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Determination of the development of settlements above earthquake susceptibility classes in Atakum district (Samsun/Türkiye)

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Abstract

It is not possible to predict and prevent earthquakes in advance. Until now only a few seconds of time can be saved with prediction studies. Therefore, the most logical solution to overcome earthquakes with the least damage is to implement risk management plans. One of the most important studies carried out within the scope of these plans is to determine the earthquake susceptibility of the regions and accordingly, to identify the suitable areas for new settlements. The purpose of the study is to evaluate the extent of earthquake susceptibility in Atakum district and analyse its impact on the developing urban area. To determine the susceptibility, Geographic Information Systems (GIS) and Analytical Hierarchy Process (AHP) were used. For the application of the AHP method, 6 main geographical factors and 28 sub-factors including lithology, slope, distance to fault lines, landforms, maximum ground acceleration and soil permeability were analysed. The rate of weight was calculated for all factors and an earthquake susceptibility map was produced by weighted overlay. Then, the urban development process of Atakum district was determined with satellite images. In order to examine the development of the urban area on earthquake susceptibility classes in the last 23 years, Landsat 7 ETM for 2000 and Landsat 8 OLI/TIRS satellite images for 2013 and 2023 were used. According to the results obtained, the residential areas of Atakum city, especially on the coastline, in the embankment areas and on the alluvial plain floors, are located in the high and very high earthquake susceptibility area.

1. Introduction

An event is labelled as a disaster when it leads to the loss of life, injuries to a substantial number of people, or material damage [1]. A natural disaster is an occurrence that is based on natural events [2]. The reason for natural events turning into disasters is the human utilization of the land [3]. Therefore, the effects of disasters occurring in areas with intensified human activities are greater.

Earthquake, being a land-based event, is the disaster that has caused the most loss of life and material damage in the world from past to present. Most of the world's earthquakes (about 90%) and the world's largest earthquakes (M>8.5) occur at active plate boundaries [4]. Turkey is located at the intersection of 3 plates: Eurasian, African and Arabian Plate [5-7]. Due to its geographical location, Turkey is one of the most seismically active countries in the world [8]. In the country where numerous earthquakes have occurred from past to present, an earthquake occurred on February 6, 2023, in an area on the Eastern Anatolian Fault Zone (slip rate 5-6 mm/yr) [9]. According to the Richter scale, the magnitude of the first earthquake was calculated as Mw = 7.7 (focus depth = 8.6 km), and the magnitude of the second earthquake was calculated as Mw = 7.6 (focus depth = 7 km). After these earthquakes, thousands of aftershocks occurred. Following the earthquakes that were felt intensely in 11 provinces and moderate and low-grade in nearly 50 provinces, more than 50,000 people have lost their lives, and thousands of buildings have collapsed. Devastating earthquakes have occurred along the North Anatolian Fault Zone, which passes through the south of the research area, in the last 100 years. These earthquakes are as follows in order of occurrence: Erzincan Earthquake (7.9 Mw) in 1939, Erbaa-Niksar Earthquake (7 Mw) in 1942, Tosya-Ladik Earthquake (7.2 Mw) in 1943, Kurşunlu Earthquake (6.9 Mw) in 1951 and Erzincan Earthquake in 1992 (6.6 Mw) (Figure 2). In addition, many earthquakes with magnitudes between 3Mw and 6Mw frequently occur along the North Anatolian Fault Zone. These earthquakes are felt as short-term tremors in the study area.

Earthquakes are particularly dangerous because seismologists cannot predict when they will occur [3]. Even earthquake early warning systems operating with the latest software provide only a few seconds to take precautions [10-13]. This situation shows that the most important task to survive earthquakes with the least damage is to be prepared for earthquakes. Therefore, it is of great importance to identify earthquake-susceptible areas and include them in risk management plans.

Disaster susceptibility is defined as the degree to which a specific area's ongoing processes or systems react negatively and are exposed to losses during or after a hazardous event occurs [14]. When evaluating a region's susceptibility to disasters, it is essential to conduct thorough field studies and analyse current information both numerically and visually. The most effective method for obtaining visual and numerical data for the comprehensive examination of the wide-reaching impacts of disasters and disaster planning efforts is the integrated use of Geographic Information Systems (GIS) and Remote Sensing (RS) technologies. GIS and RS techniques are frequently used in pre-disaster risk planning studies and post-disaster spatial analyses [15-19]. These studies are typically conducted with a focus on susceptibility, spatial distribution and hazard assessment [20-30].

Determining a region's earthquake susceptibility and considering the results in disaster risk reduction measures could potentially save many lives in the event of an earthquake. The high-resolution preparation of generated visual data and the determination of the impacts of disasters on populated areas through rating techniques are of vital importance. Additionally, it is essential to detail the studies by incorporating all factors contributing to the mechanism of disaster occurrence and all factors that could affect the safety of life and property in populated areas into susceptibility calculations. In line with this, multi-criteria decision-making methods (MCDM) are commonly used in such studies [31-35].

The preferred study area, the town center of Atakum, is situated roughly 50 km from the North Anatolian Fault Zone (NAFZ), which is one of Turkey's significant active fault zones. In case of a potential earthquake, this closeness presents a notable risk to both lives and property in Atakum. The goal is to identify earthquake-prone areas within the region, aiding decision-makers in their risk planning in preparation for a potential earthquake disaster in Atakum. The earthquake susceptibility of the Atakum district has been analysed by using the Analytic Hierarchy Process (AHP), a multi-criteria decision-making approach, considering six parameters (geology, slope, distance to fault lines, landforms, maximum ground acceleration, and soil permeability) that directly influence the earthquake susceptibility in the research area. This analysis will contribute to taking measures for pre-earthquake risk management in Atakum district and raising the awareness among the local population.

2. Method

2.1. Study area

The study area is Atakum district, which is one of the central districts of Samsun province and has developed rapidly in the last 20 years (Figure 1). The selection of Atakum as the study area was influenced by several factors, such as the district's high population density, its status as a coastal city with active tourism activities, the presence of numerous facilities benefiting a large population, such as universities, hospitals, schools, hotels, conference centers, shopping malls, and public service buildings, its proximity to the North Anatolian Fault Zone, which is part of the Alp-Himalayan Belt, and the presence of faults within the district boundaries. In recent years, the district has experienced a rapid population growth, and its residential areas have expanded significantly. The district's population has doubled in a decade, increasing from 123,904 in 2010 to 242,171 in 2022. Additionally, considering various components such as the presence of multi-story buildings, ground issues, building stock and infrastructure systems, it is crucial to determine the course of action to be followed in the event of a potential earthquake.

Atakum is one of the 17 districts of Samsun province. The city center of Atakum is approximately 50 km away from the North Anatolian Fault Zone that passes within the boundaries of Samsun (Figure 2). The distance to the fault line, the fact that most of the settlements are built on unconsolidated ground, the risk of soil liquefaction due to the high number of landfill areas and being a coastal city, are important problems in terms of earthquakes. Due to its less durable ground, even earthquakes occurring far from the fault line can potentially cause significant damage in the city.

