International Journal of Research Studies on Environment, Earth, and Allied Sciences (IJRSEAS)
| Volume-3 Issue-2 | April-2026 | ISSN: 3066-0637 | Website: https://eesrd.us

Manuscript ID:
IJRSEAS-2026-030235

OPEN ACCESS

Quick Response Code:

Website: https://eesrd.us

DOI: 10.5281/zenodo.21585979

DOI Link:
https://doi.org/10.5281/zenodo.21585979

Volume: 3

Issue: 2

Pp. 192-204

Month: April

Year: 2026

E-ISSN: 3066-0637

Submitted: 14 Mar. 2026

Revised: 25 Mar. 2026

Accepted: 15 Apr. 2026

Published: 30 Apr. 2026

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How to cite this article:
Kumar, A. (2026). Mapping of Land Degradation in Wayanad District, Kerala, India, Using GIS and Remote Sensing Techniques. International Journal of Research Studies on Environment, Earth, and Allied Sciences, 3(2), 192–204. *https://doi.org/10.5281/zenodo.21585979*

Mapping of Land Degradation in Wayanad District, Kerala, India, Using GIS and Remote Sensing Techniques

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Abstract

Land degradation can have disastrous effects on both the environment and agriculture. In addition, it can hinder sustainable development, especially in vulnerable mountain environments. The Wayanad district, in the Western Ghats of Kerala, India has been identified as one of these areas because of the extreme weather conditions associated with this area. It has a high rate of deforestation and changing land uses which lead to increased rates of soil erosion. Using geographic information systems (GIS) and remote sensing data sources, this research will attempt to determine the amount of land that is being degraded throughout the Wayanad district. Using three main components which influence land degradation: (i) climate; (ii) soil; and (iii) vegetation we will create the Climate Quality Index (CQI); Soil Quality Index (SQI); and the Vegetation Quality Index (VQI). These indexes are constructed from multiple datasets such as: precipitation, drought probability, aridness, aspect, slope, soil depth, drainage, soil parental materials, soil texture, NDVI, land use/land cover classification, and water holding capacity. The CQI, SQI, and VQI are then used together with the raster based weighted overlay method along with the geometric mean method in ArcGIS pro. Combining the results from all three indexes produces the land quality index (LQI). From the LQI, zones of different levels of degradation are determined. The results show that there is a large portion of low-quality land found in areas with steep slopes, areas with limited or no vegetative growth, areas prone to drought, and areas where the water holding capacity is poor. On the other hand, the areas that have lower gradients and that contain more forested lands have better land quality. Overall, the methodology demonstrated within this study shows how GIS may be used effectively for assessing the level of land degradation over an entire area.

Keywords: *Land degradation, GIS, Remote sensing, Land Quality Index, Soil erosion, Western Ghats, Soil Erosion.*

Introduction

Land is one of the most valuable natural resources supporting agriculture, biodiversity, water regulation, and human settlements. However, increasing pressure from population growth, unsustainable land use, deforestation, and climate variability has accelerated land degradation worldwide (Ekka et. al., 2023). The United Nations Convention to Combat Desertification (UNCCD) defines land degradation as the reduction or loss of biological or economic productivity of land resulting from natural processes or anthropogenic activities (UNCCD, 2017). Land degradation manifests through soil erosion, nutrient depletion, salinization, compaction, vegetation loss, landslides, and declining productivity (Karki & Ojha, 2021).

Land degradation refers to any alteration or disturbance that negatively affects the quality of land and is regarded as undesirable. Although natural hazards are not primary drivers, human activities can indirectly intensify occurrences such as floods and wildfires (Keller & DeVecchio, 2019). Key factors contributing to land degradation include deforestation, overuse of chemical fertilizers and pesticides, overgrazing, salinization, waterlogging, desertification, soil erosion, the development of wastelands, and landslides (Abdullahi et al., 2023).

In India, land degradation is a major concern, affecting nearly one-third of the total geographical area (SAC, 2021). Mountain regions such as the Western Ghats are particularly vulnerable because of steep slopes, intense monsoon rainfall, fragile soils, and rapid land-use conversion (Chinnasamy and Honap, 2023). Highlands of Kerala have suffered from regular landslides, soil loss and ecological disruption as a result of large-scale plantations, quarrying, highway construction, and deforestation (Irshad et al., 2025).

Traditional field-based assessments of land degradation suffer from spatial limitations and long-time requirements. GIS and remote sensing provide efficient tools for integrating multiple environmental variables and generating spatially explicit degradation maps (Jafari and Bakhshandehmehr, 2016).

Multi-criteria evaluation techniques using climatic, soil, and vegetation indicators are widely used to assess land sensitivity and quality.

The present study aims to map land degradation in Wayanad district by integrating climate, soil, and vegetation factors using GIS. Specific objectives include:

1. To generate Climate Quality Index (CQI), Soil Quality Index (SQI), and Vegetation Quality Index (VQI).
2. To integrate these indices into a Land Quality Index (LQI).
3. To identify vulnerable zones requiring conservation intervention.

Study Area

Wayanad district, located in the north-eastern part of Kerala (11.27°–11.99° N, 75.77°–76.45° E), covers an area of about 2,091 km² and lies between 700 m and 2,100 m above sea level (Irshad et al., 2025). It represents one of the most ecologically sensitive districts in South India, forms part of the Western Ghats and the Mysore Plateau, featuring hilly terrain, dense forests, and fertile valleys, Wayanad district has recently experienced increasing environmental stress. Land degradation in Wayanad district poses a threat to agriculture-based livelihoods biodiversity habitats, and watershed stability.

Chembra Peak stands as the highest elevation in the district. The area is drained by the Kabani River and sustains a wide range of agricultural activities, supported by fertile soils and a favourable climate, yielding crops such as coffee, tea, pepper, rice, and cardamom. Expansion of plantations, settlements, road networks, and tourism infrastructure has altered natural landscapes in recent decades. Approximately 885 sq. km of the district is covered by forests, of which about 344.44 sq. km consists of wildlife sanctuaries like Muthanga and Tholpetty, providing habitat for elephants, deer, and a variety of bird species.

The district enjoys a moderate and pleasant climate, with temperatures typically ranging between 20 °C and 30 °C and receiving an annual rainfall of about 250–300 cm. With a population density of 403 persons per sq. km, Wayanad district comprises approximately 2.42% of Kerala's total population. The combination of steep topography, intense rainfall, deforestation, and changing land use makes Wayanad district highly susceptible to land degradation processes such as erosion, slope failure, nutrient depletion, and vegetation loss. The figure 1 illustrating the study area map.

