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Estimation of Soil Erosion Using GIS in Pune District, Maharashtra

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Abstract

The Varandha Ghats pans approximately 14.62 km^2, where changes in temperature, vegetation, topography, and soil characteristics are causing continuous soil erosion. Catchment heterogeneity and climatic variations cause spatial variability in hydrological processes. Differences in land use, soil type, topography, and rainfall patterns influence how water moves and accumulates across regions, resulting in diverse hydrological responses. This complexity challenges accurate modeling and effective water resource management strategies across variable landscapes. This study applies Geographic Information System (GIS) techniques to divide the watershed into nearly uniform sub-regions for analysis. Soil erosion is evaluated using the Revised Universal Soil Loss Equation (RUSLE) model, which considers a number of variables, including crop cover (C), slope length (LS), rainfall erosivity (R), soil erodibility (K), and conservation practices (P). These parameters are extracted from various surface features, analyzed, and presented in raster format. The results highlight sediment distribution across the watershed and the sediment yield at the outlet.

Keywords: GIS, RUSLE, soil erosion, soil erodibility, slope length, spatial analysis

INTRODUCTION

Soil loss leads to a decline in arable land and its quality by stripping away the nutrient-rich topsoil, ultimately reducing overall land productivity [1]. Estimating soil loss in a specific location is crucial for assessing sediment deposition in any given area [2]. The integration of GIS with erosion studies is facilitated by the spatial representation of RUSLE factors [3, 4]. The Universal Soil Loss Equation (USLE), one of the most popular and successful techniques for calculating soil erosion. This model has been utilized for soil erosion assessments through spatial analysis tools in ArcGIS 9.2. The USLE algorithm is a globally recognized approach for evaluating soil loss at the catchment scale [5].

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Erosion models play a vital role in analyzing the impact of land-use practices on soil erosion, providing a foundation for developing regulations and conservation guidelines [6]. Many studies have demonstrated the effectiveness of combining GIS with USLE/RUSLE in estimating soil loss and pinpointing areas vulnerable to erosion [6–9]. In the GIS environment, the USLE model operates using raster grids to compute essential parameters such as the rainfall erosivity factor (R), conservation practice factor (P), slope length factor (LS), and soil erodibility factor (K). The advancement of remote sensing and GIS technology has proven to be a valuable tool for managing agricultural information, assessing natural resources, and implementing environmental protection strategies.

Soil erosion is a global issue that depletes nutrient-rich topsoil, increases runoff due to impermeable subsoil exposure, and reduces water availability for plant growth. Thus, estimating soil loss and identifying critical areas for conservation efforts are essential for effective soil management. Human-induced soil degradation affects approximately 2 billion hectares worldwide, with around 1,100 million hectares impacted by water erosion and 550 million hectares affected by wind erosion [10]. In India, soil erosion has had severe consequences for agriculture, reservoir siltation, and land degradation. To address these issues and prevent more harm, the government has put in place several measures. Approximately 130 million hectares, 45% of India's total land area, are severely affected by erosion caused by factors such as gully formation, shifting cultivation, wastelands, sandy areas, desertification, and waterlogging [11]. Excessive erosion and high sedimentation rates in reservoirs have resulted in significant environmental and economic concerns, necessitating urgent soil conservation measures.

STUDY AREA

The study area is a component of the Sahyadri Uplands, which lies between the shield-plateau region in the east and the Konkan Coastal Belt, which is bordered to the west by the Arabian Sea. It is adjacent to the Bhor, which forms Pune District's southwest border. The intended study area is situated along NH-965 in the Bhor region of Maharashtra's Pune district. The region under study is located between latitudes 18°00'00"N and 18°15'00"N and longitudes 73°30'00"E and 73°52'30"E, and is included in Survey of India toposheet numbers E43H12 (47F/12) and E43H16 (47F/16). By passing through the Ghat area, which is extremely vulnerable to mass movement, particularly during the rainy season, socioeconomic connection between the Konkan Coastal belt and Plateau region has increased, leading to an increase in density and communication lines. Some of these activities, both locally and regionally, create significant hazards along the ghat section roads, which leads to a traffic gridlock on the highway. Figure 1 displays the location map of the study area.

