landslide assessments are twofold: firstly, an increasing awareness of the socio-economic significance of landslides, and secondly, the increased pressure of development and urbanization on the environment (Aleotti and Chowdhury 1999). Although numerous studies have been published on the preparation of landslide susceptibility and hazard maps based on stochastic/statistical modeling, weighted hazard ratings based on environmental attributes related to landsliding, geologic or geotechnical attributes, process-based landscape models, etc., mapping studies using fuzzy approaches are limited (for example, Juang and others 1992; Davis and Keller 1997; Binaghi and others 1998).

In Turkey, economic losses and casualties due to landslides are great. In other words, landslides are the second major natural hazard in Turkey (Ildir 1995). Especially the West Black Sea region of Turkey is affected by landslides. The region exhibits slightly mountainous topographical features and it is frequently subjected to heavy precipitation. Due to these negative effects, the region is prone to extensive and severe landslides. The purpose of the present study is to produce a landslide susceptibility map of a landslide-prone area of 100 km^2 (Fig. 1) in the West Black Sea region, based on fuzzy approach. For this purpose, the study includes five main stages: (1) the preparation of a landslide inventory of the study area by field studies; (2) the application of multivariate statistical analysis (factor analysis) to determine the important weights of the parameters; (3) the use of fuzzy logic to extract the if-then

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rules; (4) the use of geographical information systems to produce the index maps representing the factors and the susceptibility map; and (5) the control of the reliability of the susceptibility map produced.

Methodology

When producing landslide susceptibility maps, some researchers (Carrara and others 1991; Anbalagan 1992; Juang and others 1992; Maharaj 1993; Gokceoglu and Aksoy 1996; Van Westen and others 1997; Atkinson and Massari 1998; Pachauri and others 1998; Guzzetti and others 1999; Gritzner and others 2001; Sakellariou and Ferentinou 2001) have employed quantitative methods, such as statistical analyses, geotechnical engineering approaches, neural networks and fuzzy logic. However, all the available methods for regional landslide assessment have some uncertainties arising from a lack of knowledge and variability. This is because regional landslide assessments require some generalizations and simplifications, although these assessments are complex. For this reason, a perfect assessment method for landslide susceptibility does not exist. The fuzzy logic introduced by Zadeh (1965) is one of the tools to solve these complex problems. Unlike classical set theory, fuzzy-set theory is flexible, and it focuses on the degree of being a member of a set (Berkan and Trubatch 1997). In addition, the advantages of the fuzzy logic approach to solve engineering geological problems can be summarized as follows (Alvarez Grima 2000):

1. it allows express explicit expression of the knowledge of the system via fuzzy if-then rules;
2. it deals with subjective uncertainty (fuzziness, vagueness, imprecision) inherent to the way experts approach their problems;
3. numerical and categorical data can be combined;
4. it provides a sound mathematical basis.

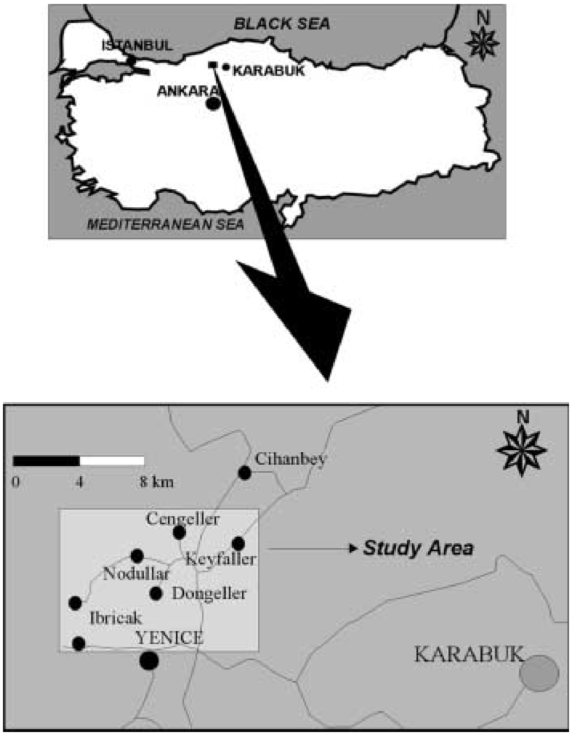

Fig. 1
Location map of the study area

To form a landslide database for the study area (see Fig. 1), an extensive field study including the description of landslide characteristics was performed. Mapping of the landslides is the first stage of the field studies. Subsequent to the mapping study, the dimensions of the landslides were measured using a steel tape 50 m long. In addition, slope angle, dip direction of movement, and weathering depth were measured. Other features, such as land use, vegetation cover, type of slope (convexity or concavity of slope) before failure, mode of failure, etc., were documented and all data were recorded on the landslide inventory sheets. During the field studies, 57 landslides were identified (Fig. 2). All the landslides occurred in the Ulus formation, and their mode of failure is circular (Fig. 3). Although geology, mode of failure and type of slope are very important in terms of landslide activity, these characteristics were accepted as constant parameters. Slope angle, slope aspect, land use, weathering depth, water conditions and topographical elevation were taken into consideration as conditioning parameters for the landslides in the study area.

The if-then rules and fuzzy sets representing each factor were extracted from the field data. These rules were employed in the preparation of index maps of the conditioning parameters and the landslide susceptibility map. When producing the index maps representing slope angle, slope aspect and topographical elevation in the study area, a digital elevation model (Fig. 4) prepared from a 1/25,000-scale topographical map of the area was employed.

General characteristics of the area

The study area (see Fig. 1) is covered completely by the Ulus formation (see Fig. 2). This formation has a flysch character and its age is Upper Cretaceous. This unit is known as being landslide-sensitive in the region. In other words, the majority of the landslides occurred in the weathering zone of the Ulus formation. This unit is formed mainly by sandstone, siltstone and marl alternations. In addition to the alternation, the flysch occasionally includes conglomerates, limestones and quartzites. Especially quartzites and limestones form the steep slopes and high topographical elevations in the area, and do not exhibit the slope instabilities.