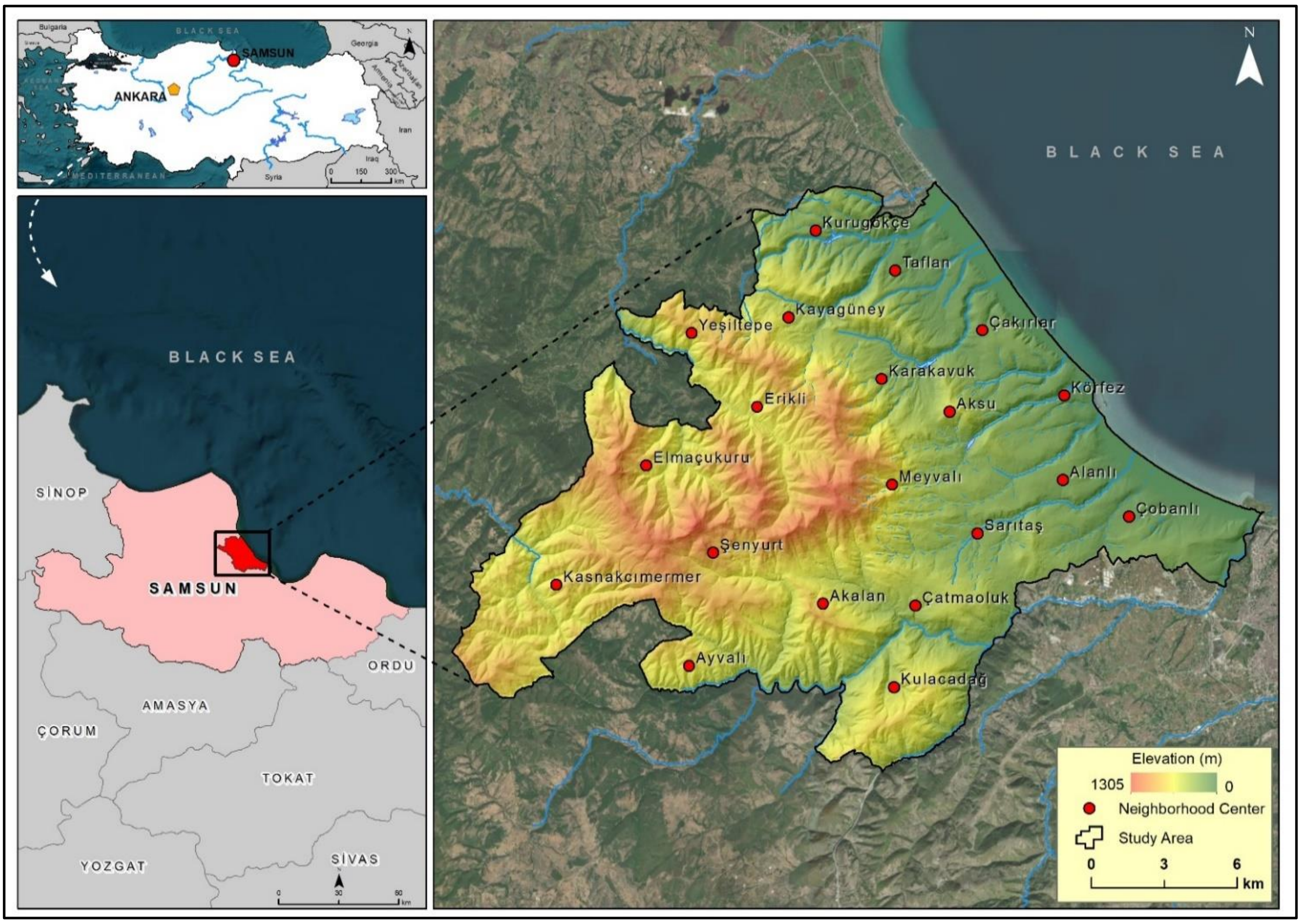


Figure 1. Atakum district location map

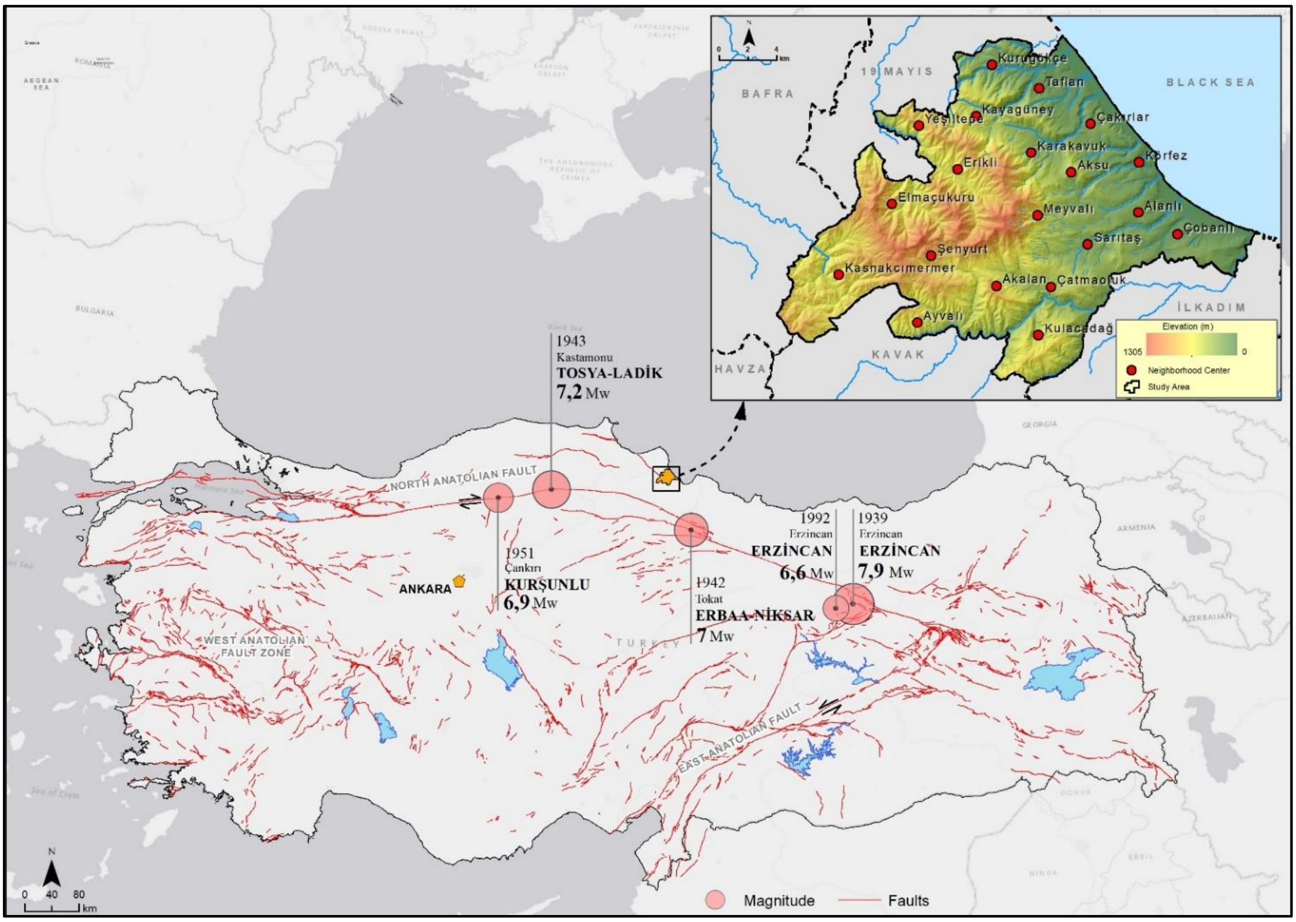


Figure 2. Location of the study area according to Turkey's fault lines and earthquakes that affected the area in the past

