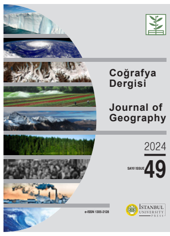

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Evaluation of Potential Soil Erosion Areas in the Ladik Lake Basin via AHP and GIS Integration (Samsun, Türkiye)*

Ladik Gölü Havzası'ndaki Potansiyel Toprak Erozyonu Alanlarının AHP ve CBS Entegrasyonu ile Değerlendirilmesi (Samsun, Türkiye)

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ABSTRACT

Soil is a fundamental element essential for living organisms, agricultural activities, and food supply. Therefore, the presence and conservation of this fundamental element are crucial for sustainable land management. The Ladik Lake Basin, which was analyzed in this study, is a tectonic basin located in the Northern part of Turkey in the Middle Black Sea Region. Within the scope of this research, soil erosion susceptibility analysis was conducted using Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS) techniques, considering multiple geographical factors in the Ladik Lake Basin. In the analyses, eight (8) geographical factors were used: slope, soil depth, lithology, elevation, land use, drainage density, drainage frequency, and precipitation. As a result of the analysis, four (4) distinct levels were identified for soil erosion susceptibility, classified as low, moderate, high, and very high, and the findings revealed that 27.44 % of the basin exhibited low susceptibility, 14.63 % moderate susceptibility, 36.30 % high susceptibility, and 21.63 % very high susceptibility to soil erosion. Preventing or slowing soil erosion is possible through various measures. In a basin with intensive agricultural use, appropriate agricultural practices and crop selection based on slope values are the primary considerations. Such studies serve as a guide for decision makers in taking on-site measures to prevent erosion. Additionally, attention is drawn to the necessary efforts for preventing and reducing erosion in the study area based on the results obtained.

Keywords: Soil Erosion, Soil Erosion Susceptibility Analysis, Analytical Hierarchy Process (AHP), Geographic Information Systems (GIS), Ladik Lake Basin

ÖZ

Toprak başta canlı yaşamı, tarımsal faaliyetler ve gıda tedariki için gerekli olan temel bir unsurdur. Dolayısıyla bu temel unsurun varlığı ve korunması sürdürülebilir arazi yönetimi için son derece önemlidir. Bu çalışmada ele alınan Lâdik Gölü Havzası, Türkiye'nin kuzeyinde, Orta Karadeniz Bölümü'nde yer alan tektonik bir havzadır. Araştırma kapsamında Lâdik Gölü Havzası'nda birden çok coğrafi faktörün Analitik Hiyerarşi Prosesi (AHP) ve Coğrafi Bilgi Sistemleri (CBS) teknikleri kullanılarak toprak erozyonu duyarlılık analizi gerçekleştirilmiştir. Analizler yapılırken eğim, toprak derinliği, litoloji, yükseklik, arazi kullanımı, drenaj yoğunluğu, drenaj sıklığı ve yağış olmak üzere sekiz (8) coğrafi faktör kullanılmıştır. Analiz sonucunda toprak erozyonu duyarlılığı için düşük, orta, yüksek ve çok yüksek olmak üzere dört (4) farklı düzey belirlenmiş ve havzanın %27,44'ü düşük, %14,63'ü orta, %36,30'u yüksek ve %21,63'ü çok yüksek düzeyde toprak erozyonu duyarlılığı tespit edilmiştir. Buradaki yüzde oranlarını %27,44'ünde düşük, %14,63'ünde orta, %36,30'unda yüksek, %21,63'ünde çok yüksek düzeyde toprak erozyonu duyarlılığı tespit edilmiştir. Toprak erozyonun önüne geçmek ya da erozyonu yavaşlatmak alınabilecek bazı önlemlerle mümkündür. Tarımsal kullanımın yoğun olduğu havzada eğim değerlerine uygun tarımsal işleme ve ürün seçimi ilk akla gelen uygulamadır. Bu tür çalışmalar karar vericilere erozyona karşı yerinde önlemler almaları için yol gösterici niteliktedir. Ayrıca çalışma neticesinde elde edilen sonuçlara yönelik çalışma sahasında erozyonun önlenmesi ve azaltılması için gerekli çalışmaların neler olduğu konusuna da dikkat çekilmiştir.

Anahtar kelimeler: Toprak Erozyonu, Toprak Erozyonu Duyarlılık Analizi, Analitik Hiyerarşi Süreci (AHP), Coğrafi Bilgi Sistemleri (CBS), Ladik Gölü Havzası

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1. INTRODUCTION

Soil, formed under different physical conditions, is considered a crucial natural resource worldwide (Duman and İrcan, 2022) and is especially essential for the conduct of agricultural activities. Additionally, soil provides raw material for many natural or artificial products (plants, drugs, food, glass, etc.) used in human life, directly or indirectly influencing their formation or production. Despite their significant importance to human life, various adverse anthropogenic impacts, such as incorrect land use and agricultural practices, disrupt the natural structure of soils, facilitating the transport of soil by interrupting the soil formation process (Duman and İrcan, 2022). Although soil transport is a fundamental process in soil formation, the acceleration of this process due to various anthropogenic disturbances adversely affects the quality of both soil and the environment (Lal, 2001; Küçüker and Giraldo, 2022). The upper layer of soil, rich in organic matter and humus, is transported by wind or water, leading to soil erosion, which is a significant environmental issue, particularly in agricultural areas (Maity and Mandal, 2019). Therefore, soil erosion resulting from interruptions in the natural soil formation process impedes the development of fertile soils.

Soil erosion, which is accepted as the most significant issue contributing to the disruption of the natural structure of lands, is recognized globally as a serious environmental threat (Pimentel, 2006; Ebabu et al., 2019; Aneseyee et al., 2020). On a global scale, approximately 25-40 billion tons of soil are eroded from the surface of the Earth each year, attributed to both physical and anthropogenic influences (Wei et al., 2018; Asfaw et al., 2020). Soil erosion continues to escalate gradually due to incorrect land use, improper agricultural practices, and the increasing frequency and impact of natural disasters (flooding, storms, hurricanes, landslides, etc.). The FAO and ITPS (2015) report on the "Status of the World's Soils" emphasizes this situation and states that without necessary precautions, soil loss will persist, resulting in the loss of 1.5 million km^2 of land (FAO and ITPS, 2015). In the specific context of Turkey, due to both topographical and climatic diversity, approximately 90% of the country's lands are affected by soil erosion (Küçüker and Giraldo, 2022). Furthermore, Turkey is highly susceptible to soil erosion not only due to its topographical and climatic features but also due to its geological and soil characteristics (Danacıoğlu and Tağıl, 2017). Despite this high susceptibility, Turkey has managed to reduce the amount of soil transported by rivers from around 500 million tons in the 1970s to 154 million tons today through various measures taken (reforestation activities, changes in irrigation techniques in agricultural areas and erosion control efforts) (UNCCD, 2018).