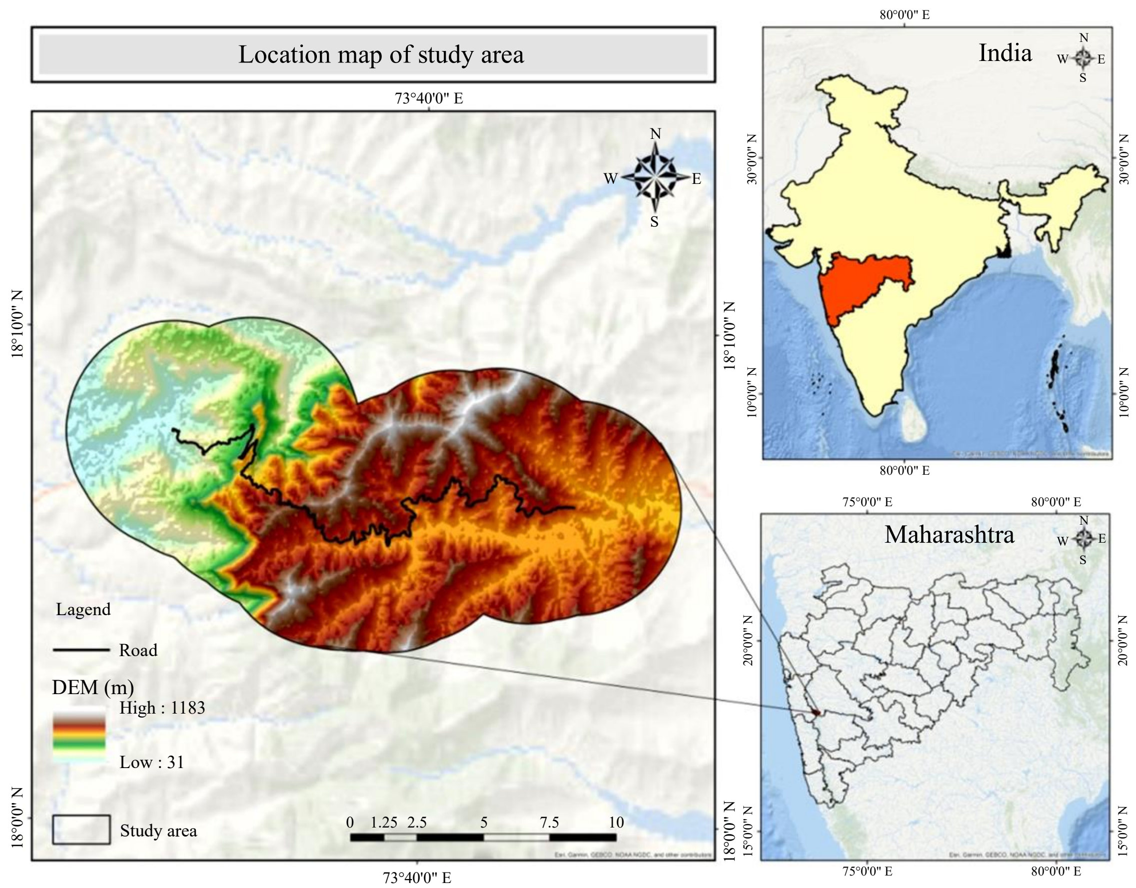

Figure 1. Varandha Ghat Study area location.

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METHODOLOGY

History of USLE

- It was created by the US Department of Agriculture (USDA) in the 1950s and 1960s.
- Introduced in *1978* by Wischmeier & Smith in Agriculture Handbook 537.
- Based on *experimental plot data* from agricultural lands in the US.
- Using variables including rainfall, soil type, slope, land use, and conservation techniques, it calculates the amount of soil that is lost each year.