The topographical elevation values of the study area vary between 106 and 1,150 m, whereas the dominant topographical elevation range is 401–500 m. The study area has a dendritic drainage pattern and slightly mountainous character. The general physiographic trend of the study

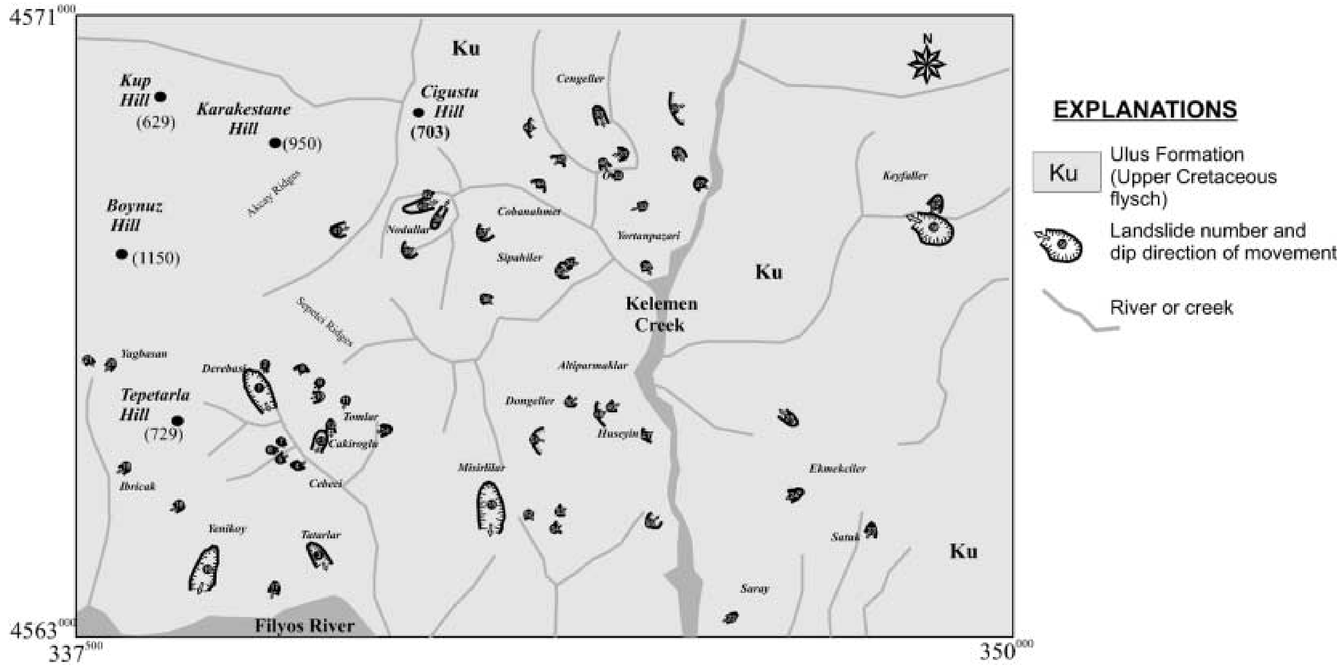

Fig. 2
Geological map of the study area and the distribution of the identified landslides

area is NW–SE. Although the range of slope angle values are 0 to 80°, the majority are between 16 and 20°. The main stream in the study area is the Filyos River, the biggest river of the West Black Sea region. The general stream direction of the Filyos River in the study area is from east to west and it discharges into the Black Sea. The other important flow in the area is the Kelemen Creek (see Fig. 2). It flows from north to south and discharges into the Filyos River. In addition, there are many subsidiary intermittent streams flowing only after rainy periods. In the study area, the highest hill is Boynuz Hill which has a topographical elevation value of 1,150 m (see Fig. 2). The largest settlement in the close vicinity of the area is Yenice, located at the south border of the study area. However, due to topographical restrictions and landslide activity, there are many small scattered villages. The majority of the area is covered by forest (83%). The other parts of the study area are utilized for agricultural (12%),

Fig. 3
General view of an identified landslide in the area

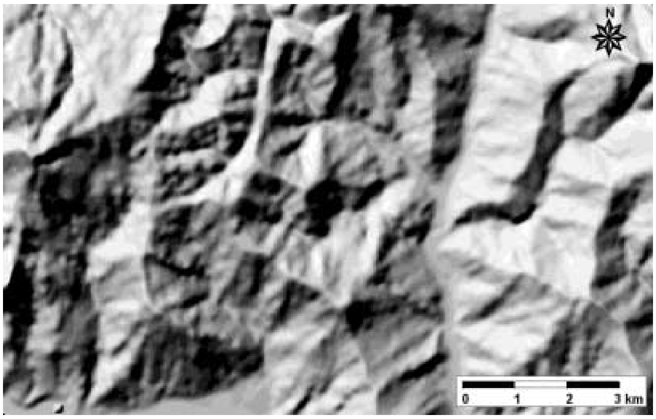

Fig. 4
Shaded relief map of the study area

settlement (3%) and pasture (2%) purposes (Demir and Ercan 1999).

Average annual total precipitation at the Yenice meteorology station was measured as 703 mm for the long period. The most rainy month is December (87.5 mm) and the driest month is September (34.7 mm). The average temperature is 14 °C in the region (DMI 1995).

Factors conditioning the landslides in the area

Slope angle

One of the most important factors controlling the stability of slopes is known to be slope angle. It is possible to determine the critical slope angle using conventional stability analysis approaches. However, in regional assessments, many researchers (Roth 1983; Koukis and Ziourkas 1991; Anbalagan 1992; Pachauri and Pant 1992; Maharaj 1993; Jager and Wieczorek 1994; Anbalagan and Singh 1996; Zezere and others 1999; Jakob 2000; Guzzetti and others 2000; Nagarajan and others 2000) prefer statistical techniques for the evaluation of slope angle in terms of landslide activity. In the study area, the steep slopes are generally formed by the hard limestones and quartzites of the Ulus formation. These units are resistant to landslide. The study area has slope angles varying in the range 0–80° (Fig. 5). However, as seen in Fig. 6, landslide frequency reached a peak value at slope angles of 26–30°. Although Pachauri and Pant (1992) indicated that the frequency of landslides is higher on steeper slopes (>35°) irrespective of the lithology, the evaluation of the results obtained from the present study did not show a similar meaning. When slopes exceed 45°, a sharp decrease in the landslide frequency values was observed.

