Identification of soil erosion-based degraded land areas by employing a geographic information system —a case study of Pakistan for 1990–2020

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Article

Identification of Soil Erosion-Based Degraded Land Areas by Employing a Geographic Information System—A Case Study of Pakistan for 1990–2020

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Abstract: Land is one of the most vital nonrenewable resources that guarantee the survival and development of humans on planet Earth. In the 21st century, rapid population growth accompanied by expeditious industrialization and urbanization has led to land degradation and irreparable damage. In Pakistan, land degradation has affected the livelihood of 3.58% of the total population. This study aimed to identify the soil erosion-based land that is degraded in Pakistan through an analytical hierarchal process (AHP). For this purpose, climatic parameters such as vis-a-vis precipitation, temperature, land use/land cover, soil parameters (i.e., soil pH, soil texture, soil bulk density, and soil moisture content), and topographic parameters (i.e., slope, elevation, aspect, and drainage density) were taken into the consideration. Weights and scores were assigned in integration with a weighted overlay analysis (WOA) to the prioritized parameters. The findings revealed that Zone A comprising high mountains is severely affected by land degradation, followed by Zone D and E (Sindh and Balochistan). Key factors operating in Zone D and E are hyper-arid climatic conditions along with inefficient land management practices. The overall results validated the hypothesis that soil erosion strongly correlates with an increase in the magnitude and severity of land degradation.

Keywords: soil erosion; land degradation; GIS; AHP; weighted overlay analysis; hyper-arid climate

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1. Introduction

Land is one of the most vital nonrenewable resources that guarantees the survival and development of humans on planet Earth [1]. Since the beginning of 21st century, rapid population growth accompanied by expeditious industrialization and urbanization has led to land degradation and irreparable damage [2]. Land degradation is defined as the prolonged damage to an ecosystem's functioning and productivity as a result of the cumulative effect of natural and anthropogenic activities, from which the land cannot recover on its own without assistance [3,4]. It is considered to be one of the most important environmental threats not only in developing countries, but also in developed countries [5]. Land degradation occurs due to a combination of changes in the natural ecosystem and social system of humans, i.e., below standard lifestyle and poor understanding towards land management practices. The interaction between these two systems determines the ecological state of land. According to the report published by the United Nations Convention to Combat Desertification [6], land degradation is more obvious in arid and semi-arid climatic areas due to unsustainable land management practices and the abrupt climatic variation in the form of frequent floods, droughts, heatwaves, and coldwaves [6]. These extreme events deteriorate the quality of land when accompanied by over-grazing, wildfires, deforestation, habitat fragmentation, and crop intensification, among others [7]. All these dynamic factors accelerate the process of land degradation by affecting the soil quality in the form of soil erosion, water logging and salinity, loss of soil biodiversity, and decline in organic matter of soil [8]. Low organic matter soil has also led to fertile lands in the Savannah belt in Africa and lands in Northwest Europe, the central United States, Brazil, India, and some countries in the Sahel turning into degraded land [9]. Land degradation has threatened 1.9 billion people, and 250 million people are already affected because of an increasing trend in the severity of land degradation all over the world [9,10]. According to the report published by the UNCCD, approximately 250 million people are directly affected due to land degradation, and most of them live in underdeveloped or developing countries. It is also becoming a major threat for food security all over the world and due to its severity, it is also in the 21st century agenda [11]. In South Asia, land degradation costs around USD 10 billion every year, and the damages span approximately 43% of the total agricultural land of the continent [12]. An overview of the extent of global land degradation is given below.

Anthropogenic activities have triggered the process of land degradation over the last few decades. The most affected degraded continent due to anthropogenic intervention is Asia, which spans 747 million hectares; the least affected area is North America, with a degraded land span of 96 million hectares (Figure 1). The following table shows the human-induced soil degradation in different continents of the world.