The North Anatolian Fault Zone has experienced numerous earthquakes from the past to the present. However, some earthquakes have been unforgettable due to the loss of life and property left behind. The Erzincan Earthquake on December 27, 1939, with a magnitude of 7.9 Mw; the Erbaa-Niksar Earthquake on December 20, 1942, with a magnitude of 7 Mw; the Ladik earthquake on November 26, 1943, with a magnitude of 7.2 Mw; the Bolu-Gerede Earthquake on February 1, 1944, with a magnitude of 7.5 Mw; the Gölcük Earthquake on August 17, 1999, with a magnitude of 7.4 Mw; and the Düzce Earthquake on November 12, 1999, with a magnitude of 7.2 Mw were recorded as the largest earthquakes along the North Anatolian Fault Zone. Among these earthquakes, the ones that have most significantly affected Samsun province were the Erbaa-Niksar Earthquake of 1942 and the Ladik Earthquake of 1943. These earthquakes caused the collapse of some buildings in Samsun. However, since Atakum city did not undergo significant development during those years, major losses were not experienced. Nevertheless, 4,000 people lost their lives in Samsun city and its rural areas. Two major earthquakes, which occurred on February 6, 2023, centred in Kahramanmaraş and referred to as the 'disaster of the century', resulted in the largest losses in Turkey. Despite being approximately 450 km away from Atakum city, the Kahramanmaraş Earthquakes has caused quakes in the city, leading to panic among the people. This situation highlights the importance of being prepared not only for earthquakes on nearby fault lines, but also for those on distant fault lines.

2.2. Data

To mitigate the effects of earthquakes, it is crucial to carefully examine certain geographical factors, especially when constructing buildings in the pre-earthquake period [35]. These geographical factors include active faults and their locations, the geological condition, permeability and the liquefaction feature of the ground, groundwater levels, building resilience, topography, slope, maximum ground acceleration, earthquake zone classification, proximity to rivers, and more [36-38]. However, to determine the earthquake susceptibility of an area, it is necessary to evaluate these geographical factors together rather than individually.

The study conducted for earthquake susceptibility in the Atakum district consists of three complementary stages: data generation through GIS, field observations, and the Analytic Hierarchy Process (AHP) (Figure 3). Initially, the necessary geographical data for analysis were acquired, then these data were categorized into subclasses for use in the pairwise comparison matrix with AHP, and finally, earthquake susceptibility analysis was conducted using GIS techniques.

This study aimed to identify earthquake-susceptible areas in the Atakum district by utilizing different geographical factors based on national and international literature (Table 1). Within this framework, earthquake susceptibility analysis was conducted using a total of 6 main and 28 sub-geographical factors, including lithology, slope, distance to fault lines, landforms, maximum ground acceleration, and soil permeability. The data structure required for the utilization of geographical factors in earthquake susceptibility analysis was created using ArcGIS for Desktop Advanced 10.5 software.

The Digital Elevation Model (DEM), which served as a source for many data in the study, was obtained through the digitization of contour lines from 1/25.000 topographic maps provided by the General Directorate of Maps. The DEM data was utilized to create data regarding the slope and landforms of the terrain. Additionally, lithology and soil permeability data for the Atakum district were produced using 1/100.000-scale geological maps obtained from the General Directorate of Mineral Research and Exploration. Additionally, the distance data to fault lines was calculated using the Distance analysis tool, a feature of ArcGIS for Desktop Advanced 10.5 software, based on values considered in the literature. The maximum ground acceleration data were prepared using a total of 118 sampling points, considering the Türkiye Earthquake Hazard Map. Land Forms map was produced from 1/25.000 scale topographic maps.

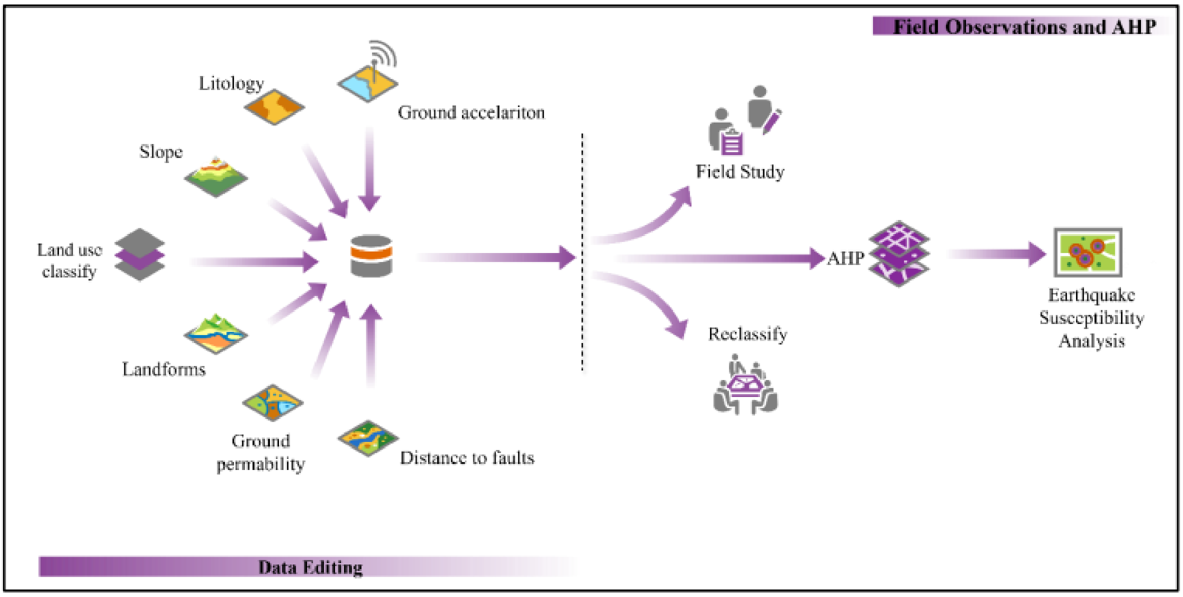


Figure 3. Earthquake susceptibility analysis workflow diagram

Table 1. Data used in earthquake susceptibility analysis and their sources

Data	Data Source	Generated Data
Geological Map (1/100.000)	General Directorate of Mineral Research and Exploration (MRE)	Lithology, Fault Lines, Ground Permeability
1/25.000 Scale Topography Maps	General Directorate of Mapping (GDM)	Contour Line, Peak, Stream, Lake Etc.
Maximum Ground Acceleration Map	Disaster and Emergency Management Presidency (DEMP)	Maximum Ground Acceleration Classes
Landsat 7-8, Satellite Images (2000, 2013, 2023)	USGS	Land Use/Land Cover

2.3 Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS)

AHP is a method in which potential problems are assessed within a hierarchical framework and the perspectives of decisionmakers or experts are considered during this evaluation [39]. Thanks to this hierarchical structure, it is determined how consistent the geographical factors considered are. At the top of the AHP hierarchy, there is always the overall objective, and to prioritize among the considered geographical factors in order to achieve this overall objective, pairwise comparison matrices are created [40]. Through pairwise comparison matrices, the degrees of importance and influence of all factors relative to each other are determined. This importance is achieved using a scale developed by [41] and scored on a scale of 1-9. In this scale, the lowest level of importance is 1, and it numerically increases up to 9 (Table 2). These importance scores are used to calculate a weight ratio for each geographical factor, resulting in a consistency ratio. While the calculated weight ratios indicate how effective the relevant geographical factors will be in the upcoming analyses, the consistency ratio allows for testing the usability of the importance scores and calculated weight ratios for geographical factors before conducting the analysis. The calculated consistency ratio should be ≤ 10% [41] to ensure that the decision hierarchy is usable in the analysis. In summary, AHP consists of the processes of (i) creating the decision hierarchy, (ii) forming pairwise comparison matrices, and (iii) calculating the weight and consistency ratios for all factors [42].