History of RUSLE

- *RUSLE (Revised Universal Soil Loss Equation)* was developed in the *1990s* as an improved version of USLE.
- It incorporated *better rainfall, topography, and soil databases*, along with improved *computational algorithms*.
- RUSLE can be applied in *diverse landscapes*, including rangelands and construction sites.
- Introduced *GIS integration*, allowing more *spatially accurate erosion predictions*.

Soil Erosion Assessment Using RUSLE

The RUSLE model estimates annual soil loss using the equation:

A=R×K×LS×C×PA=R\times K\times LS\times C\times PA=R×K×LS×C×P

Where:

- A= Annual soil loss (tons per hectare per year or t/ha/year) ,
- R= Rainfall erosivity factor,
- K= Soil erodibility factor,
- LS= Slope length and steepness factor,
- C= Crop cover management factor, and
- P= Conservation support factor.

Based on site-specific data processed in the GIS context, each factor is given a numerical value. The equation classifies the many interconnected physical and management aspects that affect the rate of erosion under six main components, each of which has numerical values particular to a given site [7].

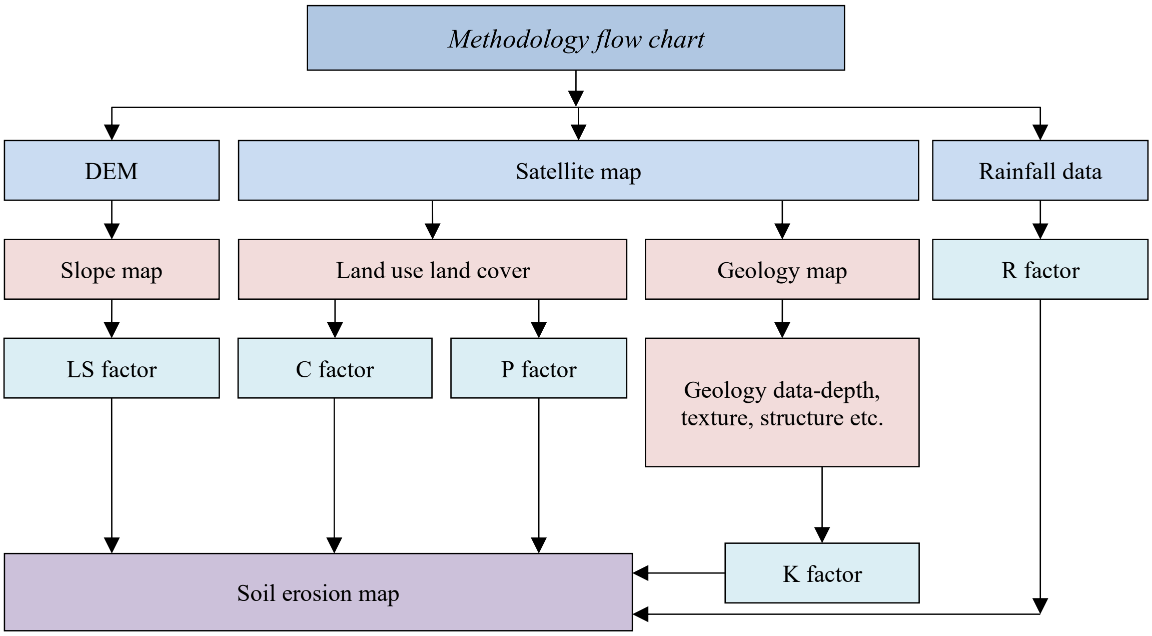

Figure 2. Flow Chart of Methodology adopted for present study area.

The chart in Figure 2 represents the methodology for RUSLE (Revised Universal Soil Loss Equation) modeling. It integrates various data sources such as DEM, satellite imagery, and rainfall data to derive essential factors (LS, C, P, K, R). These factors contribute to generating a soil erosion map for erosion assessment. Two popular empirical models for assessing soil erosion are the Universal Soil Loss Equation (USLE) and its successor, the Revised Universal Soil Loss Equation (RUSLE).

