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Application of logistic regression for landslide susceptibility zoning of Cekmece Area, Istanbul, Turkey

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Abstract As a result of industrialization, throughout the world, cities have been growing rapidly for the last century. One typical example of these growing cities is Istanbul, the population of which is over 10 million. Due to rapid urbanization, new areas suitable for settlement and engineering structures are necessary. The Cekmece area located west of the Istanbul metropolitan area is studied, because the landslide activity is extensive in this area. The purpose of this study is to develop a model that can be used to characterize landslide susceptibility in map form using logistic regression analysis of an extensive landslide database. A database of landslide activity was constructed using both aerial-photography and field studies. About 19.2% of the selected study area is covered by deep-seated landslides. The landslides that occur in the area are primarily located in sandstones with interbedded permeable and impermeable layers such as claystone, siltstone and mudstone. About 31.95% of the total landslide area is located at this unit. To apply logistic regression analyses, a data matrix including 37 variables was constructed. The variables used in the forwards stepwise analyses are different measures of slope, aspect, elevation, stream power index (SPI), plan curvature, profile curvature, geology, geomorphology and relative permeability of lithological units. A total of 25 variables were identified as exerting strong influence on landslide occurrence, and included by the logistic regression equation. Wald statistics values indicate that lithology, SPI and slope are more important than the other parameters in the equation. Beta coefficients of the 25 variables included the logistic regression equation provide a model for landslide susceptibility in the Cekmece area. This model is used to generate a landslide susceptibility map that correctly classified 83.8% of the landslide-prone areas.

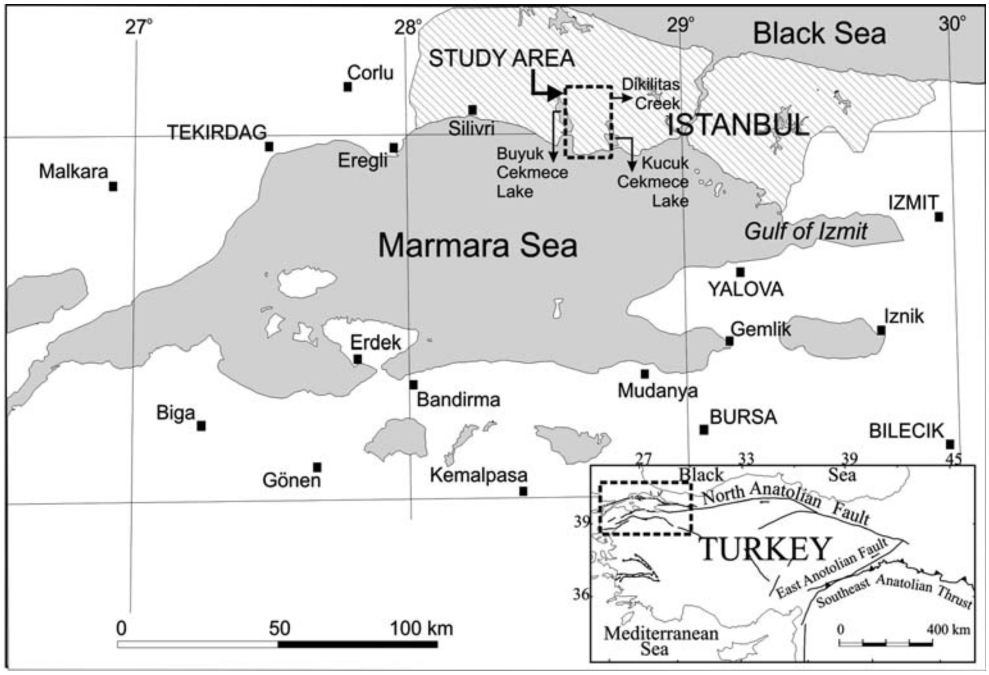
Keywords Landslide susceptibility · Cekmece (Istanbul) · Logistic regression · Landslide inventory

Introduction

In Turkey, landslides are one of the important natural hazards when considering the loss of lives, economic losses and environmental impacts. In each year, landslides damaged many buildings throughout Turkey, and resulted in deaths and destruction of farmlands and roads. Regional landslide susceptibility assessments are thus crucial for landslide-prone areas in Turkey. Within this framework, earth sciences and geomorphology in particular, may play relevant role in assessing areas at high landslide hazard and in helping to mitigate the associated risks, providing a valuable aid to a sustainable progress. Tools for handling and analysing spatial data (i.e. GIS) may facilitate the application of quantitative techniques in landslide hazard assessment and mapping (Guzzetti et al. 1999). However, it is possible to find many studies in literature for the landslide susceptibility and hazard mapping. Landslide susceptibility and hazard maps can be produced either by using direct mapping techniques or by using indirect mapping techniques. Direct (inferential) hazard mapping, in which the degree of hazard is determined by the mapping geomorphologist, based on his experience and knowledge of the terrain conditions (van Westen et al. 1999). Indirect hazard mapping, in which either statistical models or deterministic models are used to predict landslide prone areas, based on information obtained from the interrelation between landscape factors and the landslide distribution (van Westen et al. 1999). In recent years, many studies on the indirect landslide susceptibility mapping have been published that rely on advancements in GIS and the digital cartography. It is also possible to produce a landslide susceptibility map that utilizes various indirect mapping techniques such as combination of index maps (e.g. Anbalagan and Singh 1996; Gokceoglu and Aksoy 1996; Turrini and Visintainer 1998; Ayenew and Barbieri 2005), statistical analyses (e.g. Atkinson and Massari 1998; Lee and Min 2001; Pistocchi et al. 2002; Ayalew and Yamagishi 2005; Can et al. 2005), probabilistic approaches (e.g. Gokceoglu et al. 2000; Gritzner et al. 2001; Gokceoglu et al. 2005), neural networks (e.g. Lee et al. 2004; Gomez and Kavzoglu 2005) and fuzzy approaches (e.g. Juang et al. 1992; Binaghi et al. 1998; Ercanoglu and Gokceoglu 2002). Each landslide susceptibility assessment method considered by landslide community has some advantages and drawbacks. For this reason, among the landslide researchers, there is no agreement either on the methods or on the scope of producing hazard maps (Brabb 1984).

A 100 years ago, roughly five percent of the world's people lived in cities with populations over 100,000. Today, an estimated 45% about 2.5 billion people live in urban areas. In recent years, the most explosive growth has been in the developing world, where urban populations have tripled in the last 30 years. Between the years of 1950 and 1995, the number of cities with population of more than 1 million doubled, from 49 to 112: in that same period, cities of more than 1 million people in the third World increased sixfold, from 34 to 213 (Helmore 1996). One typical example among the cities having explosive growth is Istanbul. This metropolitan city, located in the northern west of Turkey, is the most crowded city of Turkey with a population of above 10 million. Due to rapid growth of Istanbul, new settlement areas are needed and the study area is one of the new settlement areas of Istanbul. In the study area (Fig. 1), new apartment buildings, houses having two or three stories and factories have been constructed, in addition to new roads, highways and lifelines. As can be seen in Fig. 2, many structures in the study area are constructed in active landslides and/or the areas susceptible to landsliding. Considering the importance of the west of Istanbul, including the study area of the present study, a geohazard reconnaissance study based on geoscientific information was performed by Duman

Fig. 1 Location map of the study area (Cekmece-Istanbul area)



