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ORIGINAL ARTICLE

National level landslide susceptibility assessment of Turkey utilizing public domain dataset

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Abstract Landslide studies have been integrated into geographic information systems with the help of technological developments using several methods like inventory, heuristic, statistic and deterministic methods in the recent years. However, since a nationwide landslide susceptibility zoning map has not been produced for the entire territory of Turkey, this study aims to produce a landslide susceptibility map of Turkey at a national scale by utilizing publicly available datasets. In order to develop a landslide susceptibility map of Turkey at the scale of 1:2,000,000, an index-based calculation, which considers six factors (slope, lithology, local relief, rainfall, land use, seismicity) that covers the entire territory of Turkey and controls the occurrence of landslides, was applied in a 500 × 500 m pixel resolution. Each layer (factor) having various effects on landslide susceptibility has been merged into the model with assigned weights. Four different weight groups were assigned to the layer sets through expert judgement in order to capture the layer variability for landslide susceptibility in Turkey. The performances of four different weight groups were compared and evaluated by using a receiver operator characteristics curve for minimizing the uncertainty of expert judgement procedure. It was observed that the W_3 group was superior to the other weight groups in prediction skills. The susceptibility map of W_3 has been classified into five groups: no, low, moderate, high and very high susceptibility. The no susceptibility class represents 4.2 % of the Turkish territory (plains and low hills), low susceptibility class 36.4 %, medium susceptibility 8.3 %, high susceptibility 47.5 % and very high susceptibility class 3.6 %, mostly in the western and middle Black Sea regions, respectively.

Keywords Qualitative analysis · Index Mapping · Country-wide · Large datasets · Small scale

The product of this study can be accepted as a milestone for further research that could be performed to obtain a complete landslide susceptibility map of Turkey.

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Introduction

Landslides are one of the most frequently encountered natural disasters in the world. According to recent studies, floods account for about 46 % of all natural disasters that are followed by hurricanes (26 %) and landslides (10 %) (CRED 2010). Turkey is one of the countries that is most affected by natural hazards with strong socio-economic impacts. Landslides are the second most destructive disasters in Turkey after earthquakes (Reis and Yomralioglu 2005; Baltacı et al. 2010). Statistical studies reveal that landslides are the most frequent disasters that have caused the most suffering and loss among all disasters that have occurred in Turkey during the last 50 years (Gökçe et al. 2008; Dag and Bulut 2012). Most of the landslides that have occurred in Turkey have typically been associated with heavy rainfall; hence, landsliding and flooding have typically occurred simultaneously. This is the main reason why experts cannot separate how much damage or loss has been caused by the landslide on its own.

Mountainous environments receiving heavy rainfall and plateaus that cover more than half of Turkey's footprint area are especially susceptible to landsliding. Landslides generally occur in areas where they have occurred in the past. This implies that landslide inventory is a must study for landslide susceptibility assessments. In Turkey, landslide related damage information has been collected by the General Directorate of Disaster Affairs since the mid twentieth century. Mineral Research and Exploration Institute has published landslide inventory maps of the country during the last decade, and 4250 settlements were affected and 197 people lost their lives during landslides in Turkey that have occurred in the period 1958–2000. According to the General Directorate of Disaster Affairs, a total of 63,000 residents have been relocated to safer places in this period (Gökçe et al. 2008).

Landslide susceptibility studies carried out in Turkey in the last decade mainly focused on relatively small areas by applying quantitative or qualitative methods. Numerous researchers have validated their landslide susceptibility assessment results with observed landslide data that have been collected from relatively small areas (Akgün and Türk 2010; Constantin et al. 2011; Eker et al. 2012, 2015; Ercanoglu and Temiz 2011; Kıncal et al. 2009; Reis et al. 2012; Rozos et al. 2011; Yılmaz 2010). Akgün and Türk (2010) have presented the results of a GIS-based landslide susceptibility map of Ayvalık using fuzzy membership functions and AHP by considering slope, aspect, lithology, weathering state of rocks, SPI, TWI, distance to drainage, lineament density, land cover and vegetation density as landslide conditioning parameters. They have easily handled 10 parameters in their study with the help of the small areal extent of the study region (420 km^2). The landslide susceptibility of the Ulus district that has an areal extent of 892 km^2 has been studied by Eker et al. (2012, 2015) using artificial neural networks and logistic regression by considering 9 landslide conditioning parameters. Ercanoglu and Temiz (2011) performed landslide susceptibility analyses using logistic regression and fuzzy approach for Azdavay (Kastamonu) that has an areal extent of 571 km^2 by considering six different input parameters; namely, elevation, lithology, land use, slope, aspect and distance to streams. Kıncal et al. (2009) presented a landslide susceptibility assessment for the city of İzmir, which has an area of 1800 km^2, by performing the logistic regression method. Landslide susceptibility of Rize, the rainiest city of Turkey, was studied by Reis et al. (2012) by considering 7 input parameters and through using the FR and AHP methods for the study region that possessed an areal extent of 2700 km^2. Yılmaz (2010) produced landslide susceptibility maps of Koyulhisar (Sivas) that is located in the North Anatolian Fault Zone (NAFZ) by using ANNs, conditional probability, LR and support vector machine models for the study region that possessed an area of 132 km^2. However, there seems to be a lack of coordination between the researchers and institutions that performed these assessments in order to merge and compile a nationwide landslide susceptibility map of Turkey. A nationwide landslide susceptibility assessment performed in a GIS environment covering as many factors as possible for the entire area of Turkey has not been performed prior to this study.

Landslide susceptibility studies performed for entire countries are still inadequate in the world literature. The main reason that lies behind this situation is the difficulty of obtaining and handling as many landslide conditioning factors as possible (Balteanu et al. 2010). Castellanos Abella and Van Westen (2005) developed a landslide risk assessment system for Cuba (app. 110,000 km^2) offering a new hierarchical approach with multi-scaled methodology. A national-scale assessment of landslide susceptibility in Greece (app. 132,000 km^2) has been studied in 1 km sized grid layers by considering 10 different causal factors (Sabatakakis et al. 2013). National scaled landslide susceptibility assessments mainly based on landslide inventory maps have been performed in some countries for the last decade, for example: Cuba (Castellanos Abella and Van Westen 2007), Romania (Balteanu et al. 2010), Greece (Sabatakakis et al. 2013) and Georgia (Gaprindashvili and Van Westen 2015). Landslide susceptibility assessment could be performed at any scale; the most important point is the suitability of the analysis with the selected map scale. Quantitative methods are the most appropriate type for medium scales (1/25,000–1/50,000) because of their ability to minimize or reduce the subjectivity (Van Westen et al. 2008). Balteanu et al. (2010) claim that qualitative methods are probably the most feasible way for assessing landslide susceptibility of large areas (small scales).

The primary aim of this study is to assess the landslide susceptibility of Turkey using a qualitative method (Susceptibility Index Mapping) that might be suitable for a country-wide analysis from publicly available datasets in a GIS environment. It is also aimed to determine landslide-prone areas of Turkey for further studies.

The study area

Turkey is a mountainous Eurasian country with a strategic importance that is located in the Anatolian peninsula, eastern Thrace (Fig. 1). Turkey is the world's 37th largest country and covers an area of 783,562 km^2 that forms a roughly rectangular shaped bridge between Europe and Asia. Turkey borders the Black Sea (to the north), the Mediterranean (to the south), the Aegean (to the west) and the Marmara Sea (to the northwest separating Europe and Asia) and has a total sea coastline length of 7200 km (CIA 2002).

Fig. 1 Map of Turkey (source: www.nationsonline.org)

The Anatolian part of Turkey that is also known as Asia Minor, Asiatic Turkey or Anatolian Plateau accounts for nearly 97 % of the country's total footprint area. Anatolia is a large semiarid plateau that is surrounded by mountains at the coastal regions. The European part of Turkey that accounts for 3 % of the country's total footprint area is also known as East Thrace. East Thrace bearing more than 10 % of the total population (TÜİK 2012), is separated from Anatolia by the Bosphorus, the Dardanelles and the Marmara Sea. Mount Ararat has the highest peak in Turkey and is located on the far eastern border with an elevation of 5137 m.

A general review of the geology of Turkey

Turkey is mostly characterized by a complex geology, whose main features have not been clearly understood until the last decade when a large amount of geological and geotechnical data have become available and the mass amount of these data increases every year. The complex geology has resulted in widely different views on the geological evolution of Turkey.

The Anatolian peninsula is surrounded on three sides by seas, which exhibit widely different geological features. The Black Sea in the north is an oceanic backarc basin. It has formed during the Cretaceous, behind and towards the north of the Pontide magmatic arc as a result of the subduction of the northern Neo-Tethys Ocean. In the pre-Cretaceous times, the Pontides were adjacent to Dobrugea and Crimea. The Aegean Sea is a geologically young sea, which started to develop during the Oligo-Miocene as a result of a north–south extension above the retreating Hellenic subduction zone. The Eastern Mediterranean represents a relic of the southern branch of the Neo-Tethys and is much older than the other seas (Garfunkel 2004).