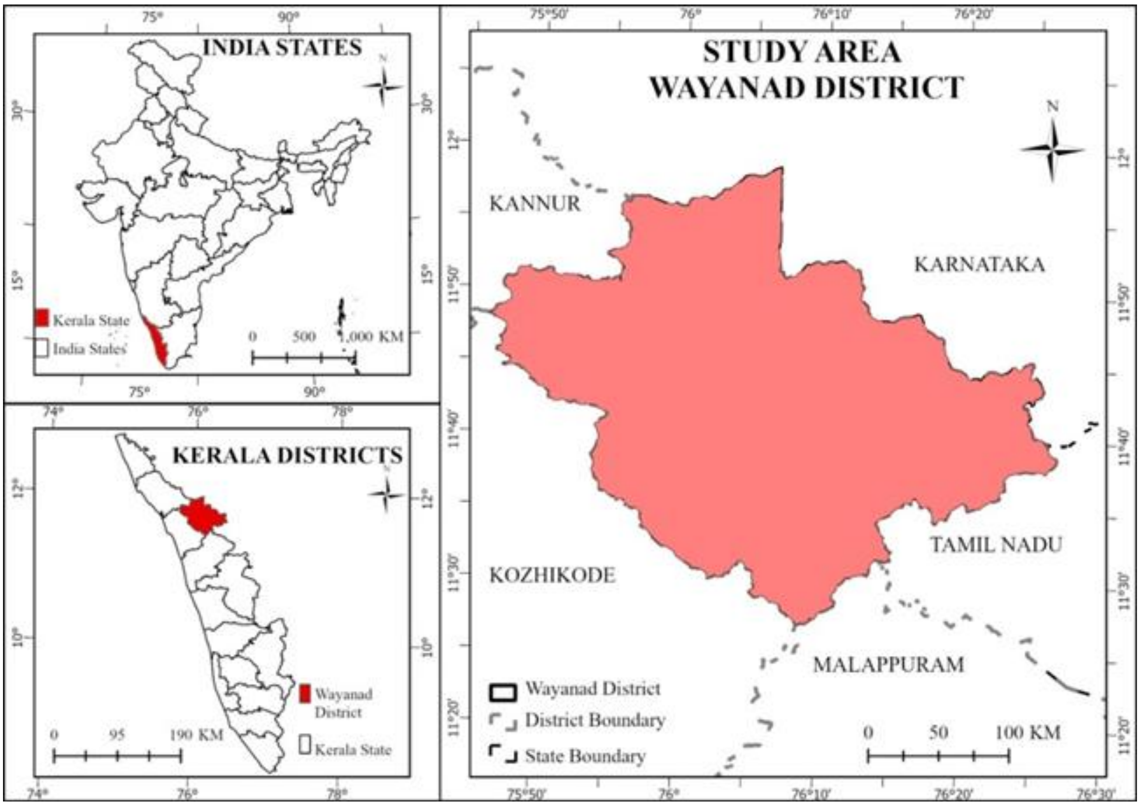

Figure 1 Map showing the location of the Wayanad District

Materials and Methods

1. **Data Sources**

A large number of datasets from various reliable sources were collected in this research project to evaluate land degradation within the area of the Wayanad district. Data related to rainfall and drought was obtained from Climate Engine; aridity data was acquired through the CGIAR-CSI; and the SoilGrids and India WRIS databases were used to obtain data regarding soil characteristics including parent material, texture, drainage, and depth. Metrics concerning vegetation were determined using Landsat 8 imagery (through Google Earth Explorer), and ESRI datasets.

2. **Methodology**

All the spatial data sets were first converted into a single Coordinate System; they were then clipped to the boundaries of Wayanad District, they were next resampled to a consistent resolution; and finally, each of them was converted to Raster Format so that they could be analyzed in ArcGIS Pro. The respective Indices CQI, SQI and VQI were then created with the use of the raster calculator. Lastly, all three of these indexes were combined by means of a raster calculator operation to create a new index called LQI.Land degradation was assessed using three major components:

1. Climate Factor
2. Soil Factor
3. Vegetation Factor

Each component was represented by thematic indicators, standardized into weighted classes. Higher scores represented better land quality or lower degradation susceptibility, depending on variable direction. Geometric mean methods were used to generate composite indices.

Climate Factor

To determine if climate affects degradation on land in Wayanad District, five important indicators were chosen for analysis: (1) Rainfall, (2) Rainfall Variability, (3) Drought Probability, (4) Aridity, and (5) Aspect. To examine how climatic conditions affect land degradation in Wayanad district, five key parameters were selected and analyzed: (i) rainfall, (ii) rainfall variability, (iii) drought probability, (iv) aridity, and (v) aspect.

Rainfall

The rainfall data were spatially interpolated so that all areas of the district could be represented; then they were grouped into three classes (Figure 2). More emphasis is placed on those districts having greater rain fall because it would reflect lower risk of degradation than those having lesser rainfall which would have greater susceptibility to degradation.

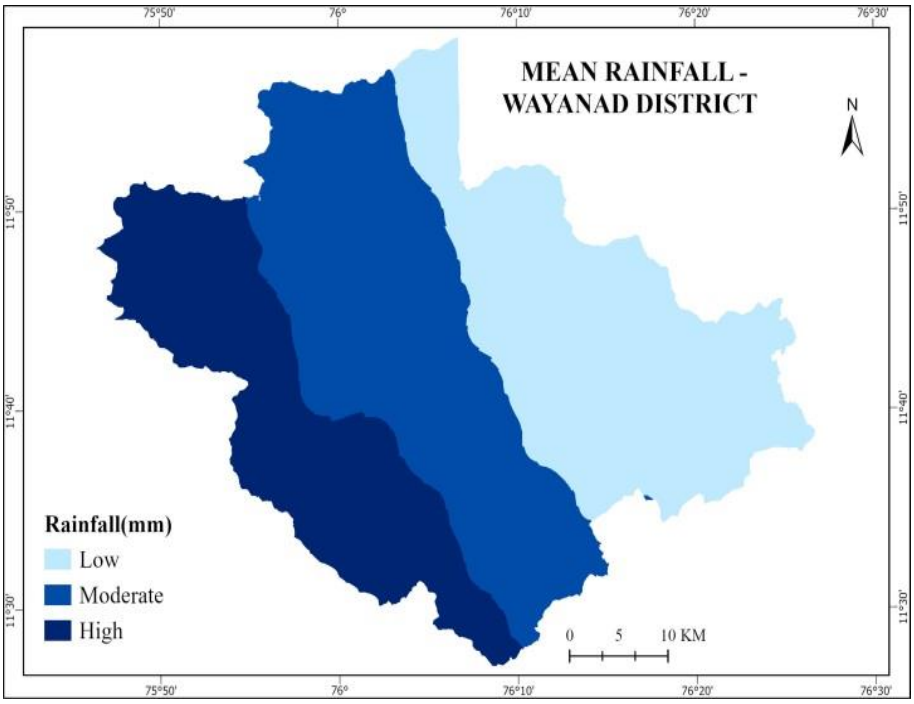

Figure 2 Mean Rainfall

Rainfall Variability

Rainfall variability was assessed using the coefficient of variation and the results were categorized into three classes (Figure 3). Areas with low variability were assigned higher weights, as they are less susceptible to degradation, while regions with high variability received lower weights due to their increased vulnerability to degradation.