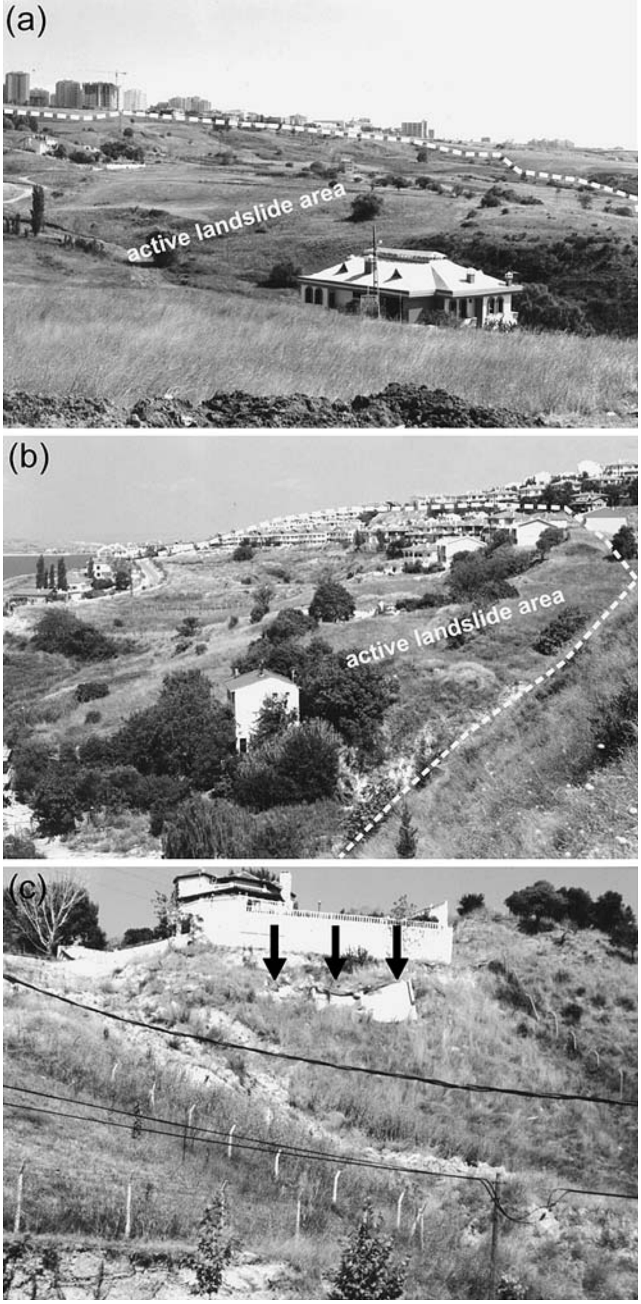


Fig. 2 Overview of the typical landslides from the study area; many buildings were constructed in the active landslides (**a**, **b**), retaining wall damaged by landslide (**c**)

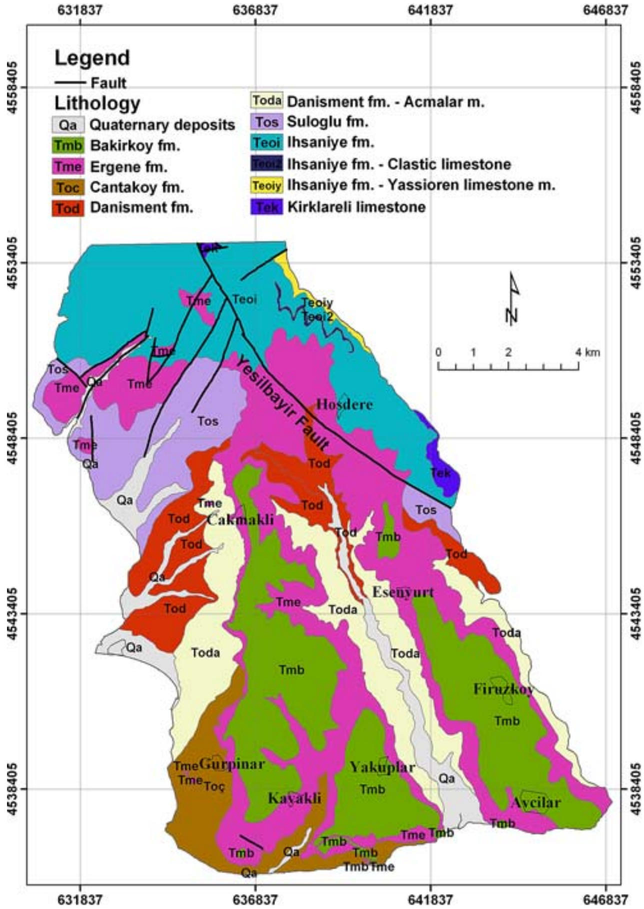


Fig. 3 Geological map of the study area (Duman et al. 2004)

et al. (2005a). However, preparation of a realistic landslide susceptibility map for the planning and correct site selection purposes is indispensable for the study area having a surface area of 174.8 km^2. Landslide susceptibility maps can be used to help land use planners and decision-makers in their decisions for appropriate site selection and zoning. In this study, a method for characterizing landslide susceptibility for the Cekmece area of Istanbul is developed using logistic regression analysis of an extensive spatial database of landslide activity. This study is composed of five main stages: (a) preparation of landslide inventory by aerial-photography studies and field checking, (b) compilation of measures of variables thought to affect landslide susceptibility in the area into a database, (c) statistical analyses of the database, (d) production of a landslide susceptibility map and (e) assessment of effectiveness of the map.

Geologic setting

The study area is located at the northern coast of the Sea of Marmara and western part of Istanbul metropolitan area (see Fig. 1). The Buyuk Cekmece lake, and the Kucuk Cekmece lake and Dikilitas creek are the western and eastern borders of the study area, respectively. The study area is in the Marmara region having a high-seismicity. Recently, Turkey has experienced some large earthquakes. The 17 August 1999, Izmit earthquake on the northern branch of the North Anatolian Fault Zone

(NAFZ) has also increased the earthquake risk in the Sea of Marmara (Parsons et al. 2000). More than 300 earthquakes are reported to have occurred between 2,100 BC and AC 1,900 (Soysal et al. 1981). The active northern branch of the NAFZ runs through the distance of 9 km from south of the study area. In the last 20 centuries, between Izmit and Gulf of Saros, 29 historically large (between 6.3 and 7.4 M_s) earthquakes occurred along the northern branch NAFZ (Ambraseys 2002).

Stratigraphically, the Kırklareli limestone (Tek) of Middle-Late Eocene is the oldest rocks of the study area, and is observed in the eastern parts of the study area. The Ihsaniye formation (Teoi), which is interfingered with the Kırklareli limestone (Tek), consists of sedimentary units such as shale-marls of the Late Eocene-Early Oligocene, and is observed in the northern parts of the study area (Fig. 3). The Danisment formation (Tod) of Late Oligocene includes alternating beds of sandstones, shales and marls (Duman et al. 2004). This formation is observed at the western parts of the study area. Sandstones and shales that include gypsum and coal layers comprise the Suloglu formation (Tos). This unit is interfingered with the Danisment formation (Tod). The Acmalar member of the Danisment formation (Toda), which is important for landslide occurrence, and is formed by claystones and mudstones. As can be seen from Table 1, 12.23% of the total surface of the study area is covered by this member, and 31.95% of the total landslide area is located at this member. Tuffs, sandstones and gravelstones form the Early Miocene Cantakoy formation (Toc), appear in the southwestern and southern parts of the area. The Middle Eocene Ergene formation (Tme) unconformably overlies the Cantakoy formation (Toc), and consists of sandstones and gravelly sandstones. This formation is observed at northern and southern parts of the area. The Late Miocene Bakirkoy formation (Safak et al. 1999) (Tmb), consists of limestones and claystones, and crops out middle parts of the area (Fig. 3). The terraces unconformably overly the oldest rocks along the margins of Buyuk Cekmece lake. The youngest unit in the study area is alluvium (Qa).

In the area, some inactive normal faults are typical. These faults trend generally northeast–southwest, but that of the most important normal fault, Yesilbayir fault trends roughly northwest–southeast (Duman et al. 2004). The dips of the sedimentary units in the area are rather low, 5–15°, and show a high variation over short distances. No significant folding is observed in the study area.

Morphologic and hydrologic characteristics of the study area

For the study, a digital elevation model (DEM) was produced by digitising 10 m altitude contours of the 1/25,000 scale topographical maps. Maps of slope, aspect, altitude, stream power index (SPI), plan curvature and profile curvature are derived from the DEM as raster images with a pixel size of 25×25 m. However, the other maps such as lithology, geomorphology, relative permeability and landslide inventory are vector maps, and these maps were converted to raster maps with a pixel size of 25×25 m for compilation in the database. Within the study area, altitude varies between 0 and 200 m with most of the area within 75–125 m (Fig. 4a). The general physiographic trend of the study area is NW–SE as can be seen in Fig. 4b. Although, the range of slope angle values is 0–90°, the majority of them are between 0 and 20° (Fig. 4c). These slope values indicate that the majority of the area has gentle slopes. The secondary topographic attributes such as plan curvature (Fig. 4d), profile curvature (Fig. 4e) and SPI (Fig. 4f) were also produced and they were used in landslide susceptibility assessments performed in this study.

