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Soil erosion estimation and mapping using detailed soil survey and GIS: Need for soil conservation in hilly areas, tropical humid region, India

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ABSTRACT

Heavy rainfall in humid tropical regions (annual average 3911 mm) causes soil erosion and damage through landslides. Using the universal soil loss equation (USLE), we estimated soil loss, sediment yield (SY) and sediment load (SL) in Elamdesam (total area 18750.51 ha) in Idukki district, Kerala, via a soil survey. The slope varied from 0 to over 33%. The USLE's rainfall erosivity R-factor was 1498.69 mm $ha^{-1}hr^{-1}yr^{-1}$; the soil erodibility factor (K) ranged from 0.41 to 0.69, and the LS factor from 0.092 to 18.37. The cropping management factor (C) was 0.006 for rubber and 0.28 for paddy. The conservation practice factor (P) ranged from 0.40 to 0.65. Estimated soil erosion was low (0-5 t $ha^{-1}yr^{-1}$) in 22 mapping units (12909.48 ha), very severe (> 40 t $ha^{-1}yr^{-1}$) in five (4694.43 ha), low (5-10 t $ha^{-1}yr^{-1}$) in two (743.32 ha), and moderate (10-20 t $ha^{-1}yr^{-1}$) in two (403.26 ha). SY varied from 0.841 to 23.196 t $ha^{-1}yr^{-1}$, and SL ranged from 372.58 to 47089.98 t $ha^{-1}yr^{-1}$. The increase in soil erosion rate can be traced to rainfall severity, land cover (LC) changes, vegetation loss, and Ap horizon erosion. S2hG2, S6iH2, S1hH2, S1fH2g1, and S9hB2 experienced soil erosion rates over 40 t $ha^{-1}yr^{-1}$, marking them as high-risk zones for erosion. Implementing soil conservation measures to achieve land degradation neutrality (LDN) and prevent further soil loss, energy depletion and economic losses is crucial.

Key words:
Hillslope erosion
Land degradation neutrality (LDN)
Soil conservation
Soil erosion
USLE

1 | INTRODUCTION

Soil erosion is a natural or human-induced process impacting all landforms. Globally, water erosion results in a loss of about 24 billion tonnes of fertile soil annually, with India facing a loss rate of 1535 t $km^{-2}yr^{-1}$, leading to nutrient losses of 5.37 to 8.4 Mt. This decrease lowers crop productivity, increases flood and drought frequency, reduces reservoir capacity by 1 to 2% yr^{-1}, and causes biodiversity loss, severely affecting the country's food, nutrition, livelihoods, and environmental security.

Soil erosion, followed by land degradation, is one of the major long-standing threats identified globally, affecting both natural and human-made ecosystems, particularly in hilly areas with steep slopes due to land use (LU) issues and increasing population pressure. In the hilly regions of India, erosion caused by variations in topography, LU/LC changes, mining, construction, faulty agricultural practices, *jhum* cultivation, and high-intensity rainfall are the primary reasons for soil erosion (Ramachandran *et al.,* 2023). The excessive soil loss resulting from poor land management has serious implications for crop production, productivity, and food security, underscoring the need for sustainable use of our natural land and soil resources (NAAS, 2017). Heavy rainfall, driven by climate change and intensive cropping patterns on steep slopes, has exacerbated soil erosion, land degradation and landslides in the Western Ghats and hilly regions (Chellamuthu and Ganapathy, 2024). Processes such as leaching of bases along with other plant nutrients, clay, and organic carbon-followed by soil acidity, deteriorating soil structure and aggregate stability, washing out of topsoil and subsoil, and exposure of endopedon-along with a reduction in soil water holding capacity due to both surface and subsurface gravelliness, contribute to flooding and landslides associated with soil erosion and land degradation (Chellamuthu and Ganapathy, 2024). The processes of soil erosion, sediment delivery, and sediment transport are significant determinants of land degradation. The magnitude of SLs transported through water erosion has significant implications for ecosystem functioning (Chinnasamy *et al.,* 2020). High SLs can lead to pollution and habitat degradation in river systems. Factors such as topography, LU, soil type and sources of sediment influence sediment transport. Measuring SY and SL is vital for designing essential soil and water conservation structures, including check dams, earthen dams and trenches. Uncontrolled sediment deposition not only reduces the capacity of reservoirs like dams but also affects hydro-power generation and decreases the availability of water for both domestic and industrial purposes (Yousuf *et al.,* 2023).

Soil erosion risk assessment is crucial for sustainable agricultural systems. Severe erosion can lead to disastrous outcomes, making it vital to understand soil loss rates for effective conservation strategies. Permissible soil loss ranges from 2.5 to 12.5 t $ha^{-1}yr^{-1}$ in tropical humid areas (Mandal *et al.,* 2010). Land topography and slope gradients cause varying erosion rates, indicating that not all land requires the same management. Sharda and Mandal (2011) found that approx. 50% of India's total geographical area (TGA) falls into five priority erosion risk classes, necessitating different management measures. Therefore, estimating and mapping soil erosion rates and prioritizing areas based on soil loss is essential in tropical humid regions. Kerala experienced excessive rainfall in Idukki (60% higher than normal) during 2018, which resulted in flooding. In such cases, soil conservation measures are paramount to controlling soil erosion, particularly in critical erosion risk areas of the Idukki district. Understanding and quantifying soil erosion is crucial for effective management and conservation practices. By assessing the erodibility of different soil types, land managers and policymakers can make informed decisions regarding LU planning, erosion control measures and sustainable land management strategies (Kanakdhar *et al.,* 2024).

This study conducted a land resources inventory via a soil survey at a 1:10000 scale in the Elamdesam block of Idukki district, Kerala, within the tropical humid region (Chandrakala *et al.,* 2017). Using field and laboratory data, soil series and mapping units were established. Erosion rates, SL and yield were estimated and mapped for each unit, prioritizing them based on erosion rates to identify areas needing conservation measures. The study aims to i) identify mapping units through the soil survey, ii) estimate and map potential soil loss and sediment for each unit and iii) classify and prioritize units by erosion rates for soil conservation measures to achieve LDN.