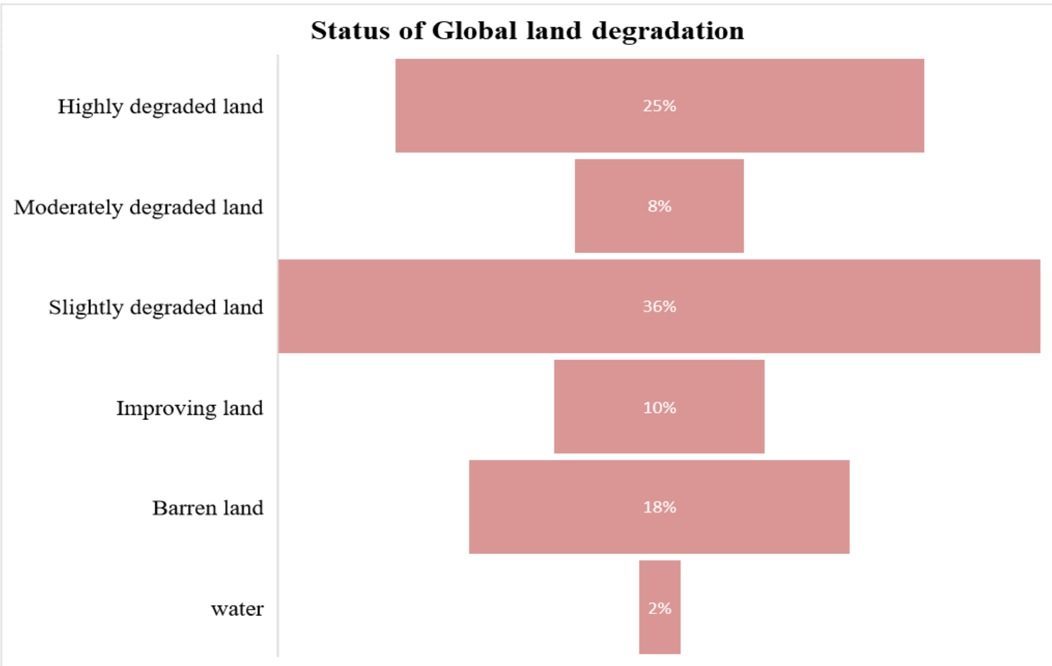

Figure 1. Status of global land degradation (SOLAW Background Thematic Report 3).

Land degradation is not a collection of local problems; it is a global issue, and it is not limited to any specific type of land. That is, the identified areas do not have a common ecosystem but rather it is a global issue (Figure 2) [13]. The list issued by the Global Assessment of Human-induced Soil Degradation (GLASOD) [14] has identified the worldwide scenario of land degradation. The top 10 countries with their rates of degradation are listed below (Table 1).

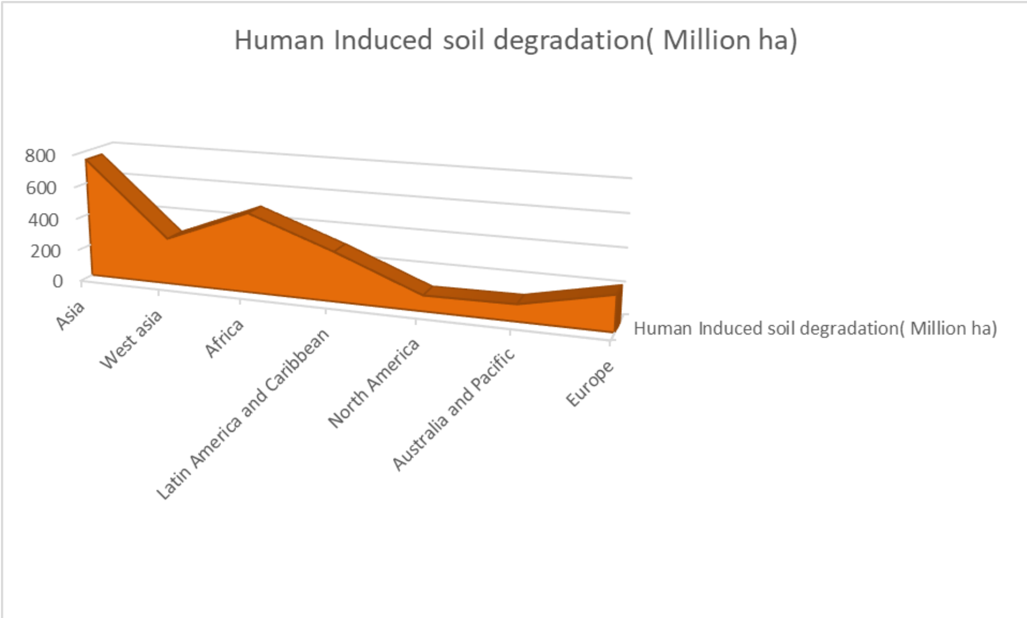

Figure 2. Human-induced soil degradation in different regions of the world (GLASOD, 2010).

Table 1. Status of the top 10 land degraded countries of the world.

