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Assessment of Erosion Vulnerability in Naganahalli Sub-watershed, Karnataka using RUSLE Model and Geospatial Analysis

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ABSTRACT

The investigation focused on quantifying land degradation within the Naganahalli sub-watershed through a geospatial framework combining RUSLE modeling and satellite-derived raster data set. The precipitation-induced erosive potential calculated from five years of rainfall data (2020-2024), exhibited between 297.15 and 627.94 MJ mm ha^{-1} h^{-1} yr^{-1}. The seasonal analysis revealed the monsoon cropping period (*kharif*) as the wettest, receiving 345.40 mm, corresponding to an erosivity index of 273.40 MJ mm ha^{-1} h^{-1} yr^{-1}, while in *Rabi* season recorded highest erosive intensity (390.20 mm and 212.76 MJ mm ha^{-1} h^{-1} yr^{-1}). The soil erodibility derived from twenty-nine sampled soil series pedons, ranged from 0.019 to 0.248 t ha h ha^{-1} MJ^{-1} mm^{-1}, with higher values observed in coarse-textured soils. Topographic influence, derived from a 15-meter resolution data using digital elevation model (PLASAR DEM data), showed slope-length and steepness indices spanning 0 to 11.67, with pronounced values in steepness and ridges of the micro-watershed boundary. Vegetative and land use dynamics, interpreted from classified surface cover data, yielded management coefficients between 0.48 and 0.49, indicating heightened vulnerability in areas with minimal canopy density. A consistent support practice value of 0.55 (slope class < 7) was adopted to reflect prevailing field interventions. The modeled annual sediment yield varied from 0 to 237 t ha^{-1} yr^{-1} with spatial categorization revealing that 71.78 per cent of the terrain experienced slight erosion, 19.82 per cent fell under moderate erosion, 5.32 per cent faced high erosion, 0.573 per cent area facing very high erosion risk and under severe and very severe risk shows the 0.409 and 0.00246 per cent area. The analysis underscored the predominance of slope configuration and vegetative cover influencing spatial erosion dynamics, reinforcing the utility of integrated geospatial techniques for prioritizing conservation strategies.

Keywords : GIS, RUSLE, Soil erosion, USLE, Prioritization

SOIL erosion stands as one of the most environmental issues, posing serious threats to agricultural sustainability, water quality and overall ecosystem. Its widespread impact undermines soil productivity, accelerates land degradation and disrupts the natural balance essential for sustainable development. According to the Food and Agriculture Organization (FAO, 2022), an estimated 24 billion tons of fertile topsoil are lost annually across the globe. This staggering loss undermines food security, diminishes land productivity and weakens the resilience of agro-ecosystems (Pandu *et al*., 2022). Beyond its agricultural impacts, erosion contributes to sedimentation in water bodies, disrupts biodiversity and heightens vulnerability to climate extremes.

In India, the scale of the problem is severe. The National Bureau of Soil Survey and Land Use

Planning (NBSS&LUP, 2023) reports that approximately 147 million hectaresnearly 45 per cent of the country's total geographical area are classified as degraded, with water erosion responsible for 68.4 per cent of degradation. The situation is especially acute in semi-arid regions such as Karnataka, where erratic rainfall, sparse vegetation and fragile soil structures accelerate surface runoff and sediment transport (Manivannan *et al.*, 2017). The physiographic and climatic vulnerabilities render such landscapes highly susceptible to rapid erosion and land degradation.

Karnataka, located in southern India, exemplifies the widespread challenge. Semi-arid zones within the state typically receive 500-750 mm of annual rainfall, often concentrated in sporadic, high-intensity downpours that intensify surface runoff and soil detachment (IMD, 2023). Given that agriculture forms the backbone of the region's socio-economic fabric, soil conservation becomes a critical imperative for long-term sustainability. Rejani *et al.* (2022) emphasize that anthropogenic pressure such as deforestation, unsustainable cultivation and the growing impacts of climate change compound the erosion threat by destabilizing soil systems. National-level assessments underscore the urgency: India experiences an estimated annual soil loss of 1,559 Mg km^{-2} yr^{-1}, with nearly 5,334 million tons of soil displaced from 113.3 million hectares, predominantly due to water erosion (Dabral *et al.*, 2008).