Table 1 Landslide densities of the lithological units in the study area

Lithology	Symbol	Grid cells with landslides		All grid cells		Landslide density (%)
		Frequency (no. of pix.)	%	Frequency (no. of pix.)	%	
Quaternary	Qa	1,127	2.10	154%	5.54	7.27
Bakirkoy fin.	Tmb	4,473	8.33	56,231	20.10	7.95
Ergene fin.	Tme	13,617	25.37	71,287	25.49	19.10
Cantakoy fm.	Toc	5,706	10.63	14,210	5.08	40.15
Danisment fin.	Tod	4,728	8.81	20,650	7.38	22.90
Danisment fm.—acmalar m.	Toda	17,151	31.95	34,213	12.23	50.13
Suloglu fin.	Tos	4,996	9.31	21,166	7.57	23.60
Ihsaniye fm.	Teoi	1,810	3.37	43,337	15.49	4.18
Ihsaniye fin.—clastic limestone	Teoi2	66	0.12	478	0.17	13.81
Ihsaniye fm.—yassioren limestone m.	Teoiy	0	0.00	1,035	0.37	0.00
Kirklareli limestone	Tek	0	0.00	1,613	0.58	0.00

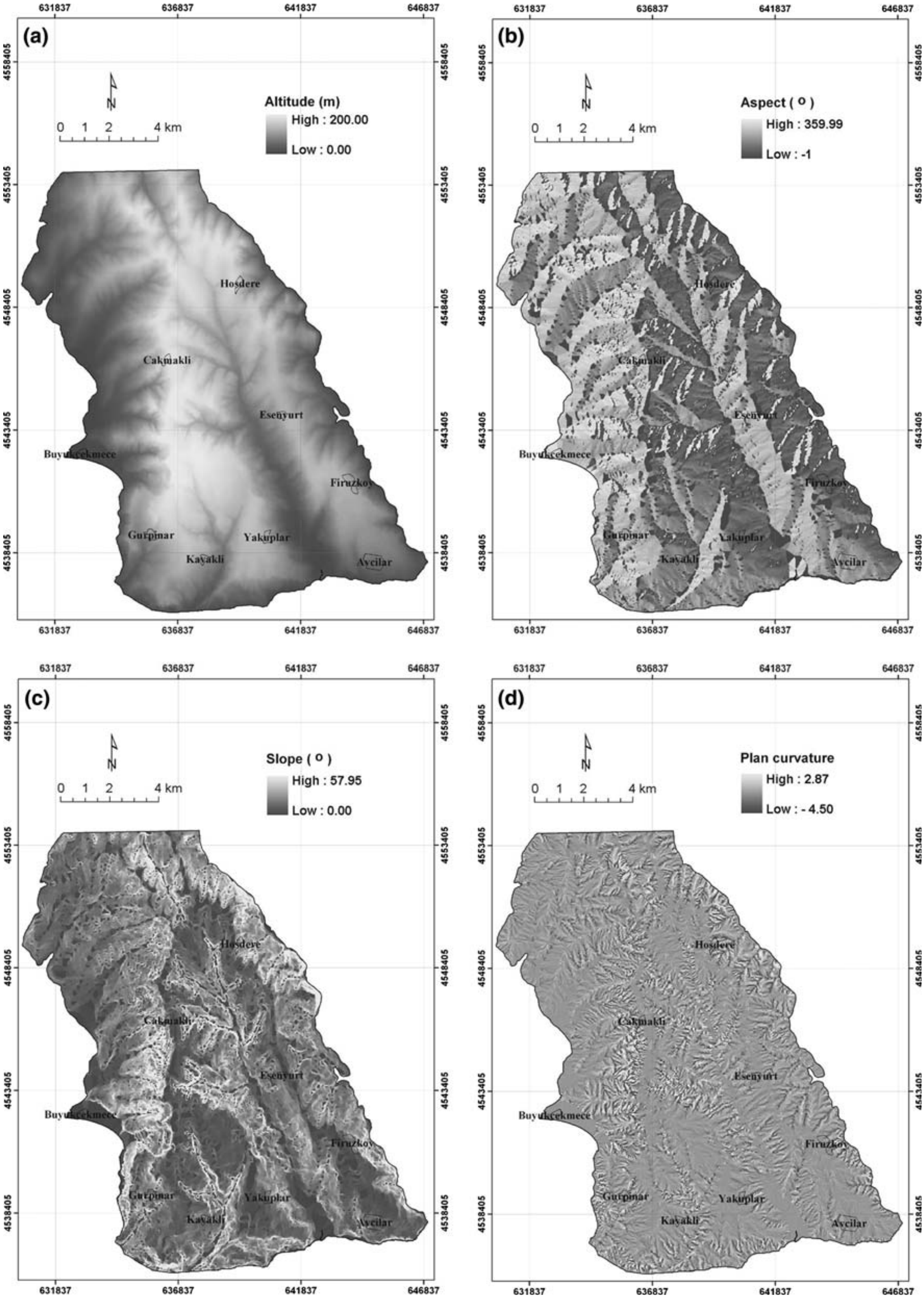


Fig. 4 **a** Altitude map, **b** aspect map, **c** slope map, **d** plan curvature map, **e** profile curvature map, and **f** stream power index (*SPI*) map of the study area

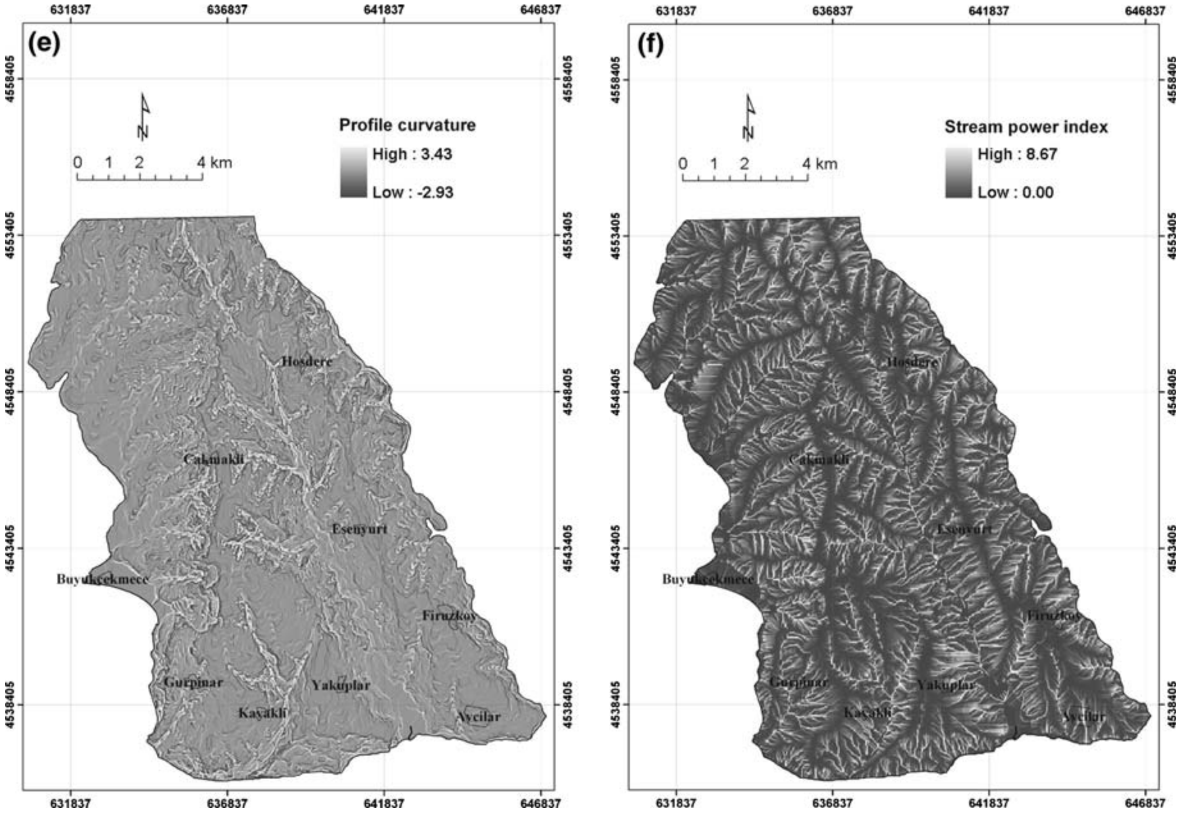


Fig. 4 (Contd.)