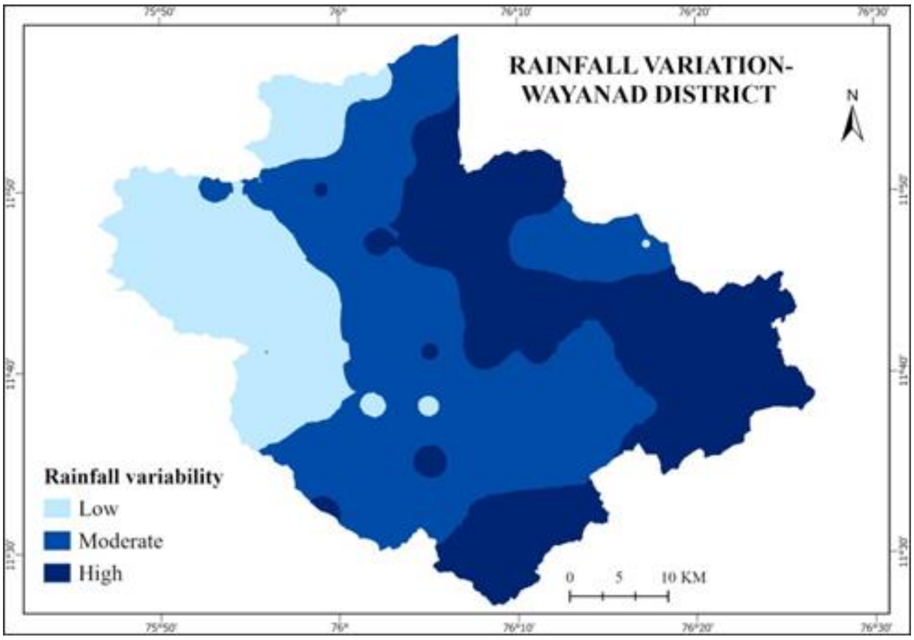

Figure 3 Rainfall Variability

Drought Probability

The drought occurrence likelihood was determined from the rainfall data over a 30-year period. The area was classified into three categories (see Figure 4) based on those classifications that use the IMD, including 'no drought' and 'mild drought'. Areas in which there is no drought have been assigned greater weights since those areas tend to be at lower risk for land degradation.

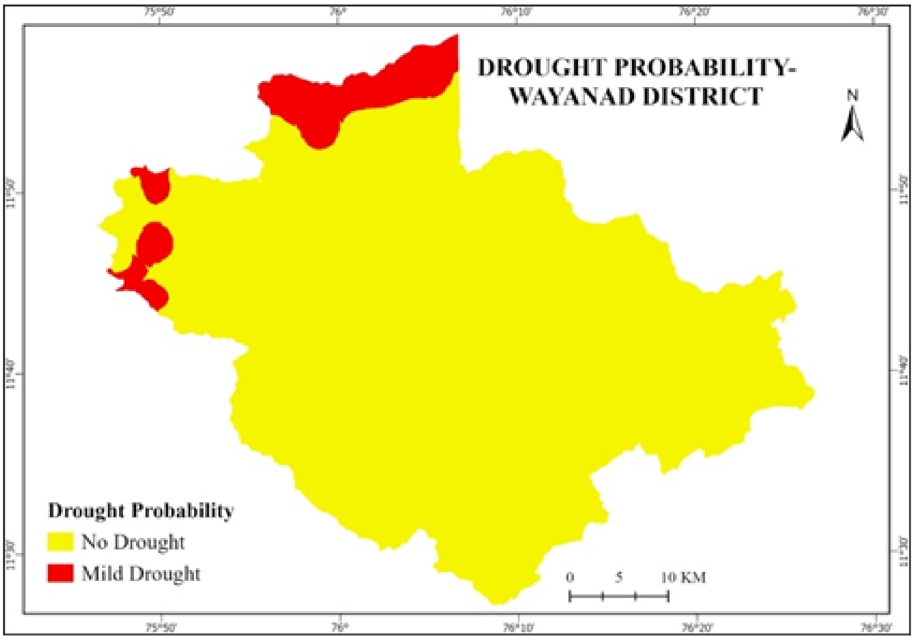

Figure 4 Drought probability

Aridity

The aridity index values were categorized into five classes (Figure 5). Areas with higher aridity were assigned lower weights due to their greater susceptibility to degradation, whereas more humid regions were given higher weights.

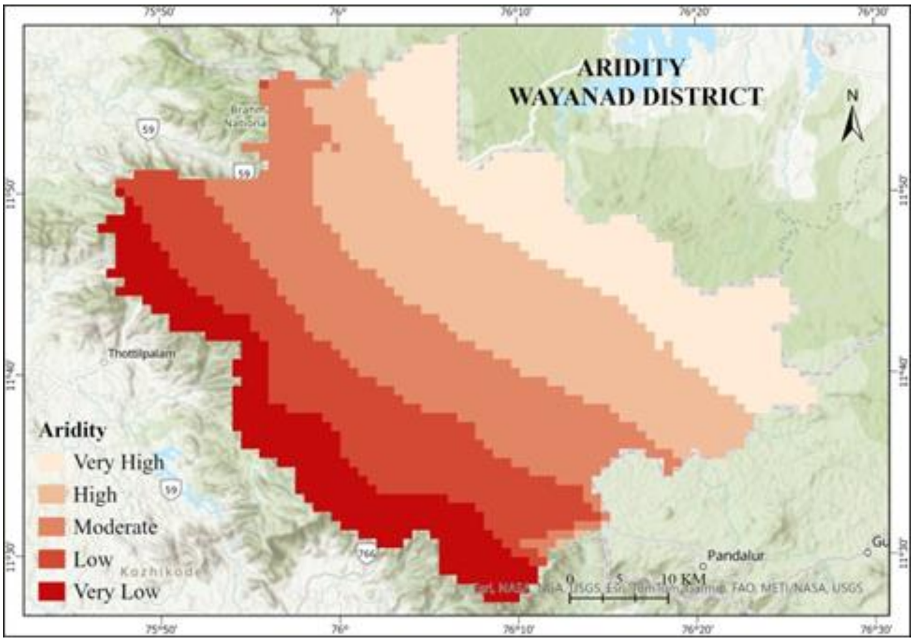

Figure 5 Aridity

Aspect

The aspect results were categorized into ten classes (Figure 6). Slopes receiving direct sunlight were assigned higher weights, whereas areas with reduced sunlight exposure were given lower weights.

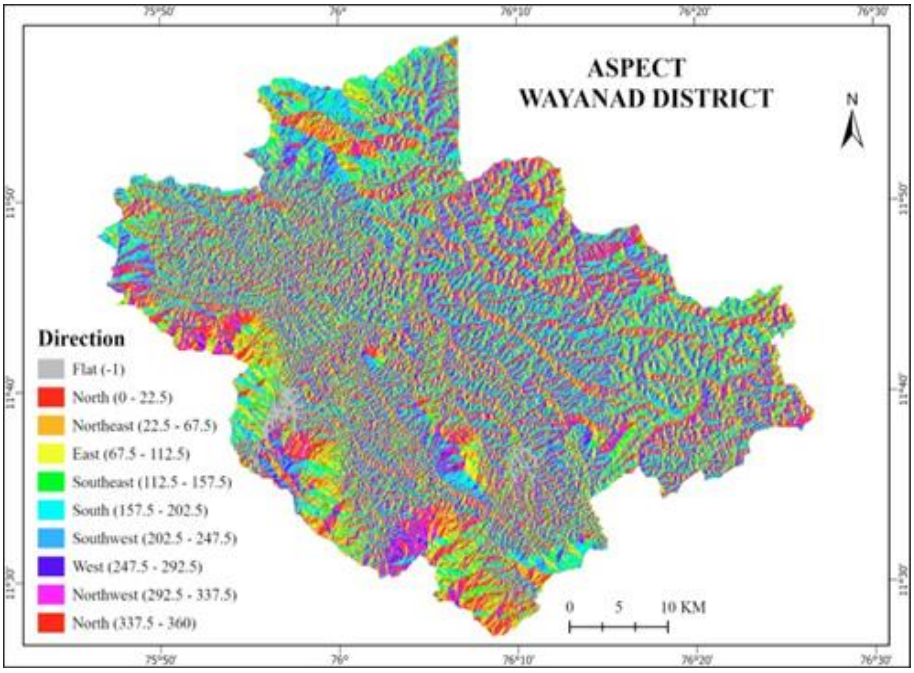

Figure 6 Aspect

Climate Quality Index (CQI)