2 | MATERIALS AND METHODS

2.1 | Study Area

The study area is the Elamdesam block, which has a TGA of 29,127.16 ha and is located in Thodupuza taluk, Idukki district of Kerala. It lies between the north latitudes of 9°46' 38.2" and 10°2'18.14" and the east longitudes of 76°42'59.49" and 76°53'46.99". The agro-ecological zones include the foothills and high hills, specifically agro-ecological units 12 and 14, which correspond to the southern and central foothills and the southern high hills, respectively. The agro-ecological sub-units 12.1 to 14.5 consist of forests, denudational hills, lateritic terrain, and lateritic valleys. The agro-ecological sub-region (AESR) is 19.2, which pertains to the central and south Sahyadris, classified as the hot, moist, sub-humid to humid eco-subregion. Elamdesam block is divided into seven panchayats: Alakkode, Karimannoor, Kodikkulam, Kudayathoor, Vannappuram, Udumbannoor, and Velliyamattom (Fig. 1). Mean annual rainfall varies from 3,462 to 3,602 mm, reflecting a Ustic soil moisture regime, while the mean annual temperature ranges between 21°C

HIGHLIGHTS

- Soil erosion was very severe (> 40 t $ha^{-1}yr^{-1}$) in five mapping units.
- The SY varied from 0.841 to 23.196 t $ha^{-1}yr^{-1}$ and SL varied from 372.58 to 47089.98 t $ha^{-1}yr^{-1}$.
- Mapping units S2hG2, S6iH2, S1hH2, S1fH2g1, S9hB2 are high erosion risk-prone zones.
- These five mapping units need soil conservation measures to bring these to LDN.

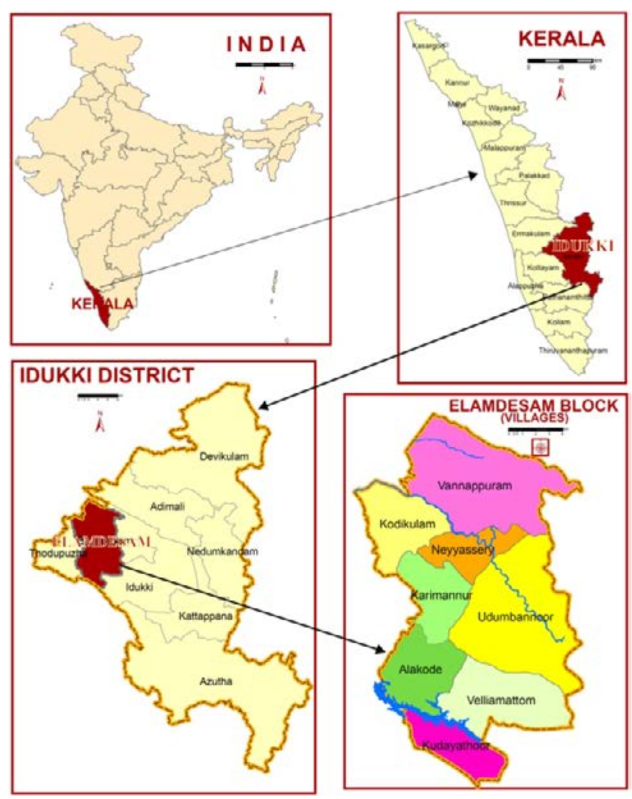

FIGURE 1 Location map of Elamdesam block, tropical humid region, Kerala

and 27°C, corresponding with an Iso hyperthermic soil temperature regime. The dry period lasts from two to two and a half months, with a cropping period exceeding 80%. The block contains rocks of Archaean age, primarily charnockites in Kudayathoor and Alakkode, while the other panchayats consist mainly of granite gneiss. Charnockite rocks are medium fine-grained with a dark bluish tinge, whereas granites and gneisses are light-coloured and coarse-grained. These rocks are acidic and characterized by minerals such as feldspar, mica, and quartz, which comprise the bedrock. Fine-grained laterites are found in the western parts of the Elamdesam block, exhibiting a honeycomb structure due to differential dissolution and removal of bases and other minerals. Occasionally, they harden irreversibly on the surface, transforming into laterite duricrusts or ironstone. These formations are hard, very fine-grained, plinthitic, and acidic, dominated by hydroxy interlayered vermiculites, kaolinites, and hydrated sesquioxide minerals.

Alluvium forms in valleys and lowlands. Elamdesam block has three landforms: western ghats (>600 m MSL) with exposed rocks, high hills (300-600 m MSL), foothills, midlands (30-300 m MSL), and lowlands (submerged paddy land). Elevation ranges from 30 m in lowlands to 850 m in high hills. Charnockite and granite-gneissic hills are steep to moderately sloping. High hills feature exposed rocks with mixed forests, while foothills and midlands are mostly rubber, coconut, pineapple, pepper, banana, areca nut, cocoa, nutmeg, and cashew plantations. Lowland valleys mainly grow paddy and raised bed crops like tapioca, banana, and coconut.

2.2 | Soil Genesis and Classification

Field investigations involved traversing the area and random checks to identify permanent features, natural boundaries, water bodies, rock outcrops, and habitations. Transects were chosen based on slope and contour across all villages. Soil profiles were excavated along the transects and studied, with additional profiles exposed where changes in land features occurred. Soils were categorized into different series based on examined pedons, focusing on characteristics like soil depth, gravel amount, geology, land-form, slope, drainage, and subsurface layers. Soil samples were collected horizon-wise for analysis, and observations on surface texture, erosion, and rockiness were recorded. A total of 12 soil series and 31 mapping units were identified based on morphological, physical, and chemical properties across all landforms (Fig. 2 and Table 1).