Countries	Degraded Area (km^2)
Australia	1,994,268
Brazil	1,881,702
Canada	1,985,085
China	2,193,697
Indonesia	1,028,042
Russia	2,082,060
USA	1,983,866
Zaire (Democratic Republic of Congo)	1,346,914
World	35,058,104

According to the global assessment report of land degradation, an area of 20,644 km^2 of Pakistan is degraded and has affected the livelihood of 3.58% of the total population of the country [3]. Land degradation is a complex phenomenon, and one factor cannot reveal the whole truth. However, soil erosion is given the maximum weighting in Pakistan's perspective, as it is considered to be one of the major barriers in achieving sustainability. Soil erosion is defined as the removal of top soil due to the action of moving water, wind, or ice. Water and wind erosion has annually reduced the land productivity from 1.5% to 7.5%, and 84% of the total soil erosion has been caused by these factors [15,16]. Water erosion has damaged about 13.05 million hectares of the total land of Pakistan as compared with wind erosion, which has affected the land by damaging approximately 6.17 million hectares. The severe impacts of water erosion can be observed in the northern areas and in the KP (Khyber Pakhtunkhwa) region of Pakistan, where 1517.6 and 1517.0 million hectares of land are damaged, respectively. The main reason for water erosion is extensive deforestation in the north of Pakistan. However, wind erosion has affected the Sindh (1686.6 million hectares) and Balochistan (100.9 million hectares) provinces because of their hyper-arid climates [12]. Other factors that contribute towards land degradation are deforestation, water logging, and a deficiency of nutrients in the soil.

The aim of this study was to identify and assess the effects of soil erosion towards land degradation and to highlight the extent and magnitude of land degradation in each climatic zone. The base hypothesis for this research was that soil erosion strongly corelates with an increase in the magnitude and severity of land degradation.

The results showed that soil erosion is positively correlated with an increase in land degradation. The identification of the highlighted areas will help policy-makers to focus on the rehabilitation of the highly affected degraded areas. This is the first step towards land resource management and helps policy-makers adapt measures according to the extent of land degradation in Pakistan. Approximately 70% population of Pakistan is dependent on agriculture in terms of their occupation. Increasing the infertility of the land resources can bring famine, a loss of natural resources, and will also reduce the capacity of land resources to cope with the climatic changes.

It is very crucial to identify the soil erosion-based land degraded areas to improve the productivity of land resources [16]. The identification of land degraded areas requires different datasets, i.e., land use/land cover changes, climatic data (precipitation and temperature), soil properties (soil moisture, soil organic content), elevation, topography of an area, etc. and their scores and weights can easily be constructed using the ARCGIS model builder through a geostatistical approach [17,18]. The GIS is a modified tool that can deal and store a large volume of different datasets and can manipulate and combine them to present desired thematic maps. Geostatistical techniques are globally used for the study of spatial variations in soil properties over a large scale [19,20]. In this study, the analytical hierarchal process (AHP) was used to identify the soil erosion-based areas of land degradation in different climatic zones of Pakistan. The analytical hierarchal approach has the ability to incorporate expert opinion into GIS and remote sensing datasets.

2. Materials and Methods

2.1. Study Area Description

Pakistan lies between the latitudes of 24° N–37° N and longitudes of 60° E–75° E in Southwest Asia and covers an area of 796,000 km^2. It borders with India and the Arabian Sea in the east, Afghanistan and Iran in the west, and China in the north. In this study, we considered five major climatic zones of Pakistan as described in the "Spatiotemporal Variations and Trends in Minimum and Maximum Temperatures of Pakistan" [21]:

- Zone A lies between 34° N and 38° N and lies in the north of Pakistan.
- Zone B lies between 31° N and 34° N and consists of sub-mountains with a mild-cold climate.
- Zone C lies between 27° N and 32° N and between 64° E and 70° E.
- Zone D consists of almost plain region and is the driest and hottest of all the zones.
- Zone E is the biggest zone among all zones and extends into Sindh and Balochistan (Figure 3).

2.2. Data Acquisition

The climatic dataset includes the total monthly precipitation (P) and temperature (Tmax, Tmin and Tmean). The datasets were obtained from the Climatic Research Unit (CRU), Version TS3.23, for the period of 30 years, i.e., 1990–2020 [22,23]. All of the climatic datasets were thoroughly evaluated and applied in the study.

The soil parameters were analyzed for the identification of the degraded land area, i.e., the soil pH, soil texture, soil water content, and soil bulk density. These datasets were obtained from the International Soil References and Information Centre (ISRIC), landforms.org, and the Soil Survey of Pakistan. The ISRIC is global 3D information system that provides more than 110,000 soil profiles with an accuracy assessment of 23–51% [22,24].