The selected climatic parameters were integrated using the following formula to compute the CQI:

CQI = (mean rainfall*rainfall variability*drought probability*aridity*slope) *1/5

The resulting CQI map was then classified into five categories: very low quality, low quality, moderate quality, high quality, and very high quality (Figure 7). Areas with unfavourable rainfall regimes and high aridity showed lower CQI values.

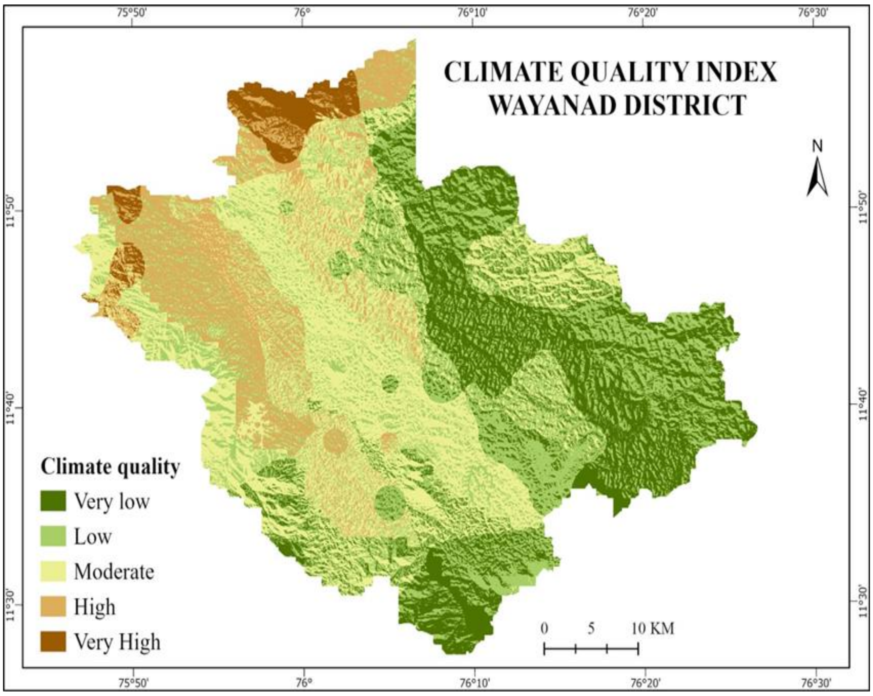

Figure 7 Climate Quality Index

Soil Factor

Soil characteristics are critical in determining the extent of land degradation. To evaluate the influence of soil conditions in Wayanad district, five key parameters were selected and analyzed: (i) parent rock material, (ii) slope, (iii) soil drainage, (iv) soil depth, and (v) soil texture.

Parent Rock Material

Parent rock material was utilized to classify the district into distinct categories based on lithological type. The study area is predominantly composed of Charnockite, Granite, Gneiss, and migmatite formations (Figure 8), and weights were assigned to each type according to their relative influence on land degradation.

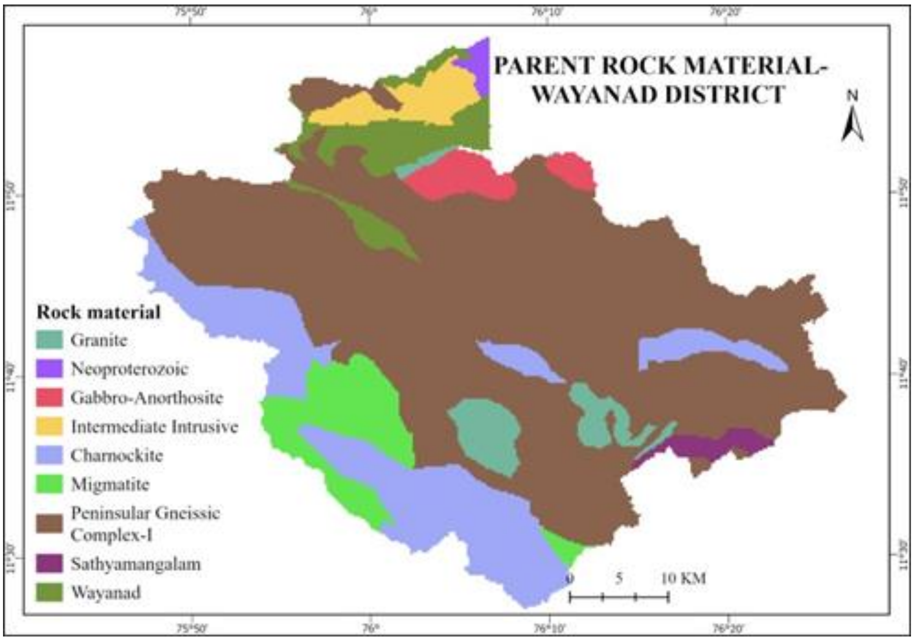

Figure 8 Parent Rock Material

Slope

Slope data were categorized based on the degree of steepness (Figure 9). Steeper areas were assigned lower weights due to their higher susceptibility to erosion, whereas flatter terrains received higher weights as they are less prone to degradation.