Table 2. Analytic hierarchy process importance scale [41]

Importance Level	Definition		Importance Level
1	Equally Important		1
3	Moderately More Important	Moderately Less Important	1/3
5	Strongly More Important	Strongly Less Important	1/5
7	Very Strongly More Important	Very Strongly Less Important	1/7
9	Extremely More Important	Extremely Less Important	1/9
2,4,6,8	Intermediate Values		1/2,1/4,1/6,1/8

While AHP enables the determination of impact ratios among the criteria identified for solving any problem, it is incomplete to transfer the calculated rates to maps spatially [40]. This deficiency of AHP is complemented by the spatial analysis capabilities of GIS (Geographic Information System). Thus, the impact of each geographical factor used in susceptibility analysis is expressed in a more concrete manner. The interaction between GIS and AHP bridges the gap between spatial and mathematical aspects, enabling GIS and AHP to become more efficient and advantageous [43]. Additionally, the integration of AHP with GIS significantly reduces the complexity of the decision hierarchy and enables tracking the distribution of all utilized factors in the field [40]. Thus, GIS provides the opportunity for the holistic assessment of both main and subcriteria, enabling decisionmakers to approach problem-solving spatially and engage in local-level planning.

In this study conducted for seismic susceptibility analysis in Atakum district, AHP and GIS techniques were preferred due to their ease of use, more comprehensible results, and the ability to be rapidly integrated with GIS. Within the scope of the study, firstly, a decision hierarchy was established among the identified geographical factors, and pairwise comparison matrices were created among all main and sub-geographical factors to calculate weight and consistency ratios. For all these calculations performed with AHP, the program designed by [44], with the version dated September 15, 2018, was used. In different studies, some common parameters were analyzed using AHP and the seismic sensitivity of the study area was determined [45-47].

2.4 Field study

developments in the tourism, entertainment, health, and education sectors. Throughout this growth, the main factors determining the direction of urban development have been the slope and proximity to the coastline. In a city where the slope increases from the coastline towards the inland areas, urban development has primarily occurred in areas with less slope, resulting in a cityscape that has developed parallel to the coastline. Due to the decrease in available land for settlement along the coast and rising land prices, the city has begun to expand towards the inland areas where the slope is steeper. Today, the primary direction of development has resulted in a cityscape that is expanding parallel to the coastline and towards the southern regions. This situation can be observed in aerial photos taken with a drone during field surveys (Figure 4).

When examining the images obtained using a drone, it is observed that buildings are densely located in the urban area. The number of spacious and open areas that can be used as assembly area is insufficient. Certain assembly areas have been allocated in the urban plan but have not been developed or constructed yet. As buildings rise in these areas, the population will increase, leading to a decrease in the number of available assembly areas for residents. With the annual increase in migration in

The city of Atakum has experienced rapid growth, particularly in the last 20 years, in parallel with its
the study area, both urban development and population have grown. In the last 10 years, the district's population has doubled, and the district has become a focal point for Samsun. The city has expanded both horizontally and vertically. The construction of multi-story buildings, particularly in areas with poor ground support, can result in a broad impact zone in the event of a potential earthquake. In this regard, it becomes of great importance to enhance disaster awareness, prepare assembly areas, identify alternative routes, and develop an earthquake emergency action plan.

3. Results

3.1. Geographic factors used in susceptibility analysis

While assessing the earthquake susceptibility of the district, the weight ratio of 6 different geographical factors has been calculated, including lithology, slope, distance to fault lines, landforms, maximum ground acceleration and soil permeability (Table 3). Each of these factors considered in the evaluation is essential in the earthquake susceptibility calculation for the Atakum district. The significance of each factor for the Atakum district is explained below.

Figure 4. Drone image of areas with very high and high susceptibility results

Table 3. Geographic factors and numerical values used in earthquake susceptibility analysis

Geographical Factor	Sub-Criterion		Area		Sub-Criterion Weight (%)	Consistency (%)	Weight (%)
			km^2	%			
Slope (°)	0-2 (Flat and Near Flat)		27,50	6,97	3,5	8	5
	2-5 (Slightly Sloping Slope)		25,55	6,47	6,8		
	5-15 (Sloping Slope)		131,00	33,19	13,4		
	15-35 Moderately Steep Slope)		201,68	51,09	26,0		
	35+ (Very Steep Slope)		9,00	2,28	50,3		
Lithology	Agglomerate	Za	0,41	0,10	4,5	10	36,6
	Volcanosedimentary	Zb	12,12	3,07	9,9		
	Sandstone, Mudstone		275,60	69,82			
	Clayey Limestone	Zc	86,57	21,93	24,1		
	Alluvial And Colluvial Deposits	Ze	20,03	5,07	61,5		
Distance To Fault Lines (km)	30-35		9,85	2,50	30,2	2	15,4
	35-40		78,78	19,96	26,6		
	40-45		93,85	23,78	18,7		
	45-50		106,66	27,02	14,1		
	> 50		105,59	26,75	10,4		
Maximum Ground Acceleration (g)	0,205-,214		101,09	25,61	14,9	2	9,2
	0,214-0,223		125,30	31,74	17,2		
	0,223-0,234		70,64	17,90	19,6		
	0,234-0,246		71,76	18,18	22,5		
	0,246-0,264		25,94	6,57	25,8		
Landforms	Mountain		5,89	1,49	4,4	6	4,7
	Erosion Surface		149,53	37,88	4,1		
	Coastal Plain		14,15	3,58	51,3		
	Slope		219,88	55,70	13,0		
	Valley Base		5,28	1,34	27,2		
Ground Permeability Condition	Permeable Ground		45,95	11,64	64,3	8	29,1
	Semi Permeable Ground		262,69	66,55	28,3		
	Impermeable Ground		86,09	21,81	7,4		

Slope: Throughout the district, there are 10 rivers that flow from south to north. These rivers are directly related to three of the six parameters used in earthquake susceptibility. These parameters are slope, landforms, and lithology. The most significant landforms in the district's topography are valleys that are deeply carved by the erosive power of rivers and plateau areas. Erosion activities that have occurred over time have led to variations in slope values in the district (Figure 5). Settlements have generally been preferred in areas with lower slopes due to the lower construction costs. However, as one moves southward in the district, settlements have also been established in areas with increasing slopes and in the valleys of rivers flowing from south to north towards the coast. The fact that settlements are established at different slope degrees will result in varying levels of resistance against earthquake forces, inertia forces, and falling forces in the event of a possible earthquake. This will lead to a difference in how the earthquake intensity is felt over short distances.

Lithology: The ground structure plays a significant role in the intensity of an earthquake and the degree of damage it causes [48]. In fact, lithology can be an even more important parameter than proximity to fault lines in some cases [49, 50]. Because settlements built on alluvial materials far from fault lines can experience stronger shaking during an earthquake compared to the shaking felt in much older mountainous terrain situated closer to the fault line. This situation explains the relationship between landforms and lithological parameters and their significance for earthquake susceptibility. Upon examining the lithological composition of the Atakum district, it is observed that the coastal areas, where the city largely extends, consist of unconsolidated alluvial and colluvial deposits (Figure 5). Additionally, a significant part of the city's coastal areas consists of filling land that has been created by filling the sea. In this case, it can be asserted that, because of lithological characteristics, the coastal areas of the city would experience the effects of a potential earthquake more intensely.

Distance from Fault Lines: When assessing the earthquake risk of settlements, the first factor to consider is the distance from fault lines. Atakum city is located 50 km away from the North Anatolian Fault Zone, one of the world's largest fault zones. There are two inactive faults in the central and southern parts of the district. Nevertheless, these are inactive fault lines, and the probability of them generating earthquakes is extremely low. Therefore, the distance to fault lines parameter was evaluated in consideration of the North Anatolian Fault Zone, which could potentially cause an earthquake in Atakum. As a result, the influence of proximity to fault lines increases from north to south within the district's boundaries The inactive fault lines within the district's boundaries are visible in (Figure 5) on the lithology map.