The cumulative impact of natural and anthropogenic pressures is negatively impact on soil health reduced groundwater recharge and increased sedimentation in downstream reservoirs and irrigation infrastructure. Addressing these multifaceted threats requires the implementation of scientifically informed soil conservation strategies. Techniques such as contour bunding, vegetative barriers, check dams and land use planning based on erosion risk zonation have proven effective in mitigating erosion and enhancing landscape resilience. Moreover, GIS-based modeling approaches particularly the Revised Universal Soil Loss Equation (RUSLE) offer robust tools for spatially explicit assessment of erosion risk, enabling targeted interventions and sustainable watershed management (Hembram *et al*., 2019 and Niranjana & Sathish, 2011).

The spatial heterogeneity of erosion drivers at sub-watershed level studies are essential for designing site-specific conservation strategies. Anees *et al.* (2018) highlight the importance of such localized assessments in tailoring interventions to physiographic realities. The Naganahalli sub-watershed in the southern dry zone emerges as a particularly erosion-prone area due to its undulating terrain, low organic matter content and intensive agricultural activity. The prevalence of sparse vegetative cover and reliance on traditional farming practices further amplifies erosion hazards (Yadav *et al*., 2024).

In this context, the present study employs a GIS-integrated RUSLE framework to assess soil erosion risk in the Naganahalli sub-watershed, aiming to inform sustainable land management and conservation planning in Karnataka's erosion-prone landscapes.

MATERIAL AND METHODS

The study was conducted in Naganahalli Sub-Watershed, located in the southeast part of Karnataka, India (Fig. 1). The magnitude of soil erosion rate is variedina given span of 4888 ha, both temporally and spatially, due to existing local conditions, primarily biophysical and land management variables. The datasets were collected from different sources and processed using the conventional methods in the Arc.GIS 10.5 environment (Ananthakumar and Meghana, 2022).

The RUSLE model integrated with GIS has been widely applied in diverse conditions, including mountainous tropical watersheds, large-scale basins, agriculture-dominated areas, regions with distinct wet and dry seasons and places experiencing dynamic land use changes. The model relies on three key data sets: 1) climate and terrain data, which provide rainfall erosivity and slope factors (LS), 2) vegetation and crop information to determine the cover factor