Soil susceptibility to erosion is directly associated with both natural factors (climate, topography, vegetation, etc.) and human-related factors (Lal et al., 1989; Oldeman, 1992; Lal, 2001). The susceptibility of soil to erosion can vary according to regional conditions. For instance, areas lacking vegetation or where vegetation is destroyed by intensive agricultural activities are more exposed to external forces, increasing soil susceptibility to erosion. On the contrary, areas with relatively dense vegetation and fewer agricultural activities tend to be more resistant to soil erosion and exhibit lower susceptibility. Climate, topography, soil characteristics (texture, type, permeability, etc.), natural elements such as vegetation, along with human factors including the type and intensity of agricultural activities, urbanization, land use, and overgrazing, are the primary factors causing soil loss, and these factors influence the intensity of erosion (Tüfekçioğlu et al., 2012; Leh et al., 2013; Tüfekçioğlu et al., 2018; Wynants et al., 2019; Olorunfemi et al., 2020; Wen and Deng, 2020; Küçüker and Giraldo, 2022).

To ensure the continuity of agricultural activities, mitigate soil-related environmental issues, and implement long-term environmental management plans, controlling soil erosion is crucial. Controlling soil erosion involves monitoring and predicting its effects. Therefore, taking preventive measures against previously predicted and monitored soil erosion is vital for the implementation of various conservation plans (Küçüker and Giraldo, 2022). Additionally, spatially mapping soil erosion is among the practices that can help minimize problems by accurately expressing their effects and facilitating the anticipation of necessary measures (Rahman et al., 2009). For this reason, Geographic Information Systems (GIS) techniques, which enable the spatial expression of elements at any location worldwide, facilitating the detection of not only local but also regional distributions and ensuring the attainment of precise results, have been preferred in this study. On the other hand, soil loss caused by various factors (Danacıoğlu and Tağıl, 2017). Understanding soil erosion and preventing soil loss through erosion require knowledge of these factors and control methods (Renard et al., 2011). There are various methods for calculating soil erosion susceptibility. Among these, the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) and its more detailed version, the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1994), along with the Analytical Hierarchy Process (AHP; Saaty, 1989), which allows the comparison of various geographical factors, have been employed

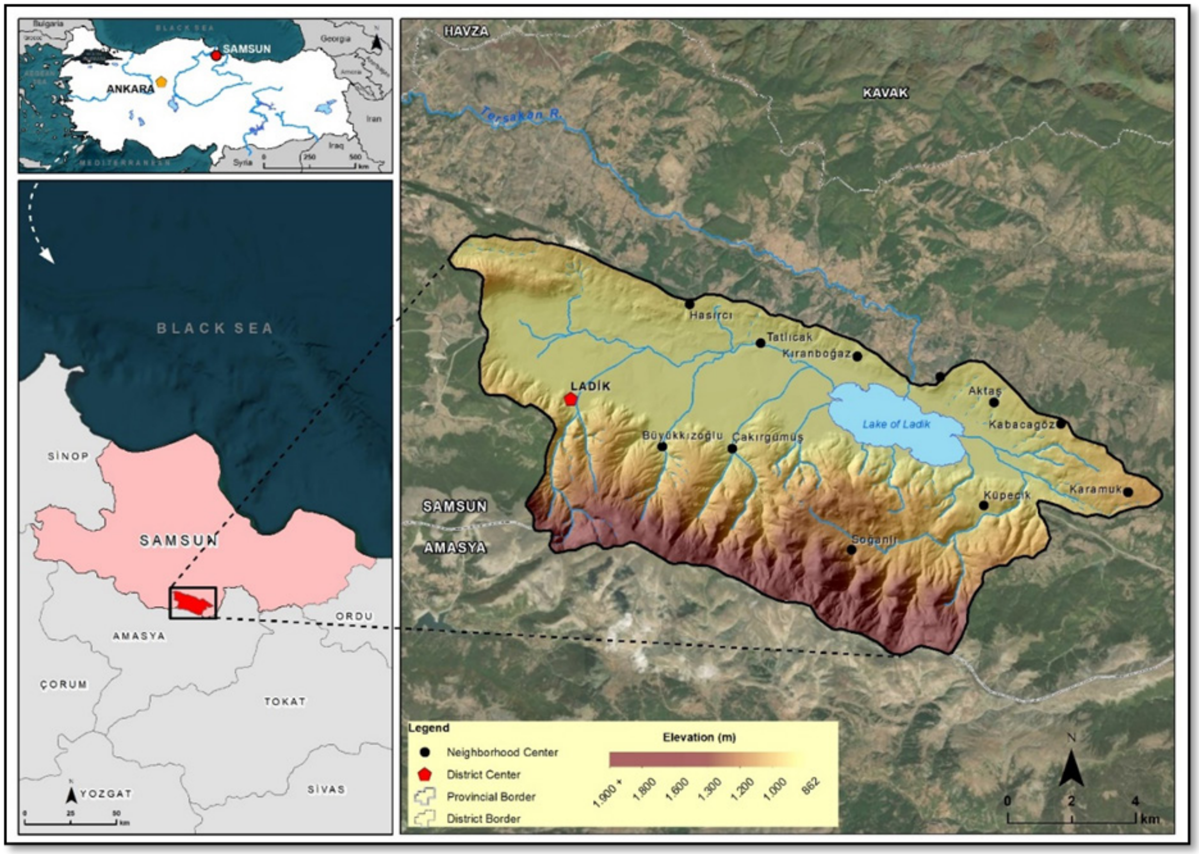

Figure 1. Basin of Lake Ladik location map.

in this study. AHP has been preferred as a multi-criteria analysis method due to its ability to facilitate the logical and numerical combination of geographical factors influencing erosion, incorporating the idea of ranking and weighting, and allowing pairwise comparisons among all geographical factors used for the identification of susceptible areas. The AHP guides decision makers and provides solutions for evaluating soil erosion susceptibility, revealing the spatial distribution of susceptible areas, and generating maps. Due to these features, the AHP has become a frequently chosen method (Küçüker and Giraldo, 2022). The AHP, developed by Saaty (1989), partly relies on subjective interpretation and expert knowledge (Intarawichian and Dasananda, 2010). Therefore, AHP is preferred for regional studies (Soeters and Van Westen, 1996; Guzzetti et al., 1999). This method allows modeling soil loss in an area, revealing soil erosion-susceptible areas, and monitoring the ongoing erosion process. Therefore, AHP was selected as the preferred method within the scope of this study.

1.1. Study Area

Due to the significant contribution of agricultural activities as essential sources of livelihoods, the Ladik Lake Basin, which is administratively within the borders of Samsun province in the Black Sea Region and recognized as a lake basin, was selected as the study area (Figure 1). The area encompasses a drainage area of 147.80 km². Within the study area, there are 18 settlements, including the Ladik city center.