Topographical elevation

Pachauri and Pant (1992) reported that the higher relief shows a greater susceptibility to sliding. However, in the area studied, the higher topographical elevations are formed by the lithological units resistant to landslide. Also, the higher topographical elevations of the study area are covered by dense forest. Due to this feature, there is good agreement between landslide frequency and topographical elevations of 100–500 m (Fig. 7). To assess topographical

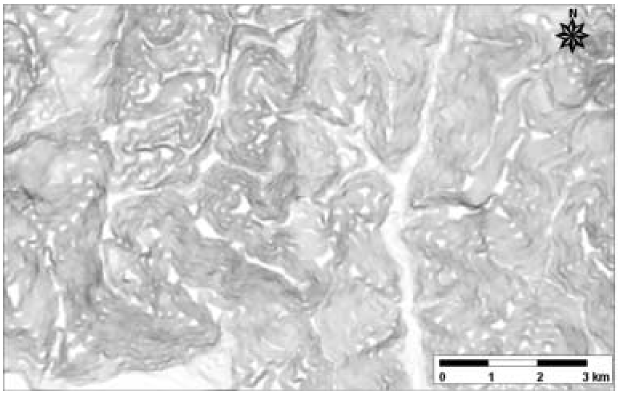

Fig. 5
Slope map of the study area

Fig. 6
Slope degree frequency of the identified landslides in the area

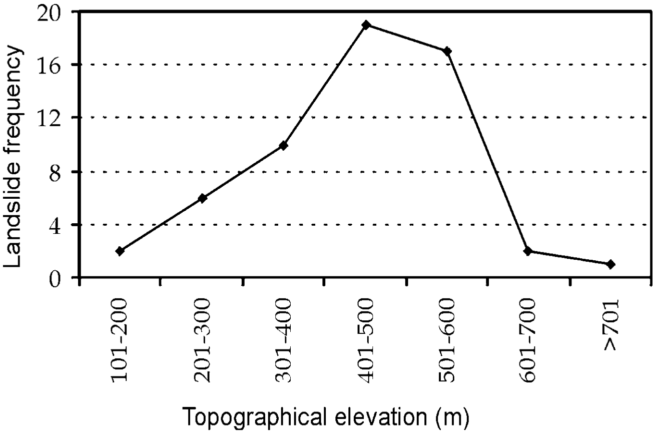

Fig. 7
Topographical elevation frequency of the identified landslides in the area

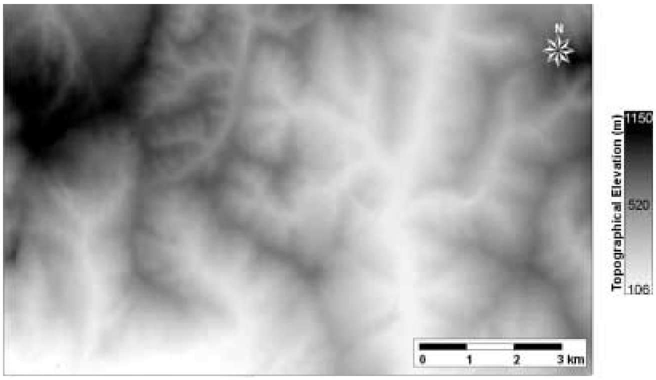

Fig. 8
Topographical elevation map of the area

elevation as an input parameter for the landslide susceptibility map, a topographical elevation map was prepared (Fig. 8) from the digital elevation model.

Slope aspect

Although the relationship between slope aspect and mass movement has long been investigated, no general agreement exists on the slope aspect (Carrara and others 1991). Some authors (Carrara and others 1991; Maharaj 1993; Gokceoglu and Aksoy 1996; Jakob 2000; Nagarajan and others 2000) have taken slope aspect into consideration as a factor controlling landslides whereas other investigators, such as Uromeihy and Mahdavifar (2000), have not considered slope aspect as a conditioning factor. In fact, the slope aspect is related to the general physiographic trend of the area and/or the main precipitation direction. The general physiographic trend of the area is NW–SE, and an important part of the landslides observed in the study area dip to the NE and SW (Fig. 9). The relationship between the dip direction of movement identified in the area and the general physiographic trend of the area is roughly perpendicular. In addition to slope and elevation maps, a slope aspect map (Fig. 10) was produced as well.

Weathering depth

Pachauri and Pant (1992) assumed the influence of weathering to be uniform, although anomalous conditions could exist in some parts in their case. For this reason, they emphasized that weathering must be taken into consideration in certain cases. Similarly, Nagarajan and others (2000) reported that weathering is a major factor influencing the potential failure surface. Field observations of the present study indicated that the failures occurred