Ultisols, Inceptisols and Alfisols are the main soils in the Elamdesam block. Loamy or clay loam soils in high hills develop from weathered rocks under forest cover, are rich in organic matter with dark brown tops and brown subsurfaces and have more roots and pores than those in the foothills and midlands. This variation arises from continuous litter addition

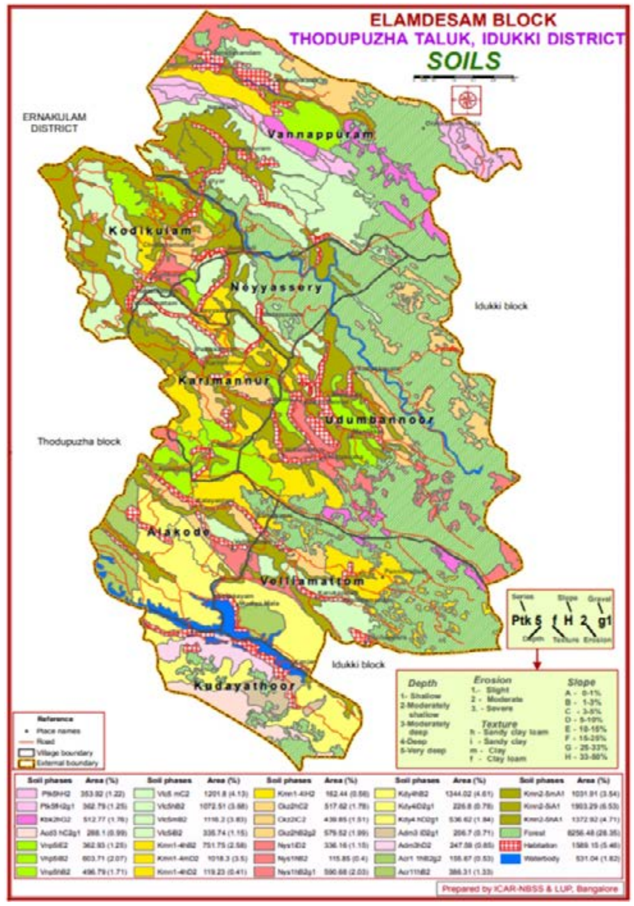

FIGURE 2 **Soils of Elamdesam block with mapping units, tropical humid region, Kerala**

and clay illuviation. In low hills and midlands, plinthites underlie soils with surface colors from brown to reddish brown and textures from sandy clay to clay, with some areas containing gravel. Overall, the soils are well-drained, shallow to very deep, with fine to medium texture and a weak to moderate blocky structure. They are slight to very sticky, very strongly acidic, and possess high to very high organic matter content.

2.3 | Determination of Erosion Rate in Mapping Units and Classification

Soil erosion is a function of rainfall erosivity, soil erodibility, slope length-gradient, LC / crop / vegetation cover, and management and conservation practice. The USLE determined the soil erosion rate in the present study.

$$E_{water} = RKLSCP \qquad ...(1)$$

Where, E_{water} is the potential annual average soil loss expressed in t $ha^{-1} yr^{-1}$.

R ($R = 79 + 0.363 \times Xa$)

Where, *Xa* is the average annual rainfall in mm over the study area is the rainfall erosivity factor (MJ mm $ha^{-1} hr^{-1} yr^{-1}$)

TABLE 1 Soil series and mapping unit's details of Elamdesam block, tropical humid region, Kerala

Series name	Mapping unit no.	Mapping unit	Descriptive legend
Foothills (300-600 m above MSL) and high hills (>600 m above MSL)- Archean Granite- gneiss landform			
Ptk	1	Ptk 5hH2	Foothills of western ghats have sandy clay loam texture having a very steep slopes of >33%
	2	Ptk 5fH2g1	Foothills of western ghats have clay loam texture having a very steep slopes of >33% with surface gravel 15-35%
Kbk	3	Kbk2hG2	Foothills of western ghats sandy clay loam texture having steep slope of 25-33%
Foothills (300-600 m above MSL) and high hills (>600 m above MSL) - Archean Charnackite landform			
Acd	4	Acd3 hC2g1	Foothills of western ghats sandy clay loam texture having gentle slope of 3 -5%
Midlands/Uplands (< 300 m above MSL) - Archean Granite - gneiss landform			
Vnp	5	Vnp5iE2	Midlands/Uplands of sandy clay texture having rolling slope of 10-15%
	6	Vnp5iB2	Midlands/Uplands of sandy clay texture having very gentle slope of 1-3%
	7	Vnp5hB2	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3%
Vlc	8	Vlc5 mC2	Midlands/Uplands of clay texture having gentle slope of 3-5%
	9	Vlc5hB2	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3%
	10	Vlc5mB2	Midlands/Uplands of clay texture having very gentle slope of 1-3%
	11	Vlc5iB2	Midlands/Uplands of sandy clay texture having very gentle slope of 1-3%
Kmn1	12	Kmn1-4hB2	Midlands/ Uplands of sandy clay loam texture having very gentle slope of 1-3%
	13	Kmn1-4mD2	Midlands/Uplands having moderate slope of 5-10%
	14	Kmn1-4hD2	Midlands/Uplands of sandy clay loam texture having moderate slope of 5-10%
	15	Kmn1-4iH2	Midlands/Uplands of sandy clay texture having very steep slope of >33%
Ckz	16	Ckz2hC2	Midlands/Uplands of sandy clay loam texture having gentle slope of 3-5%
	17	Ckz2iC2	Midlands/Uplands of sandy clay texture having gentle slope of 3-5%
	18	Ckz2hB2g2	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3% with surface very gravels of 35-60%
Nys	19	Nys1iD2	Midlands/Uplands of sandy clay texture having moderate slope of 5-10%
	20	Nys1hB2	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3%
	21	Nys1hB2g1	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3% with surface gravels of 15-35%
Midlands/Uplands (< 300 m above MSL)- Archean Charnackite landform			
Kdy	22	Kdy4hB2	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3%
	23	Kdy4iD2g1	Midlands/Uplands of sandy clay texture having moderate slope of 5-10% with surface gravels of 15-35%
	24	Kdy4 hD2g1	Midlands/Uplands of sandy clay loam texture having moderate slope of 5-10% with surface gravels of 15-35%
Adm	25	Adm3 iD2g1	Midlands/Uplands of sandy clay texture having moderate slope of 5-10% with surface gravels of 15-35%
	26	Adm3hD2	Midlands/Uplands of sandy clay loam texture having moderate slope of 5-10%
Acr	27	Acr1 1hB2g2	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3% with surface gravels 35-60%
	28	Acr11hB2	Midlands/Uplands of sandy clay loam texture having very gentle slope of 1-3%
Low lands (paddy lands)/Valley plain			
Kmn2	29	Kmn2-5mA1	Low lands of clay texture having nearly level slope of 0-1%
	30	Kmn2-5iA1	Low lands of sandy clay texture having nearly level slope of 0-1%
	31	Kmn2-5hA1	Low lands of sandy clay loam texture having nearly level slope of 0-1%