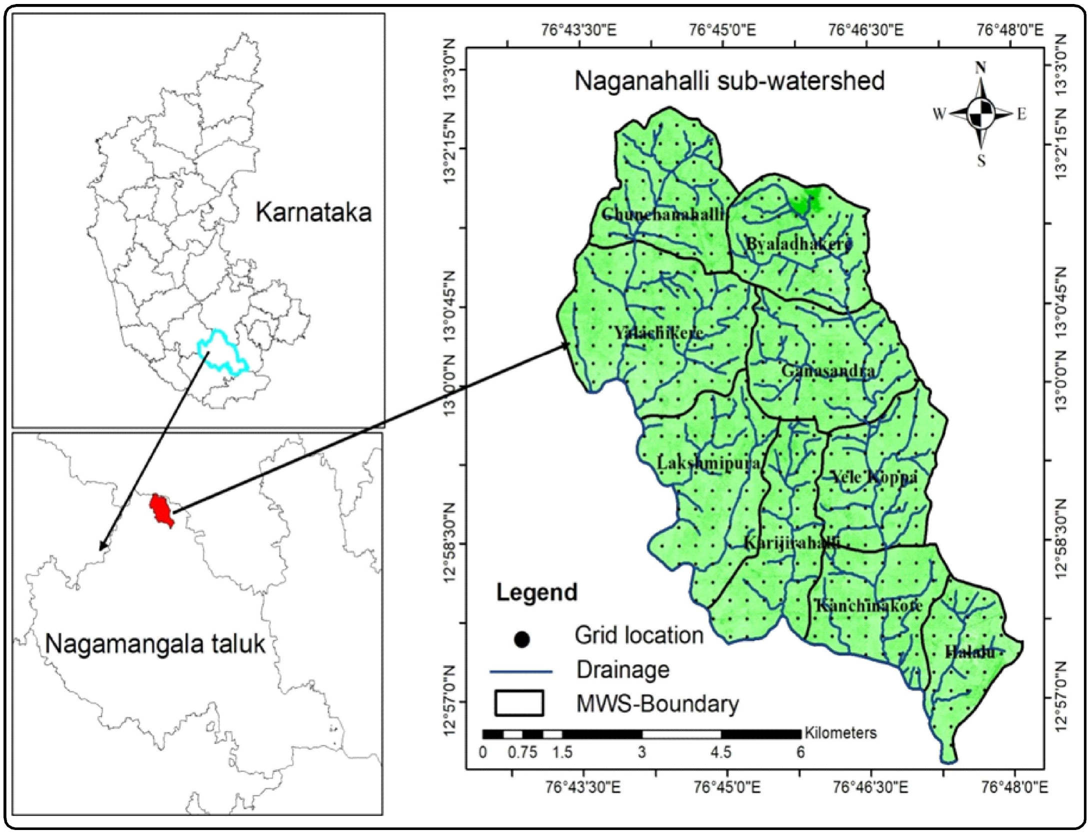


Fig. 1 : Location map of the Naganahalli sub-watershed

(C) and 3) soil survey data to assess soil erodibility (K).

Rainfall Erosivity Factor (R)

Rainfall erosivity causing soil erosion and critical component in the RUSLE model, often regarded as the most influential factor due to its strong correlation with soil loss across many regions and rainfall-monitoring sites worldwide. The kriging technique was employed to interpolate and map rainfall erosivity (R) values across the river basin, resulting in the creation of an R-factor raster layer.

In the experiment, annual rainfall data of 5 years (2020-2024, collected from KSNMDC) were used to calculate the R factor from the following Eqn. (1 & 2) used by Wischmeier and Smith, 1978.

$Y = 81.5 + 0.380\ X\ (r = 0.90)$ (Eqtn.1)

$Y = 71.9 + 0.361\ X\ (r = 0.91)$ (Eqtn.2)

Where: Y is the estimated rainfall erosivity factor

X is the mean annual rainfall

Soil Erodibility Factor (K)

The data required were extracted from theme maps of soil layer developed using intensive detailed survey of the Micro-watershed. To determine the soil erodibility factor for the water shed, the soil map serves as a base for deriving the erodibility factor layer. Erodibility factor values were assigned to corresponding soil types within the watershed. The K factor was derived using equation 4 proposed by (Kim and Julien, 2006). For the calculation of K in the present study, we have used the fraction of sand, silt, clay and organic matter from the soil profile data.

$100\ K = 2.1 \times 10^{-4} \times m^{1.14} \times (12-a) + (3.25 \times (b-2)) + (2.5 \times (c-3))$ (Eqtn.3)

Where,

m = silt (%) × sand (%) × (100-clay (%))

a = organic matter (%)

b = structure code in which (1) is very structured or particulate, (2) is fairly structured, (3) is slightly structured and (4) is solid

c = profile permeability code in which (1) is rapid, (2) is moderate to rapid, (3) is moderate, (4) is moderate to slow, (5) is slow and (6) very slow

Topography/Slope Factor (LS)

The geospatial tools using Digital Elevation Models (DEM) to derive topographic data for LS calculation. The open source DEM data was downloaded from PLASAR and prepared digitized contour maps, slope and flow accumulation. A common approach, which calculates LS by combining slope steepness and flow accumulation valuesas proposed by Moore and Burch (1986a).

$$LS = \text{flow accumulation} * \frac{cellsize}{22.13})^{0.4} \ (\sin\frac{slope * 0.01745}{0.0896})^{1.3} \quad \text{(Eqtn.4)}$$

Where,

LS= length & steepness of the slope factor

Vegetation Cover and Management Factor (C)

Surface cover, along with slope length and steepness, plays a key role in controlling soil erosion. Traditionally, the cover management factor (C) is calculated using empirical formulas based on measurements of variables like land use, canopy, surface cover and roughness from sample plots. The sub-factors are often gathered through site visits; this study uses the LULC maps for estimating the C factor by merging the common attributes that give the range of values of the unique signature (Renard *et al.*, 1997).

Support Practice Factor (P)

The support practice factor (P) represents the effect of soil conservation and management practices on erosion, expressed as a dimensionless ratio (). Practices like contouring and tillage significantly reduce soil loss, while common farming methods such as ploughing up and down slopes typically result in higher P values (Wischmeier and Smith, 1978).

Empirical equations are often used to estimate the P factor. For instance, (24) applied the Wenner method, which calculates P based on the slope derived from a digital elevation model (DEM), making it easier to apply where conservation practices are absent. In Kuala Lumpur, finding P values ranging from 0.2 to 2.58, with steeper slopes assigned higher values and flatter areas lower values using method (Wischmeier and Smith, 1978). The steepness of the slope was obtained from the DEM.