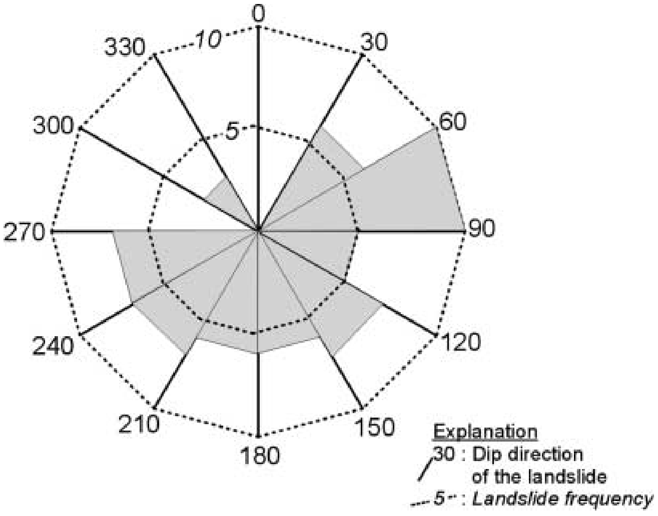

Fig. 9
Distribution of the dip direction frequency of the movements in the area

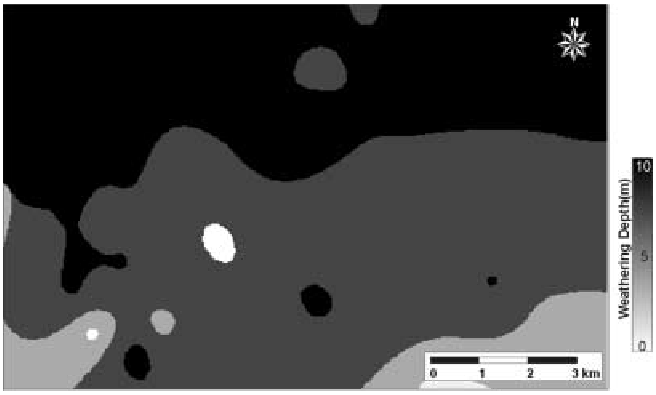

Fig. 11
Weathering depth map of the area

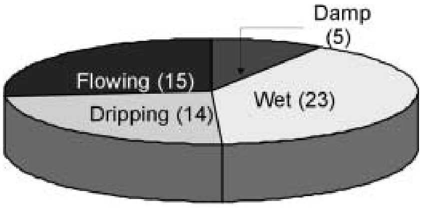

Fig. 12
Distribution of water conditions for the landslides in the area

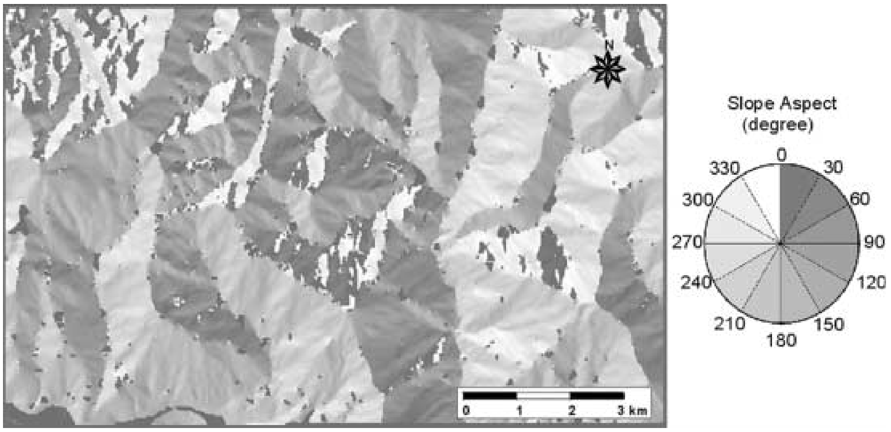

Fig. 10
Slope aspect map of the area

within the weathering zone of the Ulus formation in the form of circular failure. For this reason, weathering depth was considered as a landslide conditioning factor, and the weathering depth parameters for each landslide were recorded during the field studies. In addition, weathering depths were measured on road cuts and used for producing the weathering depth map. A weathering depth map (Fig. 11) was obtained by plotting the weathering depth values measured during the field studies on a geographic coordinate system.

Water conditions

Due to the slightly mountainous nature and dense vegetation cover of the study area, no direct evaluation of the groundwater conditions was carried out as no drill-hole data were available. However, the groundwater has a vital importance for the stability of slopes. Although Anbalagan (1992) indicated that the evaluation of observations of the behavior of groundwater on hill slopes is not possible over large areas, for quick appraisals the nature of surface indications of groundwater behavior will provide valuable information on the stability of hill slopes for hazard mapping purposes (Anbalagan 1992). To overcome the difficulties about the evaluation of water conditions, Anbalagan (1992) proposed a simple and useful classification for the assessment of water conditions when studying large areas. In the present study, the water-condition classification suggested by Anbalagan (1992) was employed to assess this parameter. According to the results obtained from the evaluation of the data, the majority of the failure surfaces are wet (Fig. 12) whereas a few are damp. According to the opinion of the authors, this map (Fig. 13) is open to discussion, because this observation depends mainly on the working season. Despite this conflict, the observational assessment has an ability to provide some useful information.

Land use

Most of the study area is covered by forest (Fig. 14). It is well known that land use and vegetation cover play important roles in the stability of slopes. Several researchers (Koukis and Ziourkas 1991; Anbalagan 1992; Maharaj 1993; Fernandez and others 1999; Jakob 2000; Uromeihy and Mahdavifar 2000) emphasized the importance of vegetation cover or land-use characteristics on the stability of slopes, and they used these parameters to assess the conditioning factors of landslides. However, these parameters, especially the influence of vegetation, is still open to discussion as mentioned by Greenway (1987), although several researchers accept that vegetation has positive effects on slope stability. It is clear that landslide frequency is very low (0.17 landslide/km^2) in forested areas whereas this value reaches 21.1 landslide/km^2 in pasturelands. According to these results, the positive influences of forest on the stability of slopes is indisputable for the study area.

Factor analysis

Some authors have used elementary and multivariate statistical techniques for the description of landslide conditioning factors (Roth 1983; Carrara and others 1991; Atkinson and Massari 1998; Luzi and Pergalani 1999; Zezere and others 1999). There are numerous approaches in the statistical techniques to allow consideration of changes in several properties simultaneously. Generally, multivariate methods are complicated, both in their theoretical structure and in their operational methodology (Davis 1973). In natural landslide activity, it is unlikely to isolate the conditioning factors individually. For this reason, to explain the important weights of the conditioning factor becomes a very complex problem. In the present study, factor analysis was preferred to explain the important weights of the conditioning factors.