considering the intensity, duration, and the frequency of rain storms.

K ($K = (0.2+0.3e^{[-0.0256SAN\ (1-SIL/100)]}) \times (SIL/CLA+SIL)^{0.3} \times [1 - \{0.25C/C+e^{(3.72-2.95C)}\}] \times [1-\{0.7SN_1/SN_1+e^{(22.9SN1-5.51)}\}]$

Where, SAN is the sand content (%), SIL is the silt content (%), CLA is the clay content (%), C is the soil organic carbon content (%) and $SN_1 = 1\text{-}SAN/100$) is the soil erodibility factor (Mg h MJ^{-1}mm^{-1}).

LS ($LS = [L/22.13]^m[(0.43+0.3S+0.043S^2)/6.613]$

Where, L = length of slope (m); S = land slope (%); M = 0.2 if $0.0<S<1.0$, 0.3 if $1.0<S<3.5$, 0.4 if $3.5<S<4.5$ and 0.5 if $S>4.5$) is the slope length-gradient factor. The slope class of the Elamdesam block is presented in Fig. 3.

C (rubber - 0.006 and paddy - 0.28) is the crop / vegetation cover / LC and management factor and P (ranging from 0.40 to 0.65) is the conservation practice factor. LS, C, and P factors are dimensionless.

In each mapping unit, potential soil loss rates were determined, and these erosion rates were categorized into five classes (Table 2), namely, very low (< 5 t $ha^{-1}yr^{-1}$), low (5-10 t $ha^{-1}yr^{-1}$), moderate (10-20 t $ha^{-1}yr^{-1}$), severe (20-40 t $ha^{-1}yr^{-1}$) and very severe (> 40 t $ha^{-1}yr^{-1}$).

2.4 | Determination of Sediment Yield (SY) and Sediment Load (SL)

SY is the rate at which sediment travels through a specific site in a drainage basin over a given time period. It is typically measured as the mass of sediment removed per unit area per unit time. SY is influenced by (1) input functions such as soil erosion, mass wasting, and dust fallout, (2) intra-basin storage (*e.g.* deposition and retention of soil in gullies, bunds, or valleys), and (3) output pathways and mechanisms, such as stream SL. Consequently, a basin's SY directly impacts stream sediment loads within a drainage basin. The SY for a watershed is directly correlated with average erosion intensity and sediment delivery ratio. (Williams, 1978).

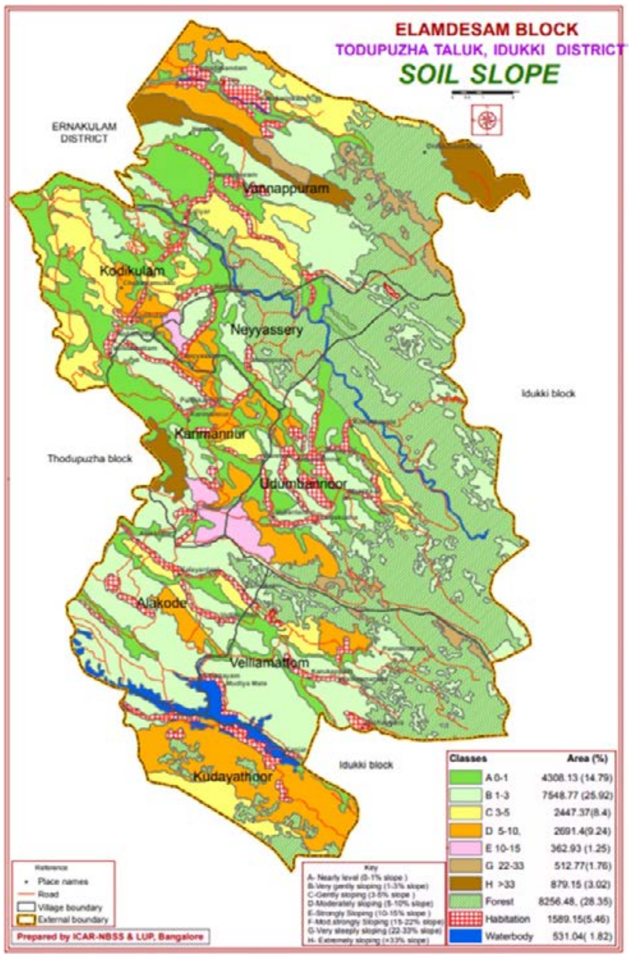

FIGURE 3 Slope classes in Elamdesam block, tropical humid region, Kerala

$$SY = SDR \times A \quad ...(2)$$

Where, A is the total gross erosion computed from USLE.

$$SDR = 0{:}627\,(SLP)^{0.403} \quad ...(3)$$

Where, SLP is the %age slope.