The study area is a tectonic-formation lake basin surrounded by high mountains (Bahadır and Uzun, 2021) and covers an area of 147.80 km². The elevation generally increases toward the south in the basin, with an average elevation of 1,085 m. Additionally, the southern slopes significantly dissected by short-length rivers, resulting in high-slope terrain. Approximately 30% of the study area was composed of high-slope terrain (Table 1). Due to the substantial elevation difference in the basin, there was variation in the amount and type of precipitation between the low and high sections. Precipitation in high elevation areas, particularly in the southern part of the basin, predominantly occurs in the form of snow, while low elevation areas and northern slopes experience more rainfall. The average annual precipitation over the study area was 602 mm (Table 1). The annual maximum average temperature in the study area is 15.6 °C, the annual average temperature is 9.4 °C, and the minimum temperature is 3.8 °C.

2. MATERIALS AND METHODS

In the scope of the soil erosion susceptibility analysis conducted in the Ladik Lake Basin, the selection of geographic factors was determined by considering existing studies in the literature, field observations, and expert opinions. Accurately selecting geographic factors is a crucial step to obtain reliable susceptibility analysis results. For the soil erosion susceptibility analysis in the Ladik Lake Basin, eight (8) geographic factors were utilized: slope, soil depth, lithology, elevation, land use, precipitation, drainage density, and drainage frequency (Danacıoğlu and Tağıl, 2017; Turan and Dengiz, 2017; Tairi et al., 2019; Bozali, 2020; Das et al., 2020; Turan and Uzun, 2021; Duman and İrcan, 2022; Küçüker and Giraldo, 2022).

The soil erosion susceptibility analysis conducted in the Ladik Lake Basin consists of three stages (Figure 2); data production using GIS, field observations, and AHP. After selecting the geographic factors, in the first stage of the study, data were obtained from various institutions for susceptibility analysis, and secondary data were derived from these sources based on the type and usage of the geographic factor. In the data production stage, lithological units from 1/100,000-scale geological maps and contour lines from 1/25,000-scale topographic maps were produced using GIS techniques. Additionally, elevation and slope analyses were conducted to create a 10-m resolution Digital Elevation Model (DEM) for the study area using contour lines. The drainage network for the basin was extracted from 1/25,000 topographic maps, drainage density was calculated using line density analysis, and drainage frequency analysis was performed using hydrology tools within GIS. Soil data were accessed through the TAD Portal (Non-Agricultural Authorization and Soil Survey Portal). Furthermore, current land use was determined using a controlled classification method with Sentinel-2 satellite images for the years 2017-2021 and finally, rainfall maps for the area were generated using interpolation techniques with precipitation data obtained from the General Directorate of Meteorology. Immediately after data collection, a geographic database was designed to calculate erosion susceptibility in the Ladik Lake Basin, and all derived primary and secondary data were categorized within this database.

The second stage of the study included the application of the AHP technique to identify areas susceptible to soil erosion in the Ladik Lake Basin and to establish the weights among the selected geographic factors. The AHP method allows the identification of the most suitable and unsuitable factors based on the impact scores assigned between multiple main and sub-criteria (ranging from 1 to 9) (Saaty, 1989). Therefore, the AHP method is widely used to determine areas susceptible to soil erosion (Küçüker and Giraldo, 2022). The AHP technique is performed in three consecutive steps: (i) creating a decision hierarchy among the selected factors, (ii) establishing pairwise comparison matrices between possible pairs in this hierarchy, and (iii) ultimately calculating weights and a consistency rate for all factors (Intarawichian and Dasananda, 2010). After establishing the decision hierarchy in the AHP procedure, it is essential to

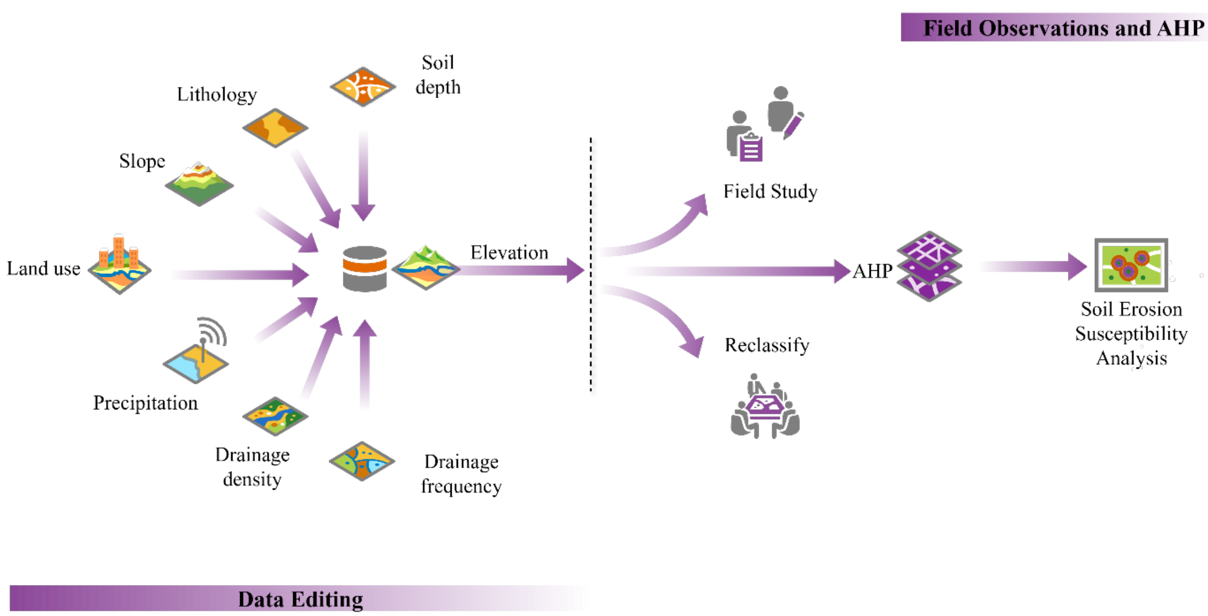

Figure 2. Soil erosion susceptibility analysis workflow diagram.

determine the superiority or ranking of geographical factors relative to each other. This stage directly influences the outcome of AHP. Therefore, expert opinions, past studies, and experience should be considered when determining impact scores among geographical factors. The ranking of importance among geographical factors is determined according to Saaty's (1989) developed importance scale, where scoring between 1 and 9 is possible (Saaty, 1989). In this scale, a high score indicates a more influential geographical factor, while a low score indicates a less influential factor. Both weights and consistency rates were calculated for the geographical factors used in the study according to Saaty (1989). According to Saaty (1989), the calculated consistency rate should be ≤ 10 %. If the consistency rate is below 10 %, the decision hierarchy should be reviewed,

Table 1. Numerical values of geographical factors used in soil erosion susceptibility analysis.