Turkey is a country of high seismicity with a complicated tectonic regime. Tsapanos and Burton (1991), as quoted by Bayrak et al. (2008), have ranked Turkey as the tenth country among 50 seismically active countries of the world, which places Turkey in the same position with

Colombia, Honduras, Panama and Iran. The most important tectonic environments in Turkey are the Aegean Arc, the West Anatolian Graben Complexes (WAGC), the North Anatolian Fault Zone (NAFZ), the East Anatolian Fault Zone (EAFZ), the North East Anatolian Fault Zone (NEAFZ), the Bitlis Thrust Zone (BTZ) and the Caucasus. The motion between Africa and Eurasia is carried by the motion of the Aegean and Turkish plates. The Aegean arc system plays an important role in the geodynamical evolution of the Aegean region. The convergence between the African and Anatolian plates in the Eastern Mediterranean takes place by subduction along the Aegean and Cyprus arcs (e.g., McKenzie 1978; Papazachos and Comninakis 1971 as quoted by Bayrak et al. 2008). Turkey is geologically divided into three main tectonic units: the Pontides, the Anatolides-Taurides and the Arabian platform (Fig. 2). These tectonic units, which were once surrounded by oceans, are now separated by sutures, which mark the tectonic lines or zones along which these oceans have disappeared. The Pontides exhibit Laurussian affinities and are comparable to the tectonic units in the Balkans and the Caucasus, as well as to those in central Europe. They all were located north of the northern branch of the Neo-Tethys. The complete closure of this ocean resulted in the İzmir-Ankara-Erzincan suture, which marks the boundary between the Pontides and the Anatolides-Taurides. The Anatolides-Taurides show Gondwana affinities but were separated from the main mass of Gondwana by the southern branch of Neo-Tethys. They are in contact with the Arabian platform along the Assyrian suture. The northern margin of the Arabian platform is represented by southeast Anatolia to the south of the Assyrian suture (Okay 2008).

The Pontides comprise the region that is north of the İzmir-Ankara-Erzincan suture. They were folded and thrust-faulted during the Alpide orogeny but were not metamorphosed. In contrast to the Anatolides-Taurides, they bear evidence for Variscan (Carboniferous) and Cimmeride (Triassic) orogenies. The Pontides consist of three terranes, which show markedly different geological

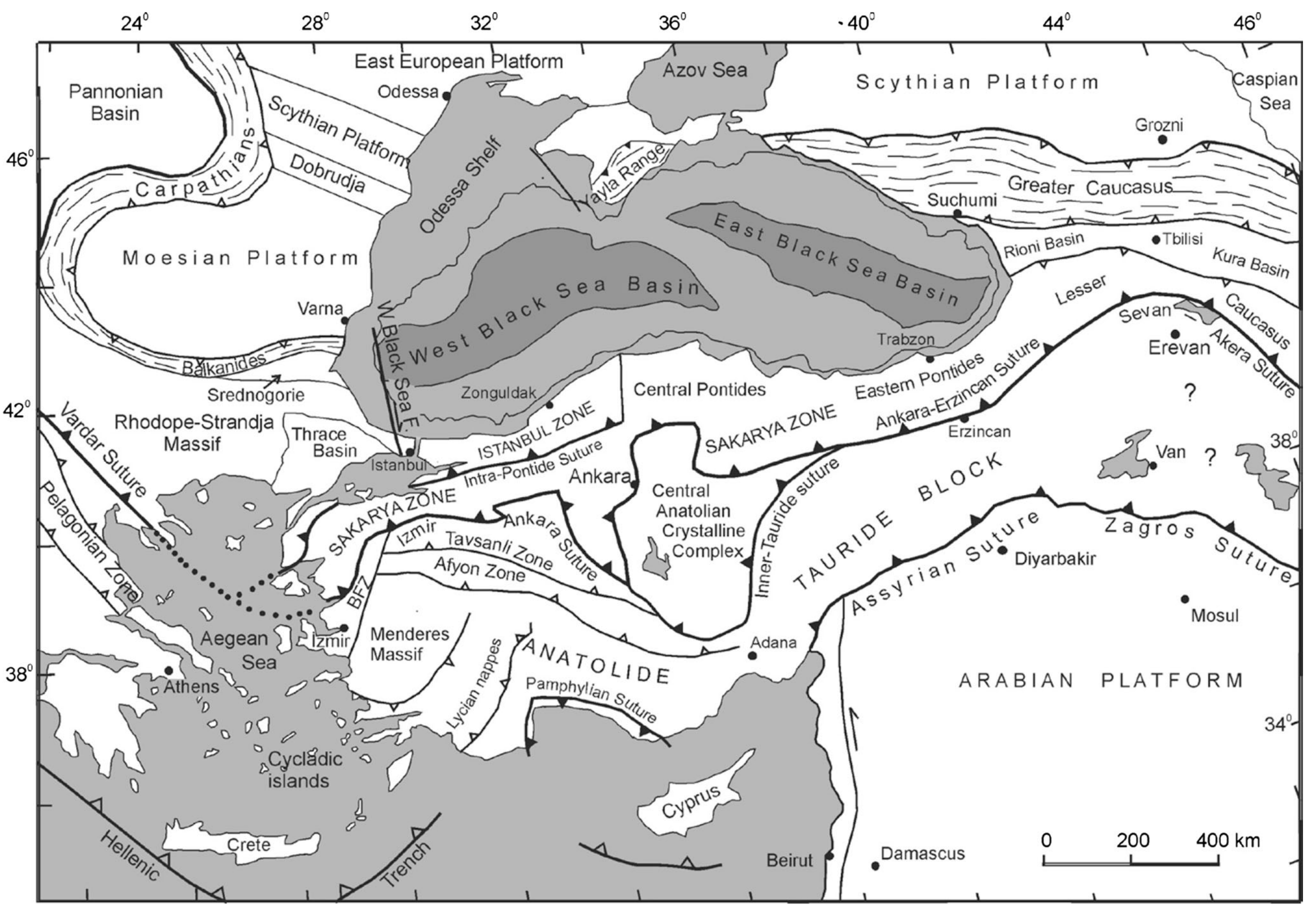


Fig. 2 Tectonic map of the north-eastern Mediterranean region showing the major sutures and continental blocks. The sutures are shown by heavy lines with the polarity of former subduction zones indicated by *filled triangles*. Heavy lines with *open triangles* represent active subduction zones. The Late Cretaceous oceanic crust in the Black Sea is shown by *gray tones*. The *small open triangles* indicate the vergence of the major fold and thrust belts. BFZ denotes the Bornova flysch zone (Okay 2008)

evolutions (Okay et al. 2006). These are the Strandja, İstanbul and Sakarya terranes (Fig. 3).

The Anatolide-Tauride terrane forms the bulk of southern Turkey and in contrast to the Pontic continental fragments shows a Palaeozoic stratigraphy similar to the Arabian platform, including common glacial deposits of Late Ordovician age (Monod et al. 2003). During the obduction, subduction and continental collision episodes in the Late Cretaceous and Palaeocene, the Anatolide-Tauride terrane was in the footwall position and therefore underwent much stronger Alpide deformation and regional metamorphism than that observed in the Pontic zones. During the mid Cretaceous a very large body of ophiolite and underlying tectonic slices of ophiolitic melange were emplaced over the Anatolide-Tauride terrane. The northern margin of the Anatolide-Tauride terrane underwent HP/LT (high pressure/low temperature) metamorphism at depths of over 70 km under this oceanic thrust sheet. Erosional remnants of this thrust sheet of ophiolite and ophiolitic melange occur throughout the Anatolide-Taurides. Although widely called a melange, it generally lacks an encompassing matrix, and represents a highly sheared Cretaceous accretionary complex. With the inception of continental collision in the Palaeocene, the Anatolide-Tauride terrane was internally sliced and formed a south to southeast vergent thrust pile. The contraction continued until Early to Mid-Miocene in western Turkey and is still continuing in eastern Anatolia. The lower parts of the thrust pile in the north were regionally metamorphosed, while the upper parts in the south form large cover nappes. The Central Anatolian Crystalline Complex (north of the Taurides) is a region of metamorphic and plutonic rocks with Cretaceous isotopic ages. The question of the affinity of the Central Anatolian Crystalline Complex, whether part of the Anatolide-Tauride terrane, or a single terrane on its own, is not yet solved (Monod et al. 2003).

The southeast Anatolia forms the northernmost extension of the Arabian platform. During the Mesozoic and Tertiary, the Arabian platform was separated from the Anatolide-Taurides by the southern branch of the Neo-Tethys, which is represented today by the Assyrian suture (Sengör and Yilmaz 1981). The Arabian platform has a Pan-African crystalline basement overlain by a Palaeozoic to Tertiary sedimentary sequence. In most areas of southeast Anatolia only the Cretaceous and younger deposits crop out on the surface. The lower parts of the sequence are exposed in a number of anticlines (Rigo de Righi and Cortesini 1964). These include the Amanos Mountains west of Gaziantep, the Derik and Hazro anticlines south and north of Diyarbakır, respectively, and the Zap anticlines south of Hakkari. In the Zap anticline between Hakkari and Çukurca, the Cambrian to Carboniferous sequence is