A map of geomorphic units within the study area was produced by Duman et al. (2004) (Fig. 5), and shows many geomorphic units such as denudation and pediment surfaces, slope zones, transition zones, alluvial floors and coastal zones, etc. (Table 2). Considering the purpose of the present study, the most important geomorphic unit is the slope zone formed by landslides occurrence (Table 2). In particular, the lower borders of the Late Miocene eroding surfaces form the failure surfaces of the landslides in the region (Duman et al. 2004). In addition, a dense landslide occurrence can be observed at the slope zones near the coastlines of the lakes and the Sea of Marmara in the area.

According to the relative permeability map of the lithologies prepared by Duman et al. (2004), considering the classification of proposed by Todd (1980), permeable, semi-permeable and impermeable units are recognized in the area (Fig. 6) and the areal extent with their statistical assessments of the relative permeability classes of the lithological units are given in Table 3. The eastern and southern parts of the area are underlain by permeable units while the western and northern parts of the area are underlain by impermeable and semi-impermeable units, which include many springs. These springs discharge along the borders of permeable and semi-impermeable units. Soft, readily eroded lithologies and low slope angles have resulted in dendritic drainage pattern. The main streams in the study area are the Dikilitas creek, Cekmece creek, Uzuncayir creek and Harami creek. The general stream direction of the Cekmece creek and Uzuncayir creek in the study area is from northeast to southwest and the both discharge to the Cekmece lake while that of Dikilitas creek is northwest to southeast and it discharges to the sea of Marmara. Besides, there are many lower order streams flowing only after rainy periods and their flowing directions are generally southwest.

The region is diagnostic of the Marmara and Western Black Sea climate. Generally, in the summer season, the weather is hot and slightly rainy while the weather of winter seasons is warm and rainy. The topography of the region and presence of lakes and dams affect the weather conditions (http://www.istanbul.meteor.gov.tr). The region receives 85% of the total annual precipitation in rainy season, September–May (http://www.istanbul.meteor. gov.tr). In this study, the data of Florya Meteorology Station, the nearest station to the study area, was used. According to the meteorological data of the period of 1937–1990, the average monthly rainfall varies between 20.5 and 102.0 mm. The annual precipitation varies between 500 and 1,000 mm in the region while average annual precipitation of long period of the

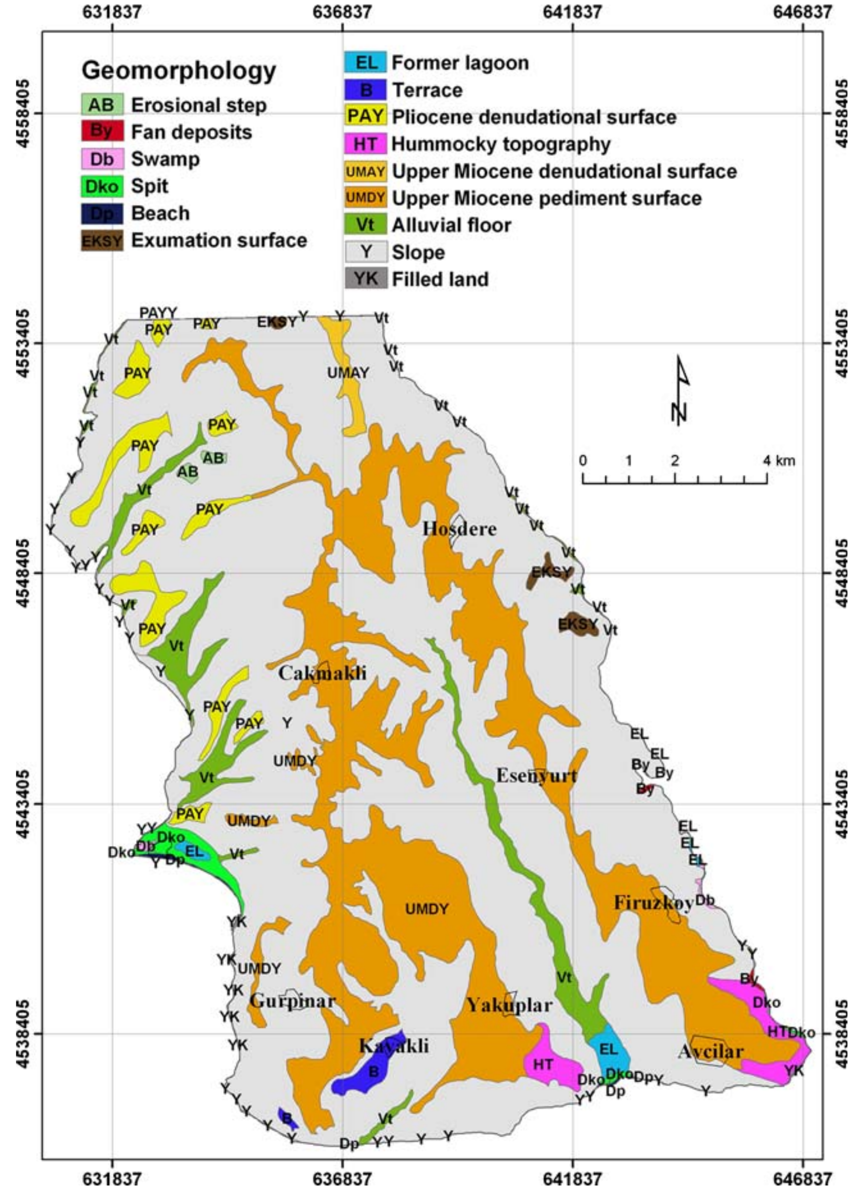


Fig. 5 Geomorpholoy map of the study area (Duman et al. 2004)

Florya Meteorology Station is 642.4 mm (DMI 1990). The average monthly temperature varies from 5.3 to 23.2°C. The coldest month is January showing average temperature of 5.3°C and the hottest month is July with average temperature of 23.2°C. In winter seasons particularly, the region sometimes shows heavy precipitation causing some floods and triggering landslides. The maximum daily precipitation recorded in the period of 1937–1990 varies between 43.8 and 112.5 mm (DMI 1990). When 112.5 mm within 24 h considered, the maximum rainfall intensity is calculated as 4.7 mm/h. As a consequence, the region is affected by the landslides triggered by earthquake and heavy precipitation. However, in this study, the conditioning factors are taken into consideration when producing landslide susceptibility map.

Landslide characteristics

For this study, a landslide inventory was prepared using black and white aerial photographs at 1/35,000 scale, dated 1955–1956 (Fig. 7). Criteria defined in the Turkish landslide inventory mapping project and initiated by natural hazards and environmental geology division of the general directorate of mineral research and exploration (MTA) were used to describe the type and activity of the landslides in the study area (Duman et al. 2001).

Table 2 Landslide densities of the geomorphologic units in the study area

Geomorphology	Symbol	Grid cells with landslides		All grid cells		Landslide density (%)
		Frequency (# of pix.)	%	Frequency (# of pix.)	%	
Erosional step	AB	0	0.00	385	0.14	0.00
Fan deposits	By	69	0.13	128	0.05	53.91
Swamp	Db	76	0.14	231	0.08	32.90
Spit	ko	51	0.11	1,702	0.61	3.35
Beach	Dp	0	0.00	142	0.05	0.00
Exumation surface	EKSY	0	0.00	1,004	0.36	0.00
Former lagoon	EL	0	0.00	1,290	0.46	0.00
Terrace	B	144	0.27	1,387	0.50	10.38
Pliocene denudational surface	PAY	0	0.00	7,194	2.57	0.00
Hummocky topography	HT	1,079	2.01	3,517	1.26	30.68
Upper miocene denudational surface	UMAY	0	0.00	1,355	0.48	0.00
Upper miocene pediment surface	UMDY	1,566	2.92	67,225	24.03	2.33
Alluvial floor	Vt	420	0.78	9,843	3.52	4.27
Slope	Y	50,242	93.61	184,260	65.87	27.27
Filled land	YK	21	0.04	52	0.02	40.38

Mass movements were classified according to the main types of classification proposed by Varnes (1978), i.e., flows, falls and slides. The landslides are also classified according to their relative depths, as shallow (depth <5 m) and deep-seated (depth >5 m). For simplicity, their activities are classified into two groups as active and inactive (Duman et al. 2005b). Active landslides are defined as those currently moving, whereas inactive ones are as relict according to WP/WLI (1993).