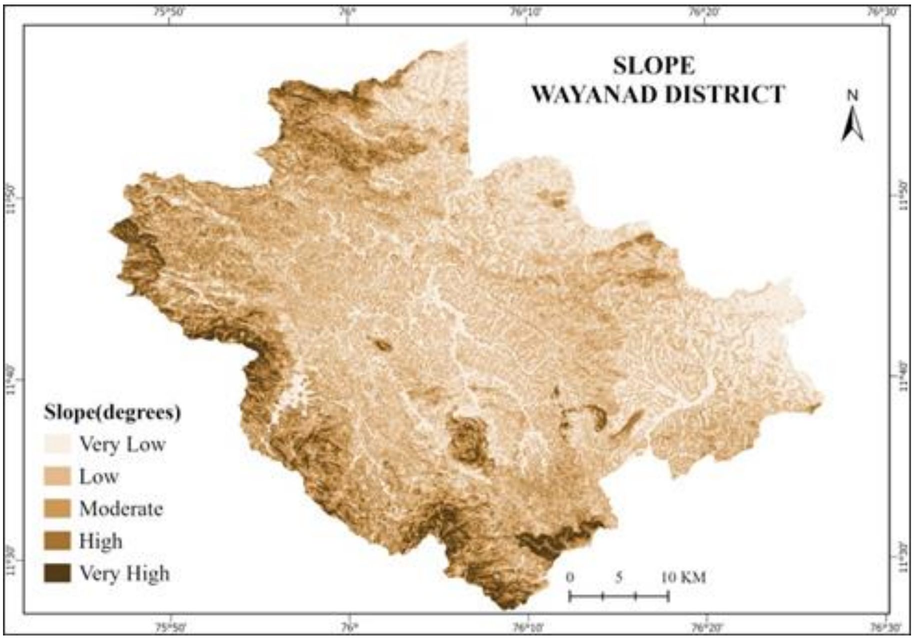

Figure 9 Slope

Soil drainage
Soil drainage characteristics were mapped by deriving them from soil texture and slope (Figure 10). Based on their impact on land degradation, areas with good drainage were assigned higher weights, reflecting a lower risk of degradation, whereas poorly drained areas were given lower weights due to their greater susceptibility.

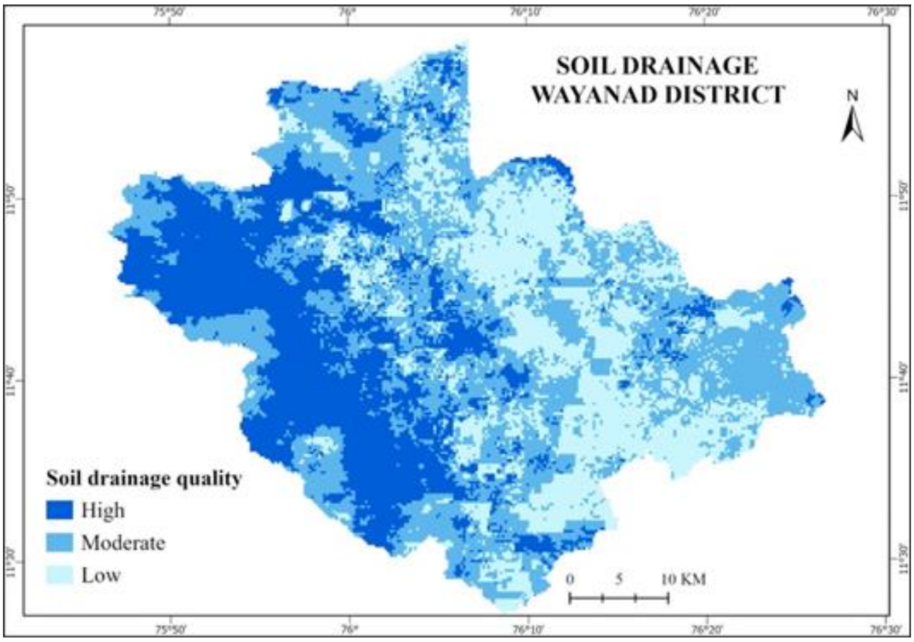

Figure 10 Soil Drainage

Soil depth
Soil depth data were categorized according to their influence on land degradation (Figure 11). Areas with deeper soils were assigned higher weights, as they are less susceptible to degradation, whereas shallow soils were given lower weights due to their higher vulnerability to degradation.

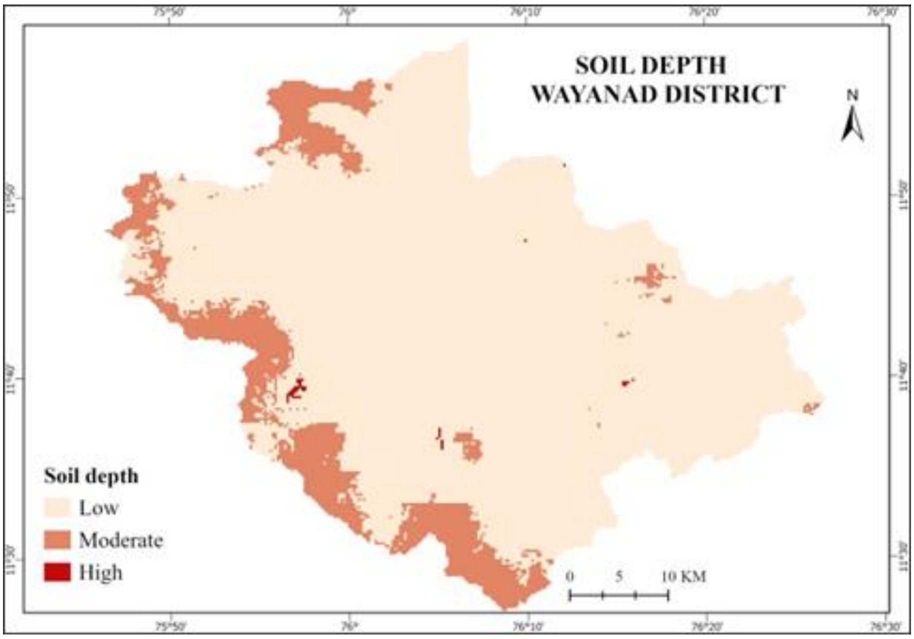

Figure 11 Soil Depth

Soil Texture

The soils of Wayanad district were categorized into rocky, clayey, loamy, and sandy types (Figure 12), and weights were assigned to each based on their relative susceptibility to degradation.

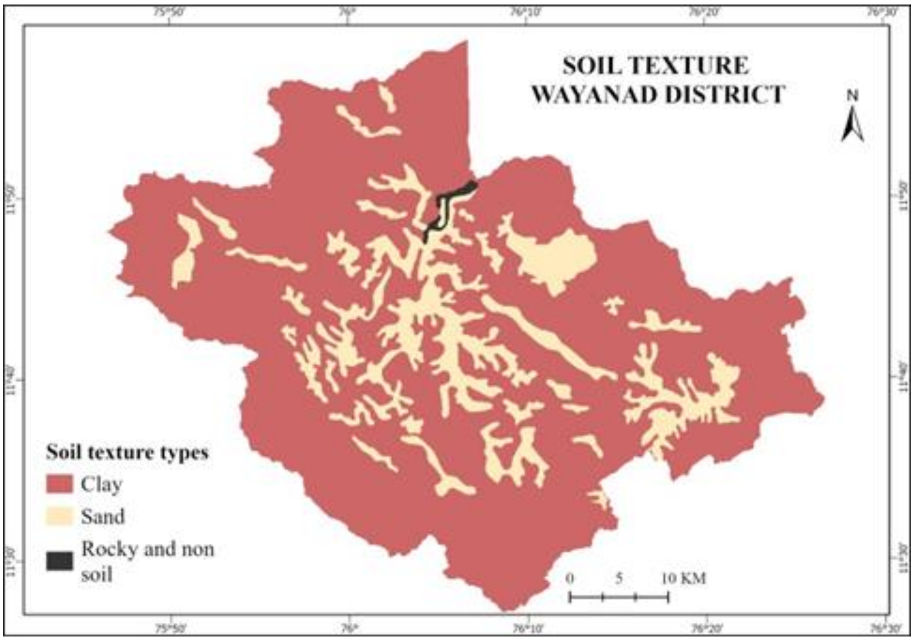

Figure 12 Soil Texture

Soil Quality Index (SQI)

All selected soil parameters were integrated using the following formula to derive the:

SQI = (parent rock material*slope*soil drainage*soil depth*soil texture) *1/5

The resulting SQI map was then classified into five categories: very low, low, moderate, high, and very high soil quality (Figure 13).