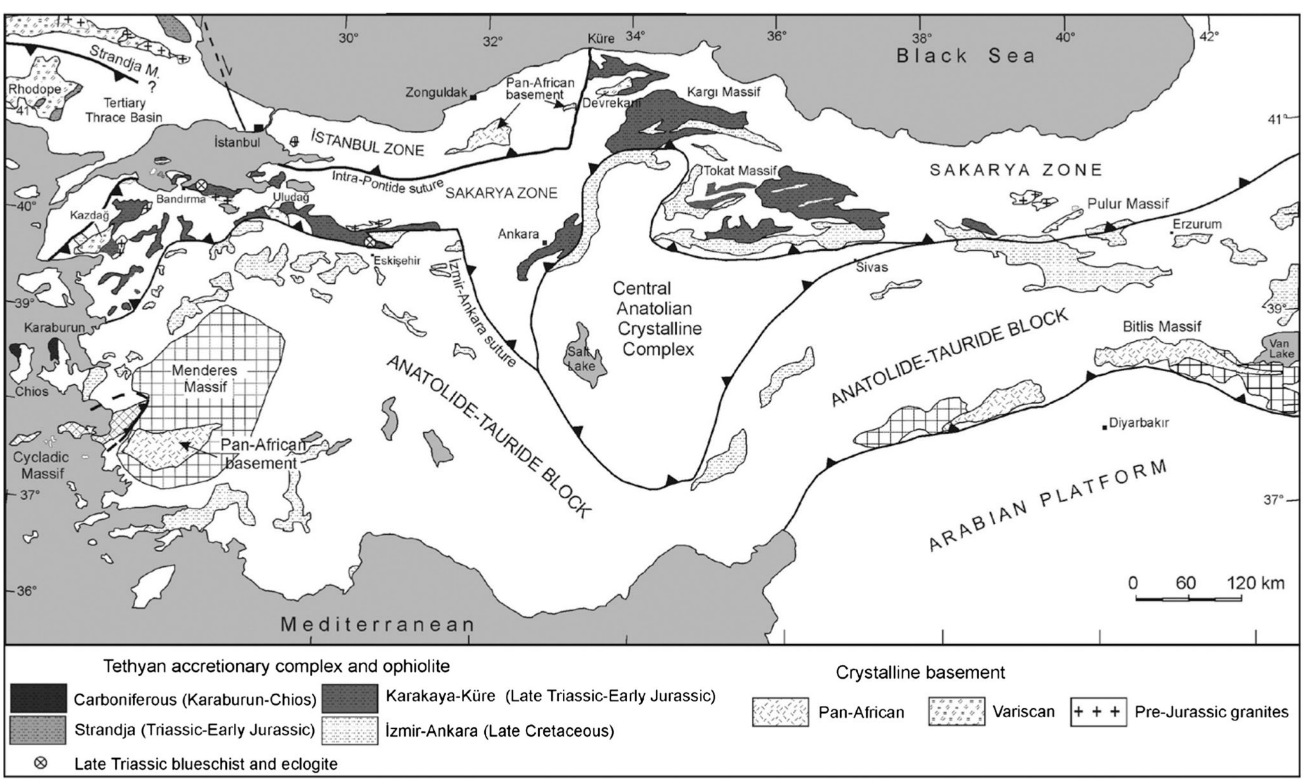


Fig. 3 The distribution of different basement types and accretionary complexes in Turkey (Okay et al. 2006)

dominated by clastic rocks, whereas the Permian to Eocene sequence is largely shallow marine carbonates.

During the Late Cretaceous and Tertiary, ophiolites, ophiolitic melanges and thrust sheets were emplaced over the Arabian platform, which are denoted as the "Lower Nappe". This was part of an extensive emplacement of the oceanic lithosphere over the continent extending from Antakya on the Mediterranean coast to Oman in Arabia. The continental collision with the Anatolides-Taurides occurred later during the Miocene, when a second set of allochthonous units including the Bitlis Massif and the underlying melange units were emplaced over the Arabian platform (Sengör and Yilmaz 1981).

The final amalgamation of the terranes in the Oligo-Miocene ushered a new tectonic era characterized by continental sedimentation, calcalkaline magmatism, extension and strike-slip faulting. Most of the present active structures, such as the North Anatolian Fault, and most of the present landscape are a result of this neotectonic phase (Okay 2008).

Climate of Turkey

The coasts of Turkey that border the Aegean Sea and the Mediterranean Sea have a temperate Mediterranean climate, with hot-dry summers and mild-wet winters. The coasts of Turkey that border the Black Sea have a temperate Oceanic climate with warm-wet summers and cool-wet winters. The Turkish Black Sea region receives the greatest amount of precipitation through the year (Fig. 4) and the eastern part of this region has an annual precipitation of 2200 mm (Şensoy et al. 2013).

The coasts of Turkey that border the Sea of Marmara have a transitional climate between a temperate Mediterranean climate and a temperate Oceanic climate with warm, moderately dry summers and cool, wet winters. Snow occurs in this region almost every winter, but usually lies no more than a few days. On the other hand, snow is rare in the western and southern coasts of Turkey.

Conditions can be much stronger and drier in central Anatolia. Mountains close to the coast prevent oceanic climate from reaching inland, giving the central Anatolian plateau of the interior of Turkey a continental climate with arid seasons.

Winters on the plateau are especially severe. Temperatures of −30 to −38 °C can occur in eastern Anatolia, and snow may lie on the ground for a period of at least 120 days during the year. In the west, winter temperatures average below 1 °C. Summers are hot and dry, with temperatures generally above 30 °C in the day. Annual average precipitation of Turkey for the 1971–2000 climatic periods is about 640 mm and has a decreasing trend of about 29 mm/100 years (Şensoy et al. 2013). The driest regions are the Konya plain and the Malatya plain, where the annual rainfall frequently is less than 300 mm. May is generally the wettest month, whereas July and August are the driest.

Methodology

The very large number of variable sets that drive and trigger landslides (i.e., geology, internal relief, precipitation, aspect, land cover, slope angle, soil texture, seismic activity, flood, phreatic line, human activity) and the difficulties of computing and analyzing large volume of datasets required for a large country like Turkey, comprise restrictive factors for developing a landslide susceptibility assessment after implementing some approaches like probabilistic methods. Geographical information systems (GIS) simplify the analysis of spatial variables through modeling the real world by describing data in layer form, and by the use of spatial analysis using raster data sets.

Raster overlay and map algebra techniques were used for manipulating spatial data (geoprocessing). The maps (variables) were expressed as raster layers and considered as terms of arithmetic operations to produce new maps in this stage (Tomlin 1990). ArcGIS Spatial Analyst and its Raster Calculator package were mainly used to develop a nationwide landslide susceptibility assessment.

In order to develop a landslide susceptibility map of Turkey at the scale of 1:2,000,000, an index-based calculation which considers six factors that controls the occurrence of landslides was applied. The selected resolution for index layers (i.e., slope, lithology, local relief, rainfall, land use, seismicity) was 500 × 500 m. This resolution is deemed to be sufficient for representing and analyzing the landslide susceptibility of Turkey at a scale of 1:2,000,000. These index layers were selected by considering the availability of the data that covers entire Turkey (Okalp 2013).

These six layers could be expanded and an index calculation method could also be enhanced if country-wide datasets would become available. Unfortunately, some datasets like groundwater level variations, soil map, intensity of precipitation, sinkholes, etc., are only locally available and these limited datasets are not suitable for performing a country-wide landslide susceptibility assessment. Therefore, this study has been conducted using only country-wide available datasets (Okalp 2013).

The digital elevation model (DEM) of SRTM (NASA Shuttle Radar Topographic Mission) was used as the major data source for slope angle and local relief analyses. Producing elevation data for about 80 % of the Earth's surface was the main purpose of the SRTM project.

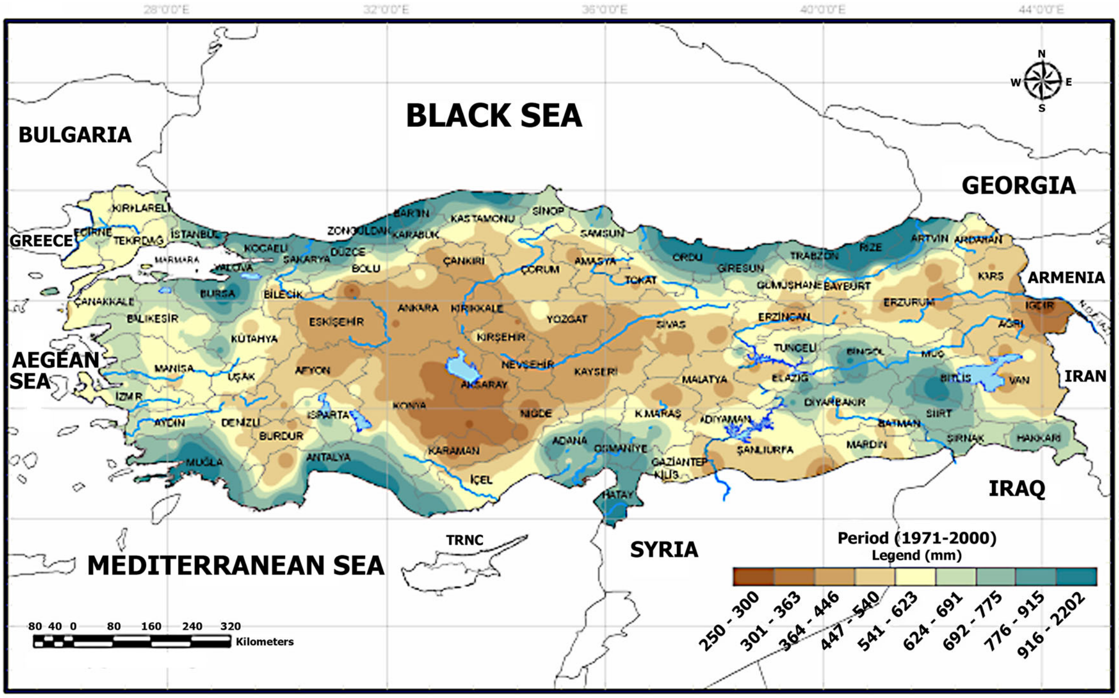


Fig. 4 Mean annual precipitation map of Turkey (Şensoy et al. 2013)

Different versions of SRTM DEM have been published by NASA. A version 3 (V3) set of SRTM DEM which has a 500 m pixel resolution was selected for this study (Fig. 5). The main problem in analyzing this DEM throughout Turkey was selecting an appropriate projection. Turkey has four different UTM projections which are not suitable for a country-wide landslide susceptibility assessment. Another alternative is Lambert Conformal Conic Projection (LCC) that uses a metric system. All layers used in this study were projected as LCC. During SRTM DEM projection transformation from geographic (lat-long) to LCC, a bilinear interpolation was selected as a resampling method.