Peak ground acceleration: The maximum ground acceleration factor is generally used in the investigation of the impact of earthquakes and hazard analyses related to earthquakes [51]. The maximum ground acceleration indicates the extent of earthquake hazard of a region. The data for the maximum ground acceleration specific to the study area was generated based on the Türkiye Earthquake Hazard Map data, which came into effect on January 1, 2019 (Figure 5).

Landforms: In the Atakum district, as one moves inland from the coast, the elevation increases. Along the coast, there are flat areas, followed by gently sloping hills behind the coast, and then, with an increase in slope, areas with elevations of 50 meters or more, resembling low-level plateaus. In the inland and southern parts of the district, there are medium-high plateaus and high plateaus. Landforms exhibit varying resistance to potential earthquakes [52, 38]. For example, lowlands with saturated, alluvial materials display relatively low resistance to earthquakes [40], while slopes composed of rigid formations exhibit higher resistance to earthquakes. The fact that the majority of casualties occurred in the Bornova Plain following the earthquake in İzmir on October 30, 2020 [53], strengthens the understanding of plains as morphological units that are relatively weak in terms of earthquake susceptibility. In the Atakum district, the presence of various landforms within short distances will lead to the earthquake's magnitude being felt in different ways (Figure 5).

Ground permeability: The permeability of the ground is one of the most crucial parameters for earthquake susceptibility studies, as it is directly related to soil liquefaction. Liquefaction occurs when the soil loses its resistance, hardness, and compactness during an earthquake [54]. Particularly common in sandy and silty soils lacking clay, liquefaction leads to increased damage during earthquakes. Buildings on soil that transitions from a solid state to a semi-solid-semi-liquid state are more prone to collapse. This situation poses a significant risk for settlements like Atakum (Figure 5) where most of the construction is built on alluvial materials near the coast and filling areas. This is because the coastal areas have high groundwater levels and a higher likelihood of soil liquefaction.

3.2. AHP, MCA and earthquake

In this study aimed at determining earthquake susceptibility, pairwise comparison matrices were created between both sub and main parameters using AHP, and weight ratios for all sub-top criteria were calculated. According to the calculations, the overall consistency ratio of the study was found to be 8% (Table 4). In addition, the standard deviations of each factor were also calculated (Figure 6). The determined weight ratios were mapped according to the following formula using GIS capabilities.

Earthquake Susceptibility Analysis = (Slope * 0.050) + (Lithology * 0.366) + (Distance to Fault Lines * 0.154) + (Maximum Ground Acceleration * 0.093) + (Landforms * 0.047) + (Ground Permeability * 0.291).

The earthquake susceptibility map created using AHP consists of 5 classes, which are labelled as very low, low, medium, high, and very high. During the representation of susceptibility classes on the map, striking colours have been preferred. Red-coloured areas represent very high susceptibility, orange areas represent high susceptibility, yellow areas represent medium susceptibility, green areas represent low susceptibility, and blue areas represent very low susceptibility classes.

When examining the earthquake susceptibility result map of the Atakum district (Figure 7), it can be observed that the very low and low susceptibility classes cover a larger area compared to the very high and high susceptibility classes. Additionally, the yellow-coloured areas, which are described as partially safe by experts and are reasonable for settlement after areas with lower earthquake risk, occupy a considerable amount of space. This situation is expressed numerically in Table 5. The fact that areas in the low seismic susceptibility class cover a large area, is favourable news for urban planners. However, for a city like Atakum, where a significant part of the existing settlement is located in areas with high and very high seismic susceptibility, implementing settlement plans based on seismic susceptibility classes has been a belated endeavour.

As you move from north to south in the Atakum district, you approach the North Anatolian Fault Zone. However, in the same direction, it can be observed that earthquake susceptibility class becomes safer. In other words, areas classified as very high susceptibility along the coast transition into high and medium susceptibility classes as you move inland. In the southern parts of the district, there are widespread areas classified as low and very low susceptibility classes. The primary reason for this contrast arises from the fact that the coastal areas, which are the farthest from the fault line within the district's boundaries, consist of alluvial soil and artificial fill materials. The lack of soil consolidation in coastal areas will cause settlements to experience the quakes more intensely. Additionally, the low elevation and the high potential for soil liquefaction in coastal areas have been the most significant factors increasing the earthquake susceptibility of these areas.

When the earthquake susceptibility map and the aerial view of the city are considered together, it can be observed that settlements are mostly located in areas with very high (red) and high (orange) earthquake susceptibility. Within the district borders, coastal areas with a low slope that are in high demand are filled with settlements. The area with a medium level of susceptibility shown in pale yellow on the susceptibility map is where residents live in summer-type houses, and they frequently visit the city center. The area highlighted in yellow is where the settlement boundary is located. This is because the areas shown in red and orange, which indicate very high and high susceptibility, are already filled with settlements (Figure 8). As the coastal settlement areas have filled up, the demand for settlement locations has shifted southward. The shift of citizens towards areas with lower earthquake susceptibility is not a conscious decision but rather a result of following the direction of urban development. According to the susceptibility map, areas with very low and low earthquake susceptibility correspond to mountainous regions where elevation increases. These areas are typically covered with forests or used as pastures.