Field observations indicate that the Cekmece area in the Trakya region hosts the highest density of landslide occurrence. The landslides are most frequently located in the permeable sandstone layers and impermeable layers such as claystone, siltstone and mudstone layers. The majority of the landslides (approximately 60%) occurred in two formations such as Danisment formation-Acmalar member (Toda) and Ergene (Tme) formations. Another factor governing the landslides is the sandstone bedding planes. If the orientation of slope and bedding plane are roughly similar, some large landslides occur. In these areas, the beginning of the landslides is controlled by the bedding planes as planar failure, and then in the displaced and accumulated material, some rotational landslides are observed (Fig. 8). Rarely, in this material, some earth flows may occur depending on the heavy rainfalls. However, throughout the susceptibility analyses, only deep-seated circular failures were considered. The average failure surface depth of the landslides described in the study area is about 15 m (Arpat 1999). Based on cross-sections, however, the estimated maximum failure is about 20–25 m deep. The pixel number of the landslide areas is 53,674; this indicates that 19.2% of the study area is covered by the landslides.

An important control on landslide occurrence is the slope angle. In regional landslide susceptibility or hazard assessments, slope angle in terms of landslide activity is taken into consideration as an conditioning factor. In the study area, most landslides occurred on hillslpoes with gradients between 5 and 15° (Table 4).

Although, the relation between slope aspect and mass movement has long been investigated, no general agreement exists on the effect of aspect on landslide occurrence (Carrara et al. 1991). However, slope aspect is related to the general physiographic trend of the area and/or the main precipitation direction, and direction of the landslides is roughly perpendicular to general physiographic trend. The general physiographic trend of the study area is NW–SE and an important part of the landslides observed in the area studied has failure directions to NE and NW (Table 4).

Some authors (i.e. Pachauri and Pant 1992; Ercanoglu and Gokceoglu 2002) reported that the altitude is a good indicator of landslide susceptibility. Although, in the area studied, there is not a considerable difference between the lowest and the highest altitude values, only about 200 m, some descriptive statistical parameters show considerable differences. As can be seen from Table 4, the mode and skewness values of grid cells with landslides and grid cells without landslides are 10 and 0.185, and 180 and −0.037, respectively. These values indicate that the altitude distribution of the pixels without landslides has higher altitudes dominantly while the distribution of the pixels with landslides has lower altitudes. As a consequence, there is a relation between landslide frequency and altitude. For this reason, the altitude should be taken into consideration in the analyses.

In this study, the secondary topographical attributes such as plan and profile curvatures, SPI were also used. The term curvature is generally defined as the curvature of a line formed by intersection of a random plane with

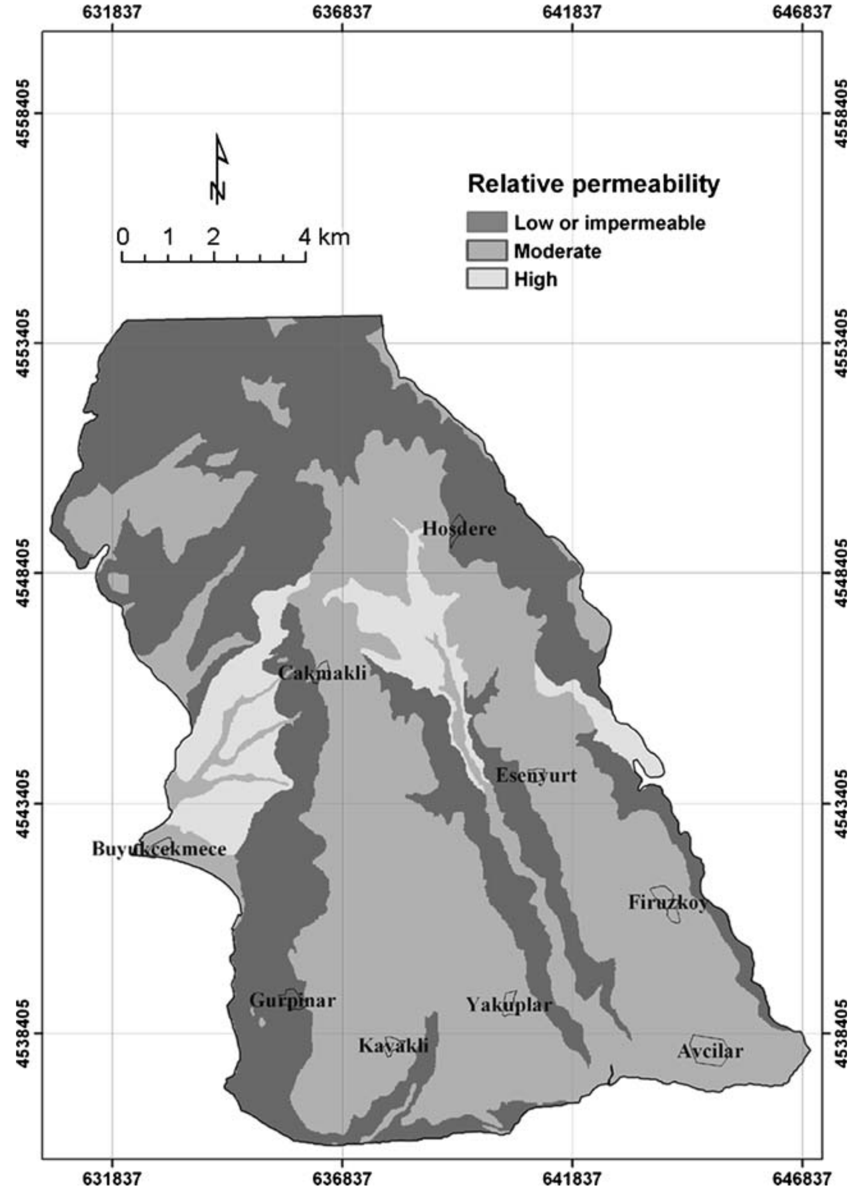


Fig. 6 Relative permeability map of the lithologies (Duman et al. 2004)

the terrain surface. The curvature value can be evaluated calculating the reciprocal value of the radius of curvature of the line. Hence, while the curvature values of broad curves are small, the tight ones have higher values. Plan curvature is described as the curvature of a contour line formed by intersection of a horizontal plane with the surface. The influence of plan curvature on the erosion processes is the convergence or divergence of water during downhill flow. In addition, this parameter constitutes one of the main factors controlling the geometry

Table 3 Landslide densities of the relative permeability classes in the study area

Relative permeability	Symbol	Grid cells with landslide		All grid cells		Landslides density (%)
		Frequency (no. of pix.)	%	Frequency (no. of pix.)	%	
Low or impermeable	L	29,729	55.39	113,404	40.54	26.22
Moderate	M	4,728	8.81	20,650	7.38	22.90
High	H	19,217	35.80	145,661	52.07	13.19