Resampling methods that are generally preferred are the nearest neighbor, bilinear interpolation and cubic convolution methods. After testing the performances of these methods, the bilinear interpolation method seems to yield the most appropriate results. The interpolation as a whole is not linear but rather quadratic, it interpolates linearly the values of four neighboring cells in both x and y directions to calculate a new central cell value. The elevation errors (originally coming from SRTM DEM, like pits, etc.) at pixel level were improved by using a void filling algorithm during DEM preprocessing.

The slope angle calculation was processed by using the methodology proposed by Hickey (Dunn and Hickey 1998; Hickey 2000; Van Remortel et al. 2001) in an "AML" application running over ArcGIS. The slope angle was actually calculated as a part of the RUSLE equation that is developed for soil erosion estimation, in conjunction with other factors like slope length. This method leads to a maximum downhill slope angle which constrains the slope angle calculations to one cell length (or 1.4 cell lengths in the diagonal) in a downhill direction. Rozos et al. (2013) have claimed that the RUSLE equation could also be used as a tool during the landslide susceptibility mapping procedure.

It is recognized that there exists large differences between slope angle calculation methodologies (Dunn and Hickey 1998; Guth 1995; Skidmore 1989). A comparison of Hickey's and ArcGIS application's slope angle calculation results over SRTM data was made and it was confirmed that only 45 % of the area had equal slope angle values. The maximum downhill slope angle map that was produced through AML script was selected as the slope angle map of this study (Fig. 6). The slope angle map having a 500 m pixel resolution represents the worst situation for slope angle calculation and does not have any "averaged" slope value that the built-in algorithm of ArcGIS produces.

The local (internal) relief is defined as the height difference per square kilometer or per hectare. This factor has an importance on landslides triggered by earthquakes (Paus 2005). For generating the local relief layer, a square window with a side length of 1 km was used to define the neighborhood area and the focal range function of ArcGIS Spatial Analyst was used. Due to the fact that the SRTM DEM used in this study had a spatial resolution of 500 m, a

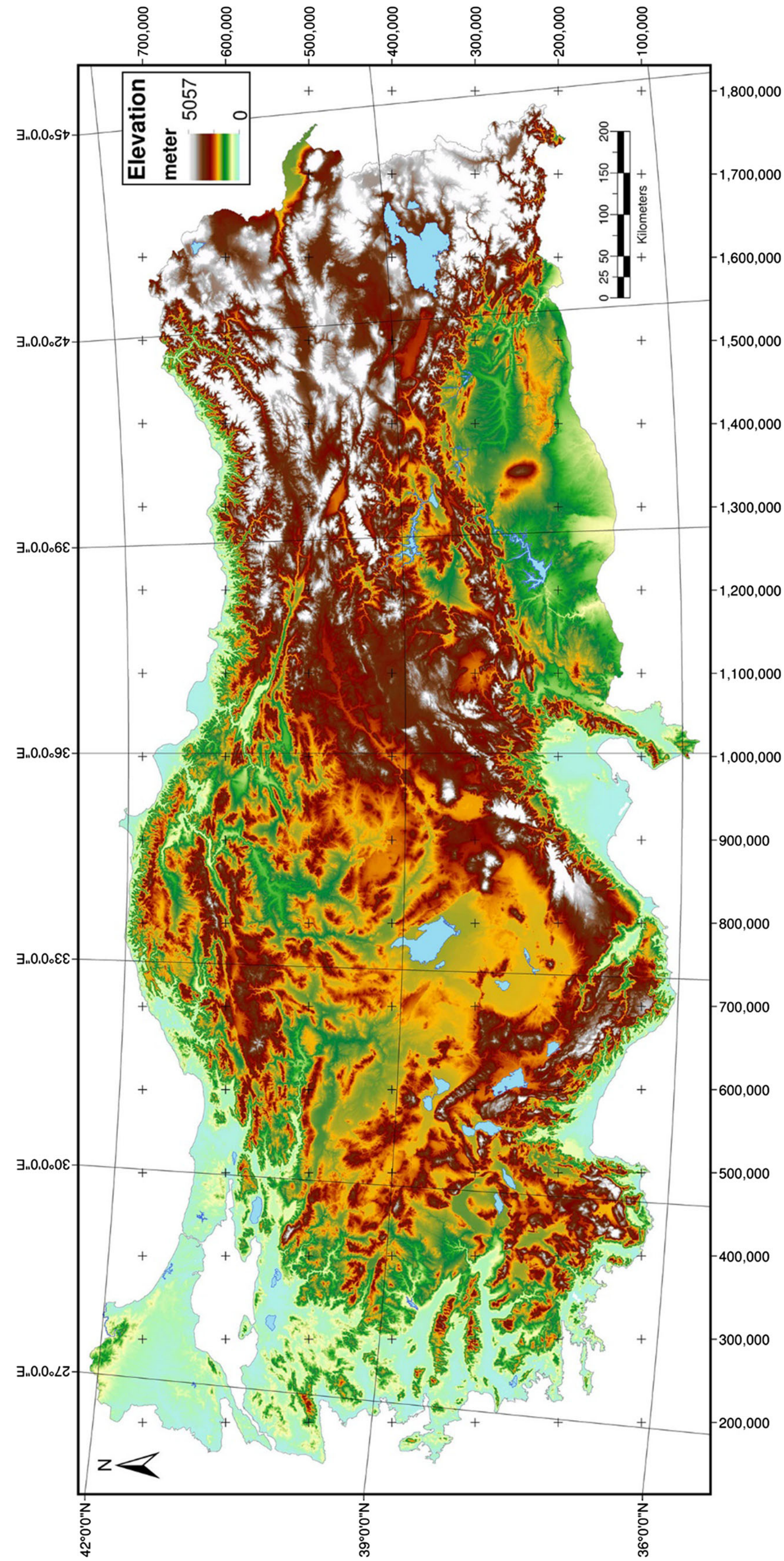


Fig. 5 Elevation map of Turkey (based on SRTM DEM)

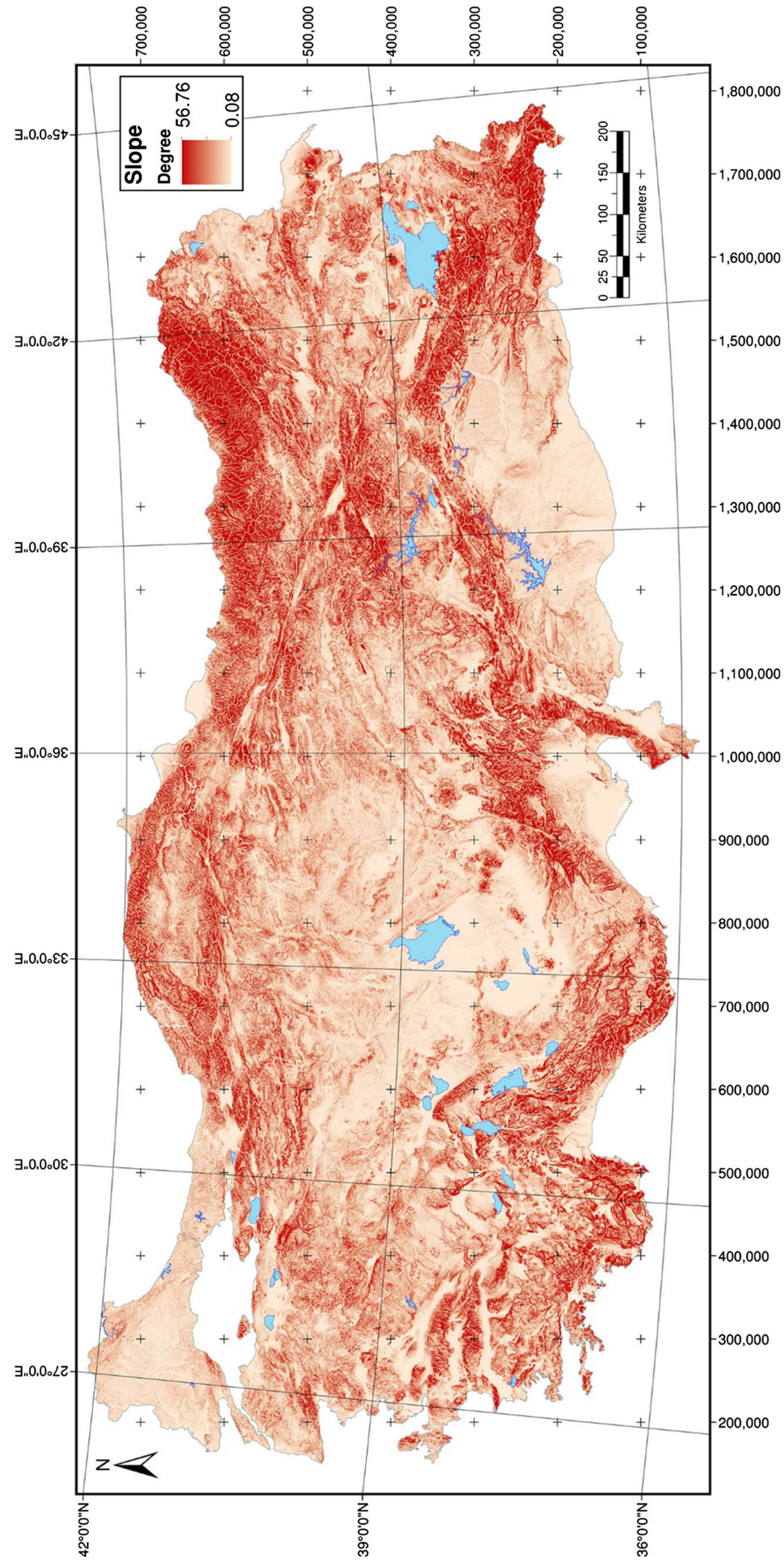


Fig. 6 Slope angle map of Turkey (based on SRTM DEM)

window of 2 × 2 pixels (1 km^2) was selected for calculating the local relief. The legend of the local relief map that was produced in a 500 m pixel resolution varied from 0 to 869 m per square kilometer. The areas having higher local relief values were located on the north–east and south–east parts of Turkey (Fig. 7).