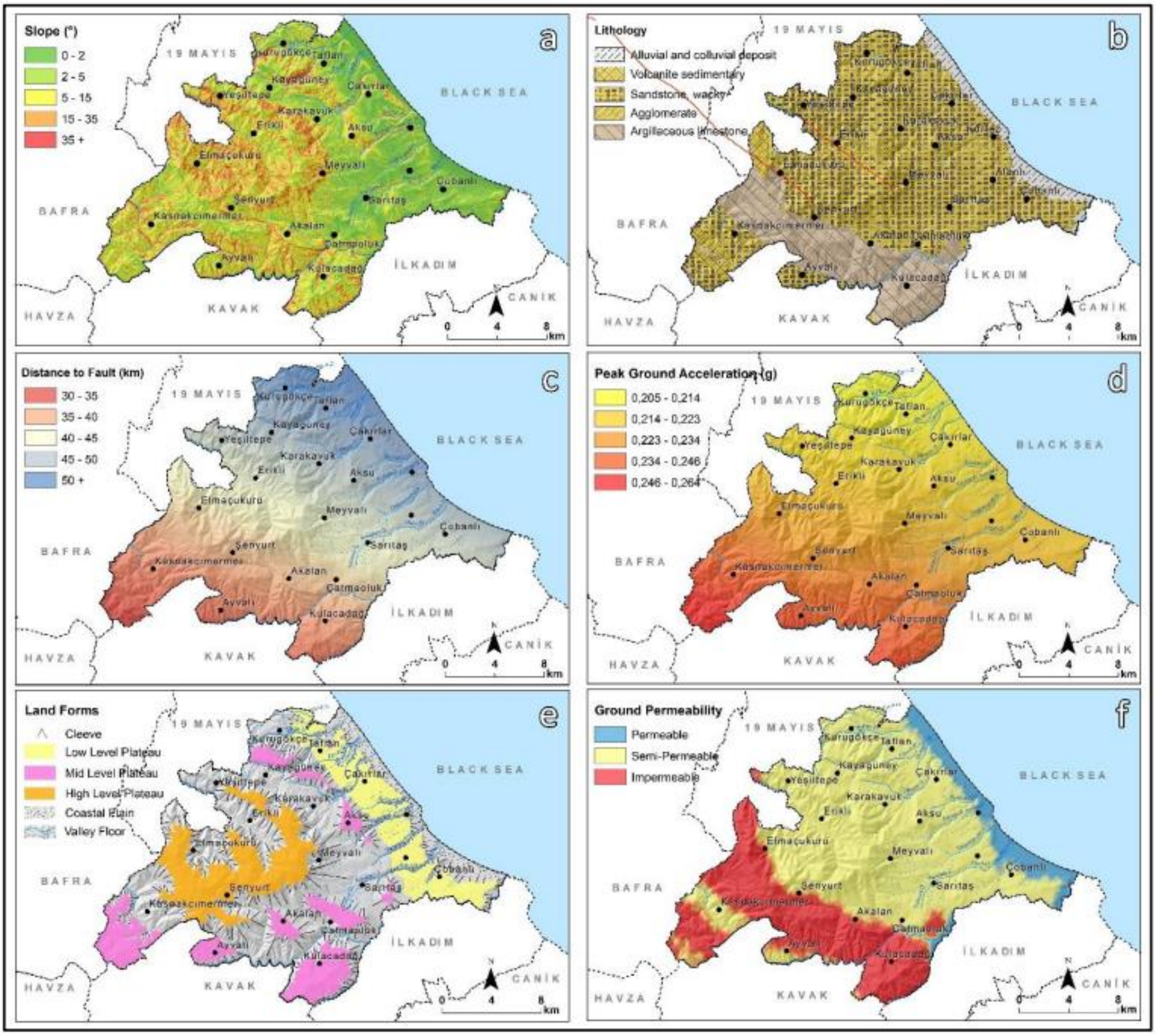


Figure 5. Geographical factors used in susceptibility analysis; a) slope, b) lithology, c) distance to fault lines, d) maximum ground acceleration, e) landforms, f) ground permeability

Table 4. Pairwise comparison matrix of main geographical factors

Geographical Factor	(A)	(B)	(C)	(D)	(E)	(F)
(A) Slope	1	1/5	1/3	1/3	1	1/5
(B) Lithology	5	1	5	5	7	1
(C) Distance To Fault Lines (m)	3	1/5	1	3	5	1/3
(D) Maximum Ground Acceleration (g)	3	1/5	1/3	1	2	1/3
(E) Landforms	1	1/7	1/5	1/2	1	1/5
(F) Ground Permeability Condition	5	1	3	3	5	1
Consistency Rate (%)			8			