CALCULATION OF RUSLE FACTORS

- *Rainfall erosivity factor (R)*
  The R factor quantifies rainfall's potential to cause erosion, calculated as:

  R=0.5×P×1.73R=0.5\times P\times 1.73R=0.5×P×1.73

  Where P represents mean annual rainfall.
  Rainfall data from multiple gauge stations are spatially interpolated using ArcGIS.
- *Soil erodibility factor (K)*
  The K factor evaluates the permeability, structure, organic content, and texture of soil to determine its susceptibility to erosion. It is computed using the formula:

  K=2.8×10−7M−1.14(12−a)+4.3×10−3(b−2)+3.3×10−3(c−3)K=2.8\times 10^{–7}M^{–1.14}(12–a)+4.3\times 10^{–3}(b–2)+3.3\times 10^{–3} (c–3)K=2.8×10−7M−1.14(12−a)+4.3×10−3(b−2)+3.3×10−3(c−3)

  Where:
  - M=(% silt +% very fine sand)×(100–% clay),
  - a= Organic matter content (%),
  - b= Soil structure classification, and
  - c= Profile permeability class.

  Rasterization of these values allows for spatial analysis of erodibility.
- *Slope length and steepness factor (LS)*
  The LS factor represents the impact of slope on runoff velocity and sediment transport. It is calculated as:

  LS=(n+1)×(As/22.13)n×(sinβ/0.0896)mLS=(n+1)\times(As/22.13)^n\times (sin\beta/0.0896)^mLS=(n+1)×(As/22.13)n×(sinβ/0.0896)m

  Where:
  - n= Constant (0.4),
  - β= Slope angle,
  - m= Constant (1.3), and
  - As= Contributing area.

  Higher LS values indicate steeper slopes with higher erosion potential.

Rainfall's effect on soil erosion is measured by the rainfall erosivity factor (R factor) [12]. It measures the rain's ability to dislodge and transport soil particles, making it a critical parameter in the Revised Universal Soil Loss Equation (RUSLE). This factor is expressed in tons per hectare per year.

The R factor is calculated using the formula:

R=0.5×P×1.73R=0.5\times P\times 1.73R=0.5×P×1.73

Where P represents the mean annual rainfall (mm).

Rainfall data from three rain gauge stations located across different parts of the study area were collected and spatially interpolated using the Spatial Analyst tool in ArcGIS 9.2 to generate a continuous surface representation of rainfall erosivity.

Calculation of Soil Erodibility Factor (K-factor)

The K factor measures the soil's vulnerability to detachment and transport by erosion agents such as water and wind. It varies across the study area, as depicted in Figure 3. The K factor is estimated using the following equation:

$$K = \frac{[2.1\times10^{-4}\cdot(12-a)\cdot M^{1.14}+3.25\cdot(b-2)+2.5\cdot(c-3)]}{100}$$

Where:

- K= Soil erodibility factor,
- M= Particle size parameter (% silt +% very fine sand)×(100–% clay),
- a= Organic matter content (%),
- b= Soil structure code (1: very fine granular, 2: fine granular, 3: medium or coarse granular), and
- c= Profile permeability class (1: rapid, 2: moderate to rapid, 3: moderate, 4: slow to moderate, 5: slow, 6: very slow).

Soil reports from the study area were used to derive these parameters for different soil types. The K factor values were then calculated and converted into a raster grid format in GIS, where each pixel represents a specific K factor value.

Lower K values indicate soils with higher resistance to erosion, whereas higher values suggest greater susceptibility. Areas with lower K factor values correspond to regions where detached soil sediments accumulate in surface water bodies.