The land use/land cover maps were prepared by using ESACCI satellite data. This satellite has a spatial resolution of 300 m and provides the best land use/land cover maps. The given table shows the land use/land cover (LULC) of the 5 climatic zones of Pakistan. The LULC has been divided into 9 major classes, named agricultural land, built-up area, forests/shrubs, grasses, ice, open spaces, shrubland, water, and wetland.

The topographic datasets used in this study were aspect, elevation, and slope. All of these topographic sheets were extracted from the digital elevation model provided by the Space Shuttle Radar Topographic Mission (SRTM) which has spatial resolution of 30 m.

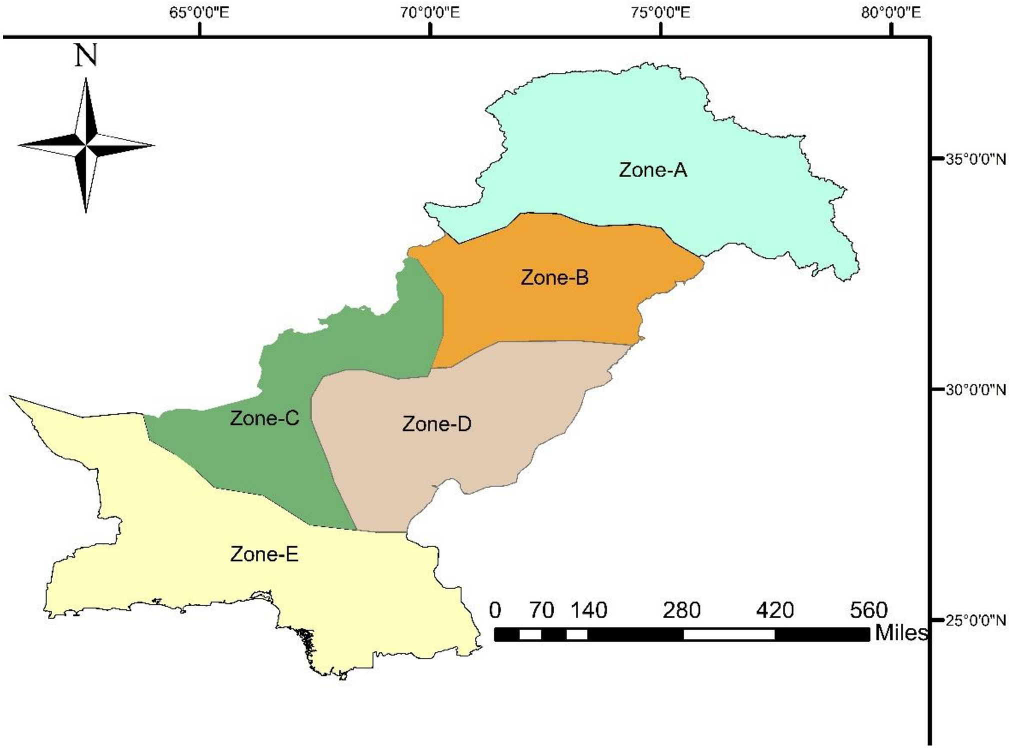

Figure 3. Climatic Zones of Pakistan (Source: [21]).

The water bodies dataset were extracted from the official GIS Pakistan website and Open Street Map. (https://www.openstreetmap.org (accessed on 1 June 2020)); these maps were then digitized for the creation of the final degraded land map (Table 2).

Table 2. Summary of data acquisition.

Data	Data Source
Precipitation	Climatic Research Unit (CRU)
Temperature	Climatic Research Unit (CRU)
Soil pH	International Soil references and information Centre (ISRIC), landforms.org
Soil texture	International Soil references and information Centre (ISRIC), landforms.org
Soil water content	INTERNATIONAL SOIL REFERENCES AND INFORMATION CENTRE (ISRIC), LANDFORMS.ORG
Soil Bulk Density	INTERNATIONAL SOIL REFERENCES AND INFORMATION CENTRE (ISRIC), LANDFORMS.ORG
LULC Map	PROBA V (100 m Spatial Resolution)
Aspect	SRTM DEM
Elevation	SRTM DEM
Slope	SRTM DEM
Water Bodies/Water Channels	Open Street Map (https://www.openstreetmap.org) accessed on 1 June 2020.