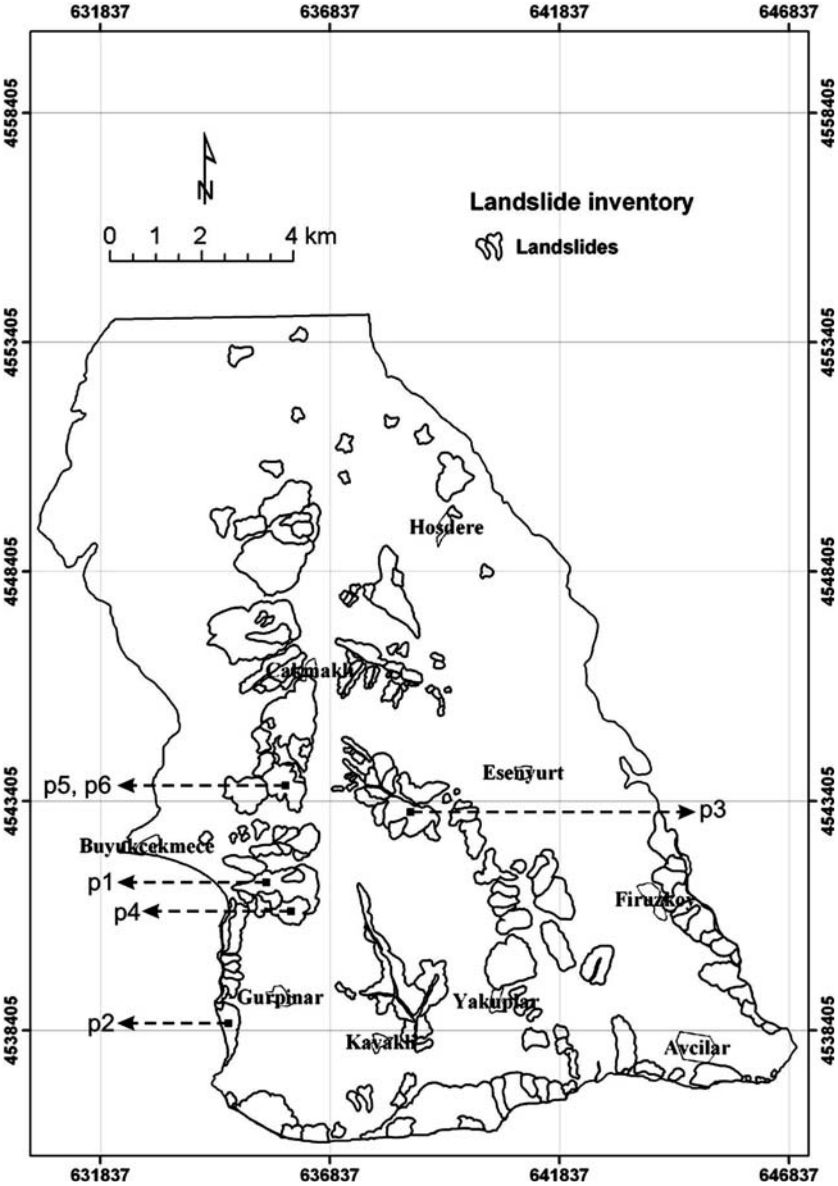


Fig. 7 Landslide inventory map of the study area; p1, p2, and p3 are given in Fig. 2 as **a**, **b**, and **c**, respectively; p4, p5, and p6 are given in Fig. 8 as **a**, **b**, and **c**, respectively

of the terrain surface where landslide is occurred. This can be obviously realized when comparing the mean plan curvature values of the pixels representing landslide areas (−0.013) and pixels representing free from landslides (0.004) (Table 4). These values indicate that the plan curvature can be accepted as a conditioning parameter when applying a landslide susceptibility analysis. The profile curvature is the curvature in the vertical plane parallel to the slope direction. It is the measure of the rate of change of slope. For this reason, this parameter directly controls velocity of water flow, and so erosion. While the values of mean profile curvatures of landslide areas and the areas free from landslides are 0.023 and −0.004, respectively (Table 4). This descriptive statistical evaluation suggests that the profile curvature parameter also strictly controls landslide occurrence.

One of the secondary topographical attributes used in this study is SPI (Fig. 4f). It is a measure of erosive power of water flow based on assumption that discharge (q) is proportional to specific catchment area (A_s) (Eq. 1) (Moore et al. 1991).

$$\mathrm{SPI} = A_3 \tan \beta, \tag{1}$$

where, A_s is the specific catchment area ($m^2 m^{-1}$), β is the slope gradient in degree. The index, SPI, is one of the main factors controlling the erosion processes. Besides, the erosion processes can be considered as one of the main conditioning factors of landslide occurrence. Descriptive statistical evaluations (Table 4) suggest that

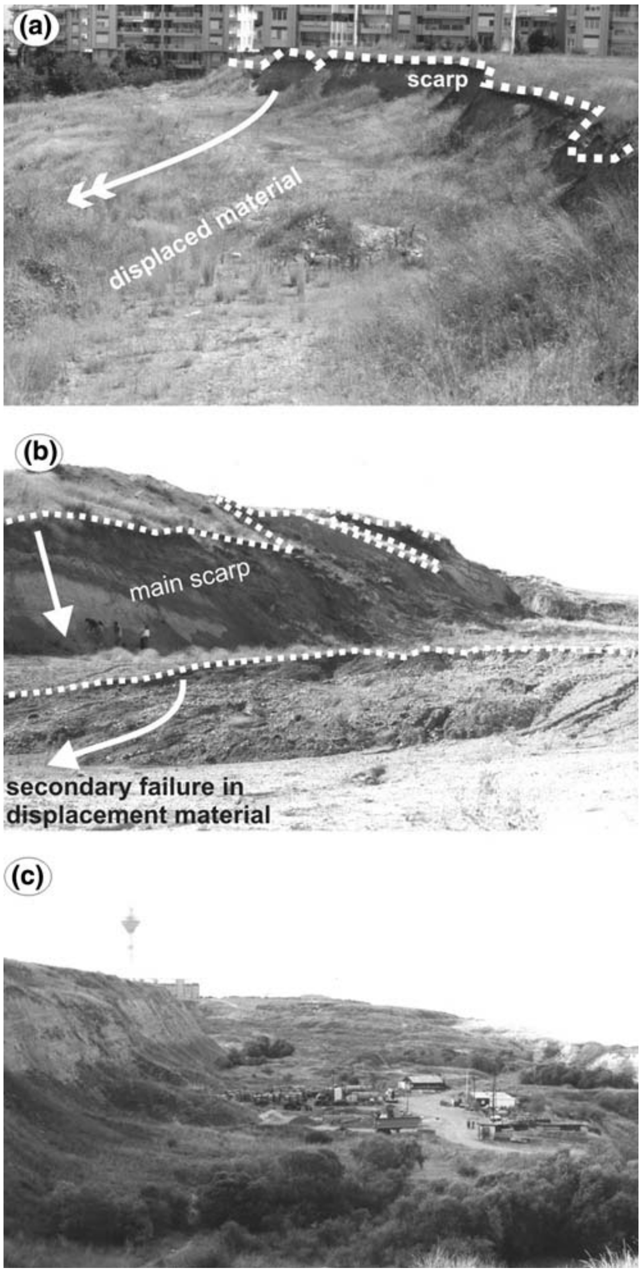


Fig. 8 Some typical views from the landslides in the area

particularly the mean values of SPI for landslide areas (0.724) and for areas free from landslides (0.453), the importance of the index SPI in landslide occurrence is also comprehensible.

In addition to the lithological features, the relative permeability map of the units is taken into consideration as the conditioning factors of the landslides. One of the main conditioning factors is a permeability characteristic of the units. The geomorphic units and land-units are considered in the landslide susceptibility analyses. As an expected result, most of the landslides are located in the slopes (Y).

Logistic regression analysis

Landslide susceptibility evaluation involves a high level of uncertainty due to data limitation and model shortcomings (Zezere 2002). For this reason, the landslide researchers have considered different techniques for preparation landslide susceptibility maps. One of these techniques is statistical analysis. In this study, a multivariate statistical analysis in the form of logistic regression was used to produce the landslide susceptibility map of Cekmece area. The fundamental principle of logistic regression is based on the analysis of a problem, in which a result measured with dichotomous variables (such as zero and one or true and false) is determined from one or more independent factors (Menard 1995). Generally, logistic regression involves fitting the dependent variable using an equation in the following form:

$$\begin{aligned} Y &= \text{logit}\,(P) = \ln\,[p/(1-p)] \\ &= C_0 + C_1X_1 + \cdots + C_nX_n, \end{aligned} \tag{2}$$

where p is the probability that the dependent variable (Y) is 1, $p/(1-p)$ is the so-called odds or likelihood ratio, C_0 is the intercept, and C_1, C_2,···, C_n are coefficients that measure the contribution of independent factors (X_1, X_2,···, X_n) to the variations in Y. In this study, the dependent variable is defined as the presence or absence of landslide deposits, while the independent variables are those thought to affect landslide susceptibility.