The general purpose of factor analysis is to interpret the structure within the variance-covariance matrix of a multivariate data collection. The technique which it uses is extraction of the eigenvalues and eigenvectors from the matrix of correlations or covariances (Davis 1973). For this reason, in the first process of the statistical studies, a covariance matrix was obtained (Table 1) using the data collected from the field to perform the factor analysis. All statistical calculations were carried out using

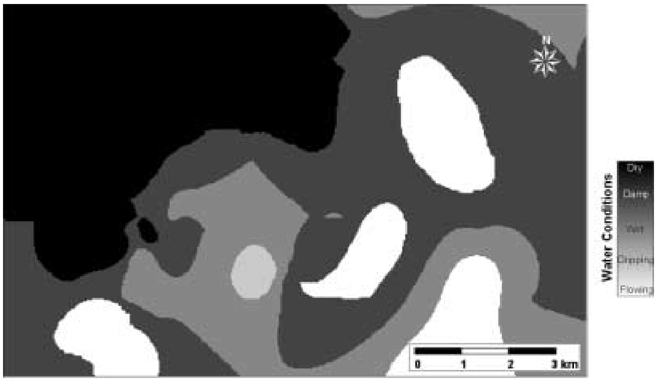

Fig. 13
Water condition map of the area

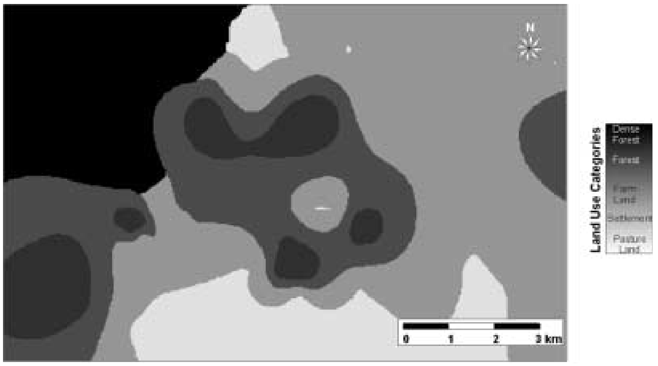

Fig. 14
Land-use map of the area

Table 1
Covariance matrix obtained from the data of the conditioning factors

Parameter	Covariances					
	Slope angle	Land use	Topographical elevation	Dip direction of movement	Water conditions	Weathering depth
Slope angle	0.07262	−0.03488	0.00377	−0.01557	0.00537	0.01544
Land use	−0.03488	0.17343	0.01935	0.02026	0.03290	0.00316
Topographical elevation	0.00377	0.01935	0.04214	−0.00141	0.00406	0.00674
Dip direction of movement	−0.01557	0.02026	−0.00141	0.03637	−0.00075	0.00848
Water conditions	0.00537	0.03290	0.00406	−0.00075	0.06888	0.03013
Weathering depth	0.01544	0.00316	0.00674	0.00848	0.03013	0.04318

Table 2
Factor analysis results obtained from STATGRAPH

Parameter	Eigenvalue	Percent variation	Cumulative percent
Slope angle	0.19739	45.2	45.2
Land use	0.09762	22.4	67.6
Topographical elevation	0.05470	12.5	80.1
Dip direction of movement	0.03862	8.8	88.9
Water conditions	0.03512	8.0	97.0
Weathering depth	0.01317	3.0	100.0

the statistical software STATGRAF (STSC 1991). The final process of the statistical studies is the factor analysis employing the covariance matrix (see Table 1). The results obtained from the factor analysis are given in Table 2. According to these results, the important weight of slope angle is the highest whereas that of weathering depth is the lowest.

Rule consequents and fuzzified maps

For inference in a rule-based fuzzy model, the fuzzy propositions need to be represented by an implication function. The implication function is called a fuzzy if-then rule or a fuzzy conditional statement (Alvarez Grima 2000).

A fuzzy set is a collection of paired members which consist of members and degrees of "support" or "confidence" for those members. In a discrete form, the fuzzy set "about 7" might be expressed as (0.1/5, 0.7/6, 1/7, 0.7/8, 0.1/9). In a fuzzy-set notation, the members after the slash (/) are members of the set (or appropriate numerical grades in each case), and the values before the slash are the degrees of confidence or "membership" of those numbers. The use of fuzzy sets to represent linguistic terms enables one to represent more accurately and consistently something which is fuzzy (Juang and others 1992). A linguistic variable whose values are words, phrases or sentences are labels of fuzzy sets (Zadeh 1973). In the present study, the following fuzzy sets were used to express the input parameters in linguistic forms:

1. Very low=(1/1, 0.75/2, 0.5/3, 0.25/4, 0/5)
2. Low=(0/1, 0.25/2, 0.75/3, 1/4, 0/5)
3. Moderate=(0/1, 0.5/2, 1/3, 0.5/4, 0/5)
4. High=(0/1, 1/2, 0.75/3, 0.25/4, 0/5)
5. Very high=(0/1, 0.25/2, 0.5/3, 0.75/4, 1/5).

In addition to input sets, the outputs of each parameter were also classified into five groups in terms of landslide susceptibility. All data-driven output membership graphs together with their inputs are illustrated in Fig. 15. The degrees of memberships in the fuzzy-set representations for the outputs were obtained from the results of factor analysis. The increase in membership values of the outputs indicates their higher susceptibility to landslide. The fuzzy-set representations of the conditioning parameters of the landslides are obtained as follows:

1. Slope angle=(0/1, 0.453/2, 0.38/3, 0.06/4, 0/5)
2. Land use=(0/1, 0.03/2, 0.04/3, 0.13/4, 0.224/5)
3. Topographical elevation=(0/1, 0.06/2, 0.125/3, 0.01/4, 0/5)
4. Slope aspect=(0/1, 0.088/2, 0.059/3, 0.04/4, 0/5)
5. Water conditions=(0/1, 0.02/2, 0.08/3, 0.05/4, 0.06/5)
6. Weathering depth=(0/1, 0.03/2, 0.01/3, 0.009/4, 0/5).

Rules

Employing the fuzzy sets representing the inputs and outputs as expressed above, the following rules were extracted.