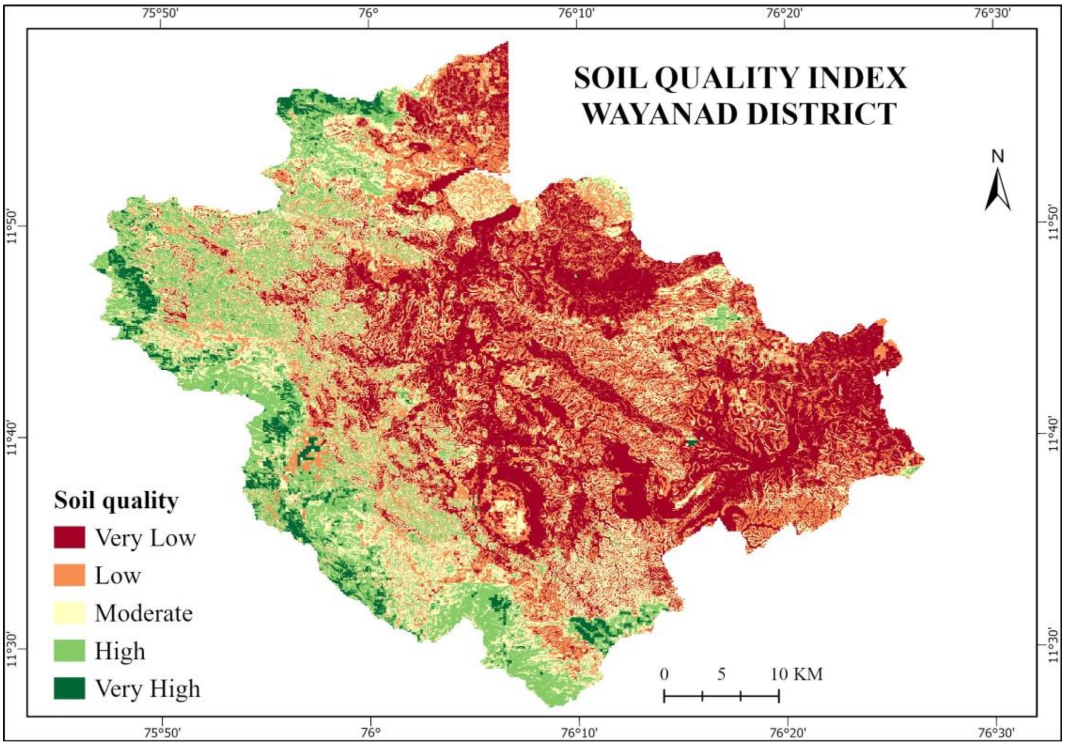

Figure 13 Soil Quality Index

Vegetation Factor

The parameters considered under vegetation factor included (i) vegetation cover, (ii) availability of water capacity, and (iii) erosion protection by vegetation.

Vegetation Cover

NDVI was generated using Band 4 (Red) and Band 5 (NIR) to evaluate vegetation cover. The NDVI results were classified into five categories: very low, low, moderate, high, and very high vegetation quality (Figure 14). Areas lacking vegetation, such as water bodies, built-up settlements, and rocky terrains were excluded from the analysis.

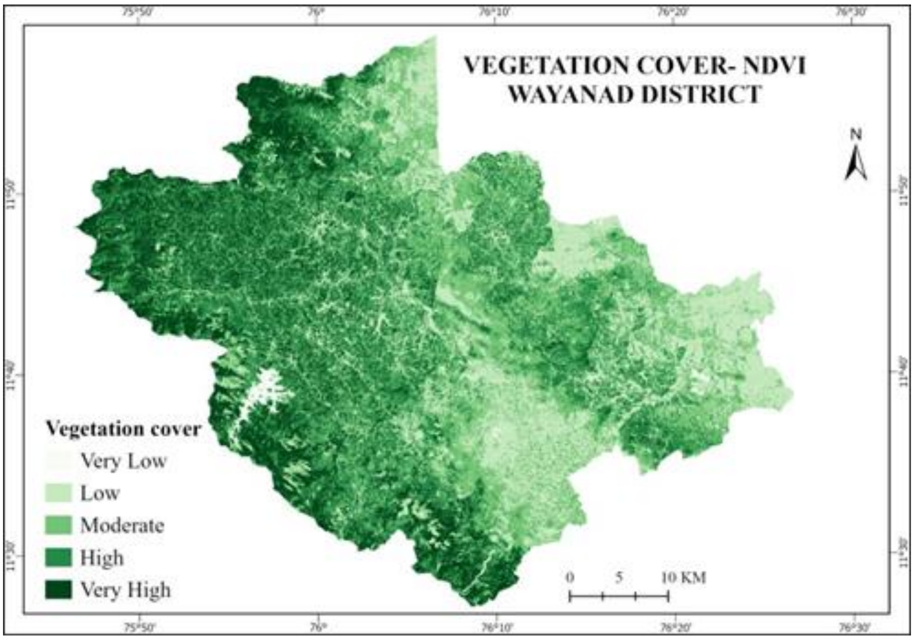

Figure 14 Vegetation Cover

Availability of Water Capacity

Available water capacity was estimated using volumetric water content data obtained from SoilGrids. Based on the soil's ability to retain moisture under vegetative cover, the data were categorized into five classes: very low, low, moderate, high, and very high (Figure 15).

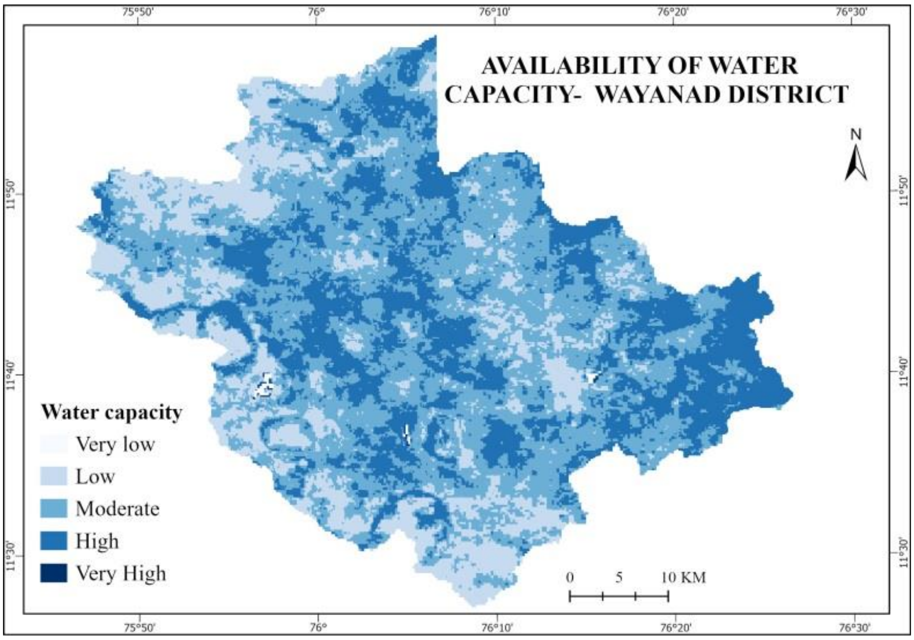

Figure 15 Availability of Water Capacity

Erosion Protection by Vegetation

Land Use/Land Cover (LULC) data were utilized to assess vegetation's capacity to prevent soil erosion. Weights were assigned to each category based on their effectiveness in protecting the soil (Figure 16).