The land use map was processed in a 500 m pixel resolution using the Corine Land Cover 2006 database (CLC 2009), a harmonized and comparable snapshot of land cover for entire Europe in the year 2006, based on high resolution Landsat ETM + imagery (Nunes de Lima 2005). This European reference dataset contains 49 land cover classes grouped in 3 levels. For the proposed landslide susceptibility assessment, a synthetic classification was performed by combining Corine levels 2 and 3 (Fig. 8).

The lithology was obtained from the 1:500,000 scale geological maps published by the Turkish Mineral Research and Exploration General Directorate during the last decade. The attributes derived from these maps are historical units and lithological descriptions. The large number of lithologic units were digitized and grouped into 24 synthetic classes through a 500 m pixel resolution (Fig. 9).

The seismicity data layer was digitized as a 500 m pixel resolution from the 1:1,800,000 scale Earthquake Zoning Map of Turkey prepared by the Ministry of Public Works and Settlement considering the latest knowledge that was approved by the Government of Turkey and published in 1996, which differentiates five classes, representing peak ground acceleration with 10 % probability of exceedance in 50 years (Fig. 10).

The map of the annual mean total rainfall was based on monthly total rainfall records from the 823 meteorological stations that kept a record for a period of 65 years. Unfortunately, most of these stations were not operated for a period of 12 months in some years. For this reason, only years that had recorded values of 12 months were selected. For example, Station-A had been operated for 65 years, but 25 of those years had missing monthly records. For this station, the remainder 40 years were selected, every monthly total rainfall value was summed and then divided by 40. This procedure was carried out for every station and finally, each station was represented with only one annual mean total rainfall value. These values were interpolated by using the Inverse Distance Weighting (IDW) method where eventually the mean total rainfall map for Turkey was developed in a 500 m pixel resolution (Fig. 11).

The factors used in this study were classified and each subclass was rated from 1 to 10 by means of expert judgement considering their importance on producing a landslide. The classification procedure was mainly performed for estimating sliding type slope movements rather than rock-fall type movements. A slope angle having a value between 6° and 12° was determined to be more susceptible to sliding. Areas having a local relief value between 10 and 50 m per square kilometer were noticed to be more prone to landslides. These ranges and rating values are summarized in Table 1.

Water bodies and wetlands were assigned the lowest susceptibility ratings, while forest areas and agricultural areas were assigned the highest ratings during land use classification. The annual mean total rainfall and also seismicity rating values were assigned values depending on their intensities.

It is a well-known phenomenon that the type of lithology is a dominant factor that controls the spatial distribution of landslides. The geotechnical properties, mechanical strength (Hoek et al. 1998; Marinos and Hoek 2001), Geological Strength Index (Hoek et al. 1998) and also the types of geological formations (metamorphic, igneous and sedimentary rocks) were considered during assigning rating values to the lithological classes. The analysis of these factors led to a simplification that reduced the lithological classes from 25 major groups down to 8 subclasses, where the assigned ratings are presented in Table 2.

After obtaining the values from 1 to 10 for each of the six factors (layers) by re-classifications, the data layers have been transformed into grids having a 500 m pixel resolution that is assumed to be sufficient for a final map having a scale of 1:2,000,000. It has been considered that each factor had a different impact on landslide susceptibility, weighted after expert judgement procedure and integrated into the assessment. In this stage, 4 different weight groups (W_i) were assigned to the layer sets in order to capture the layer variability for landslide susceptibility in Turkey and also to minimize the uncertainty of the expert judgement procedure (Table 3).

All of the preliminary maps (layers) were weighted individually and merged in order to represent the landslide susceptibility map. Eq (1) was used to calculate a Landslide Susceptibility Index (LSI):

$$\mathrm{LSI} = \frac{1}{100}\sum_{j=1}^{6}\left(\mathrm{W}_{ij}\mathrm{L}_{j}\right) \tag{1}$$

The LSI was processed in an ArcGIS environment using various operators of Spatial Analyst. The flowchart shown in Fig. 12 summarizes the steps that were performed to obtain the landslide susceptibility map of Turkey.

After obtaining the landslide susceptibility map of Turkey, a grid mask was produced. The philosophy of this grid was to mask areas (water bodies, wetlands, areas having slope angles between 0° and 1°) where there would be no

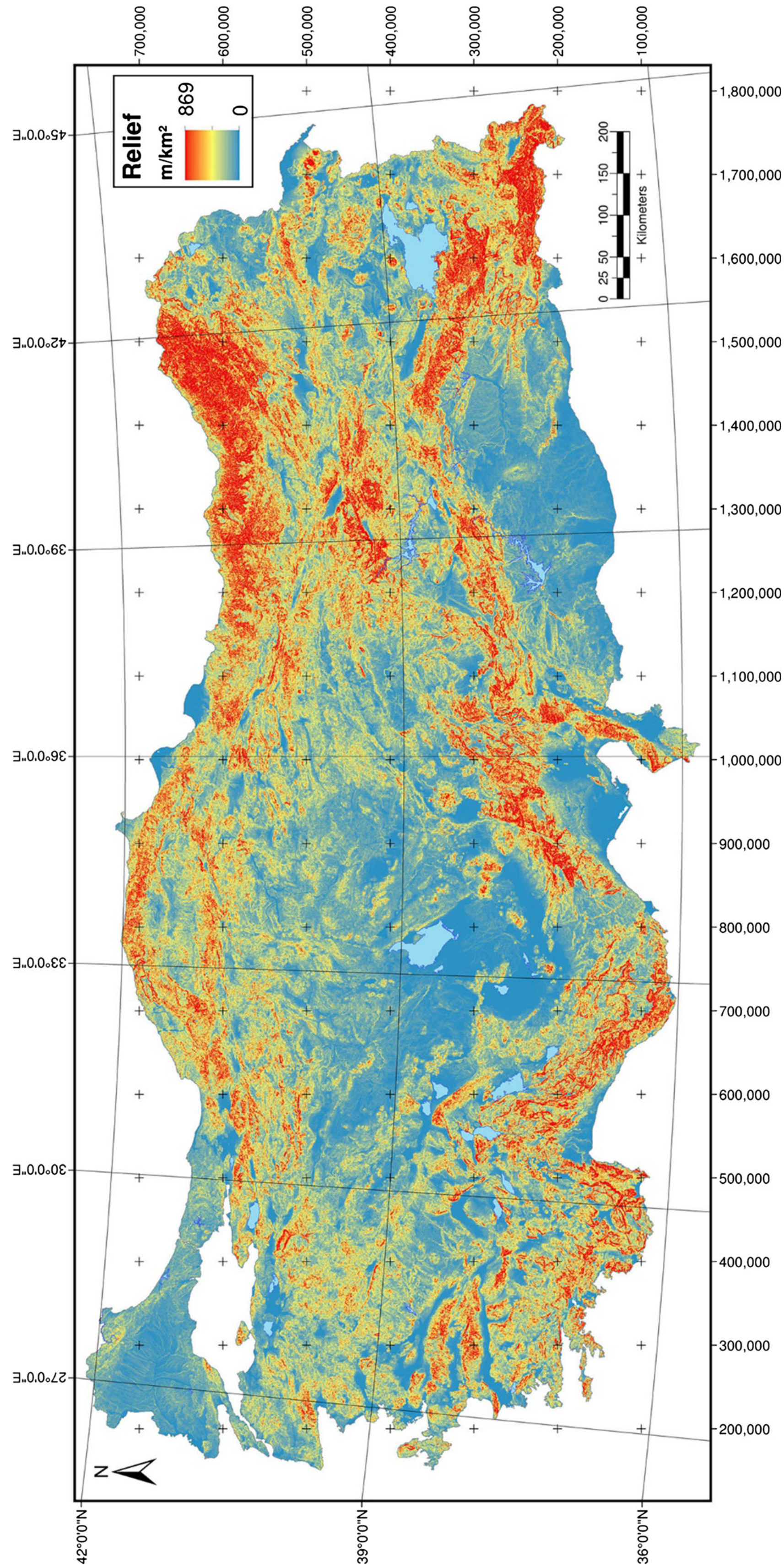


Fig. 7 Local relief map of Turkey (based on SRTM DEM)