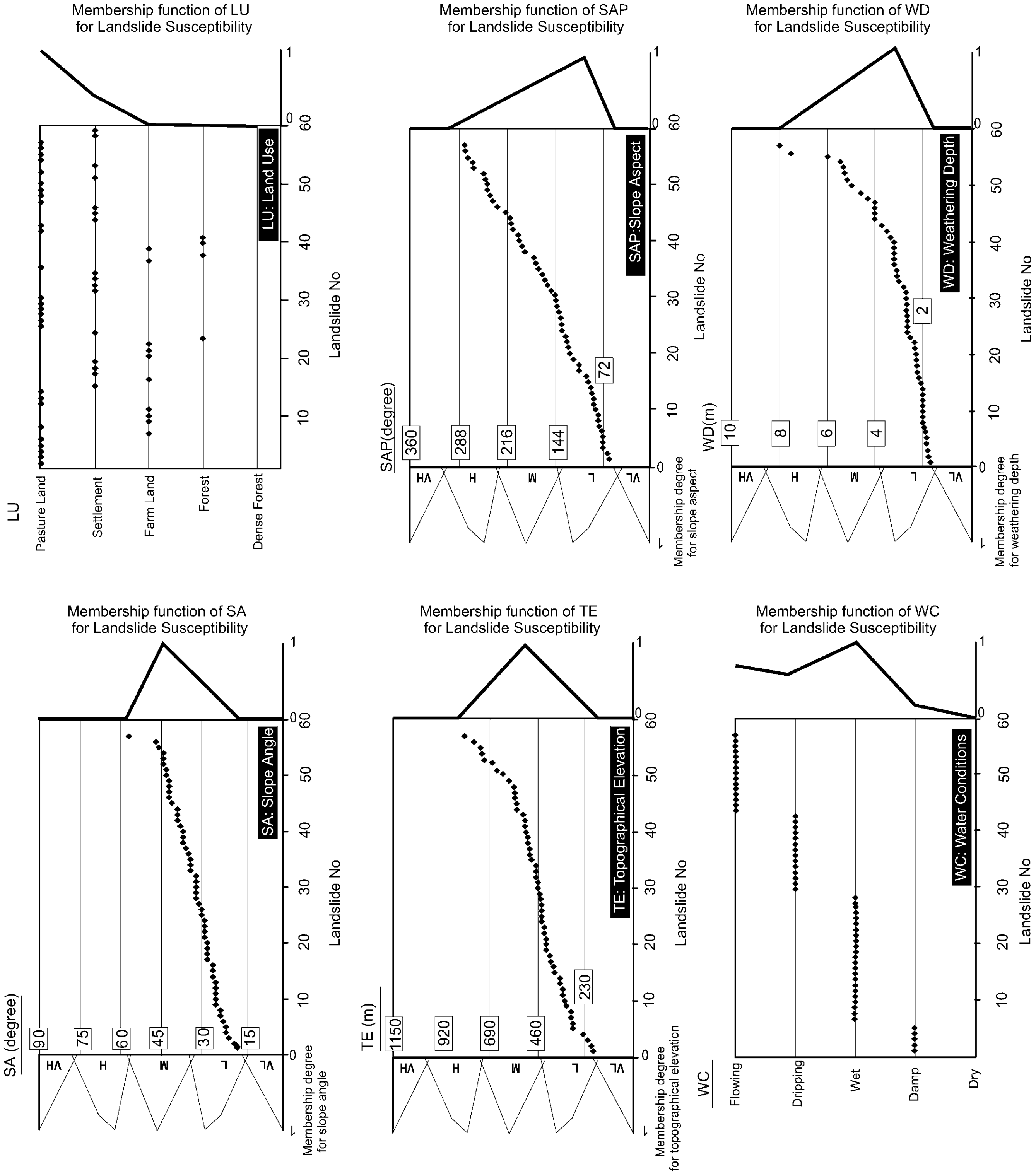

Fig. 15
Membership graphs of the inputs and outputs

Rule 1

1. If slope angle is low or moderate then landslide susceptibility is high.
2. If slope angle is high then landslide susceptibility is low.
3. If slope angle is very high or very low then landslide susceptibility is non-susceptible.

Rule 2

1. If land use is forest or farmland then landslide susceptibility is low.
2. If land use is settlement then landslide susceptibility is moderate.

3. If land use is pastureland then landslide susceptibility is high.
4. If land use is dense forest then landslide susceptibility is non-susceptible.

Rule 3

1. If topographical elevation is moderate then landslide susceptibility is high.
2. If topographical elevation is low then landslide susceptibility is moderate.
3. If topographical elevation is high then landslide susceptibility is low.
4. If topographical elevation is very low or very high then landslide susceptibility is non-susceptible.

Rule 4

1. If slope aspect is low then landslide susceptibility is high.
2. If slope aspect is moderate then landslide susceptibility is moderate.
3. If slope aspect is high then landslide susceptibility is low.
4. If slope aspect is very low or very high then landslide susceptibility is non-susceptible.

Rule 5

1. If water condition is wet then landslide susceptibility is high.
2. If water condition is dripping or flowing then landslide susceptibility is moderate.
3. If water condition is damp then landslide susceptibility is low.
4. If water condition is dry then landslide susceptibility is non-susceptible.

Rule 6

1. If weathering depth is low then landslide susceptibility is high.
2. If weathering depth is moderate then landslide susceptibility is moderate.