Geographical Factor	Sub-Criteria	Area		Sub-criterion Weight (%)	Consistency (%)	Weight (%)
		km²	%			
	<2	39,87	26,98	4,7		
	2-5	18,56	12,56	10,5		
Slope (°)	5-15	43,45	29,40	19,8	**4**	**25,4**
	15-35	44,16	29,88	28		
	>35	1,76	1,19	37		
	Very shallow	31,30	21,18	41,3		
Soil Depth	Shallow	82,06	55,52	41,3	**2**	**15,2**
	Moderate	28,72	19,43	12,1		
	Deep	5,72	3,87	5,3		
	Alluvium III	42,51	28,76	9,6		
	Limestone	15,18	10,27			
	Pebbles, sandstones, claystones, limestone II	7,25	4,91	25,1		
	Serpentine, sandstone, agglomerate, and tuff	0,93	0,63			
Lithology	Shist, phyllite, catechist, limestone	0,65	0,44		**2**	**18,6**
	Pebble, sandstone, marl, and mudstone I	2,7	1,83	65,3		
	Pebble, mudstone	8,77	5,93			
	Limestone, claystone, and marl	59,51	40,26			
	Conglomerate, sandstone	10,3	6,97			
	<900	37,28	25,22	2,7		
	900-1.000	39,57	26,77	3,9		
	1.000-1.200	35,55	24,05	5,8		
Elevation (m)	1.200-1.400	18,29	12,37	8,7	**6**	**9,5**
	1.400-1.600	10,21	6,91	12,6		
	1.600-1.800	5,85	3,96	23,8		
	>1.800	1,05	0,71	42,5		
	Wetlands	11,71	7,92	2,6		
	Woodlands	58,47	39,56	4,4		
Land Use	Agricultural areas	46,02	31,14	26,3	**8**	**15,9**
	Settlement areas	7,69	5,20	18,1		
	Bareland	0,52	0,35	39		
	Pasture	23,39	15,83	9,6		
	<1,57	12,18	8,24	6,2		
	1,58-2,05	17,21	11,64	9,9		
Drainage Density (Dd)	2,06-2,37	62,05	41,98	16,1	**2**	**3,7**
	2,38-2,82	47,09	31,86	26,2		
	>2,83	9,27	6,27	41,6		
	<45	19,31	13,06	9,8		
Drainage Frequency (Fs)	45-60	87,33	59,09	33,4	**3**	**4,8**
	>60	41,16	27,85	56,8		

and the impact scores assigned to the geographical factors should be checked.

Due to the advantages mentioned above within the scope of the study, the AHP method was selected. Using this method, pairwise comparison matrices were created among the identified geographical factors for soil erosion susceptibility analysis in the Ladik Lake Basin. Initially, the seven (7) main geographical factors were divided into sub-categories, and pairwise comparison matrices were established for both sub-categories and main factors. By conducting these pairwise comparison matrices, weight rates were calculated for each geographical factor to be used to identify areas susceptible to soil erosion. Consistency rates, which provide foresight for the use of geographical factors in susceptibility analysis, were also calculated. The weight and consistency rates of the geographical factors used in soil erosion susceptibility analyses were calculated using the version of the program designed by K.D. Goepel died on September 15, 2018 (Goepel, 2013).

The AHP provides a numerical expression of natural disaster susceptibility; however, it alone is not sufficient to represent geographical factors. To give spatial significance to the weight rates calculated by AHP for the susceptibility assessment of natural disasters, additional techniques based on location are required to determine where susceptibility is high or low. In this context, among the techniques that give spatial identity to calculated weight rates, Geographic Information Systems (GIS) stand out. GIS facilitates the spatial determination of susceptibility to soil erosion, as in many natural disasters by using geographical factors that are spatially considered and used. In the final stage of the study, various spatial analysis processes (data transformation, reclassification, cell size, extent adjustment, etc.) were conducted using GIS techniques for all main and sub-geographical factors for which weight ratios were calculated, as in the initial stage. Finally, for the soil erosion susceptibility analysis, all data were converted to raster data format, each with a resolution set at 10m, and a weighted overlay tool was used to perform the soil erosion susceptibility analysis for the study area. The resulting output was classified into four (4) different categories: low, moderate, high, and very high. Additionally, drone shots were taken in the field to reveal the dimensions of erosion and were incorporated into the study.

3. RESULTS AND DISCUSSION

In this study, which conducted a soil erosion susceptibility analysis in the Ladik Lake Basin, eight (8) different thematic data, including slope, soil depth, lithology, elevation, land use, precipitation, drainage density, and drainage frequency, were utilized as geographical factors (Table 1).

Slope

Slope is one of the most crucial factors influencing the erosion process by controlling surface runoff, sun exposure duration, evaporation, transpiration, and soil moisture accumulation (Arabameri et al., 2018). Simultaneously, soil erosion occurring in the thin topsoil layer, which is easily transportable and constitutes the upper layer of the soil, is directly proportional to an increase in slope (Duman and İrcan, 2022). Indeed, slope is a morphological factor that affects the soil's water retention capacity, drainage network, groundwater, soil formation, vegetation cover, and soil thickness (Gómez and Kavzoglu, 2005; Altun et al., 2016; Ersayın, 2022). The generally accepted view is that there is a direct correlation between slope and soil erosion, and as slope increases, the rate of soil erosion also increases (Liu et al., 2001; Bozali, 2020).

The Ladik Lake Basin has an average slope of 10.68°, with the highest slope reaching 58° on the steepest slope. Although the slope values in the study area are generally quite low in depression areas, there was a gradual increase toward the southern slopes, especially from the southern shore of Lake Ladik. The southern slopes of the basin comprise the areas with the steepest slope (Akdağ and Karaömer Mountain) (Figure 3a; Table 2).

In the context of soil erosion susceptibility analysis conducted with AHP, the pairwise comparison matrix highlighted the proportional impact of slope inclination on soil erosion. Consequently, lower impact scores were assigned to flat and near-flat slopes, low to moderately inclined slopes, high scores to moderately inclined and moderately steep slopes, and highest scores to very steep slopes (Table 2).

Table 2. Pairwise comparison matrix of the sub-criteria of the slope factor.

Slope Groups (°)	(A)	(B)	(C)	(D)	(E)
(A) >2	**1**	1/3	1/4	1/6	1/6
(B) 2-5	3	**1**	1/3	1/3	1/3
(C) 5-15	4	3	**1**	1/2	1/2
(D) 15-35	6	3	2	**1**	1/2
(E) <35	6	3	2	2	**1**

Soil Depth

The primary geographical factor affected by erosion is soil. Soil exhibits varying resistance against erosion based on the lithology it forms, the presence of vegetation cover (Duman and İrcan, 2022), slope inclination, and land-use characteristics.