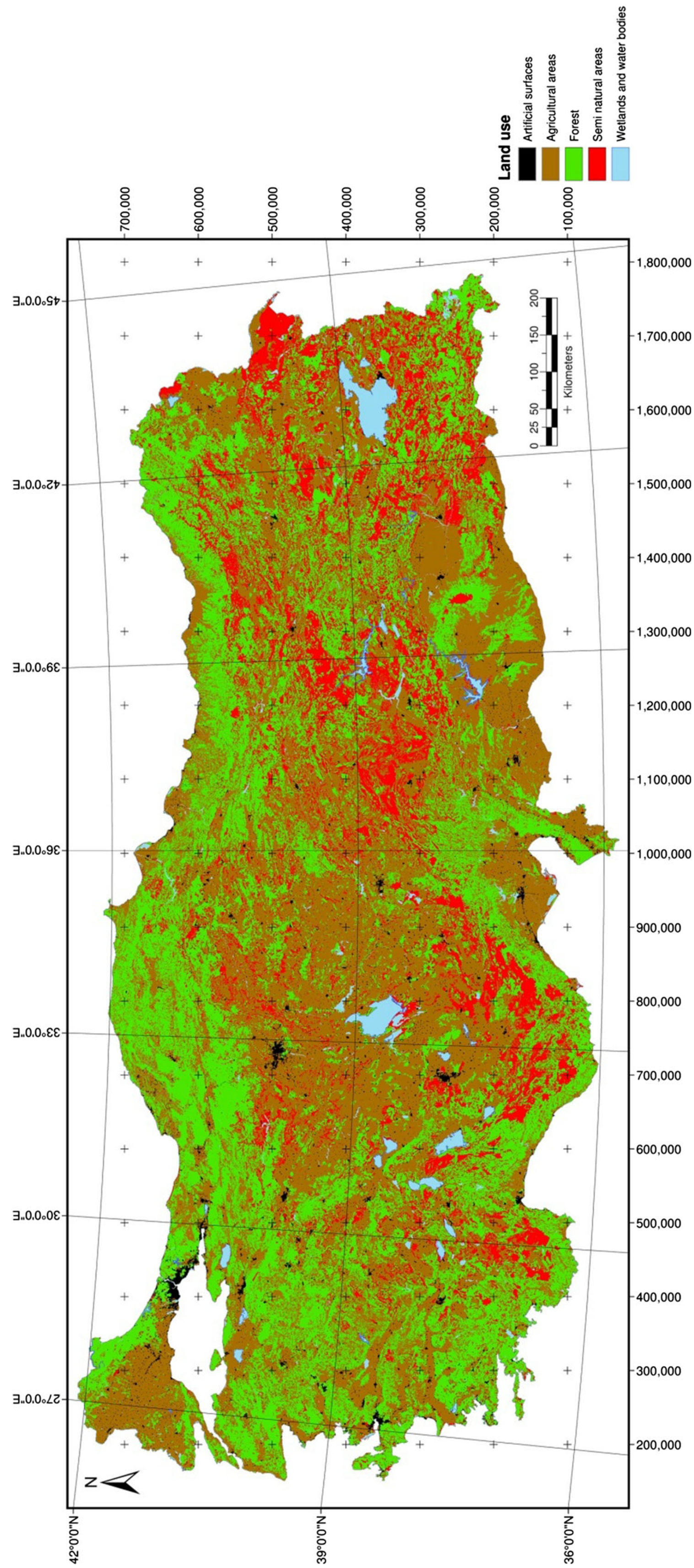


Fig. 8 Land use map of Turkey (based on CLC (2009))

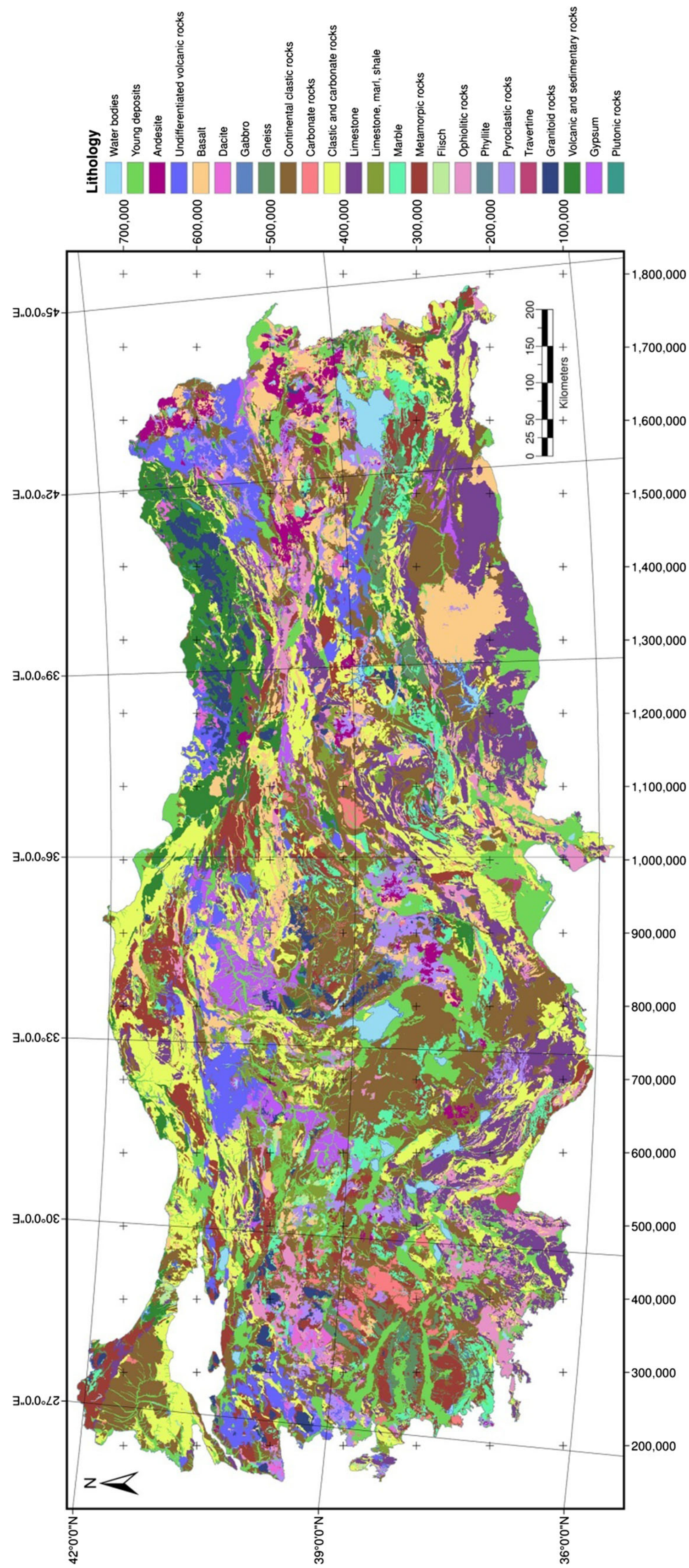


Fig. 9 Lithology map of Turkey (based on 1:500,000 scaled geological maps)

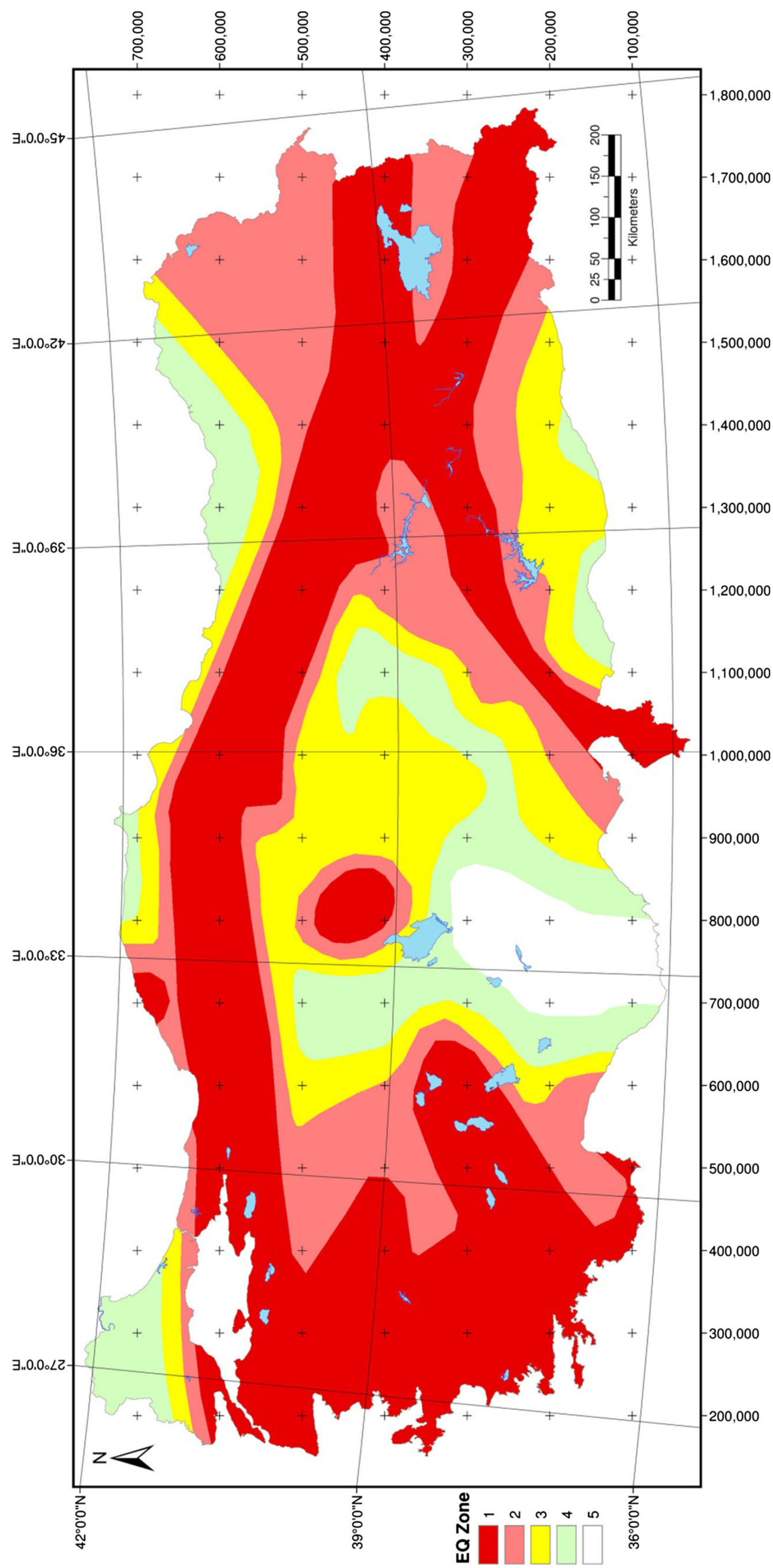


Fig. 10 Earthquake zoning map of Turkey (source: Ministry of Public Works and Settlement, 1996)