Stream SL, measured in tonnes per year, refers to the amount of sediment transported by rivers and streams (Evans and Seamon, 1997) and is the function of SY and area of the study region.

$$SL = SY \times \text{Area of the specific mapping unit} \quad ..(4)$$

2.5 | Mapping of Potential Soil Loss, SY and SL based on Mapping Units

The digital terrain model (DTM) was used to calculate slope, contour, drainage, and hill shades. Roads, settlements, water bodies, and forests were digitized using Google images, Sentinel-2 satellite imagery, and toposheets. These served as the foundational layers from which highly accurate and quantitative information was generated to create landforms and base maps. By utilizing base maps created from Google imagery, publicly available satellite images, and toposheets at a scale of 1:50000 (58C/13 and 58B/16), a comprehensive soil survey at a scale of 1:10000 was conducted. Although data from Cartosat-1 and IRS LISS IV P6 with a resolution of 5.8 m were acquired, they proved ineffective, as the dense vegetation of the Elamdesam block rendered all false colour composite (FCC) images entirely red, making interpretation impossible. Through the detailed soil survey, 12 series were identified. Mapping units (31) were created by incorporating soil information such as soil series, various surface soil textures, slope classes, erosion rates, and gravel content. For each mapping unit, potential soil loss rates, SY and SL were calculated as outlined above. Base maps, soil profile location points and laboratory soil profile data were used to delineate the soil borders and boundaries using soil phases as mapping

TABLE 2 Classification of mapping units based on erosion rates at Elamdesam block, tropical humid region, Kerala

	Erosion category (t $ha^{-1}yr^{-1}$)				
	<5 (Very low)	5 to 10 (Low)	10 to 20 (Moderate)	20 to 40 (Severe)	>40 (Very severe)
Mapping units	S5iB2, S8hB2g1, S7iC2, S7hB2g2, S8hB2, S11hB2g2, S5hB2, S6hB2, S11hB2, S4hB2, S5mB2, S4iB2, S3hC2g1, S7hC2, S5mC2, S8iD2, S9hD2g1, S5iB3, S8hB2g2, S7iC3, S7hB2g3, S8hB3	S12iA1, S4iE2	S12mA1, S12hA1	-	S2hG2, S6iH2, S1hH2, S1fH2g1, S9hB2

units. Using these soil borders and their respective mapping units, potential soil loss rates, SY and SL were mapped in Arc-GIS 10.7.1, generating the corresponding maps: potential soil loss, SY and SL maps.

3 | RESULTS AND DISCUSSION

The study area experienced an average annual rainfall of 3,911 mm; consequently, the calculated R-factor was 1,498.69 MJ mm $ha^{-1}hr^{-1}yr^{-1}$. The higher R-factor value indicates increased erosion (Yousuf *et al.,* 2023). The soil erodibility factor K (Fig. 4) reflects the soil's susceptibility to erosion based on its physico-chemical properties, which ranged from 0.39 to 0.69 Mg hr MJ^{-1} mm^{-1}. A total of 39.33% of the area falls under class g (K-factor ranging from 0.60 to 0.69 Mg hr $MJ^{-1}mm^{-1}$), followed by class f (0.53 to 0.59 Mg hr MJ^{-1} mm^{-1}), with 4.69% of the area having a K-factor between 0.39 and 0.48 Mg hr $MJ^{-1}mm^{-1}$. The lower K-factor is attributed to the reduced clay content and a higher %age of sand particle size, making the soil more susceptible to erosion (Chandrakala *et al.,* 2022). The calculated topographic factor (LS) indicates that 49.10% of the area has an LS value of <0.5. In comparison, 10.48% has an LS factor between 1.1 and 3.0 (Fig. 5). The highest LS factor was observed in areas with the steepest slopes, correlating with higher surface runoff velocities, which in turn increased soil erosion rates (Yousuf *et al.,* 2023). The crop / vegetation cover / LC and management factor (C) for rubber is 0.006, while for paddy, it is 0.28. The conservation practice factor (P) in the Elamdesam block ranged from 0.40 to 0.65. Generally, land covered with various types of vegetation (forest, plantation, agricultural lands) is less prone to erosion compared to fallow, barren, and uncultivated lands. Thus, by multiplying all these factors, the potential soil loss in the Elamdesam block was assessed (Fig. 6), revealing that 68.85% of the area was categorized as very low erosion (<5 t $ha^{-1}yr^{-1}$) across 22 mapping units (Table 2). Additionally, 25.04% of the area in five mapping units experienced very severe erosion (>40 t $ha^{-1}yr^{-1}$). In comparison, 3.96% of the area in two mapping units faced low erosion (5-10 t $ha^{-1}yr^{-1}$), and a minimal 2.15% was classified as having moderate erosion (10-20 t $ha^{-1}yr^{-1}$) status.

In this area, slope varies from 0 to over 33%, but erosion remains low due to soil conservation practices like contour and earthen bunds, cover crops, strip terraces, and perennial