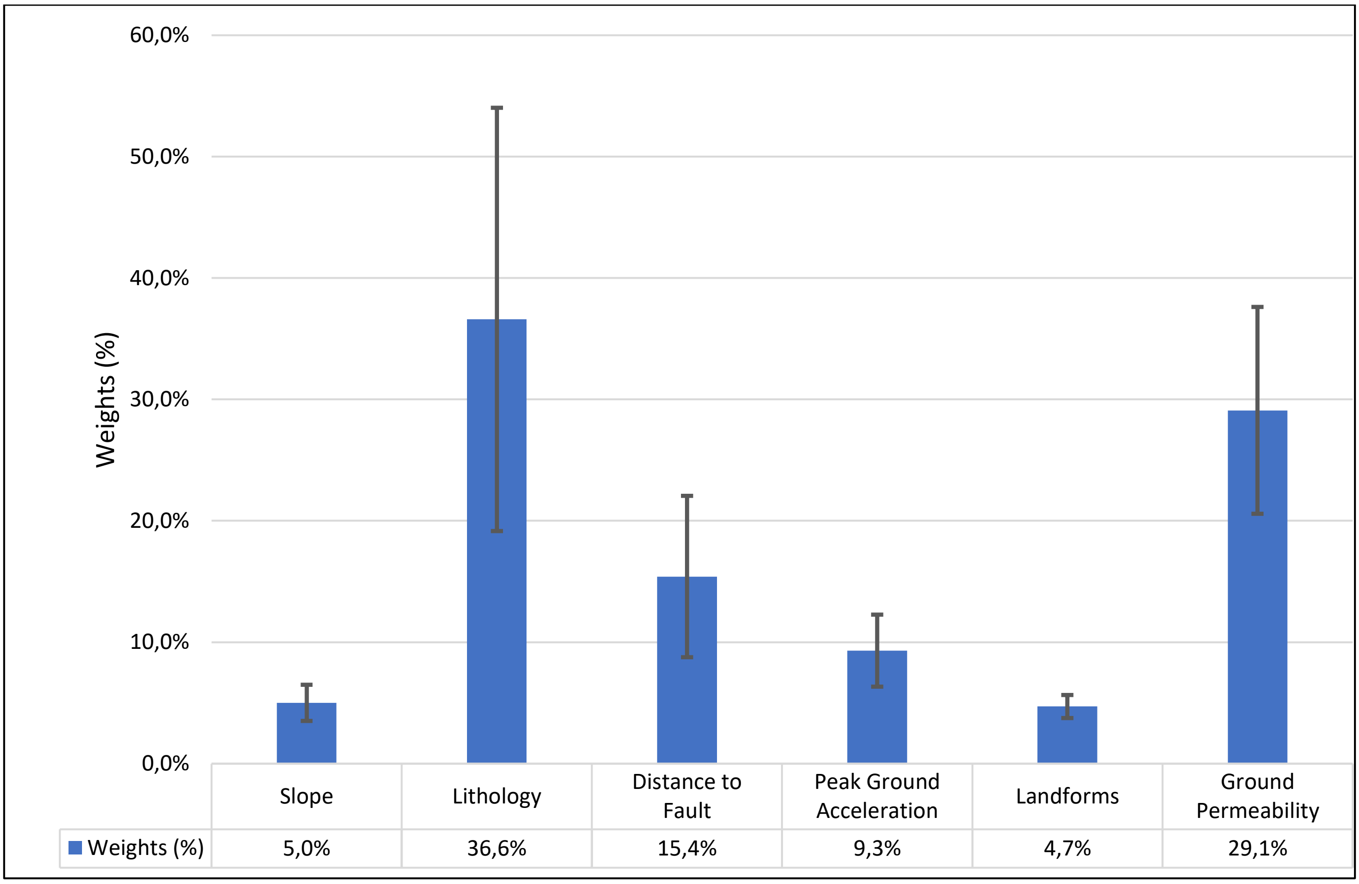


Figure 6. Weight distributions and standard deviations of geographical factors

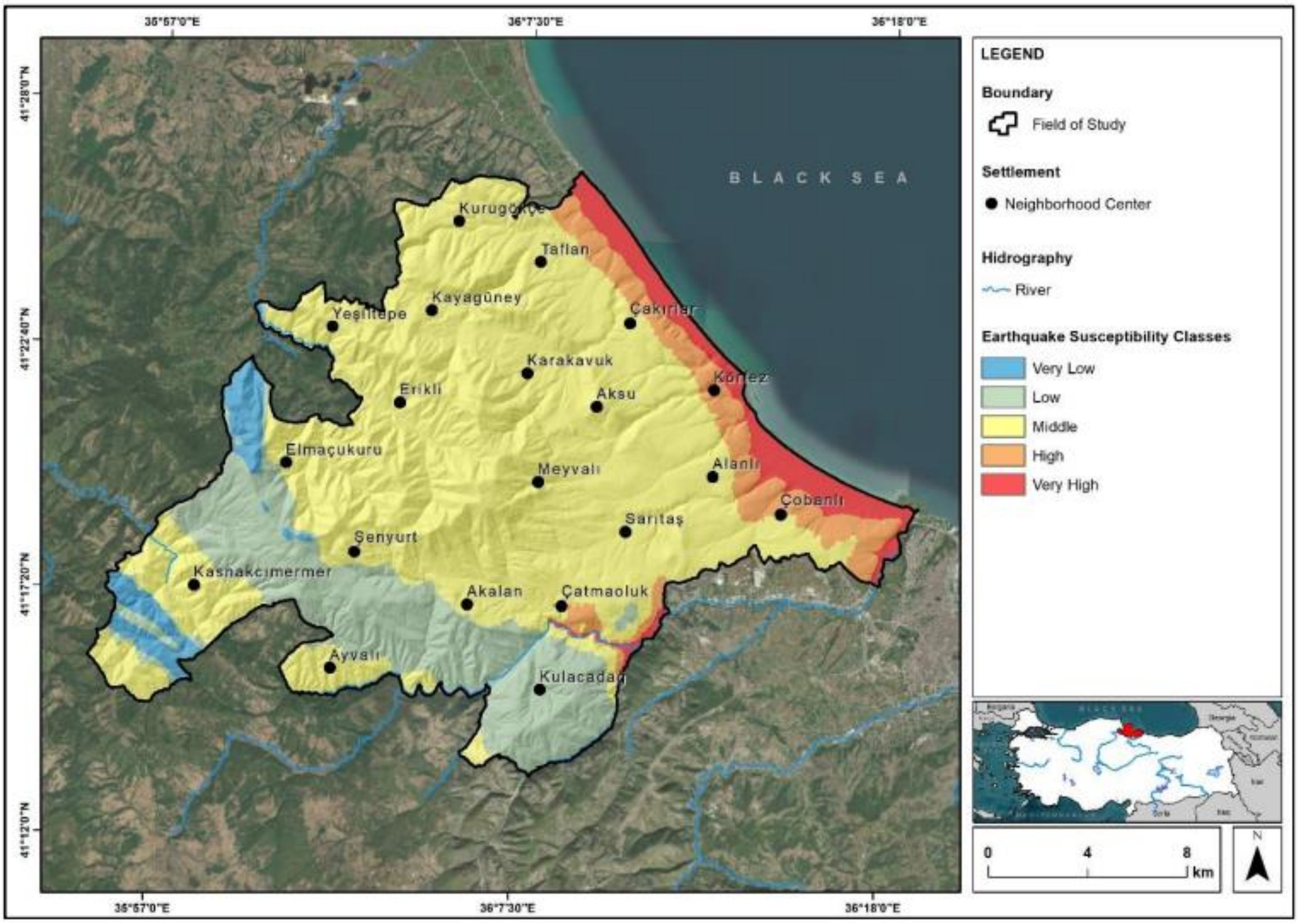
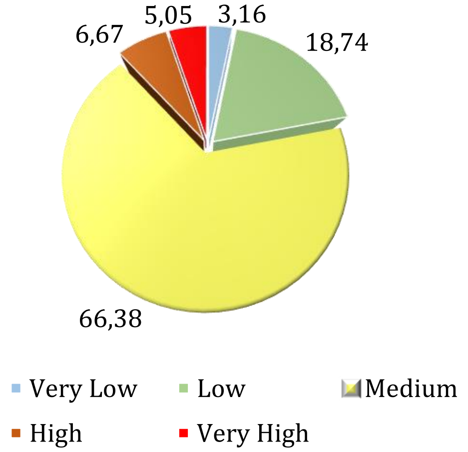


Figure 7. Atakum district earthquake susceptibility map

Table 5. Spatial distribution and percentage rates of earthquake susceptibility classes

Earthquake Susceptibility Classes	Area	
	km^2	%
Very Low	12,47	3,16
Low	73,96	18,74
Medium	262,04	66,38
High	26,32	6,67
Very High	19,94	5,05
Total	394,73	100



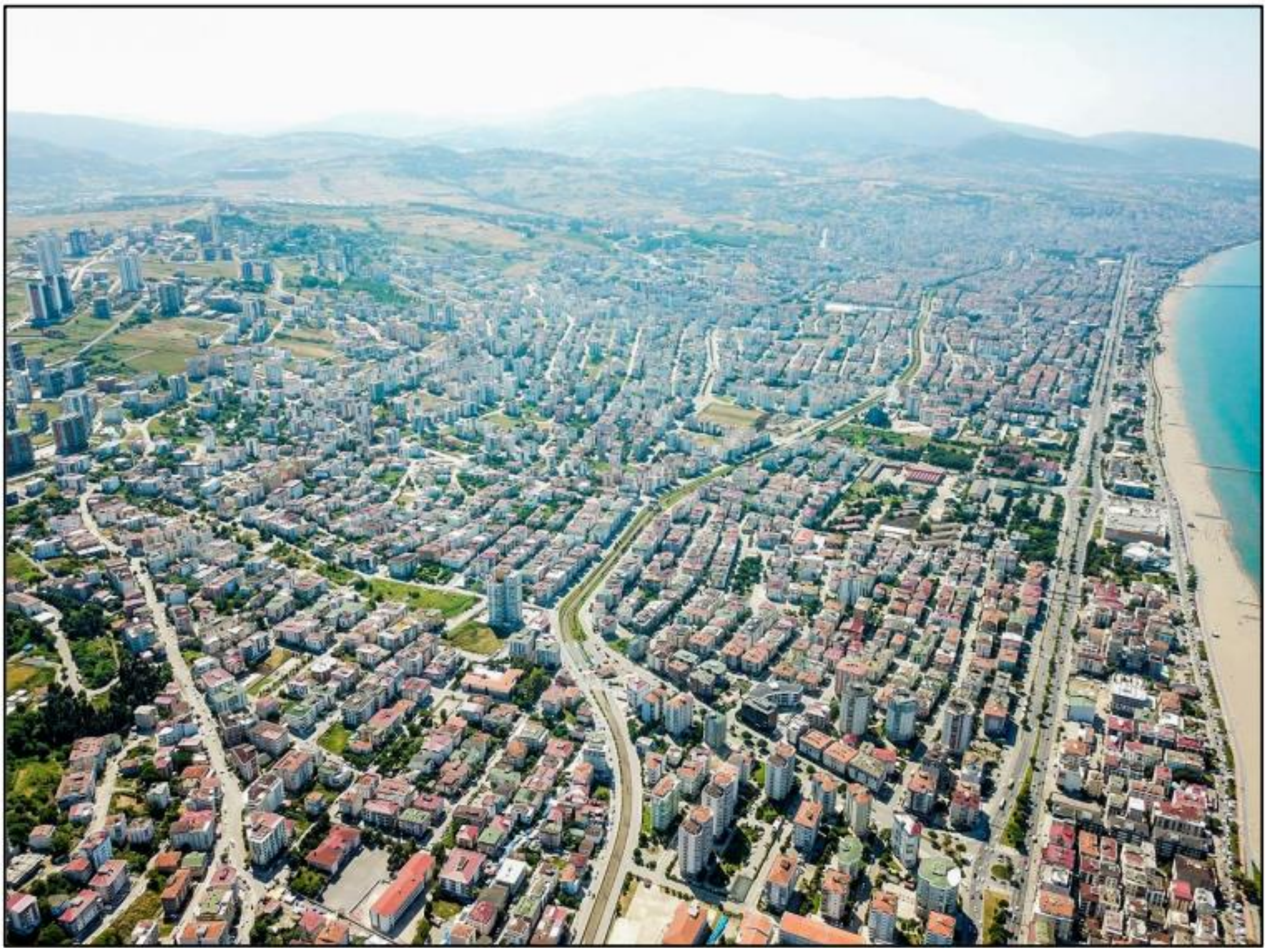


Figure 8. Aerial photo of the city of Atakum taken from a height of 400 meters using a drone