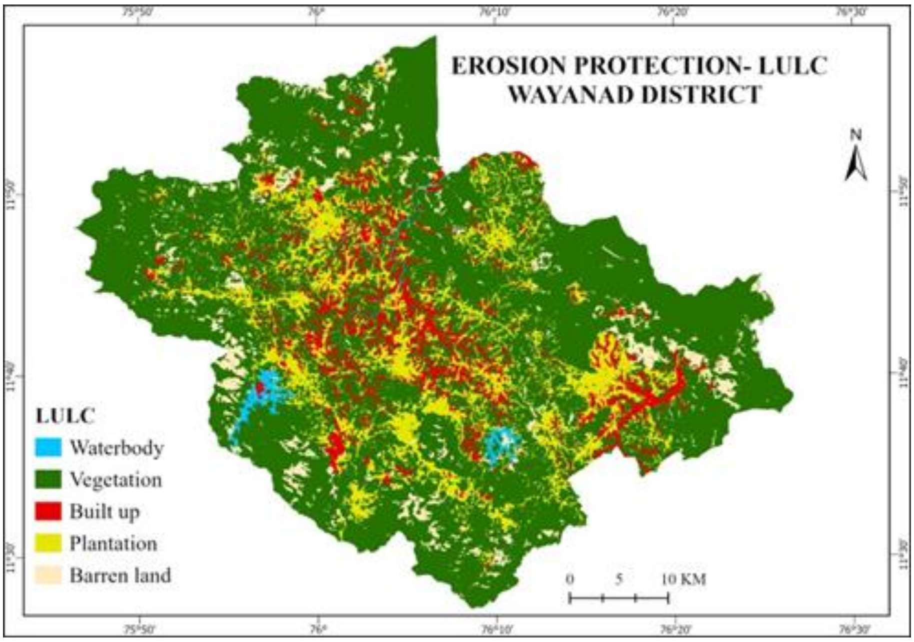

Figure 16 Erosion Protection by Vegetation

Vegetation Quality Index (VQI)

The selected vegetation parameters were integrated using the following formula to derive the VQI:

VQI = (NDVI *availability of water capacity *erosion protection by vegetation) *1/3

The resulting VQI map was then classified into five categories: very low, low, moderate, high, and very high vegetation quality (Figure 17).

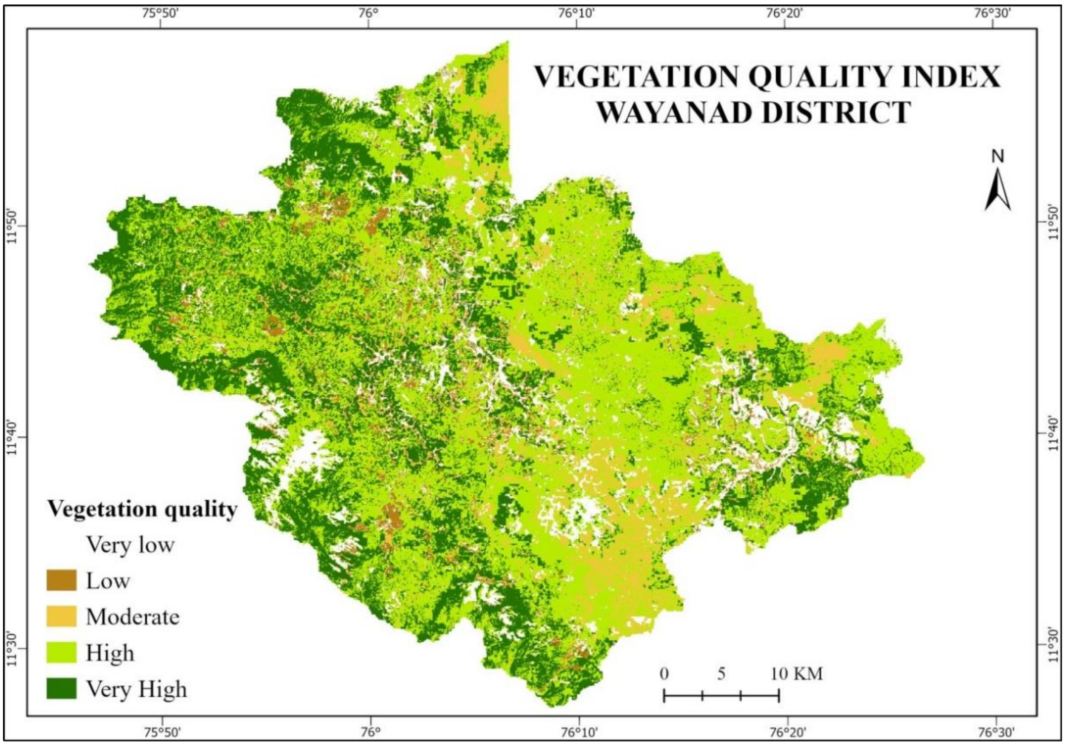

Figure 17 Vegetation Quality Index

Land Quality Index (LQI)

The LQI was generated by integrating the CQI, SQI, and VQI maps by using given formula.

LQI = (CQI * SQI * VQI) * 1/3

The LQI represents the overall condition of land across Wayanad district and was categorized into five classes: very low, low, moderate, high, and very high (Figure 18). Areas with higher LQI values reflect better environmental quality and a lower risk of degradation, whereas lower values indicate more degraded conditions.