Within the scope of soil erosion susceptibility analysis, soil depth, a crucial factor in soil movement, was considered. The Ladik Lake Basin has soils of different types, textures, and depths. For more accurate results, the soils in the basin have been categorized into four (4) different groups: very shallow, shallow, moderate, and deep (Figure 3b; Table 3).

Given their ease of transportation by external forces, the highest impact score in the pairwise comparison matrix was assigned to soils with very much shallow depths. Conversely, due to their relatively more challenging transportability, moderate-depth soils received a moderate impact score, whereas soils with greater depths were assigned a lower impact score compared to other soil groups (Table 3).

Table 3. Pairwise comparison matrix of the sub-criteria of the soil depth factor.

Soil Depth	(A)	(B)	(C)	(D)
(A) Very shallow	**1**	1	4	7
(B) Shallow	1	**1**	4	7
(C) Moderate	1/4	1/4	**1**	3
(D) Deep	1/7	1/7	1/3	**1**

Lithology

Although it does not directly impact soil erosion, lithology is another geographical factor used in susceptibility analysis due to its influence on soil formation. Lithology is a commonly preferred geographical factor for assessing a region's susceptibility to soil erosion and desertification processes (Turan et al., 2019). Lithological units influence soil formation based on various characteristics, such as type, permeability, porosity, hardness, or softness. In this study area, lithological units have been categorized into three (3) different groups, following the classification outlined in the studies of Nicholson and Hencher (1997).

The research area contains rocks with different permeability characteristics (Figure 3c; Table 4). Considering the lithological properties of the rocks, in the pairwise comparison matrix, alluvial units with permeable characteristics received the lowest impact scores, moderately permeable karstic rocks received intermediate scores, and rocks with low permeability received the highest impact scores (Table 4).

Table 4. Pairwise comparison matrix of the sub-criteria of the lithology factor.

Lithology	(A)	(B)	(C)
(A) I	**1**	3	6
(B) II	1/3	**1**	3
(C) III	1/6	1/3	**1**

Elevation

Elevation is a geographical factor considered in determining the susceptibility of an area to soil erosion due to its influence on many natural factors (such as slope, river flow, precipitation, etc.). For example, increased rainfall at higher elevations leads to more runoff and faster weathering of soil in these areas, facilitating soil transport. Concerning soil erosion, as elevation increases, the permeability of soil on steeper slopes decreases, resulting in increased susceptibility to erosion in these areas (Vijith et al., 2012; Thakurdesai and Pise, 2016)

The research area is a tectonic origin basin (Bahadır and Uzun, 2021), and therefore, there is a significant difference in elevation; there is a height difference of 1,112 m between the lowest and highest points. The average elevation in the Ladik Lake Basin is 1,085 m. In particular, the high slopes south of Lake Ladik were considerably high. Therefore, when examining the elevation gradients in the research area, it is observed that, where the elevation is high, the slope values are also high. To highlight the effect of elevation on soil erosion susceptibility in the research area, elevation was categorized into seven (7) different classes (Figure 3d; Table 5).

Table 5. Pairwise comparison matrix of the sub-criteria of the elevation factor.

Elevation (m)	(A)	(B)	(C)	(D)	(E)	(F)	(G)
(A) < 900	**1**	1/2	1/3	1/4	1/5	1/7	1/9
(B) 900-1.000	2	**1**	1/2	1/3	1/4	1/6	1/8
(C) 1.000-1.200	3	2	**1**	1/2	1/3	1/5	1/7
(D) 1.200-1.400	4	3	2	**1**	1/2	1/4	1/6
(E) 1.400-1.600	5	4	3	2	**1**	1/3	1/5
(F) 1.600-1.800	7	6	5	4	3	**1**	1/3
(G) >1.800	9	8	7	6	5	3	**1**

Land Use

The presence of land cover in an area promotes soil transport. In areas covered with vegetation, soil transport by external forces becomes more difficult, whereas soil transport on bare ground is easier. Vegetation acts as a natural shield against the erosive effects of rainfall (Küçüker and Giraldo, 2022) and provides the necessary organic matter for soil formation. Incorrect agricultural practices (such as improper crop planting or cultivation, parallel plowing to the wind, etc.) and the use of productive agricultural land for settlement areas are the most common anthropogenic activities that increase susceptibility to soil erosion. The continuous occurrence of human activities in agricultural lands and settlement areas, along with increasing demands, leads to disturbance of the natural soil structure. Therefore, anthropogenic activities are considered a factor that accelerates the soil erosion process (Küçüker and Giraldo, 2022), whereas vegetation is considered a geographical factor that slows soil erosion.

The soil erosion susceptibility analysis in the Ladik Lake Basin included the identification of six (6) different land use types/coverages (Figure 3e; Table 6). In the pairwise comparison matrix of land use types in the research area, the highest score was assigned to bare lands as described above, while the lowest score was given to forested areas because of their complete saturation with water and their presence in the flat areas of the basin. Agricultural land and residential areas were deemed significant in the pairwise comparison matrix because they are the areas where anthropogenic activities are most pronounced and were assigned scores close to the highest. Pasture areas were evaluated with moderate importance, and score assignments were made accordingly (Table 6).

Table 6. Pairwise comparison matrix of the sub-criteria for land use factor.

Land Use	(A)	(B)	(C)	(D)	(E)	(F)
(A) Wetlands	**1**	1/3	1/8	1/7	1/9	1/5
(B) Woodlands	3	**1**	1/7	1/6	1/8	1/4
(C) Agricultural areas	8	7	**1**	2	1/2	4
(D) The settlement areas	7	6	1/2	**1**	1/3	3
(E) The bare land	9	8	2	3	**1**	5
(F) Pasture	5	4	1/4	1/3	1/5	**1**

Drainage Density (Dd) and Drainage Frequency (Fs)

Drainage density (D_d) is obtained by dividing the total length of all streams in a basin by the basin's area (Horton, 1945), while drainage frequency represents the number of streams per unit area in a basin (Küçüker and Giraldo, 2022). Drainage density and frequency indicate the water-carrying capacity of a basin, the development of streams, the flood-creating capacity of the drainage network, and the extent to which the basin is dissected by streams and areas where streams are concentrated. In areas with high drainage density, soil erosion is easier. However, in areas with low drainage density, water infiltrates soil more, making soil erosion more difficult. When expressed in numerical terms, a drainage density of less than 1.75 indicates a low density, between 1.75 and 2.5 indicates a high density, and more than 2.5 indicates a very high drainage density (Reddy et al., 2004). The average drainage density in the Ladik Lake Basin was calculated as 0.80. This value indicates rapid infiltration in the basin and low resistance of the soil in the basin to external transport. In addition to drainage density, drainage frequency, especially in areas with steep slope gradients, leads to terrain fragmentation and the rapid transport of soil by short streams.