3.3. Earthquake susceptibility and settlement development

When the development of residential areas in Atakum city is examined from the year 2000 onwards, it can be observed that there is a density in coastal and near-coastal areas. The city's development along the coastline is influenced by both the favourable topographical features and people's desire to be close to the beach. However, Atakum city, which has rapidly expanded its urban area until the present day, has completely filled its coastlines with construction and has started to require new development areas. This new need has directed people towards the west, to the 19 Mayıs district, and to the southern parts of Atakum city, as they follow the coastline. Because the northern side of the city is bordered by the sea and İlkadım district center is located in the east. However, the continued development to the west in the Atakum district still extends towards coastal areas with similar characteristics to the coastal region of Atakum, which means that these areas will still have a high earthquake susceptibility. In this case, considering the current conditions in Atakum city, the most suitable and realistic residential areas are those symbolized in yellow, indicating a medium level of earthquake susceptibility. When examining the susceptibility map, it is evident that areas with very low and low susceptibility are primarily located in the southern parts within the district boundaries. Therefore, suggesting the establishment of a disconnected new settlement area to the south of the district, separate from the coastal areas where the district center is situated, may not be realistic. However, these areas in the south of the district, represented in blue and green on the map, could be considered for the installation of various industrial facilities.

When we examine the development of Atakum city over the last 20 years through remote sensing techniques and analysis (Figure 9, Table 6), it is evident that the urban area has expanded rapidly. Particularly, a substantial increase in land area has been observed between 2000 and 2023. In the year 2000, Atakum city's area constituted approximately 4% of the total area, whereas by 2023, it had reached approximately 12%. Unfortunately, while this rapid urbanization has been occurring, the rapidly developing urban areas have consistently been located in areas with high and very high earthquake susceptibility. As a result, the newly established and developing city has always continued its development under the risk of earthquakes. In contrast, with realistic and rational planning, if the city had been constructed on ridges with resilient foundations, it wouldn't have faced such a significant risk. According to the 2022 census, the district's population is 242,171, with approximately 200,000 of them residing in areas with high and very high earthquake susceptibility. Therefore, 80% of the city is at a first-degree risk in terms of earthquakes (Figure 9).

Table 6. Relationship between changes in the settlement area and earthquake susceptibility classes

Susceptibility Classes	Settlement Area in 2000 (km^2)	Settlement Area in 2013 (km^2)	Settlement Area in 2023 (km^2)
Very Low	0,16	0,18	0,36
Low	2,48	3,34	2,75
Medium	6,50	14,69	16,23
High	2,53	7,88	10,63
Very High	7,97	15,83	16,26
	19,64	41,92	46,23

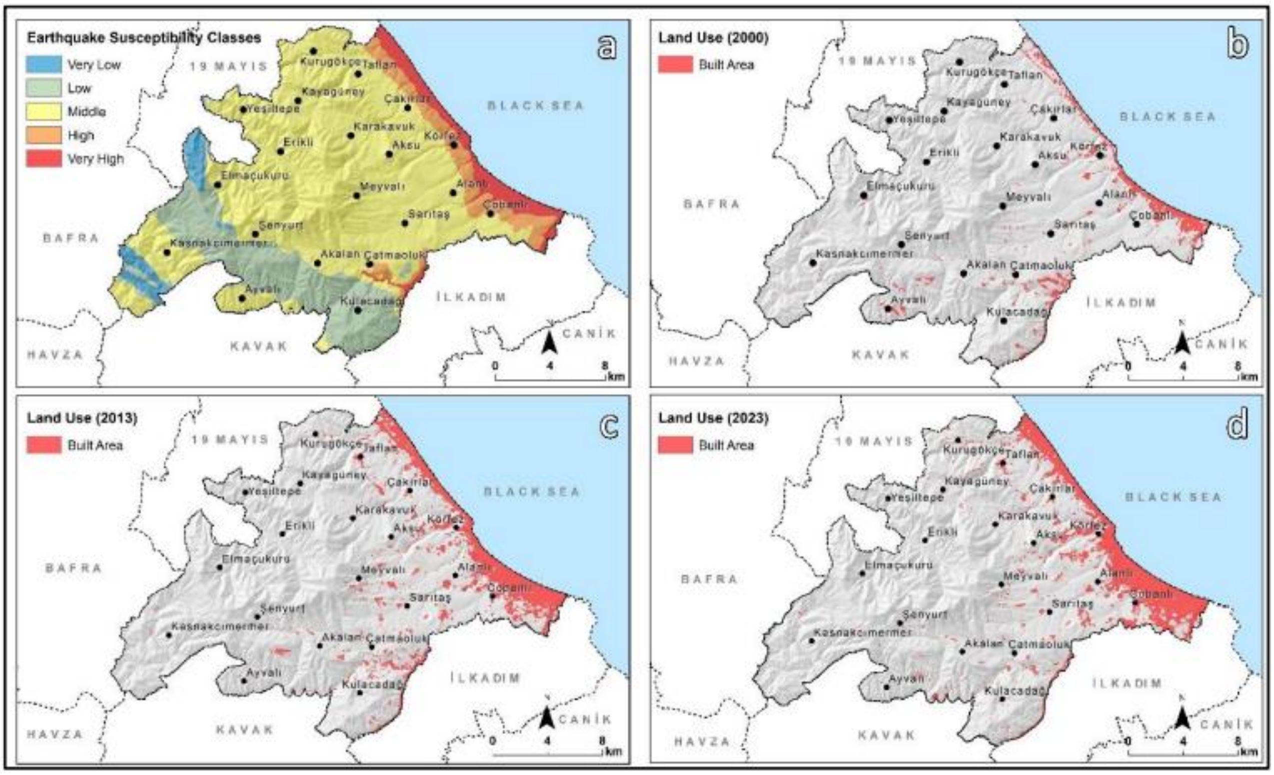


Figure 9. Development of Atakum city in the last 23 years according to earthquake susceptibility classes

4. Conclusion

This study analyses the relationship between the development and earthquake susceptibility of the Atakum district, located in the province of Samsun, over the past 20 years using remote sensing and Geographic Information Systems.

The majority of the study area is highly susceptible to earthquakes in terms of lithology. Specifically, the presence of alluvial deposits in the coastal plain and its vicinity increases the earthquake risk, as it can facilitate both liquefaction and the oscillation of seismic waves. Although morphologically the coastal plain and its vicinity are distant from the fault line, they exhibit high susceptibility due to problematic ground conditions.

Over the past 20 years, the district has expanded threefold, and the developing urban area has grown in lithologically unstable alluvial coastal plains with the potential for liquefaction. This has increased the earthquake susceptibility of the area. More than half of the district's lands have been categorized as having high and very high earthquake susceptibility. Consequently, in the event of a probable earthquake, approximately 80% of the 242,171 residents in the district, or around 200,000 people, would be directly exposed to high and very high risks.

In light of all these factors, the absence of an earthquake disaster information system and action plan in the district, along with insufficient earthquake awareness, will lead to significant losses in the event of a potential disaster. Therefore, it is imperative to urgently establish assembly areas, implement appropriate earthquake action plans, and shift the newly developing urban areas to resilient foundations. Additionally, reducing building storey numbers and taking the necessary measures for compliance with earthquake regulations are essential steps to be taken.

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Author contributions

Muhammet BAHADIR: Conceptualization, Text Writing, Field study; **Fatih OCAK:** Data curation, Software, Mapping; **Halithan ŞEN:** Visualization, Text Writing, Field study.

Conflicts of interest

The authors declare no conflicts of interest.

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