2.3. Data Processing

2.3.1. Preparation of Spatial Datasets

For this study, the eleven parameters presented in Figure 4, precipitation, temperature, soil pH, soil texture, soil bulk density, soil water content, LULC map, aspect, elevation, slope, and water bodies for drainage density were selected for the identification of degraded land areas of Pakistan.

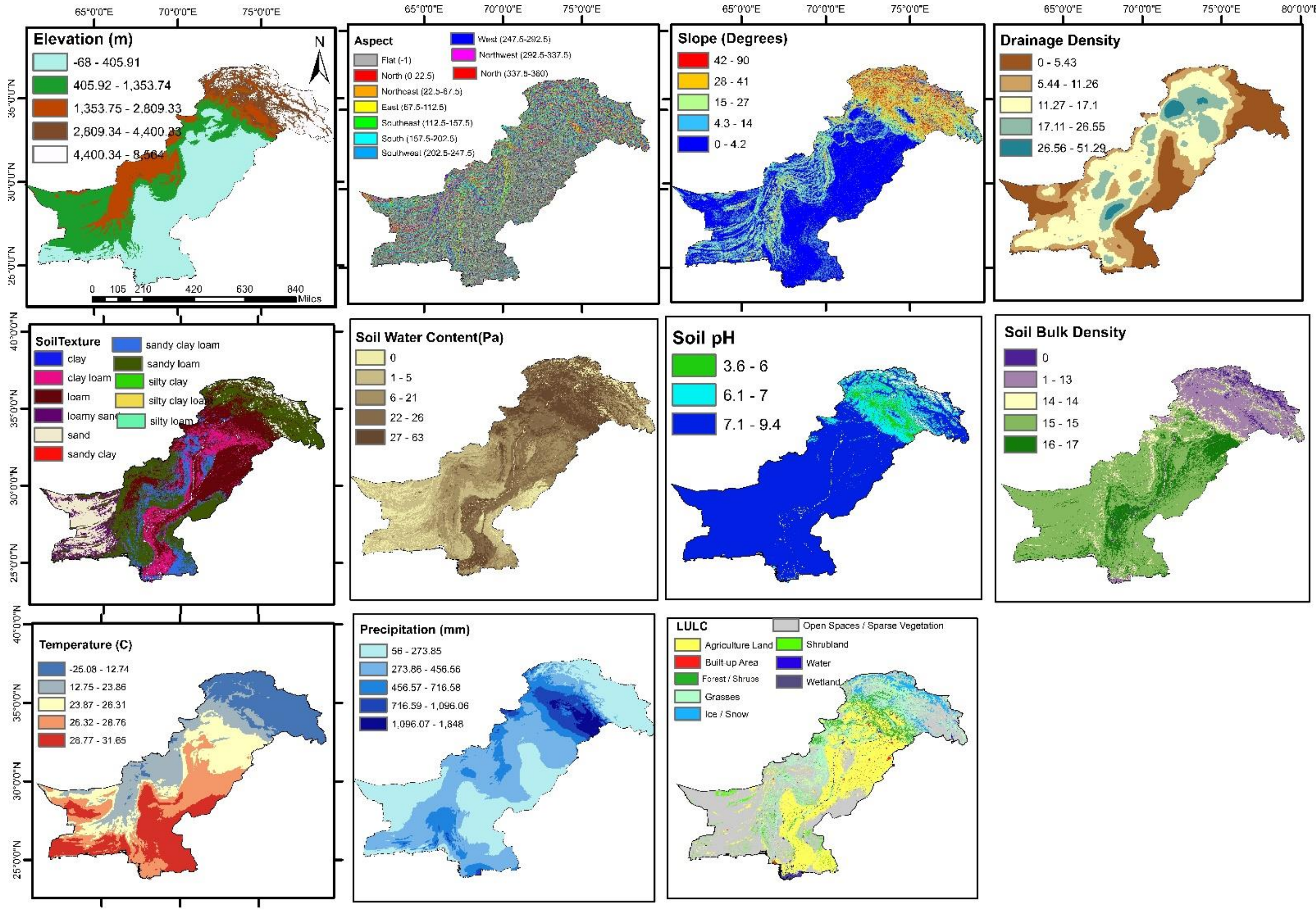

Figure 4. GIS based criterion maps for: precipitation; temperature; soil pH; soil texture; soil bulk density; soil water content; LULC map; aspect; elevation; slope; and water bodies for drainage density.