Calculation of Slope steepness: Length Factor (LS factor)

Estimating the LS factor is one of the most challenging aspects of applying the Revised Universal Soil Loss Equation (RUSLE), especially in GIS-based studies. The primary difficulty arises due to the complex nature of real landscapes. To determine the LS factor, data layers such as aspect, land use, and

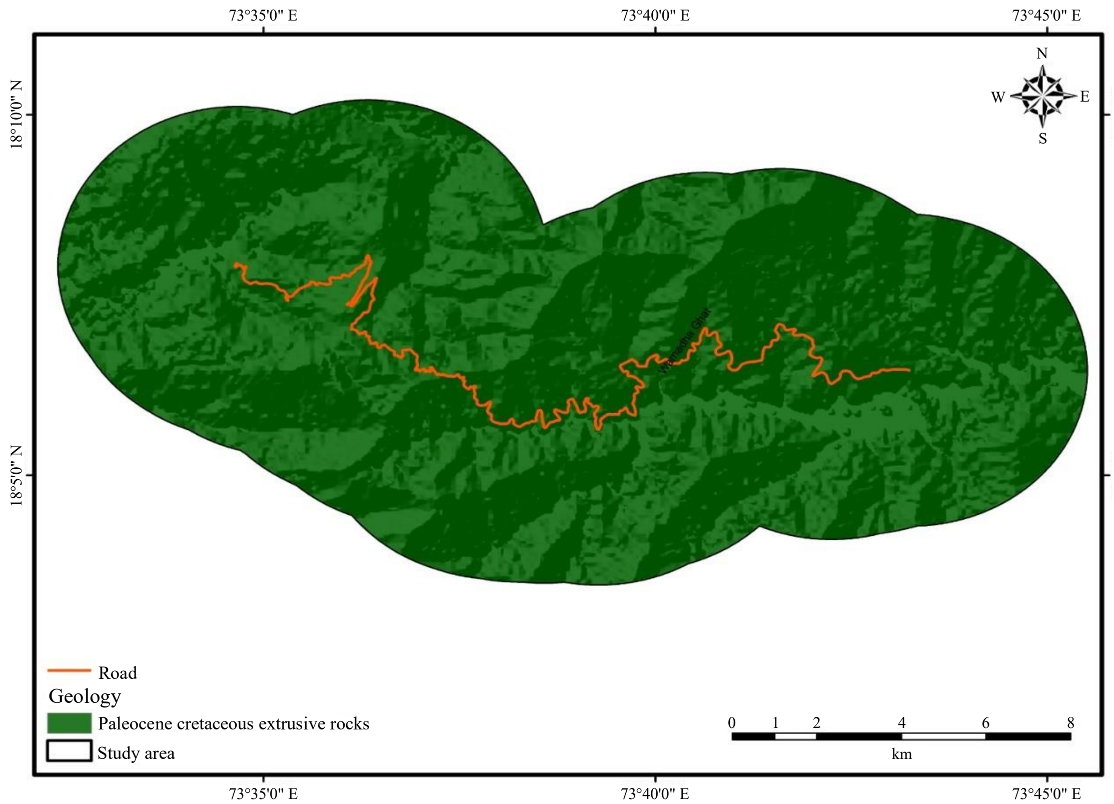

Figure 3. Geological map of the study area.