$P = 0.2 + 0.03 \times S$ ………………………(Eqtn.5)

Where:

S = slope grade(%)

Soil Loss

To estimate soil loss, spatial layers representing key factors are combined using GIS to create a soil erosion map,

$A = R \times K \times L \times S \times C \times P$ ………….. (Eqtn.6)

Where

A = predicted long-term average of annual sheet and rill soil loss, t ha^{-1}yr^{-1},

R= rainfall- runoff erosivity factor, MJ mmha^{-1}h^{-1} yr^{-1}

K = soil erosivity factor, Mg h MJ^{-1} mm^{-1}

L = slope length, m

S = slope steepness, %

C = cover and management factor

P = support practice

RESULT AND DISCUSSION

Rainfall Erosivity (R factor)

The results of rainfall intensity and monthly, seasonal and annual rainfall distribution revealed that average monthly rainfall ranged from 2.46 mm in January to

233.00 mm in October. Average seasonal rainfall ranged from 275.80 mm in *Summer* to 390.20 mm in *Rabi* and annual rainfall ranged from 567.50 mm in 2023 to 1438.00 mm in 2022 with an average annual rainfall of 1011.40 mm. The rainfall erosivity factor (R) for the years 2020-2024 was found to be in the range of 297.15-627.94 MJ mm ha^{-1} h^{-1} y^{-1}. The average R factor was observed to be 465.83 MJ mm ha^{-1} h^{-1} y^{-1}. The highest value (627.94MJ mm ha^{-1} h^{-1} y^{-1}) of the R factor was observed in 2022 and the lowest value (297.15 MJ mm ha^{-1} h^{-1} y^{-1}) was in 2023. The mean seasonal erosivity factor values for the *kharif* (monsoon), *Rabi* (post-monsoon) and summer seasons were 273.40, 212.76 and 171.46, respectively. The average monthly and annual rainfall erosivity indices and seasonal and annual rainfall erosivity indices revealed that October poses a higher erosivity risk than any other month in the study area, whereas for seasonal erosivity risk, *kharif* posed the highest risk, followed by *Rabi* and *Summer*.

TABLE 1

Mean monthly rainfall (mm) and rainfall erosivity (R) factor (MJ mm ha^{-1})

Months	2020	2021	2022	2023	2024	Mean
Jan.	0.00	6.30	0.00	0.00	6.00	2.46
Feb.	0.00	18.20	0.00	0.00	0.00	3.64
Mar.	0.00	0.00	28.50	19.00	0.00	9.50
Apr.	69.50	61.20	46.50	66.00	11.00	50.84
May.	181.50	126.80	358.00	97.50	283.00	209.36
Jun.	190.50	57.40	140.50	34.00	77.50	99.98
Jul.	100.00	97.90	154.00	79.00	90.50	104.28
Aug.	25.50	108.50	301.50	1.00	104.50	108.20
Sep.	114.20	51.50	55.50	96.50	71.00	77.74
Oct.	132.50	343.00	298.50	68.50	322.50	233.00
Nov.	32.70	166.00	20.00	84.00	83.00	77.14
Dec.	4.80	50.00	35.00	22.00	64.50	35.26
Total	851.20	1086.80	1438.00	567.50	1113.50	1011.40
R Factor	404.96	494.48	627.94	297.15	504.63	465.83

TABLE 2

Mean seasonal rainfall (mm) and rainfall erosivity (R) factor (MJ mm ha^{-1})

Period	*Kharif*		*Rabi*		*Summer*	
	Rain fall	K Factor	Rain fall	K Factor	Rain fall	K Factor
2020	170.00	215.29	430.20	227.2	251.00	162.51
2021	559.00	340.75	315.30	185.72	212.50	148.61
2022	353.50	310.37	651.50	307.09	433.00	228.21
2023	174.50	188.28	210.50	147.89	182.50	137.78
2024	470.00	312.29	343.50	195.90	300.00	180.20
Mean	345.40	273.40	390.20	212.76	275.80	171.46

Soil Erodibility (K) Factor

The soil erodibility was derived from horizon-wise samples of soils of the Naganahalli sub-watershed. The sampling locations were chosen in such a way that the soil samples represent the different physiographic, geomorphologic, as well as land use types of the basin. A data of soil organic matter, per cent of silt, sand and clay were calculated for the profile, which was then averaged in proportion to the area of each constituent soil series of a particular mapping unit. Soil erodibility factor of twenty-nine soil profiles computed. After the computation of the K factor of the soil samples in the Naganahalli sub-watershed, a continuous raster surface of K was generated by applying the kriging interpolation techniques in Arc.GIS (Fig. 2). The values of the K factor are found to range between 0.019 and 0.248 t ha h ha^{-1} MJ^{-1} mm^{-1}. Soils with lower K factor values are less prone to soil erosion compared to soils with higher K factor values.