2.3.2. Analytical Hierarchal Process (AHP)

The analytical hierarchal process (AHP), developed by Satty in 1980, is one of the best multi-criteria decision-making methods used to evaluate multiple objectives by using a logical analytical hierarchy. This method has the ability to self-check the weights assigned with the help of CR value. If the value is less than 0.1, it indicates that appropriate weights has been assigned to all of the parameters. After developing this hierarchy, a pairwise comparison matrix is developed for all elements, and scores and weights are assigned to each criterion based on mathematical calculations. In this study, we have also used the AHP method to identify the degraded land areas of Pakistan. The following steps of AHP were adhered to:

i. The preparation of thematic layers.
ii. Weight determination by using a pairwise comparison matrix based on experts' opinions.
iii. A standardization of criteria
iv. Overlay of all thematic layers to generate the final map.

Preparation of Thematic Layers

In this study, the thematic layer of precipitation and temperature were developed by using CRU datasets. For this purpose, an average of 30 years, 1990–2020, were prepared for both thematic layers. Four soil parameters were selected for the identification of degraded land areas, as all of these play an important role in land resource management. The selected soil thematic layers were soil pH, soil texture, soil water content, and soil bulk density, which were prepared using the International Soil References and Information Centre (ISRIC) and landforms.org datasets. The ISRIC is a global 3D information system that provides more than 110,000 soil profiles with an accuracy assessment of 23–51% [23,24]. The thematic layer of LULC was produced by the ESACCI datasets and had a spatial resolution of 300 m. The LULC of the present study was classified into agricultural land, built-up area, Forests/shrubs, grasses, ice/snow, open spaces/sparse vegetation, shrubland, water, and wetlands. Aspect, slope, and elevation were extracted from the digital elevation model (DEM) provided by the Shuttle Radar Topographic Missions (SRTM). The drainage density was calculated by using Open Street Maps. The obtained map was digitized for the desired study.

Weight Determination

In the present study, a pairwise comparison matrix was used for the determination of weights for all thematic layers. The assigned values ranged from 1 to 9, where 1 shows the least importance and 9 indicates the most importance [25–27]. The AHP method also measures the level of consistency as a consistency ratio (CR) index [26]. A CR value of less than 0.1 indicates that the pairwise comparison matrix is holding an acceptable consistency [27–29]. The consistency ratio of this study was 0.019947617, indicating that all of the weight values are logically valid.

Standardization of Criteria

In this step, all vector layers were converted to thematic layers by using the reclassifying tool in the ArcGIS software. During this classification, all parameters were classified into five categories scoring from 1 to 5, where 1 notes the least importance and 5 notes the greatest importance. The weights and scores of each thematic layer are given in Table 3.

Weight Overlay of Thematic Layers

In this step, all thematic layers were overlapped by performing a weight overlay analysis in the ArcGIS software. In this step, the weight value was multiplied with the cell value of each raster in ArcGIS.

Table 3. Pairwise comparison matrix of the selected parameters.

	Elevation	**Slope**	**Aspect**	**Land Use Landcover**	**Temperature**	**Precipitation**	**Drainage Density**	**Soil Texture**	**Soil Bulk Density**	**Soil Water Content**	**Soil pH**	**Sum**	**CV**
Elevation	0.2777	0.4076	0.4467	0.4335	0.3907	0.3317	0.2653	0.2658	0.1860	0.1501	0.1320	3.2870	11.8356
Slope	0.1389	0.1489	0.2978	0.3251	0.3125	0.2764	0.2274	0.2325	0.1628	0.1313	0.1174	2.3710	11.6347
Aspect	0.0926	0.0542	0.1489	0.2168	0.2344	0.2211	0.1895	0.1993	0.1395	0.1125	0.1027	1.7115	11.4953
Land use Landcover	0.0694	0.0260	0.0744	0.1084	0.1563	0.1658	0.1516	0.1661	0.1163	0.0938	0.0880	1.2162	11.2218
Temperature	0.0555	0.0138	0.0496	0.0542	0.0781	0.1106	0.1137	0.1329	0.0930	0.0750	0.0734	0.8499	10.8774
Precipitation	0.0463	0.0076	0.0372	0.0361	0.0391	0.0553	0.0758	0.0997	0.0698	0.0563	0.0587	0.5817	10.5233
Drainage Density	0.0397	0.0055	0.0298	0.0271	0.0260	0.0276	0.0379	0.0664	0.0465	0.0375	0.0440	0.3881	10.2400
Soil Texture	0.0347	0.0033	0.0248	0.0217	0.0195	0.0184	0.0190	0.0332	0.0465	0.0563	0.0440	0.3214	9.6764
Soil Bulk Density	0.0309	0.0023	0.0213	0.0181	0.0156	0.0138	0.0126	0.0166	0.0233	0.0375	0.0293	0.2213	9.5190
Soil Water Content	0.0361	0.0016	0.0186	0.0155	0.0130	0.0111	0.0095	0.0111	0.0116	0.0188	0.0293	0.1762	9.3932
Soil pH	0.0305	0.1300	0.0165	0.0135	0.0112	0.0092	0.0076	0.0083	0.0116	0.0094	0.0147	0.2626	17.8966
						Pairwise Comparison Matrix							
	CI = Lambda-n/n-1				0.3012				10			0.0301209	
	11.3012-11/11-1												
	CI = 0.041695				0.030121								
	CR = CI/RI												
	CR = 0.041695/1.51				**0.019948**								