Different drainage density classes were identified in the Ladik Lake Basin, with five (5) different drainage density classes (Figure 3f; Table 7) and three (3) drainage frequency classes (Figure 3g; Table 8) created.

Table 7. Pairwise comparison matrix of the sub-criteria of the drainage density factor.

Drainage Density	(A)	(B)	(C)	(D)	(E)
(A) 0,57-1,57	**1**	1/2	1/3	1/4	1/5
(B) 1,58-2,05	2	**1**	1/2	1/3	1/4
(C) 2,06-2,37	3	2	**1**	1/2	1/3
(D) 2,38-2,82	4	3	2	**1**	1/2
(E) 2,83-3,80	5	4	3	2	**1**

Table 8. Pairwise comparison matrix of the sub-criteria of the drainage frequency factor.

Drainage Frequency	(A)	(B)	(C)
(A) <45	**1**	1/4	1/5
(B) 45-60	4	**1**	1/2
(C) >60	5	2	**1**

Precipitation

Among the geographical factors influencing soil erosion, precipitation is a unique element that directly affects soil loss, unlike other geographical factors. In particular, the intensity, type, duration, amount, and severity of precipitation are the most important characteristics affecting soil loss (Das et al., 2020). Both the intensity and type of precipitation, as well as its duration and intensity, make it difficult for the soil to adhere to the ground, accelerating soil loss. Therefore, areas continuously exposed to external influences cannot resist soil erosion. The physical condition of the area where precipitation occurs also affects soil erosion. This is because precipitation directly or indirectly affects all other geographical factors involved in soil erosion.

In the Ladik Lake Basin, where the average precipitation is 602 mm, precipitation is most significant on the high slopes

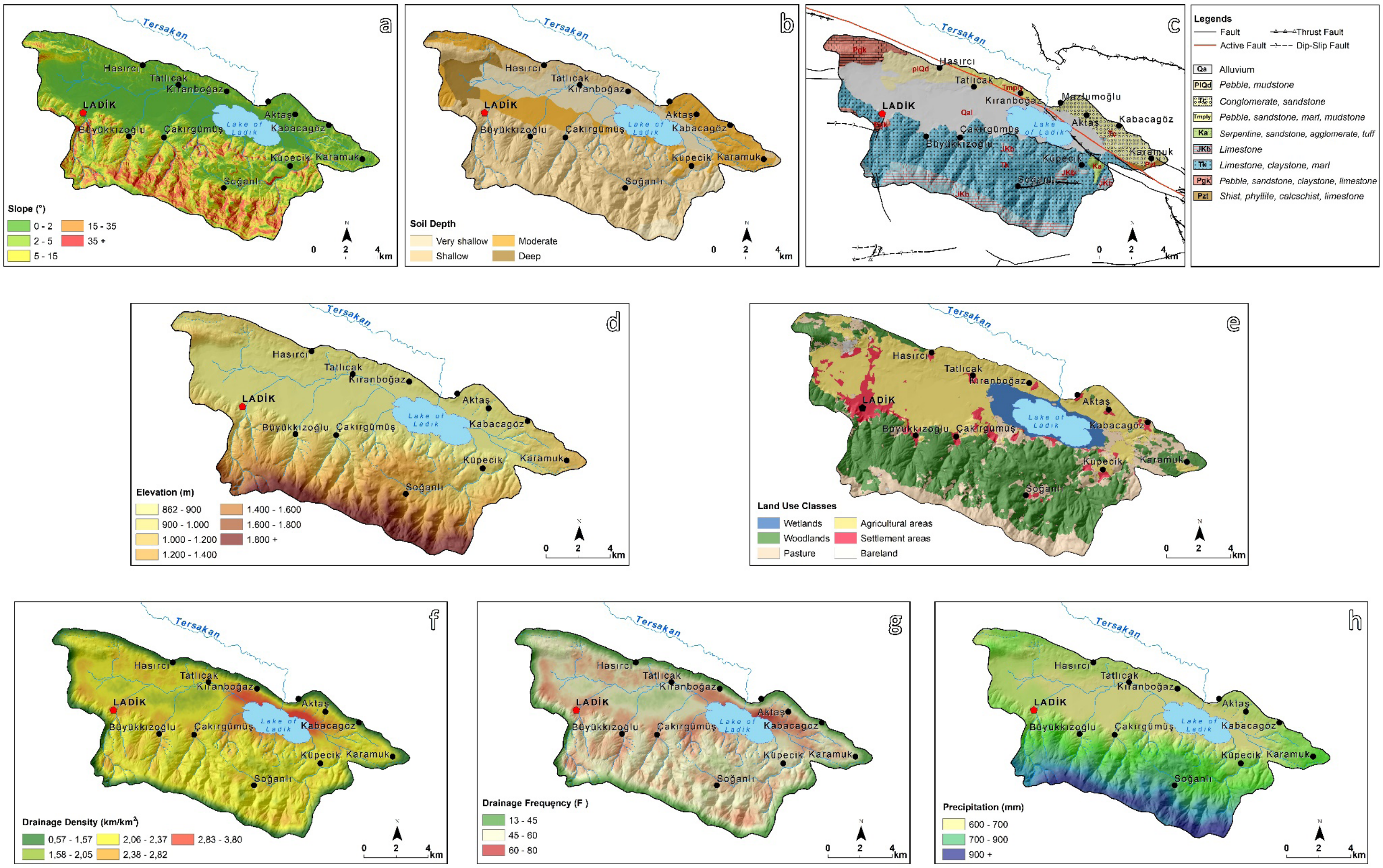

Figure 3. Geographic factors; a) Slope, b) Soil depth, c) Lithology, d) Elevation, e) Land use, f) Drainage density, g) Drainage frequency, and h) Precipitation.

south of the basin (> 1,150 mm). In the lowlands of the basin, the rainfall decreased to 600 mm. To assess the impact of rainfall on soil erosion, rainfall values have been categorized into seven (7) different categories (Figure 3h). Considering the explanations above, in the pairwise comparison matrix, high scores are assigned to areas with high rainfall, and low scores are assigned to areas with low rainfall (Table 9).

Table 9. Pairwise comparison matrix of the sub-criteria of the precipitation factor.