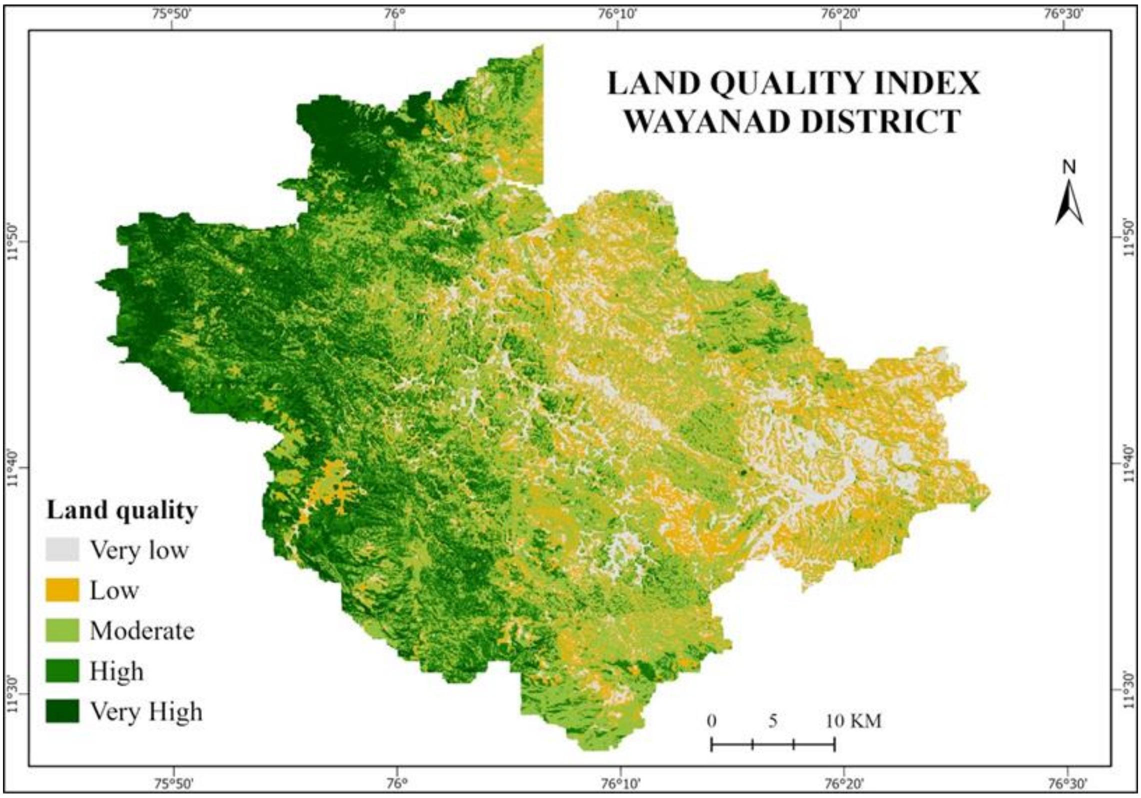

Figure 18 Land Quality Index

Results and Discussion

The findings of this research reveal a strong regional variability in both environmental quality and potential for degradation across the entire region of Wayanad District. It was found that climatic (slope), edaphic (soil) and biotic (vegetation) elements contribute significantly to the determination of land quality based on spatial variations in land cover conditions, physical or chemical properties of soils, as well as levels of human influence. Spatial heterogeneity in mountainous regions like Wayanad arises from the interactions among processes of slope development, climate-driven processes (rainfall intensity) and changes in land-use patterns which collectively determine the degree of environmental stability (FAO, 2015; Lal, 2001).

Areas designated as having low or very-low quality were most commonly located within the steepest hill slopes; shallow rocky terrain; locations with high rates of surface run-off; poor vegetation density; and climatically-stressed pockets. High rates of surface run-off on steep slopes increase soil erosion through increased sediment transport. Limited root development due to shallow soils will result in lower nutrient retention, and less ability to retain water, therefore making them more susceptible to decreased productivity and increased instability on sloping land (Morgan, 2005; Oldeman et al., 1991). Vegetation density plays an important role in protecting the soil from rain drop impacts and sheet flow erosion, however in these areas the lack of protective vegetation increases the vulnerability of the soil to be degraded.

The medium quality zone includes a variety of landscape types including agricultural mosaics; transitional slope zones; and plantations. These zones have partial preservation of their original ecosystems. However, they are under moderate environmental pressures due to human activities altering natural vegetation. Medium quality values indicate that while current productivity may exist, it is at risk for long-term degradation if land management practices are not modified. Common threats to these semi-managed landscapes include: soil compaction; excess agro-chemicals; monoculture cropping; loss of organic matter (Pimentel & Burgess, 2013). Therefore, proactive conservation practices should be applied to these areas prior to extensive restoration.

High and very high land quality zones were generally found in forested valleys, bottomland forests, rich soil, moist environments, and well-established plantation areas. Forested areas in Wayanad District exhibited excellent vegetation cover, good soil structure, strong organic matter levels, and improved ability to resist erosion compared to other parts of the region. Also, lower-sloped terrains or valley bottoms displayed a higher LQI level than their steeper counterparts as a result of deeper soils which aid in retaining moisture and decreased surface run-off velocities. These locations represent an important environmental resource for providing several ecosystem functions, such as carbon storage, wildlife preservation, groundwater replenishment, and flood control (MEA 2005), in addition to possibly having positive impacts from perennials in plantations like coffee or spice gardens provided that sustainable soil and water management methods are implemented.

Results suggest that land degradation in Wayanad District is related to both the physical characteristics of the land itself and to the nature of anthropogenic activities. Even though steep slopes and heavy rainfall create conditions inherently vulnerable to degradation, unsustainable land use practices can significantly increase the rate at which degradation occurs. Such conclusions are similar to those identified by researchers throughout the world examining mountain systems where deforestation, slope agriculture, and construction have increased rates of erosion and ecological deterioration (FAO 2015; Lal 2001). Similarly, in Wayanad District, growth in tourism, highway construction, quarrying, and land changes could potentially exacerbate the instability of already precarious hillside environments. Thus, local land use planning approaches such as contour farming, afforestation, slope stabilization, watershed treatment, and controlled land use expansion are needed to decrease degradation risks and provide for long term sustainability of lands in the district.

Conclusion

This study utilized climatic, soil and vegetation quality factors, integrated together as composite indexes (CQI, SQI, VQI) to identify how land quality varies spatially throughout the study area. Results indicated that land quality was generally lowest within the steepest sloping, shallowest or most rocky soils, least vegetated, and those experiencing extreme climate conditions. Conversely, land quality was highest in forested valleys where deep fertile soils exist, moisture rich lands are present, and relatively stable agriculture occurs.

GIS based multi-criteria Analysis has proven to be effective in determining sensitive ecosystems and providing guidance toward developing sustainable land use plans. Additionally, the ability to rapidly monitor larger scales and assess multiple layers of data using geospatial analysis reduces costs compared to traditional on-site assessments. Therefore, the produced land quality maps will provide decision-makers such as regional planners, local administrative bodies, forestry departments and disaster relief organizations valuable tools for allocating funds toward conservation/restoration initiatives.

Land quality zones determined in this study indicate the need for priority actions regarding afforestation, contour bunding, terracing, slope stabilization, watershed treatment, control of land use practices soiled moisture conservation in low quality and high-risk areas. Preventative management strategies should be implemented in moderate quality zones to avoid potential declines. High quality zones should have regulations placed upon them to ensure continued protection against anthropogenic or ecological disturbances and biodiversity preservation through regulated planning.

Future studies may utilize finer resolution images from satellites, detect changes temporally, validate findings through ground surveys and include socio-economic parameters in addition to Machine Learning methodologies to enhance degradation modelling. Monitoring long term trends in land quality could also assist researchers in evaluating the success of land restoration programs and policy implementations. In summary, this research provides strong evidence that geospatial technologies provide scientific foundations for addressing and managing land degradation issues found in highly vulnerable ecosystem environments.

Acknowledgment
The authors express their sincere gratitude to the Department of Geography, School of Earth Sciences, Central University of Karnataka, for providing the necessary facilities, academic guidance, and support to carry out this research work successfully.

Financial Support and Sponsorship
Nil

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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