3. Results

The scores and weights of all thematic layers were determined by a pairwise comparison matrix of the AHP method. After this, all thematic layers were overlayed in ArcGIS by using a weighted overlay analysis.

The weights for each layer were normalized by a multi-criteria decision analysis. The normalized weight for the elevation was 2.777. For the slope, it was 0.2038. Aspect had a weight of 0.1489. The normalized weights for land use/land cover, temperature, precipitation, and drainage density was 0.1084, 0.781, 0.0553, and 0.379, respectively. For soil texture, soil bulk density, soil water content, and soil pH, the normalized weights were 0.032, 0.0233, 0.0188, and 0.0147, respectively. The total sum of all normalized values was 1.00. The pairwise comparison matrix is shown in Table 3.

In the last step, all the normalized weights were combined by applying the weight linear combination in ArcGIS, and the final map was produced which shows the degraded land areas in Pakistan (Figures 4 and 5).

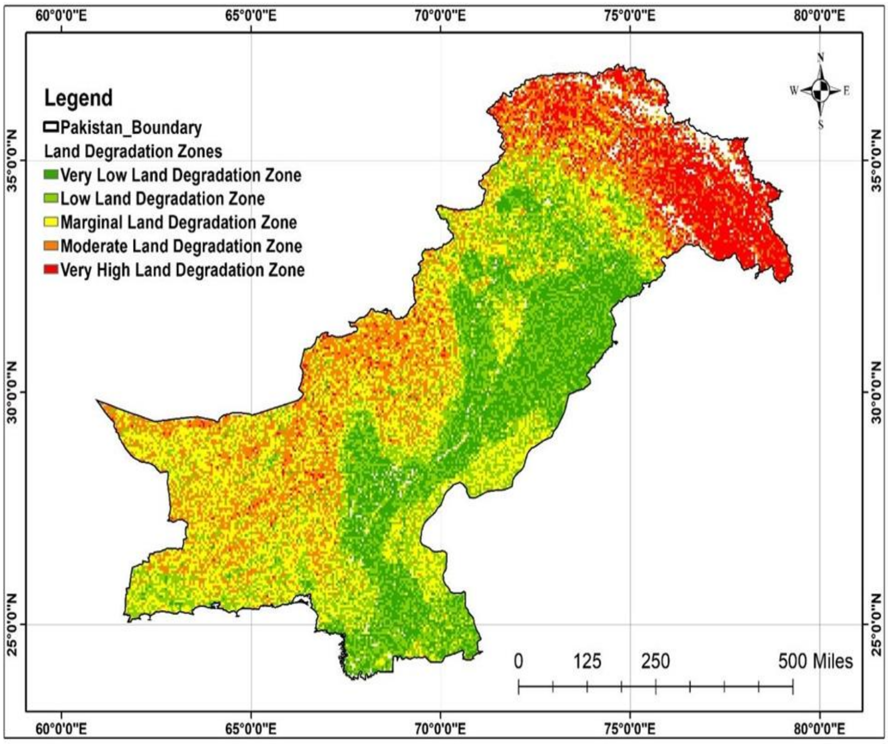

Figure 5. Identified degraded land areas of Pakistan from the AHP analysis.

The consistency ratio (CR) of the study was 0.019 and it represents the appropriate allocation of scores and weights to all thematic layers. The consistency ratio (CR), which is evaluated according to the AHP analysis for the validation of model, should be less than or equal to 0.1 to best fit the model. If the consistency ratio is $\geq$0.1, it means that the AHP analysis requires a reassignment of weights and scores. At a value of 0.019, it was less than 0.1, proving that all the weights assigned to the thematic layers were appropriate.