In recent literature, many studies have been published on the assessment of the landslides by logistic regression (e.g. Bernknopf et al. 1988; Atkinson and Massari 1998; Guzzetti et al. 1999; Gorsevski et al. 2000; Dai et al. 2001; Lee and Min 2001; Dai and Lee 2002; Ohlmacher and Davis 2003; Lee 2004; Ayalew and Yamagishi 2005; Can et al. 2005).

To identify those factors that most strongly influence deep-seated landslide activity in the Cekmece area, and to develop a multivariate model for landslide susceptibility, a data matrix consisting of values for 37 variables for each of the 279,715 25×25 m pixels in the area was constructed, and evaluated using logistic regression analyses. The variable list used in logistic regression is given in Table 5. Values for slope, aspect, elevation, SPI, plan curvature, profile curvature, geology, geomorphology and relative permeability of lithological units were compiled. Each lithologic and geomorphic units and relative permeability classes were considered as binary data. Other continuous variables such as slope, aspect, elevation, etc. were taken as continuous variables. In a logistic regression analysis, it is preferable that the portion of the number of pixels representing no-landslide area and the number of pixels representing

Table 4 Results of descriptive statistical assessments of topographical parameters with respect to landslide inventory

Data	Variable	Min.	Max.	Mean	Mode	Median	Variance	Std. deviation	Skewness	Kurtosis
Grid cells with landslides (*N* = 53,674)	Elevation (m)	0.000	194.680	85.099	10.000	81.220	2,039.875	45.165	0.185	−1.020
	Slope (°)	0.000	57.950	7.966	0.000	7.180	28.169	5.307	1.439	4.751
	Plan curvature	−3.130	2.870	−0.013	0.000	0.000	0.056	0.238	−0.780	10.431
	Profile curvature	−2.930	3.080	0.023	0.000	0.000	0.092	0.303	0.629	8.887
	Aspect (°)	−1.000	359.970	165.940	−1.000	176.600	10,893.048	104.370	−0.097	−1.170
	Stream power index (*SPI*)	0.000	8.330	0.724	0.000	0.410	0.872	0.934	2.410	7.127
Grid cells without landslides (*N* = 226,041)	Elevation (m)	0.000	200.000	98.229	180.000	100.000	2,742.648	52.370	−0.037	−1.051
	Slope (°)	0.000	55.230	4.642	0.000	4.080	15.395	3.924	1.874	7.808
	Plan curvature	−4.500	2.690	0.004	0.000	0.000	0.019	0.137	−1.383	34.587
	Profile curvature	−2.920	3.430	−0.004	0.000	0.000	0.035	0.188	0.835	21.260
	Aspect (°)	−1.000	359.990	152.642	−1.000	144.010	11,691.808	108.129	0.071	−1.277
	Stream power index (*SPI*)	0.000	8.670	0.453	0.000	0.190	0.600	0.775	3.852	19.571

landslide area should be same (Ayalew and Yamagishi 2005). This means that the ratio of presence (1)/absence (0) should be equal to one in the training data set. For this purpose, a random data selection was performed. While whole data matrix includes 279,715 cases, the training data set contains 107,348 cases. By using the training data set, an forwards step-wise logistic regression analysis was carried out. It was performed iteratively within a 95% confidence interval. In addition,

Table 5 List of variables used in logistic regression analysis

Name	Symbol
Lithology	
Quaternary	Qa
Bakirkoy fm.	Tmb
Ergene fm.	Tme
Cantakoy fm.	Toc
Danisment fm.	Tod
Danisment fm.—Acmalar m.	Toda
Suloglu fm.	Tos
Ihsaniye fm.	Teoi
Ihsaniye fm.—Clastic limestone	Teoi2
Ihsaniye fm.—Yassioren limestone m.	Teoiy
Kirklareli limestone	Tek
Digital elevation model (DEM)	
Elevation (m)	Elev
Slope (degree)	Slp
Plan curvature	Plncurv
Profile curvature	Prfcurv
Aspect (degree)	Asp
Stream power index	SPI
Geomorphology	
Erosional step	AB
Fan deposits	By
Swamp	Db
Spit	Dko
Beach	Dp
Exumation surface	EKSY
Former lagoon	ELI
Terrace	B
Pliocene denudational surface	PAY
Hummocky topography	HTK
Upper miocene denudational surface	UMAY
Upper miocene pediment surface	UMDY
Alluvial floor	Vt
Slope	Y
Filled land	YK
Relative permeability	
Low or impermeable	RP_Low
Moderate	RP_Mod
High	RP_High

Table 6 Beta coefficients and test statistics of the variables in the equation

Variable	β	SE	Wald	Significance
Lithology				
Tmb	−0.227	0.053	18.129	0.000
Tme	0.202	0.050	16.236	0.000
Toc	0.644	0.0363	16.962	0.000
Toda	0.933	0.030	970.816	0.000
Teoi	−2.432	0.037	4,329.766	0.000
Teoi2	−1.987	0.170	137.059	0.000
Teoiy	−22.867	2,370.493	0.000	0.992
Tek	−22.606	1,753.946	0.000	0.990
Geomorphology				
By	3.356	0.465	52.054	0.000
Db	3.509	0.442	62.935	0.000
Dko	2.226	0.415	28.828	0.000
B	2.691	0.396	46.187	0.000
PAY	−3.005	1.071	7.871	0.005
HT	3.870	0.386	100.315	0.000
UMDY	1.394	0.383	13.223	0.000
Vt	2.307	0.386	35.778	0.000
Y	3.763	0.382	97.054	0.000
YK	5.303	0.609	75.922	0.000
Digital elevation model (*DEM*)				
Elevation	0.002	0.000	103.907	0.000
Slope	0.142	0.002	4,395.564	0.000
Prfcurv	0.147	0.033	19.621	0.000
Aspect	−0.001	0.000	338.918	0.000
SPI	0.231	0.009	624.260	0.000
Relative permeability				
RP_Low	0.188	0.033	32.499	0.000
RP_High	−0.104	0.053	3.852	0.050
Constant	−4.371	0.383	130.201	0.000

Degrees of freedom is taken as one for all variables classification cut-off value was selected as 0.5 and maximum iteration was set to 12. As a result of the forwards step-wise logistic regression analysis, corrected percentage value was obtained as 83.8%. Eight lithological units and ten geomorphic units, five topographical parameters and two permeability classes were found as meaningful when the significance level of 0.05 is selected (Table 6). By considering the Wald test statistical values, the Acmalar member of the Danisment formation (Toda) is the main landslide-conditioning factor among the lithological units while the Ihsaniye formation has negative effect on landslide occurrence (Table 6). The significances of β coefficients were also checked by using Wald test statistics. Depending on the increment of the Wald test statistical values, the significances of β coefficients also increase. Among geomorphologic units, hummocky topography and slopes are the main landslide conditioning factors as expected. As can be seen from Table 6, slope angle and SPI are very effective on landslide occurrence. The other significant parameter on the landslide occurrence is low permeability class of relative permeability as a normal result because these class units are formed by claystone and mudstone. Prime attention should be paid to the fact that the sign "-" in front of β coefficients in Table 6 has a meaning of decreasing in the possibility of being a landslide occurrence, and for the sign "+", vice versa. The lithologies the Yassioren limestone member of the Ihsaniye for-