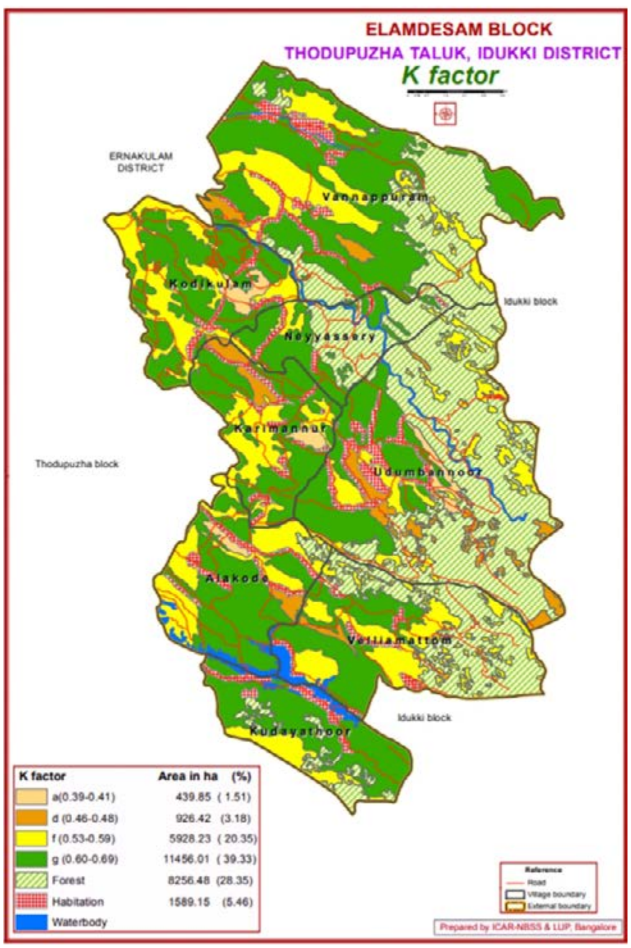

FIGURE 4 Soil erodibility factor (K) classes in Elamdesam block, tropical humid region, Kerala

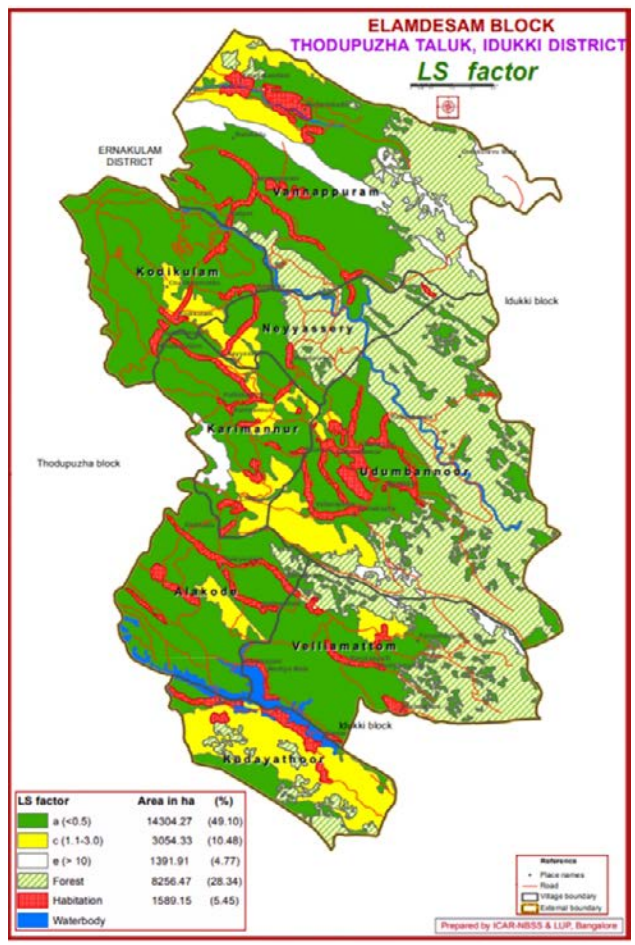

FIGURE 5 Topographic factor (LS) classes in Elamdesam block, tropical humid region, Kerala

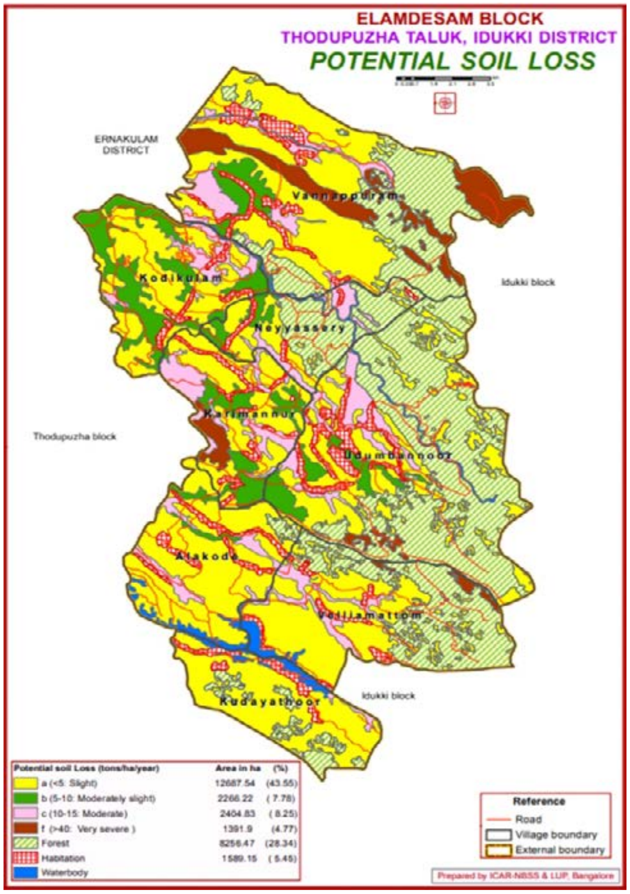

FIGURE 6 Soil erosion classes in Elamdesam block, tropical humid region, Kerala

crops, including pineapples, adopted by farmers in the humid tropics for rubber plantations (Fig. 7a and 7b). In lowlands, graded bunds support paddy cultivation (Chandrakala *et al.,* 2017).

However, 25.04% of the area across five mapping units-S2hG2, S6iH2, S1hH2, S1fH2g1, and S9hB2 (Table 2) is experiencing very severe erosion (> 40 t $ha^{-1}yr^{-1}$) within the block, which necessitates higher priority for conservation measures aimed at controlling soil erosion and achieving LDN in these mapping units (Mandal *et al.,* 2021). This approach is essential to prevent further soil, energy, economic stability, and monetary losses (Sharda *et al.,* 2019). Due to financial constraints, it is neither practical nor feasible to apply suitable soil conservation measures across the entire block; therefore, the five mapping units with erosion rates exceeding 40 t $ha^{-1}yr^{-1}$ (very severe) should be identified as priority units for conservation strategies. Assessing soil erosion through plot-wise or mapping unit information is crucial for identifying site-specific, effective soil conservation measures to promote sustainable crop production.