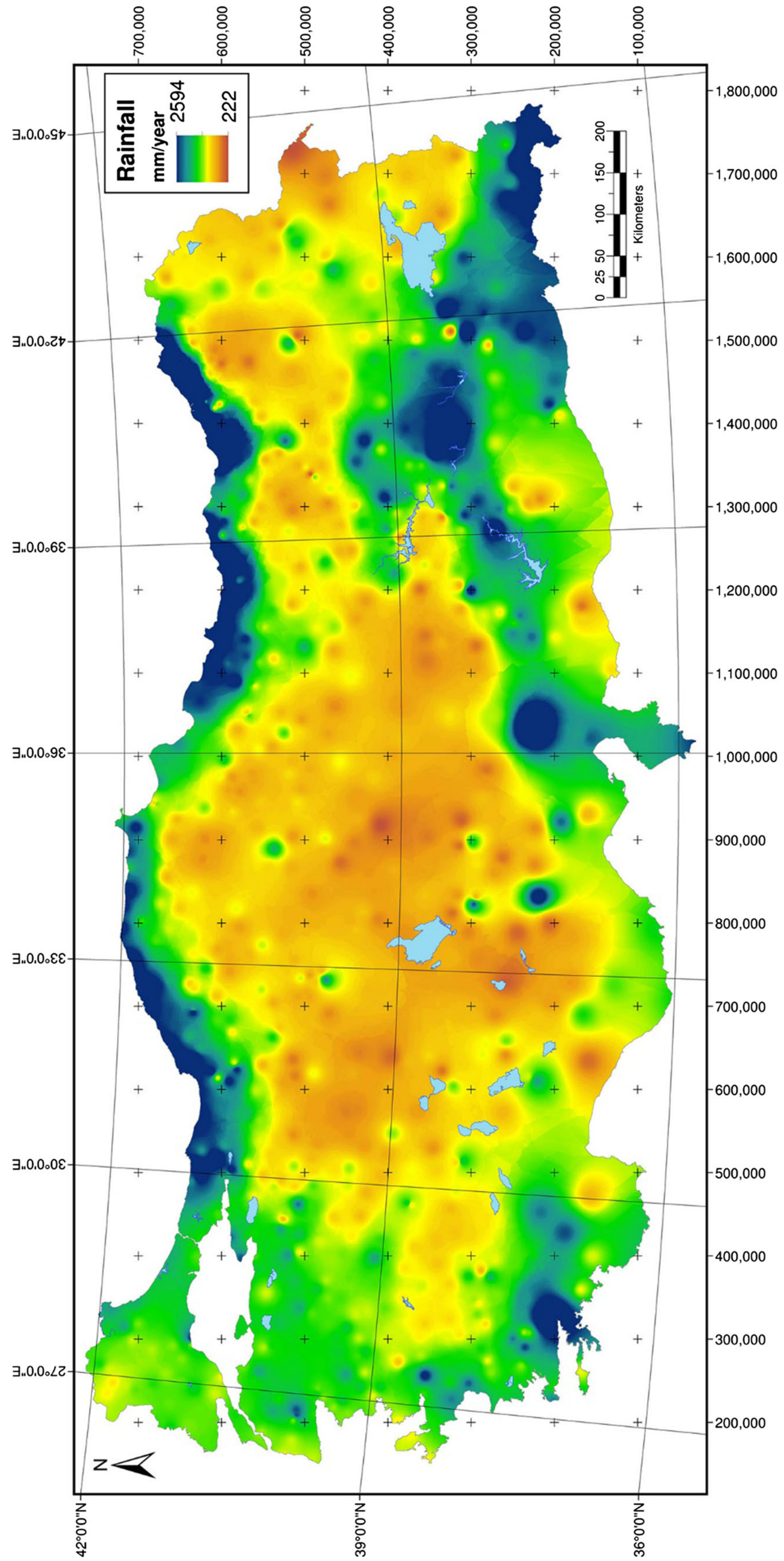


Fig. 11 Mean total rainfall map of Turkey

Table 1 Distribution of slope angle and local relief classes in Turkey

Slope				Local relief			
Class (°)	Rating	Area (km^2)	%	Class (m/km^2)	Rating	Area (km^2)	%
<2	0	154,615	19.732	0–50	6	63,939	8.16
2–4	4	171,282	21.859	50–70	8	159,298	20.33
4–6	6	111,864	14.276	70–90	10	127,799	16.31
6–8	9	86,814	11.079	90–110	9	102,255	13.05
8–10	10	66,346	8.467	110–130	7	79,688	10.17
10–12	8	51,098	6.521	130–150	4	62,215	7.94
12–14	5	38,537	4.918	150–180	3	66,838	8.53
14–20	7	73,239	9.347	180–270	5	92,539	11.81
20–30	3	27,365	3.492	270–600	2	28,913	3.69
30–45	2	2377	0.303	>600	1	78	0.01
>45	1	25	0.003				

Table 2 Rating values assigned to different lithology classes in Turkey

Lithology	Rating
Clastic and carbonate rocks	10
Continental clastic rocks	8
Limestone	6
Undifferentiated volcanic rocks, basalt	5
Volcanic and sedimentary rocks	4
Metamorpic rocks, ophiolitic rocks, gypsum	3
Young deposits, andesite, pyroclastic rocks	2
Dacite, gabbro, gneiss, carbonate rocks, limestone, marl, shale, marble, flysch, phyllite, travertine, granitoid rocks, plutonic rocks	1
Water bodies	0

Table 3 Assigned weights in the landslide susceptibility assessments

Layer	Layer no.	W_1 (%)	W_2 (%)	W_3 (%)	W_4 (%)
Slope	L_1	25	35	30	25
Local relief	L_2	5	5	5	10
Land use	L_3	10	10	10	10
Rainfall	L_4	15	20	15	15
Earthquake	L_5	10	10	10	10
Lithology	L_6	35	20	30	30

landslide. Finally, these areas were multiplied with a value of 0 and the others multiplied with a value of 1 by using a grid mask in order to obtain the final landslide susceptibility map of Turkey.

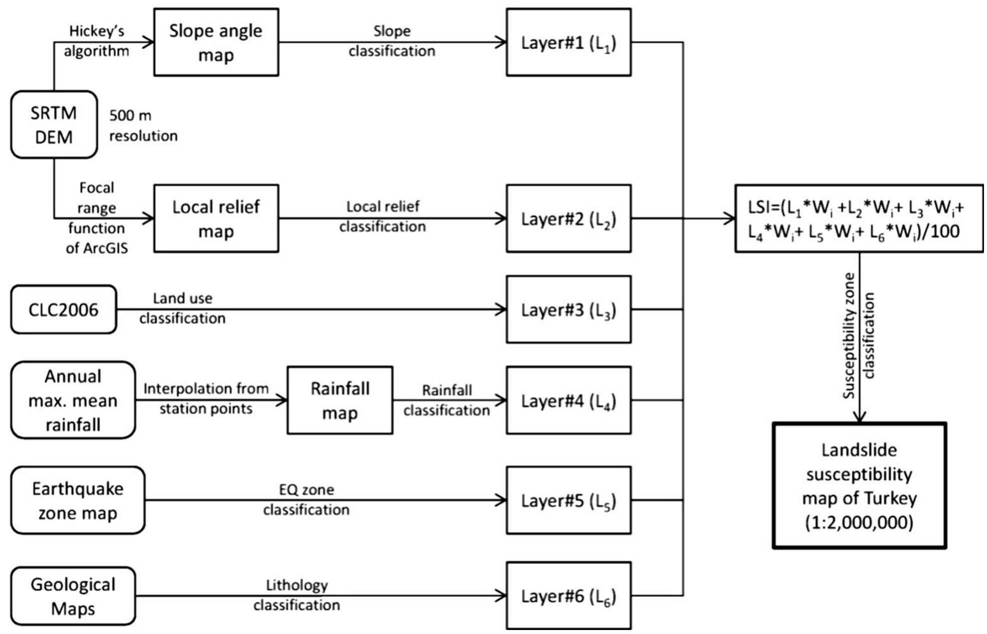
Discussion of the results

Criteria ranking (weighting) is the main source of uncertainity in qualitative landslide susceptibility assessments (Bathrellos et al. 2013). The performances of four different weight groups given in Table 3 were compared and evaluated using a receiver operator characteristics (ROC) curve. It is not an easy task for any expert to judge all of the weights properly. In order to overcome this situation, a weight range was assigned for layers instead of assigning only one constant weight that is summarized in Table 3. This subjectivity has been tried to be minimized by running ROC analysis for comparing the performances of these weight groups. The area under the ROC curve showed the global accuracy statistics for each of the four maps. When the area under the ROC curves (Fig. 13) was considered, it was observed that the W_3 group was slightly superior to the other W_i groups in prediction skills.

The Landslide Susceptibility Index (LSI) was computed by merging six different factors that may range from a value of 0 to 10. These values have been grouped into five susceptibility classes, namely, no susceptibility (0–2), low (2–4), moderate (4–6), high (6–7) and very high (7–10) susceptibility (Fig. 14), respectively. The no susceptibility class represents 4.2 % of the Turkish territory (plains and low hills), low susceptibility class 36.4 %, medium susceptibility 8.3 %, high susceptibility 47.5 % and very high susceptibility class 3.6 %, mostly in the western and middle Black Sea regions, respectively.