Precipitation (mm)	(A)	(B)	(C)	(D)	(E)	(F)	(G)
(A) <650	**1**	1/2	1/3	1/5	1/6	1/8	1/9
(B) 650-700	2	**1**	1/2	1/4	1/5	1/7	1/8
(C) 700-800	3	2	**1**	1/3	1/4	1/6	1/7
(D) 800-900	5	4	3	**1**	1/2	1/4	1/5
(E) 900-1.000	6	5	4	2	**1**	1/3	1/4
(F) 1.000-1.100	8	7	6	4	3	**1**	1/2
(G) >1.100	9	8	7	5	4	2	**1**

3.1. Analysis and Evaluation

To identify areas susceptible to soil erosion in the Ladik Lake Basin, a multi-criteria decision-making analysis was conducted using the AHP based on eight (8) main criteria (slope, soil depth, lithology, elevation, land use, drainage density, drainage frequency and precipitation), along with 46 sub-criteria depending on these main criteria. Within this scope, pairwise comparison matrices were created for all upper and lower criteria, assigning scores between 1 and 9 according to Saaty's scale (1989). Subsequently, Then, the weight ratios and standard deviations of all criteria were calculated (Figure 4; 5).

The consistency rate for the multicriteria decision analysis conducted for soil erosion susceptibility analysis in the Ladik Lake Basin was calculated as 2% based on eight (8) main geographical factors used (Table 10).

Table 10. Pairwise comparison matrix of main geographical factors.

Geographical Factors	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
(A) Slope	**1**	2	1	3	2	6	5	4
(B) Soil Depth	1/2	**1**	1	2	1/2	5	4	2
(C) Lithology	1	1	**1**	2	1	5	4	3
(D) Elevation	1/3	1/2	1/2	**1**	1	3	2	1
(E) Land Use	1/2	2	1	1	**1**	4	3	2
(F) Drainage Density	1/6	1/5	1/5	1/3	1/4	**1**	1	1/2
(G) Drainage Frequ-ency	1/5	1/4	1/4	1/2	1/3	1	**1**	1
(H) Precipitation	1/4	1/2	1/3	1	1/2	2	1	**1**
Consistency Rate (%)					**2**			

After performing pairwise comparison matrices with AHP, the calculated weight rates of all sub- and upper parameters were integrated into attribute tables of parameters using GIS techniques to spatially determine the impact areas in the basin. Following this process, again using GIS techniques, first, the weight rates of the sub-criterion were reclassified according to their importance. Then, the weight rates calculated using AHP for the main geographical factors were transferred to the map according to the following formula, conducting the soil erosion susceptibility analysis of the Ladik Lake Basin (Figure 5).

Soil Erosion Susceptibility Analysis = *(Slope*0.253) + (Soil Depth*0.153) + (Lithology*0.187) + (Elevation*0.096) + (Land Use*0.157) + (Drainage Density*0.037) + (Drainage Frequency*0.048) + (Precipitation*0.069).*

Table 11. Ladik Lake Basin soil erosion susceptibility classified by distribution area and rates.

Susceptibility Classes	Area km²	Area %
Low	40,56	27,44
Moderate	21,62	14,63
High	53,65	36,30
Very High	31,97	21,63
TOTAL	**147,80**	**100**

4. CONCLUSION

Soil erosion poses a significant threat to sustainable land management (Küçüker and Giraldo, 2022), particularly in terms of ensuring the continuity of agricultural activities. Agriculture is a crucial economic activity in the Ladik Lake Basin; therefore, soil conservation is essential in the basin. To improve land management and implement preventive measures, a soil erosion susceptibility analysis was conducted in the Ladik Lake Basin. The analysis revealed that more than 50% of the area in the basin exhibits high to very high susceptibility to soil erosion (Table 11).

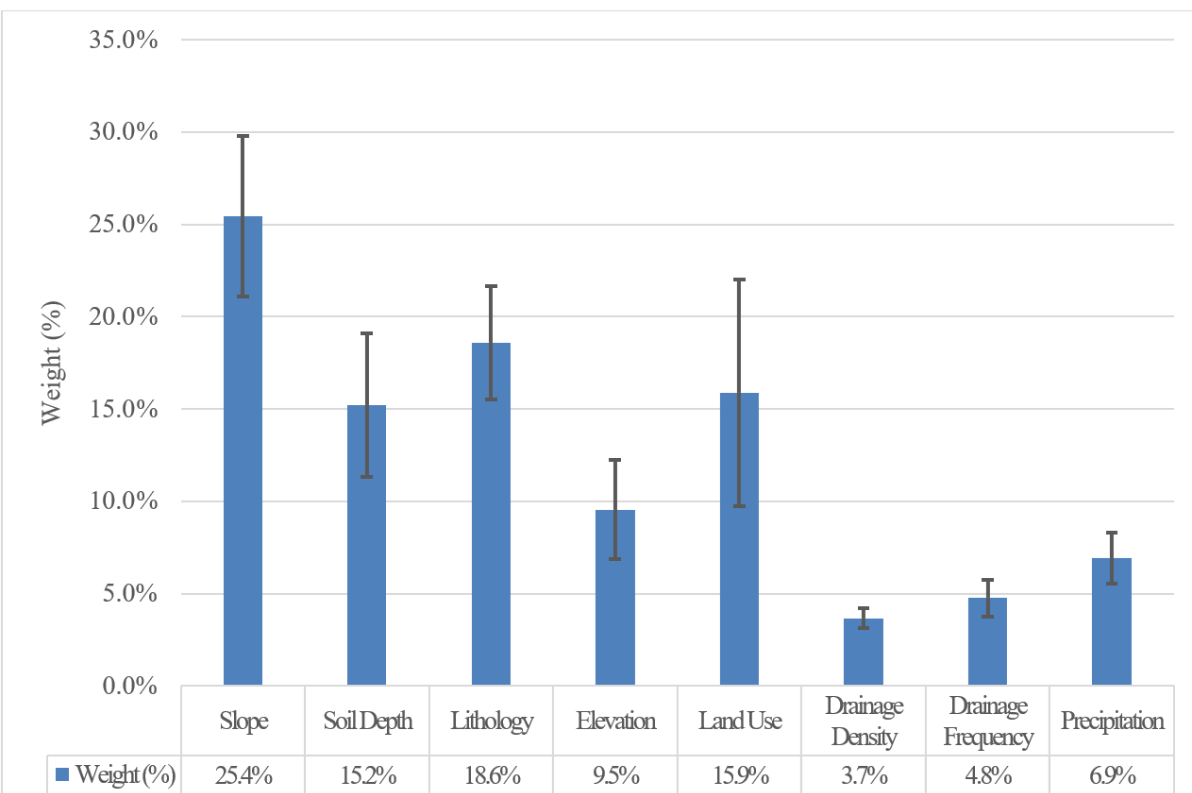

Figure 4. Distribution of weight rates of main geographical factors.