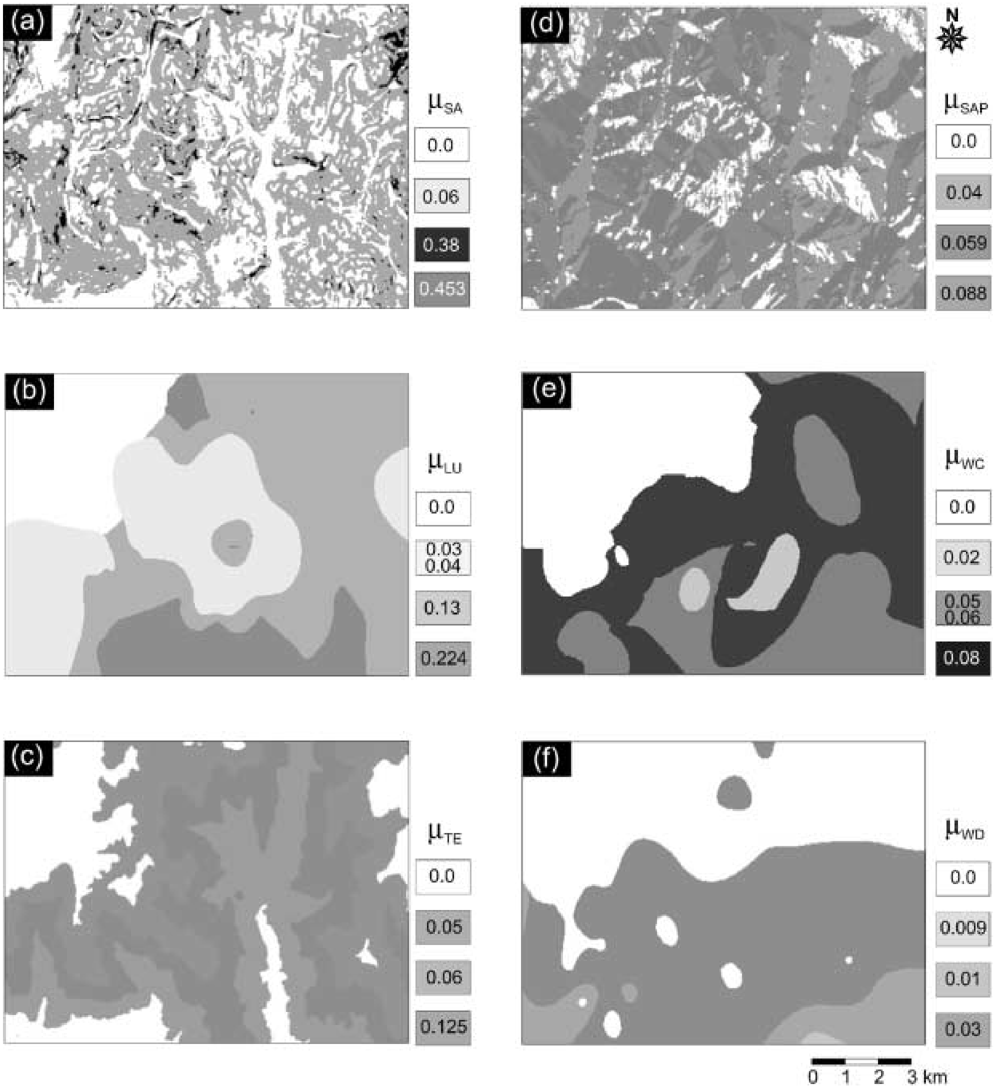

Fig. 16a–f
Fuzzified index maps representing **a** slope angle, **b** land use, **c** topographical elevation, **d** slope aspect, **e** water conditions, and **f** weathering depth

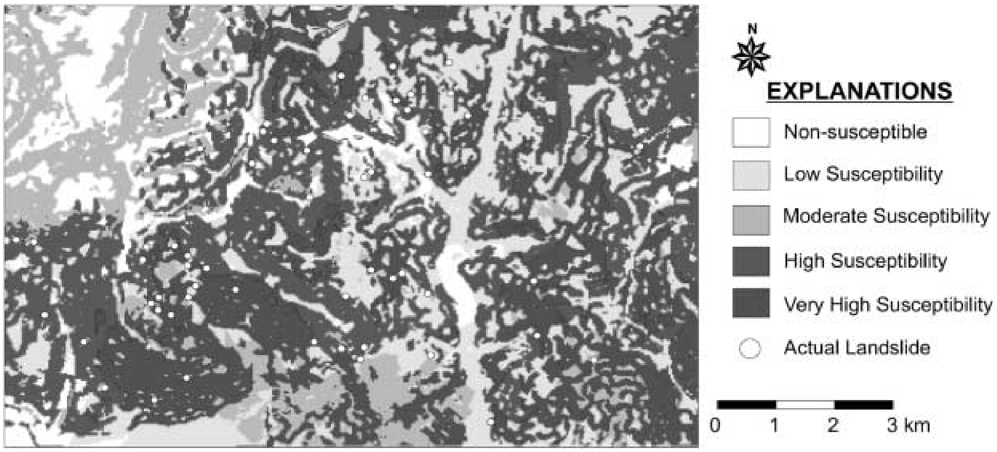

Fig. 17
Landslide susceptibility map of the study area

Table 3
Summary of the results obtained from the landslide inventory and the landslide susceptibility map

Landslide susceptibility class	Area (km^2)	Number of landslides observed	Number of landslides per km^2
Non-susceptible	10	0	0
Low susceptibility	23	1	0.04
Moderate susceptibility	14	3	0.21
High susceptibility	29	28	0.97
Very high susceptibility	24	25	1.04

3. If weathering depth is high then landslide susceptibility is low.
4. If weathering depth is very low or very high then landslide susceptibility is non-susceptible.

Considering the fuzzy if-then rules expressed above, the fuzzified index maps representing slope angle, land use, topographical elevation, slope aspect, water conditions and weathering depth were produced (Fig. 16) using the previously produced maps (see Figs. 5, 8, 10, 11, 13 and 14). When producing the fuzzified index maps, a grid-based geographic analysis system, namely IDRISI (Eastman 1992), was used. For example, when producing the fuzzified slope index map, the slope map of the area (see Fig. 5) and the rules 1.1, 1.2 and 1.3 were processed together using the macros developed in this study for IDRISI (Eastman 1992).
Finally, all the fuzzified index maps were combined by overlaying and a landslide susceptibility map condensed to five classes for the study area was produced (Fig. 17).

Reliability of the produced susceptibility map

In fact, the procedure followed during the study should find the locations of the landslides identified in the area, because the employed rules were extracted from the field data. For this reason, to control the performance of the produced susceptibility map, a comparison between the landslide susceptibility class zones on the map and the number of landslides per km^2 was carried out (Table 3). Fifty-three of the landslides in the area were located in the high and very high susceptible zones. In other words, 93% of the landslides are in these zones. This is an acceptable result for a medium-scale landslide susceptibility map, and the use of fuzzy sets in the preparation of the landslide susceptibility map seems to be a reliable approach.

Results and conclusions

In the present study, landslide susceptibility in a landslide-prone area located in NW Turkey was assessed using fuzzy sets and if-then rules. For this purpose, an extensive field study to obtain the landslide inventory database for the area, a factor analysis to determine the important weight of each conditioning factor, fuzzy sets and if-then rules to produce the fuzzified index maps, and a grid-based geographic analysis system to overlay the fuzzified index maps and to produce the landslide susceptibility map for the study area were used.
The actual landslides observed in the area are generally of shallow-circular type. Since the study area is covered completely by flyschoid formations, namely the Ulus formation, the geology was accepted as a constant parameter for the study area. According to the results obtained from the factor analysis, slope degree is the major factor controlling the landslides in the area whereas weathering depth has a minor effect. In all, 23 if-then rules were extracted to produce the fuzzified index maps representing each parameter influencing the landslides identified in the area. The final stage of the study is the production of the landslide susceptibility map showing the five relative landslide susceptibility zones. According to the classification results of the susceptibility map, the percentage of high and very high susceptible zones was found to be 53%, the great majority of the identified landslides being located in these zones. Consequently, the results of the procedure

followed herein are acceptable for a medium-scale landslide susceptibility map.