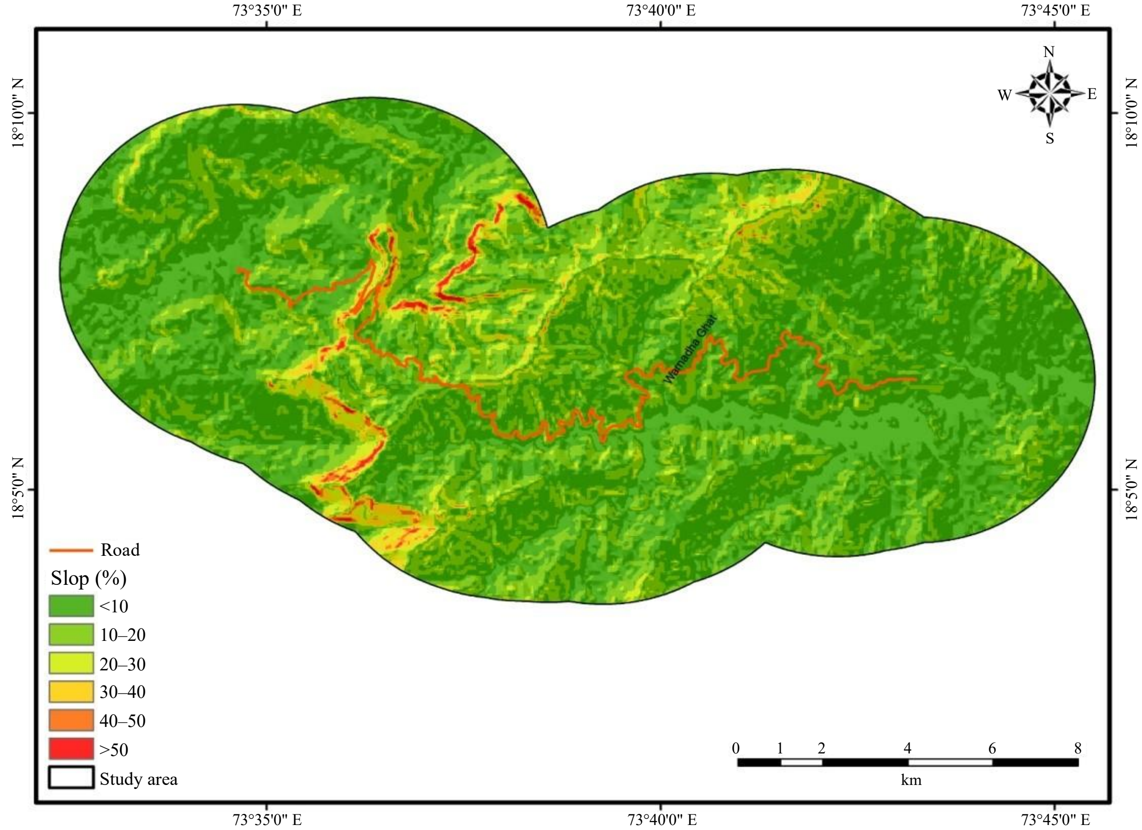

Figure 4. Slope steepness Map: length (LS) factor of Varandha Ghat.

slope maps are overlaid to extract slope length information. The LS factor distribution across the study area is illustrated in Figure 4.

The LS factor is calculated using the following formula:

LS= (22.13As)n×(0.0896sinβ)m

Where:

- LS= Slope length and steepness factor,
- n= 0.4 (constant),
- β= Local slope angle,
- m= 1.3 (constant), and
- As= Contributing area.

The L factor (slope length) influences runoff accumulation, with longer slopes generating higher runoff volumes. The S factor (slope steepness) impacts runoff velocity, with steeper slopes leading to more rapid water flow and higher erosion potential [13]. Analysis of the LS factor map shows that the northwestern and southeastern parts of the study area exhibit steeper slopes, making these regions more susceptible to high erosion rates.

Calculation of Support Practice Factor-(P)

The efficiency of soil conservation and watershed management strategies in lowering soil erosion is reflected in the conservation practice factor (P factor). These practices influence various factors such as:

- *Flow speed*: Slowing down runoff reduces soil detachment.
- *Surface roughness*: Rougher surfaces enhance infiltration and decrease erosion.
- *Infiltration capacity*: Higher infiltration rates reduce surface runoff and soil loss.

Table 1. Bureau of Indian Standards Values of "P" Factor for Different Land Uses (NRSC, Hyderabad, 2011).

S.N.	Class I	Class II	Slope range	P Factor
1	Agriculture	Crop land	<10	0.50
2	Forest	Mixed forest	10 to 20	0.50
3	Fallow land	Barren Land	<10	0.90
4	Shrub land	Shrub land	10 to 30	1.00
5	Water Body	Dam	0–1	1.00