TABLE 3
K factor (t ha h ha^{-1} MJ^{-1} mm^{-1}) for different profiles of Sub-Watershed

Series	K Factor
Anthapura (ANT)	0.194
Aregujjanahalli (AJH)	0.127
Balapur (BPR)	0.080
Bidanagere (BDG)	0.019
Bidarakatte (BDK)	0.134
ChikkaMadhure (CKD)	0.231
Chikkamegheri (CKM)	0.059
Chikkasamudrakaavalu (CKS)	0.041
Gulur (GLR)	0.139
Hallikere (HLK)	0.129
Hatti (HTI)	0.091
Hooradhahalli (HDH)	0.103
Jedigere (JDG)	0.105
Kaggalipura (KGP)	0.248
Kanchikere (KKR)	0.167
Kethahalli (KTH)	0.066
Kethanapura (KTP)	0.144
Kumachahalli (KMH)	0.099
Kutegoudanahundi (KGH)	0.062
Lakkur (LKR)	0.083
Marihosahalli (MHH)	0.060
Nagalapura (NGP)	0.056
Patravanapalli (PVP)	0.106
Ramanahalli (RNH)	0.041
Ranatur (RTR)	0.121
Santhemarahalli (SMH)	0.119
Shynadrahalli (SNH)	0.140
Thamadahalli (TDH)	0.091
Thimmasandra (TSD)	0.106

Slope Length and Steepness (LS) Factor

The determination of slope length and steepness factor is an integral part of most soil erosion prediction models. The LS factor was derived from the PLASAR DEM (15×15 m) source, where the LS factor is transformed from the pixelated complex slope and drainage basin length and slope of a standard USLE plot. PLASAR DEM of the Naganahalli sub-watershed and a derived LS factor map are presented in Fig. 2. The value of the LS factor in the study area ranges from 0 to 11.67. The higher LS factor values are found in small areas, particularly on the mainstream of the Naganahalli sub-watershed towards the south west, where the slope is generally high.

Crop Management (C) Factor

The C factor (Wischmeier and Smith, 1978) is the ratio of soil loss from land harvested under specific conditions to the corresponding loss from clean-tilled, continuous fallow. Currently, a variety of researchers use various spectral vegetation indices as well as the fraction images from spectral mixture analysis of remotely sensed images for computing the C factor due to the variety of land cover patterns with spatial and temporal variations. The C factor value is derived using the LULC and depicted in the map (Fig. 2). Although the C factor vary from 0 for very well protected soils to 1.5 for finely tilled, ridged surfaces. The narrow range of the C factor in the sub-watershed was derived with a value of 0.48 to 0.49, indicating the soils are well protected with bunds and cultivation with plantation crops.

Support Practice (P) Factor

The factor encompasses all anti-erosion practices like contour cropping, alternating bands or terraces, bush reformation, mounding and ridging. P values range from 0.2 to 2.08, with 0 representing a very good environment for resistance to erosion and 2.08 indicating a lack of anti-erosive practice. In the present study, the anti-erosion practices and slope based land use/land cover classes collected through field surveys and the DEM database as used by Zhang *et al*. (1999) is used to calculate the P factor. The majority of the farming area in this sub-watershed has <7 per cent slope and bunds and contours are commonly used to prevent sediment loss from the field. The P factor used estimation in the sub-watershed is 0.55.