For a better understanding, the final map of degraded land zones is divided into 5 subclasses, i.e., the very low land degradation zone, low land degradation zone, marginal land degradation zone, moderate land degradation zone and very high land degradation zone. This map shows the extreme level of degradation in the north of Pakistan, while some parts of the Sindh and Balochistan provinces also have certain points where there is a high level of degradation. Moderate or low levels of soil erosion-based land degradation are shown in some parts of the Sindh province, and Punjab showed much less land degradation. The alarming rate of soil erosion in the north is due to the excessive rate of deforestation, which has led towards the highest level of degradation [12]. In India, approximately

175 million hectares of land has degraded due to severe soil erosion, and this erosion is a result of deforestation and has badly affected the Lesser Himalayas [29–31]. Areas covered with trees and other shrubs hold the soil and prevent soil erosion, minimizing the risk of land degradation; however, in the Thar desert, the fewer number of trees and shrubs have triggered the soil erosion and are leading the land towards desertification [32,33]. Furthermore, the Thar desert also suffers from overgrazing and a lack of proper agricultural management, and the problem of land degradation is becoming more alarming day-by-day [34].

4. Discussion

Land degradation is not a local issue but has threatened the livelihood of 1.9 billion people all over the world, with its most drastic impacts in Asia due to the damaging of 747 million hectares of the land. Pakistan is a dry-land country in South Asia with 80% of its land being arid in nature. Due to unsuitable land management practices, the quality of the land is deteriorating at a very fast rate [32,33]. The reason for this is the growing population rate, which is exerting pressure on natural resources to produce more food; as a result, various environmental issues are arising in the region, such as soil and water erosion, land ecosystem degradation, etc. [35–38] If the land degradation is not stopped, it will bring famine, loss of the natural ecosystem, reduction in the land capacity to cope with climatic changes, and decrease in the ecosystem's quality, as well as reducing the quantity of freshwater resources and reducing the soil quality [39,40].

For the identification of degraded land areas, the selected climatic thematic layers were precipitation and temperature. The reason for adding these particular layers is their important role in vegetation health. If there is less rainfall than usual, then it may lead towards droughts. If there is more rainfall over a long period of time, the soil will lose its ability to hold water and will bring flooding. In this way, it is directly linked with the rate and extent of land degradation in an area [37,38]. Similarly, an increase in temperature also suppresses the vegetation and leads to permanent damage to the land ecosystem. The second most important selected factor was soil pH, as it plays an important role in plant growth and provides information about the nutrient health of vegetation. If the soil pH is optimum, i.e., 6.5–7.5, the vegetation will be healthy and is less prone to degradation; if it is more acidic or alkaline in nature, it can easily convert into degraded land. Soil texture also plays an important role in land degradation. Clay and sandy areas trigger the degradation process. When the soil bulk density is low, it will cause more land degradation. Optimum soil moisture content is also important. If there is less water content in the soil, it will lead to droughts and desertification; if there is a high moisture level in the soil, it leads to water logging. Both of these extreme conditions exaggerate land degradation [17]. The LULC map of the study is divided into nine main classes: built-up area, bare land, cultivated land, forest, grassland, permanent snow/ice, shrubland, water bodies, and wetlands. The topography describes the land features; the greater the slope and elevation is, the higher the land degradation will be in those areas. Drainage density presents the total length of all water bodies in the study area. Areas close to bodies of water will suffer less from land degradation as compared with areas that are far from bodies of water. All of the above results obtained from the AHP method indicate that the land degradation has significantly increased over the last few decades [40] and is considered to be a threat to global food security, making the agricultural areas more prone to climatic extremes and limiting the options of adaptation planning [40,41] vs. the threat.

5. Conclusions

The results of this investigation indicates that Pakistan is severely affected from land deg-radation and Zone A is highly prone as compared to the other zones. The cause is the rapid urbanization and construction due to the CPEC leading the area towards deforestation. In Zone D and E, the increase in the frequency of climatic extremes in the form of floods and droughts are deteriorating the land. The degradation process is also accelerated due to the mining activities in these zones. These zones are already hyper-arid in nature, and the poor land management practices are leading the land towards irreparable damage. This study has provided a clear picture of the extent of land degradation in Pakistan. This study will help policy-makers develop strategies that help to mitigate the detrimental effects of barren land and will help in the rehabilitation of the degraded land areas by applying proper agricultural management practices and by training the local communities and farmers. The selected AHP procedure was also very efficient and is a cost-effective process that can deal with many criteria at a time for the identification of degraded land areas.

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