The Indian Institute of Soil and Water Conservation (Hombegowda *et al.,* 2021) reported on the status of soil erosion, priority treatment areas, and conservation measures for various districts in Kerala. According to this study, soil erosion affects 15.12% of the TGA, with an erosion rate exceeding 10 t $ha^{-1}yr^{-1}$. Of this, 0.11% of the area is severely affected, exceeding 40 t $ha^{-1}yr^{-1}$, particularly in the eastern and central midlands and undulating uplands with high rainfall

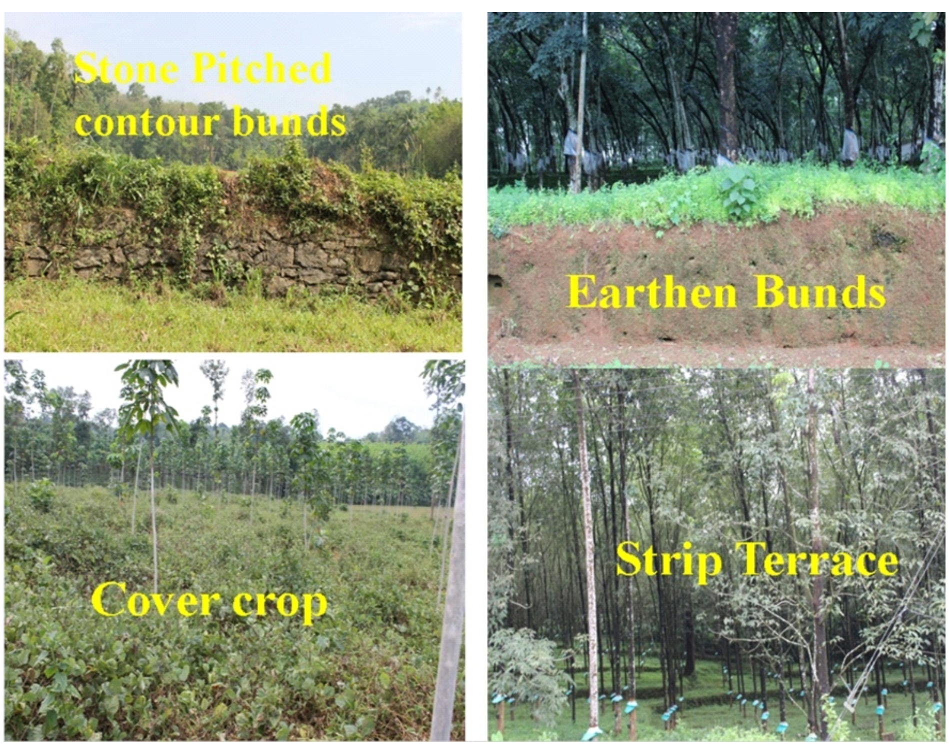

FIGURE 7a Soil conservation measures adopted in Elamdesam block, tropical humid region, Kerala

FIGURE 7b Soil conservation measures adopted in Elamdesam block, tropical humid region, Kerala

intensity and steep slopes. These areas have been classified as high priority for soil and water conservation. In contrast, our findings indicate that approx. 25.04% of the TGA in five mapping units (S2hG2, S6iH2, S1hH2, S1fH2g1, S9hB2, as shown in Table 2) experience very severe erosion (> 40 t ha^{-1} yr^{-1}) in the block, predominantly within G (22-33%), H (>33%) slopes, and gravelly uplands/midlands (1-3% slope). Special erosion issues in these areas include soil piping, mining, steep slopes with high-intensity rainfall, gully erosion, and landslide susceptibility. Therefore, these steep lands with 22-33% and greater than 33% slopes, along with uplands and midlands, require a higher priority for implementing soil and water conservation measures. These may include various agronomic methods, vegetative practices, mechanical engineering methods, trenching, terracing, drainage line treatment, and water harvesting (Hombegowda *et al.,* 2021) in Elamdesam block, located in the tropical humid regions of Kerala.

The average erosion rate in Kerala in January 2018 was 31.79 Mt $ha^{-1}yr^{-1}$. However, the increased soil erosion rate can be attributed to the intensity of rainfall, changes in LC due to washout from heavy rainfall, and the associated loss of vegetation and tree cover. As a result, the topsoil may have been eroded, as noted in the study, leading to an increased soil erosion rate. These high erosion rates resulted from the concentration of rainfall events and the unsustainable conversion of land from natural areas to settlements (Chinnasamy *et al.,* 2020). The magnitude of soil erosion and degradation depends on the soil's vulnerability and the stress caused by water erosion. This pedological soil attribute can be modified through LU management strategies. Soil erosion and degradation have impacted not only the topsoil but have also resulted in total production losses at the national level (13.44 million Mg), amounting to a monetary valuation of 205 billion INR (Sharda and Dogra, 2013). Developing conservation management strategies to combat land degradation from soil erosion in hilly regions is particularly challenging due to several biophysical and socio-economic factors. The most significant biophysical factors include steep slopes, complex geomorphology and biodiversity, a seasonal precipitation pattern and LU mismatch.

SY for the Elamdesam block, as shown in Fig. 8, ranges from 0.27 to 185.59 t $ha^{-1}yr^{-1}$ in mapping units S5iB2 and S1fH2g1, respectively. Similarly, the sediment load illustrated in Fig. 9 varies from 37.24 to 67330.95 t $ha^{-1}yr^{-1}$ in mapping units S8hB2 and S1fH2g1, respectively. There is a direct relationship between erosion rate and SY, and SL; thus, higher SY, and SL are recorded due to an increased erosion rate (Chinnasamy *et al.,* 2020). The higher value of SDR may be attributed to the smaller catchment area with steep slopes. Larger catchment areas typically exhibit lower SDR values because the detached and transported sediment has more space and time to settle in the watershed area. Therefore, it is essential to implement appropriate soil and water conservation measures on steeper slopes and in hilly regions and to conduct drainage line treatments for effective soil erosion control (Yousuf *et al.,* 2023).