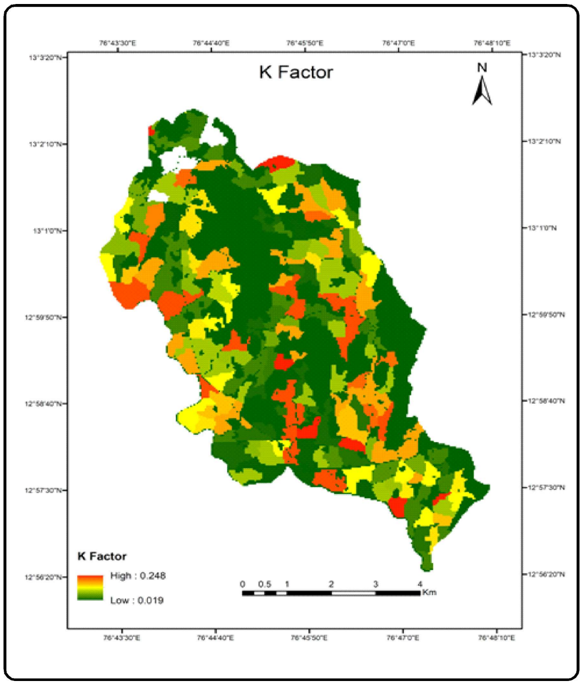
TABLE 4

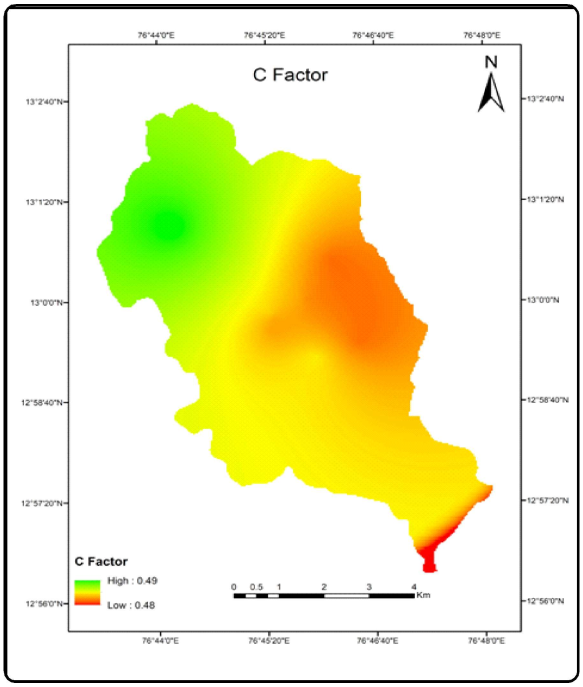
\Soil erosion classification with erosion rate and area covered

Soil erosion classes	Rate of soil loss (t/ha/yr)	Area (ha)
Slight erosion	0-5	3509.0
Moderate erosion	5-10	969.0
High erosion	10-20	260.0
Very high erosion	20-40	28.0
Severe erosion	40-80	2.0
Very severe erosion	>80	0.12

Potential Annual Soil Loss Estimation

Annual soil loss based on the 5 year average rainfall erosivity factor is termed as average annual soil loss. The annual soil loss for the sub-watershed was calculated by the annual average R (based on the annual average rainfall data of 2020-2024) and K, LS, C and P factors. The soil erosion rate (t/ha/yr) was estimated as the total soil loss of MW (t/yr) divided by the total geographical area of MW (ha). All the layers, *viz*., R, K, LS, C and P, were generated in GIS and overlaid to obtain the product, which gives the annual soil loss (A) for the Naganahalli sub-watershed. These values gave the annual soil loss per hectare per year at pixel level. These values are converted to the loss per pixel in m^2 and all values are added in the GIS domain to obtain the total annual soil loss per hectare for the Naganahalli sub watershed as a whole. The average soil erosion rate estimated for the Naganahalli sub-watershed ranged from 0 to 237 t