The reliability of the heuristic landslide susceptibility assessment based on the Landslide Susceptibility Index (LSI) has been evaluated in nationwide scale using landslide inventory maps published by MTA in a 1:500,000 scale. The predictability of the proposed landslide susceptibility map was evaluated by using delineated real landslide inventory boundaries that covers an area of approximately 30,000 km^2 of Turkey. LSI values that are classified as "located in these boundaries" or "located

Fig. 12 Flow chart of the study



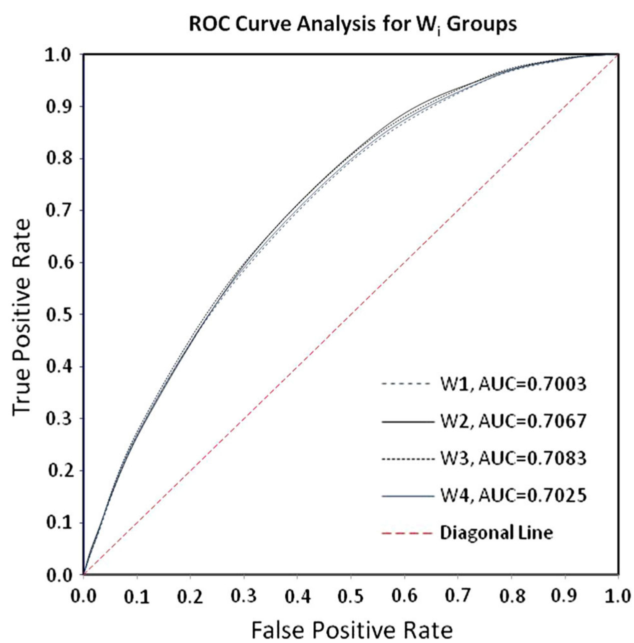


Fig. 13 ROC curves for different weight groups in LSI

outside of these boundaries", are summarized in Table 4 and Fig. 15. It is clear that the predicted LSI values located in real landslide boundaries has a left skewed graphic that implies that most of the real landslide areas were predicted by the approach. Distribution of off side real landslide boundaries represents an M shaped graphic. There is a clear cut located approximately on moderate class at the boundary between no–low class and high–very high class. A moderate class value could be used as a "threshold", where values below this threshold may be assigned as "no landslide" and others as "landslide susceptible" to interpret these results in a convenient way.

The reason for such an output could be modeling Turkey in its entirety in one simple mathematical expression with only six parameters. Each of these parameters has been weighed with a constant value for entire Turkey. According to Cascini (2008), preliminary zoning levels could be obtained by considering only basic methods (i.e., heuristic procedures) in small scale landslide susceptibility assessments. The purpose of these studies that have a small scale is for information only. In fact, a 1:2,000,000 scale is very small to obtain a detailed landslide susceptibility assessment for entire Turkey. The pixel size was selected as large as 500 m for satisfying a 1:2,000,000 scale. On the other hand, data sets (layers) used for this stage had approximately 3,134,248 pixels (in 500 m resolution) that led to a very large data file size for analyzing with a traditional PC. If the pixel size would be selected as 90 m, the data sets would have approximately 96,736,049 pixels. This value is not a feasible data file size to be handled by any PC during the analyses stages. The only reason for handling this sort of extremely large data is not the capacity the of the PC, or the speed of the processor; the main reason is the architecture of the GIS software in the market. Most of these softwares use only one core of the processor without considering the other cores. Briefly, the GIS software is as powerful as the core speed of the processor utilized which is the main limitation factor for handling huge amount of datasets.

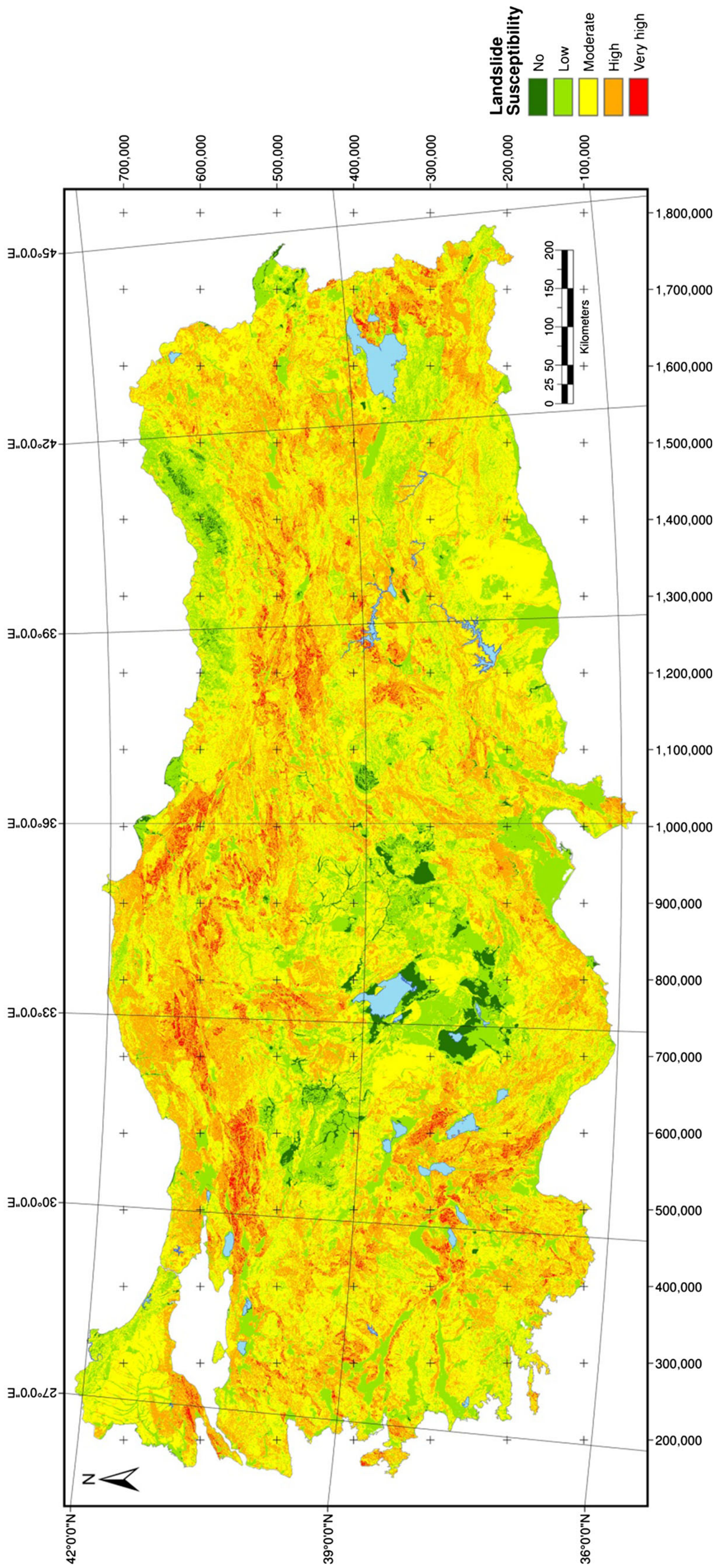


Fig. 14 Landslide susceptibility assessment map of Turkey using LSI (W_3)

Table 4 Distributions of landslide susceptibility classes by test polygons

Class	Areas in the landslide boundaries		Areas outside of the landslide boundaries	
	Area (km^2)	%	Area (km^2)	%
No	38.7	0.13	32,624.2	4.33
Low	1280.4	4.31	279,880	37.13
Moderate	11,401.6	38.34	63,164.8	8.38
High	15,241.4	51.25	351,815.1	46.67
Very high	1777	5.98	26,338.9	3.49
Total	29,739.1	100	753,823.0	100

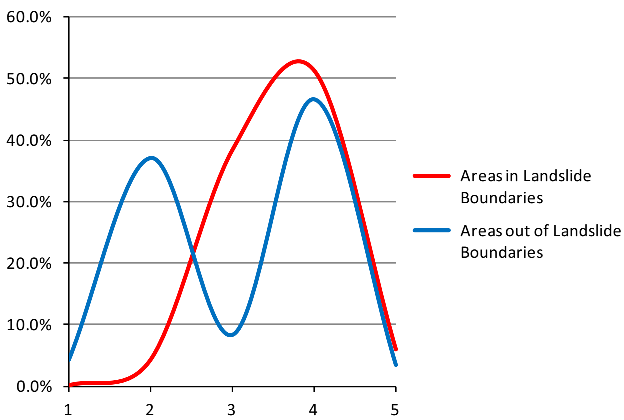


Fig. 15 LSI class distributions pertaining to in-landslide and off-landslide areas

Conclusions and recommendations

In this study, the difficulties in obtaining the landslide susceptibility map of Turkey from publicly available datasets at a national level scale by using heuristic techniques have been discussed. A landslide susceptibility index methodology has been proposed for Turkey by incorporating a scoring system with weighted controlling factors based on a heuristic model (expert judgement). In the final map, five different landslide susceptibility classes have been presented. The high and very high susceptibility classes mainly occur in the western and middle Black Sea regions, characterized by the presence of landslide-prone sedimentary rocks, high seismicity and the highest intensity value distribution of the mean total rainfall (the main landslide triggering factor). The predictive capability of the proposed landslide susceptibility map has been evaluated in the landslide inventory maps of MTA (app. 30,000 km^2). The defined landslide boundaries on these maps only cover about 4 % of Turkey's total footprint area. The landslide susceptibility map that is proposed for the nationwide study represents limited results, owing to the small scale utilized and considering the size of the area, its complexity and the limited number of factors. This map could be used as a planning tool for land development and hazard prevention despite its shortcomings (Bathrellos et al. 2009, 2012; Papadopoulou-Vrynioti et al. 2013).

The product of this study can be accepted as a milestone for further studies that could be performed to obtain a complete landslide susceptibility map of Turkey. For a complete landslide susceptibility study, the scale of the study region could be larger and the number of the parameters considered could also be increased. But it needs to be stressed that these kinds of studies need serious coordination between different institutions, trained personnel, time, funding and of course reliable datasets.

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Compliance with ethical standards

Conflict of interest The research performed in this study was supported by the University Research Project No. BAP-03-09-2010-01 which the second author (Haluk Akgün) has received from the Middle East Technical University (METU) Research Fund.

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