4 | CONCLUSIONS

The study assesses the soil erosion rate and its mapping based on mapping units in the Elamdesam block, including SY and SL. The erosion rate is very low (<5 t $ha^{-1}yr^{-1}$) in 22

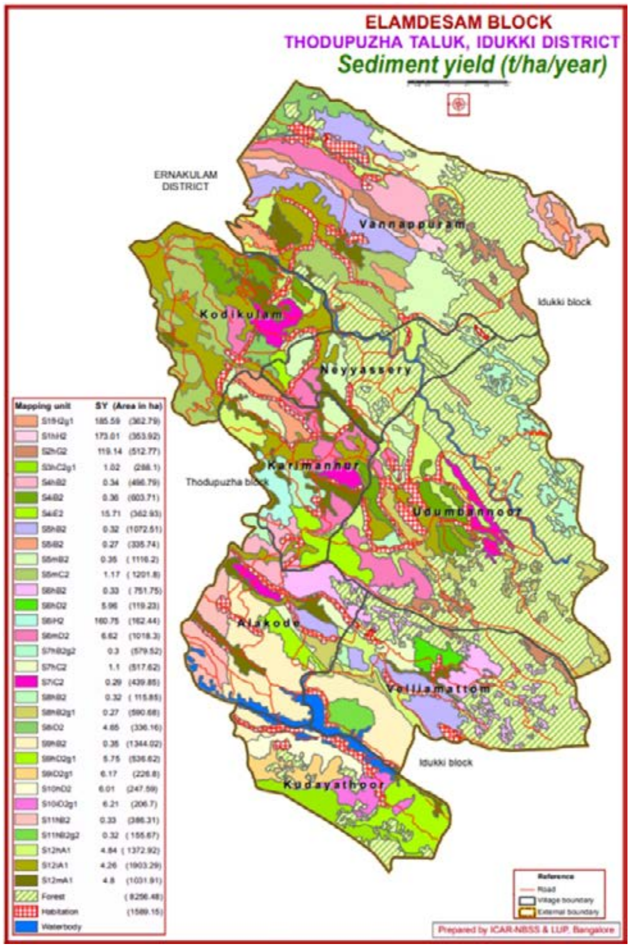

FIGURE 8 **SY classes in Elamdesam block, tropical humid region, Kerala**

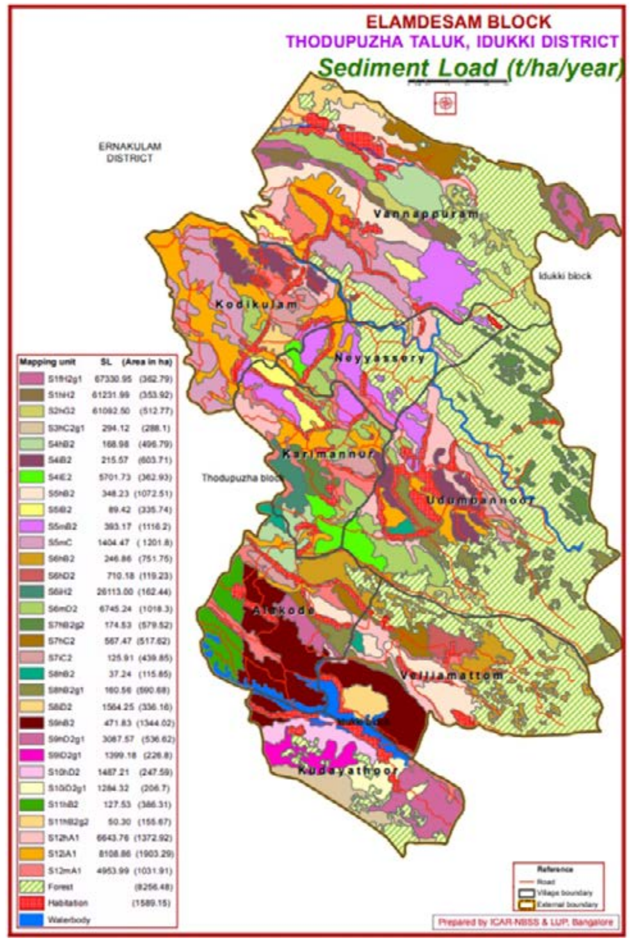

FIGURE 9 **SL classes in Elamdesam block, tropical humid region, Kerala**

mapping units, covering about 68.85% of the area; however, 25.04% of the area in five mapping units-S2hG2, S6iH2, S1hH2, S1fH2g1, and S9hB2-recorded very severe erosion (> 40 t $ha^{-1}yr^{-1}$). These units, mainly located on steep slopes and uplands/midlands, require higher priority for conservation management measures to control soil erosion, aiming to achieve LDN and prevent further soil loss, along with associated energy, economic, and monetary losses. Although there are constraints to implementing suitable soil conservation measures on steep slopes, there is an urgent need to minimize erosion rates and land degradation in these five mapping units. This can be achieved through various soil and water conservation practices, such as agronomic practices, vegetative measures, mechanical/engineering interventions, trenching, terracing, drainage line treatment and water harvesting. The results of this study will aid managers and farm planners in identifying the most critical areas where soil erosion rates are severe, enabling them to adopt appropriate soil conservation management strategies for agricultural land use in the block and work towards achieving LDN in these priority mapping units.

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DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and will be provided as and when required.

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CONFLICT OF INTEREST

There are no conflicts of interest.

AUTHOR'S CONTRIBUTION

CM is the principal investigator of the present study, having conducted the investigation and written the manuscript. SM and AKKS are part of the project and assisted with the soil survey and classification. PS contributed to laboratory soil

analysis. RC assisted in the review of literature. KKS helped obtain cadastral maps from the soil survey department in Kerala for the study. RKSC and RV have coordinated the work.

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