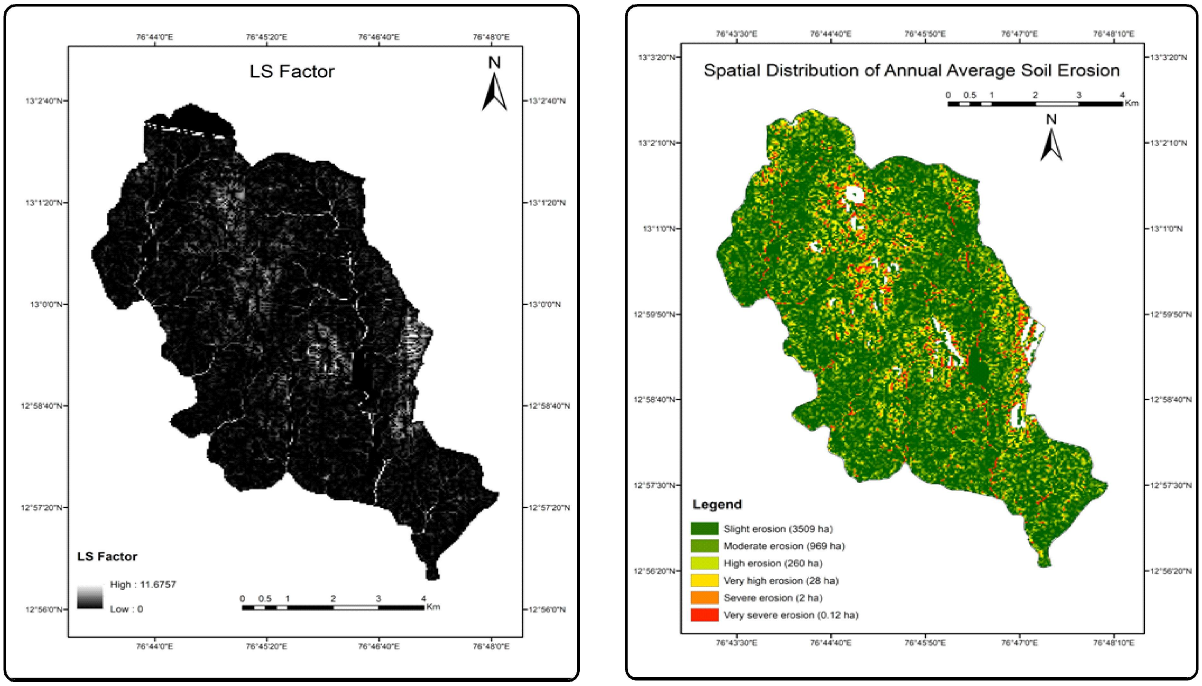


Fig. 2 : Spatial distribution of K, C, LS and Annual average soil loss in the study area

ha^{-1} y^{-1} in the sub watershed. The assessed average annual soil loss of the Naganahalli sub-watershed was grouped into different classes erosion quantity: slight (0-5 t ha^{-1} yr^{-1}), moderate (5-10 t ha^{-1} yr^{-1}), high (10-20 t ha^{-1} yr^{-1}), very high (20-40 t ha^{-1} yr^{-1}), severe (40-80 t ha^{-1} yr^{-1}) and very severe (>80 t ha^{-1} yr^{-1}). The results presented in Table 4 and Fig. 2 show that the highest study area is classified as having slight erosion (0-5 t ha^{-1} yr^{-1}), while the rest of the area is under moderate, high, very high, severe and very severe erosion zones of the sub-watershed area, respectively. The spatial pattern of classified soil erosion ranging from high to very severe risk zones occurred on the ridges of the micro-watershed boundary.

Prioritization

The results of the study reinforce the growing urgency of watershed management in India's arid and semi-arid regions, where accelerated soil erosion has significantly reduced soil fertility. The observed degradation is closely linked to unchecked soil erosion, unsustainable land use and overexploitation of watershed resources. In semi-arid zones such as Karnataka, the fragile equilibrium between soil, water and vegetation is easily disrupted by erratic rainfall and developmental pressures, leading to increased runoff, sediment transport and topsoil loss. The findings of present study validate the need for a strategic, cost-effective approach for watershed rehabilitation. The delineation of sub-watersheds and micro-watersheds proved to be a pragmatic solution, allowing for targeted interventions in areas with the highest erosion risk and potential runoff index.

The application of the potential runoff index (PRI) method effectively ranked sub-watersheds based on their sediment contribution to downstream reservoirs. PRI scores, derived from rainfall erosivity, soil erodibility, slope gradient and land use data, provided a reliable metric for prioritization. For example, sub-watersheds with LULC mapping *via* remote sensing and GIS further supported the identification of erosion-prone areas. The results also highlight the vulnerability of semi-arid soils, which are typically shallow, poorly aggregated and low in organic matter. High-intensity rainfall events exacerbate erosion risks, particularly along main drainage lines and stream channels in uplands with higher