The main benefits of the fuzzy approach for the present study are to provide a mathematical basis expressing each conditioning factor and a combination of numerical and categorical data.

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References

Aleotti P, Chowdhury R (1999) Landslide hazard assessment: summary review and new perspectives. Bull Eng Geol Environ 58:21–44

Alvarez Grima M (2000) Neuro-fuzzy modeling in engineering geology. Balkema, Rotterdam

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

Anbalagan R, Singh B (1996) Landslide hazard and risk assessment mapping of mountainous terrains – a case study from Kumaun Himalaya, India. Eng Geol 43:237–246

Atkinson PM, Massari R (1998) Generalised linear modelling of susceptibility to landsliding in the central Appenines, Italy. Comput Geosci 24(4):373–385

Berkan RC, Trubatch SL (1997) Fuzzy systems design principles, building fuzzy if-then rule bases. IEEE Press, New York

Binaghi E, Luzi L, Madella P, Rampini A (1998) Slope instability zonation: a comparison between certainty factor and fuzzy Dempster-Shafer approaches. Nat Hazards 17:77–97

Carrara A, Cardinali M, Detti R, Guzzetti F, Pasqui V, Reichenbach P (1991) GIS techniques and statistical models in evaluating landslide hazard. Earth Surf Proc Landforms 16:427–445

Davis JC (1973) Statistics and data analysis in geology. Wiley, Chichester

Davis TJ, Keller CP (1997) Modeling uncertainty in natural resource analysis using fuzzy sets and Monte Carlo simulation: slope stability prediction. Int J Geogr Inf Sci 11(5):409–434

Demir B, Ercan S (1999) Yenice ilcesindeki heyelanlar uzerine bazi gozlemler. In: Abstr Book 3rd Natl Symp Landslides of Turkey, Cukurova University, Adana, pp 16

DMI (1995) Annual book of rainfall and temperature records. State Meteorological Organisation, DMI Press, Ankara

Eastman JR (1992) IDRISI: A grid-based geographic analyses system, user's guide, version 4.1. Clark University, Massachusetts

Fernandez CI, Del Castillo TF, El Hamdouni R, Montero JC (1999) Verification of landslide susceptibility mapping: A case study. Earth Surf Proc Landforms 24:537–544

Gokceoglu C, Aksoy H (1996) Landslide susceptibility mapping of the slopes in the residual soils of the Mengen region (Turkey) by deterministic stability analyses and image processing techniques. Eng Geol 44:147–161

Greenway DR (1987) Vegetation and slope stability. In: Anderson MG, Richards KS (eds) Slope stability – geotechnical engineering and geomorphology. Wiley, Chichester, pp 187–230

Gritzner ML, Marcus WA, Aspinall R, Custer SG (2001) Assessing landslide potential using GIS, soil wetness modeling and topographic attributes, Payette River, Idaho. Geomorphology 37:149–165

Guzzetti F, Carrara A, Cardinali 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

Guzzetti F, Cardinali M, Reichenbach P, Carrara A (2000) Comparing landslide maps: A case study in the Upper Tiber River Basin, central Italy. Environ Manage 25(3):247–263

Ildir B (1995) Turkiyede heyelanlarin dagilimi ve afetler yasasi ile ilgili uygulamalar. In: Onalp A (ed) Proc 2nd Natl Landslide Symp Turkey, Sakarya University, pp 1–9

Jager S, Wieczorek GF (1994) Landslide susceptibility in the Tully Valley Area, Finger Lakes Region. US Geol Surv Open-File Rep 94-615

Jakob M (2000) The impacts of logging on landslide activity at Clayoquot Sound, British Columbia. Catena 38:279–300

Juang CH, Lee DH, Sheu C (1992) Mapping slope failure potential using fuzzy sets. J Geotech Eng ASCE 118(3):475–493

Koukis G, Ziourkas C (1991) Slope instability phenomena in Greece: A statistical analysis. Bull Int Assoc Eng Geol 43:47–60

Luzi L, Pergalani F (1999) Slope instability in static and dynamic conditions for urban planning: the "Oltre Po Pavese" case history (Regione Lombardia-Italy). Nat Hazards 20:57–82

Maharaj R (1993) Landslide processes and landslide susceptibility analysis from an upland watershed: a case study from St. Andrew, Jamaica, West Indies. Eng Geol 34:53–79

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

Pachauri AK, Pant M (1992) Landslide hazard mapping based on geological attributes. Eng Geol 32:81–100

Pachauri AK, Gupta PV, Chander R (1998) Landslide zoning in a part of the Garhwal Himalayas. Environ Geol 36(3-4):325–334

Roth RA (1983) Factors affecting landslide susceptibility in San Mateo County, California. Bull Assoc Eng Geol 20(4):353–372

Sakellariou MG, Ferentinou MD (2001) GIS-based estimation of slope stability. Nat Hazards Rev 2(1):12–21

STSC (1991) Statgraphics. Statistical procedures reference manual, version 5. STSC Inc

Uromeihy A, Mahdafivar MR (2000) Landslide hazard zonation of Khorshrostam area, Iran. Bull Eng Geol Environ 58:207–213

Van Westen CJ, Rengers N, Terlien MTJ, Soeters R (1997) Prediction of the occurrence of slope instability phenomena through GIS-based hazard zonation. Geol Rundsch 86:404–414

Zadeh LA (1965) Fuzzy sets. Inf Cont 8:338–353

Zadeh LA (1973) Outline of a new approach to the analysis of complex systems and decision processes. IEEE Trans Syst Man Cyber 3:28–44

Zezere JL, Ferreira AB, Rodrigues ML (1999) Landslides in the north of Lisbon region (Portugal): Conditioning and triggering factors. Phys Chem Earth (A) 24(10):925–934