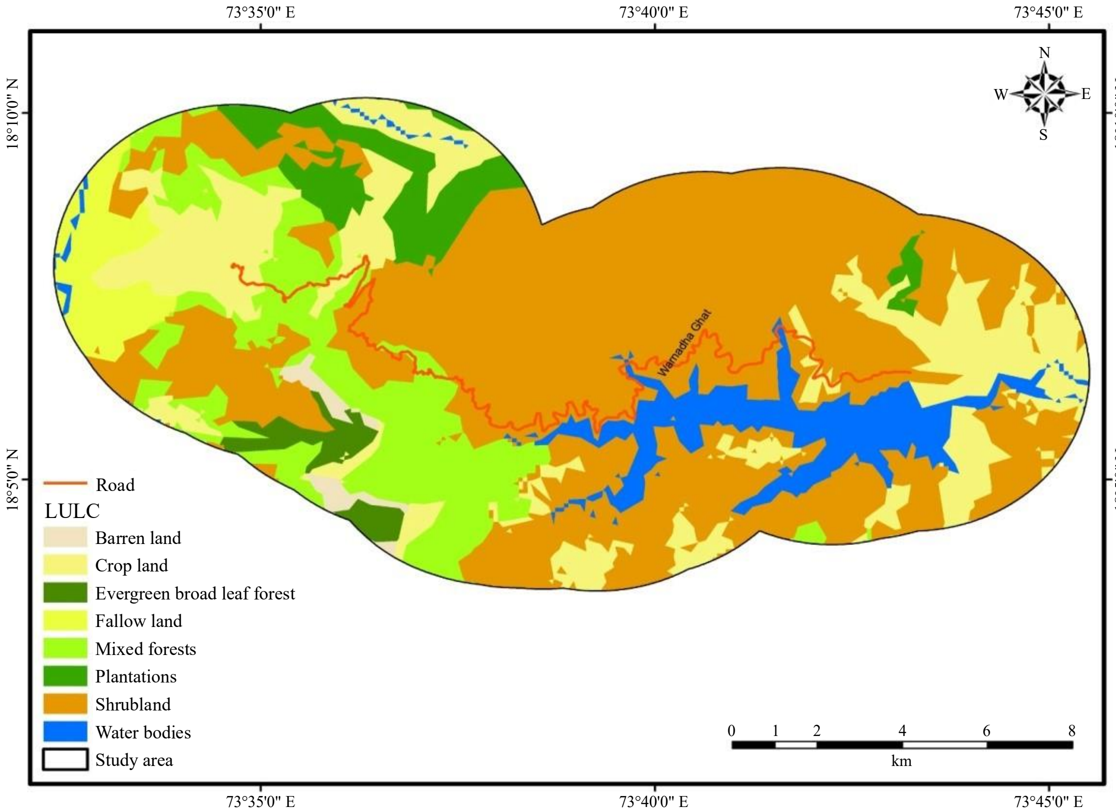

Figure 5. (LULC) Land use land cover map.

Based on these parameters, standard P factor values for different soil types have been determined by calculating their mean coefficients, as summarized in Table 1 and that can be observed in Figure 5.

ESTIMATION OF SOIL LOSS USING RUSLE EQUATION

The factors and parameters required for soil loss estimation using the Revised Universal Soil Loss Equation (RUSLE) were analyzed using the Spatial Analyst Tools in ArcGIS 9.2. The 3D Analyst Tool was utilized to generate spatial layers for the R (rainfall erosivity), K (soil erodibility), L (slope length), S (slope steepness), and P (conservation practice) factors.

Each raster grid of the R, K, LS, C, and P variables was multiplied using the RUSLE method to get the annual soil loss per hectare, expressed in metric tons. The analysis was conducted spatially to assess soil erosion intensity across every grid cell. The final output layer was then reclassified to categorize the study area based on soil erosion severity, classifying regions into:

- Severe erosion zones,
- Moderate erosion zones, or
- Low erosion zones.

CONCLUSION

This study demonstrates the application of GIS and the RUSLE model in soil erosion assessment. The findings aid in understanding the sediment yield distribution and identifying erosion-prone areas. Out of the total study area, most of the land experiences low to moderate erosion, but targeted soil conservation measures are necessary for high-erosion zones. These insights can support sustainable road transportation facility in the Varandha Ghat region.

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