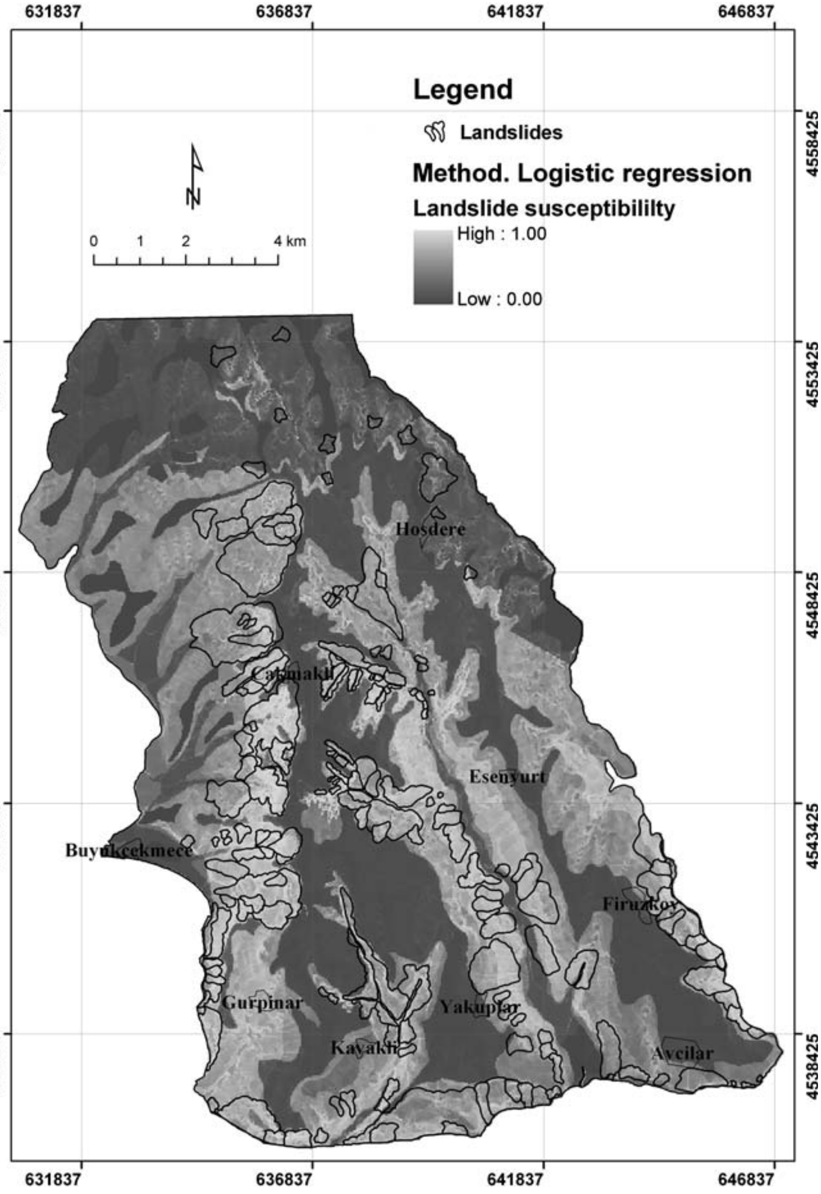


Fig. 9 Landslide susceptibility map of the Cekmece (Istanbul) area

mation and the Kirklareli limestone have high values of -β (Table 6). This is an expected result, because the landslide distribution on these units is zero. This means that these lithologies have no capacity to cause landslide. For this reason, although the significances of these lithologies are too small, it was decided to be used in the logistic regression equation. By using β coefficients in Table 6 to the whole data set (279,715 cases), the landslide susceptibility map is obtained (Fig. 9). In addition, effectiveness of the landslide susceptibility map was evaluated considering the areal distributions of observed landslides and susceptibility intervals (each of 10%). While 43.8% of the study area was found as high susceptible with a probability interval of 0.5–1.0, 56.2% of the region was located on the less susceptible areas with a probability less than 0.5. An important stage of the landslide susceptibility mapping is the assessment of the effectiveness of the landslide susceptibility map produced. To assess the performance of the susceptibility map, two decision rules, introduced by Can et al. (2005), were considered. These decision rules are:

1. On the map, most of the actual landslides should have to be located in the pixels included in high susceptibility classes.
2. On the map, these high susceptibility classes should have to cover small area as possible. If high susceptibility classes cover large areas, all described landslides are included by high susceptibility classes.

For this purpose, two different curves for landslides were drawn (Fig. 10). The first (curve-a) is landslide susceptibility versus observed cumulative percentage of the number of pixels that include only landslides. In an effective landslide susceptibility map, the actual landslides should be included by the areas having high susceptibility values. Considering the cut-off value of 0.5, approximately 80% of the observed landslides locate in the high susceptibility values (Fig. 10). For this reason, it is possible to say that the curve “a” satisfies the rule-i. The second (curve-b) is landslide susceptibility versus cumulative percentage of the number of pixels representing the landslide-susceptibility intervals. The curve-b defines the areal distribution of the susceptibility values in the region. To satisfy the rule-ii, the cumulative area obtained form this curve should be small as possible. If 0.5 susceptibility value is considered as cut-off, the cumulative area of the high susceptibility values is obtained as 37%. This means that the curve “b” also satisfies the rule-ii. Consequently, it is evident that both of two decisions rules are satisfied sufficiently on both curves “a” and “b”.

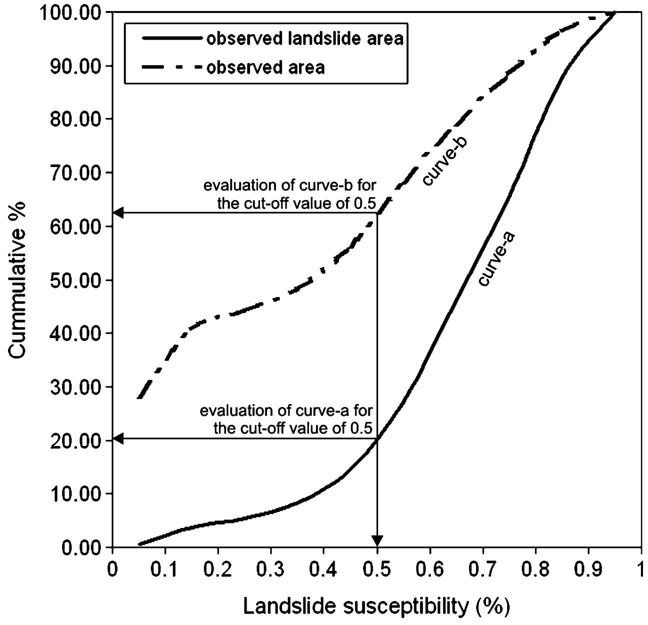


Fig. 10 Graph showing effectiveness of the produced landslide susceptibility map

Results and conclusions

Considering the results of the present study the following conclusions can be drawn: When making a close inspection to the produced susceptibility map, it can be observed that a considerable part of the slopes showing NW–SE direction have the most susceptible zones prone to landsliding. This outcome is mainly related with the physiographical trend of the study area. For this reason, it is important to use topographical aspect as a conditioning parameter in such kind of regions. On the other hand, the most important conditioning factors are topographical slope and litology. It was also revealed that some of the secondary topographical parameters such as slope curvatures and SPI can be helpful to construct similar landslide susceptibility models in such kind of regions. As a different approach, relative permeability assessment was used directly in the landslide susceptibility model as a conditioning factor in this study. The outcomes of the model showed that this approach is reasonable, and can be applied in such kind of studies.

The results of logistic regression analyses also indicate that the Acmalar member of the Danisment formation, hummocky topography, slope units, slope degree, SPI, low permeability class are the fundamental landslide conditioning factors decreasing the stability while clastic limestones of the Ihsaniye formation, the Yassioren limestone member of the Ihsaniye formation, the Kirklareli limestone are the most important conditioning factors increasing the stability. Also, high permeable units have -β coefficient, which means that these units allow to drainage and this affect the stability positively. These findings are in a good accordance with the field observations. Beta coefficients of the 25 variables included the logistic regression equation provide a model for landslide susceptibility in the Cekmece area. This model is used to generate a landslide susceptibility map that correctly classified 83.8% of the landslide-prone areas. This percentage (83.8%) belongs to correct classification of the landslide information of being only "one". When also considering the information of being "zero", the overall correct classification value becomes 76.0%. However, according to the authors of the present study, the correct classification value of the landslide information of being only "one" should be considered in such kind of studies, because the overall correct classification value includes the correct classification value of landslide information of being "zero" also. Nevertheless, to obtain the correct classifications of the information of being "zero" is not one of the fundamental targets of such kind of analyses. Contrary, to search the possible information of being "one" in the information of being "zero" constitutes the main goal of the analyses employed.

Finally, the produced landslide susceptibility map will help to the decision makers during site selection and site planning processes. The map may also be accepted as a basis for the landslide risk-management studies to be applied in the study area.

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