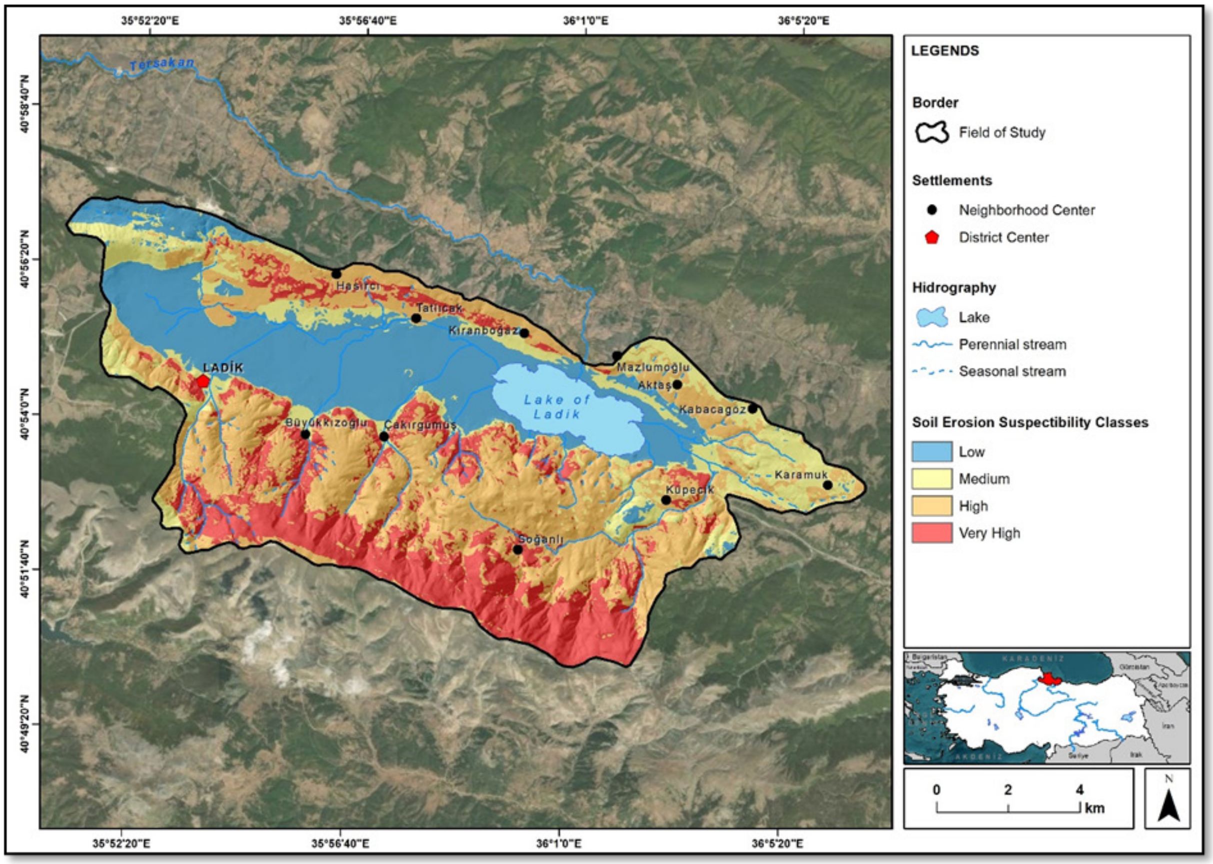

Figure 5. Ladik Lake Basin soil erosion susceptibility analysis map.

The results obtained from the soil erosion susceptibility analysis, conducted using the combined use of AHP and GIS techniques, were classified into four (4) distinct categories: low, moderate, high, and very high (Figure 5).

Low-Level Soil Erosion Susceptibility Class

The proportion of areas with low soil erosion susceptibility in the Ladik Lake Basin was 27.44% (Figure 6). These areas, where soil erosion susceptibility is low, include the basin's base and the northwest, characterized by meadows, forests and limited agricultural fields. In these areas, the slope gradient is low. A low slope gradient makes soil transport difficult, or there is a lower potential for soil loss, resulting in low soil erosion susceptibility in these areas.

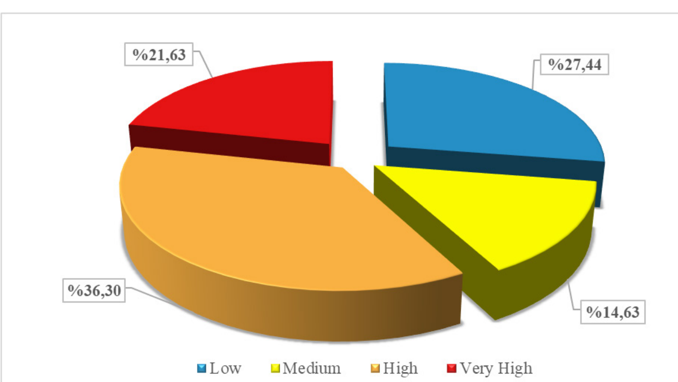

Figure 6. Distribution rates of soil erosion susceptibility classes in Ladik Lake Basin.

Moderate-Level Soil Erosion Susceptibility Class

The proportion of areas with moderate soil erosion susceptibility in the Ladik Lake Basin was 14.63% (Figure 6). The class of moderate soil erosion susceptibility generally corresponds to the eastern slopes of the basin, where the slope is relatively increased and agricultural fields and pastures are located. Moderate slope gradient and the presence of pasture and vegetation contribute to moderate soil erosion susceptibility in this area.

High-Level Soil Erosion Susceptibility Class

The proportion of areas with high soil erosion susceptibility in the Ladik Lake Basin was 36.30% (Figure 6). High-level soil erosion susceptibility class corresponds to areas with low slopes to the south of Ladik Lake, where forests are present and agricultural fields are present in the north and northeast. Despite forest cover, it is believed that short-length rivers originating from high slopes, especially in the south, are the most significant factors contributing to the high susceptibility of these areas. Additionally, the north-facing slopes of Akdağ have been deeply incised by these rivers and possess high slope values. Another factor contributing to the high susceptibility in these areas is the steep slopes.

Very High-Level Soil Erosion Susceptibility Class

The proportion of areas with very high soil erosion susceptibility in the Ladik Lake Basin was 21.63% (Figure 6). The very high-level soil erosion susceptibility class corresponds to the foothills of high slopes in the south (Akdağ and Karaömer Mountain), pasture areas located on high plateaus, and agricultural fields in the north. The lack of vegetation cover at high southern elevations significantly contributed to the very high susceptibility. Moreover, the very high susceptibility of agricultural areas in the north indicates the need for measures in these areas.

The combined use of AHP and GIS techniques for soil erosion susceptibility analysis provides a comprehensive understanding of potential soil loss areas in each region. Also, it serves as a guiding tool for decision-makers in taking preventive measures against erosion. The results of this study will assist decision makers in identifying priority areas for intervention. Furthermore, mitigating soil erosion or reducing its impact requires minimizing human activities, such as converting forested areas into agricultural and settlement areas, leaving agricultural lands fallow and minimizing incorrect agricultural practices.

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