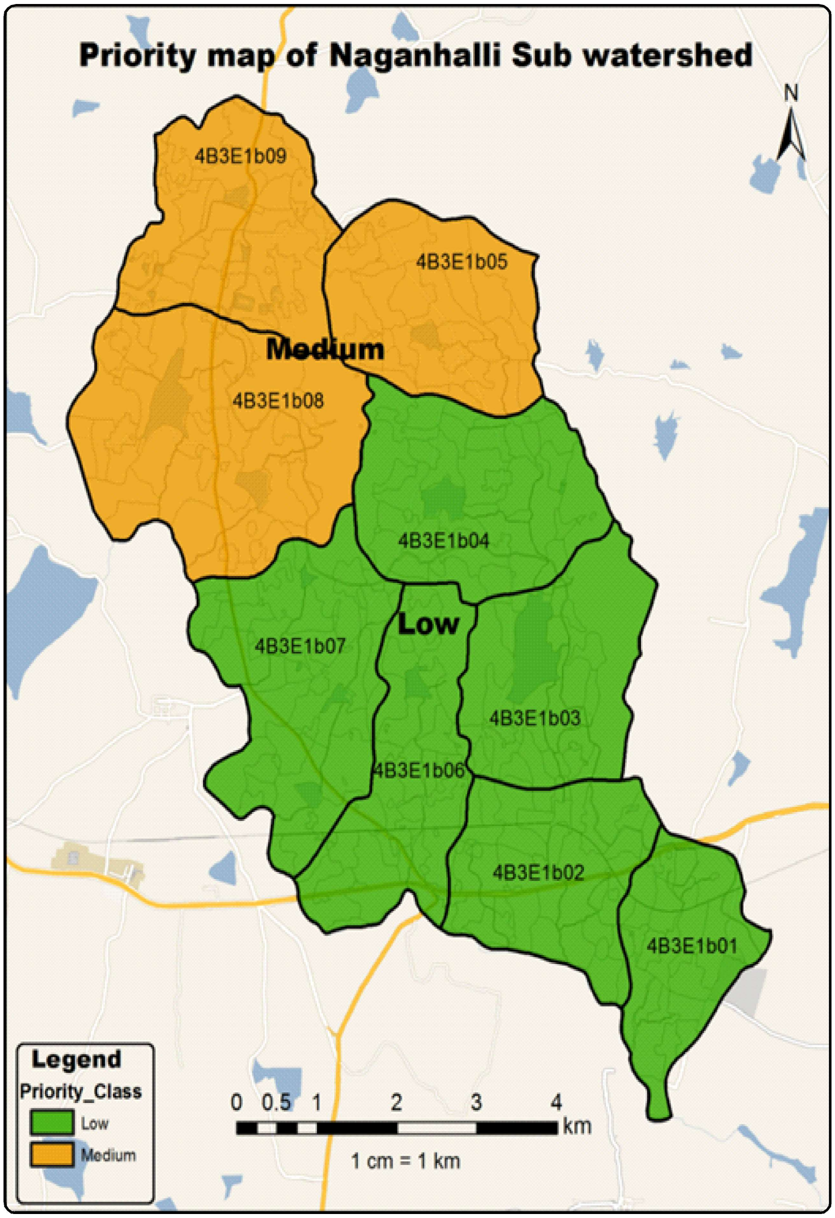


Fig. 3 : Erosion-Based Prioritization of micro-watersheds in the study area

elevation. The implementation of water harvesting structures-check dams, percolation tanks and contour bunds-along these pathways was shown to reduce runoff velocity, trap sediments and enhance groundwater recharge.

Complementary vegetative measures, including agro-forestry and conservation agriculture practices, contributed to soil stabilization and improved land productivity. These interventions, when aligned with land use planning that discourages cultivation on steep slopes and promotes minimum tillage and mulching, proved effective in reducing erosion and improving infiltration. The prioritization framework developed in the study aligns with national goals for sustainable development and climate resilience. Empirical evidence from studies by Koradia & Patel (2024), Arun Kumar *et al*. (2021) and Pan *et al*. (2025) support the validity of the applied methodologies.

It is essential to intervene in erosion-prone micro-watersheds, particularly along stream channels and drainage lines, where stakeholders can adopt ecologically sound and economically viable technologies. The findings also indicate that localized interventions not only reduce erosion but also strengthen community participation and ensure long-term sustainability. Overall, the study highlights the importance of scientific prioritization in watershed management and shows that integrated, evidence-based strategies can effectively tackle the dual challenges of soil erosion and water scarcity. This is especially critical in the upland areas of the sub-watershed, where micro-watersheds at higher elevations such as Byaladakere (4B3E1b09), Chunchanahalli (4B3E1b05) and Yalachikere (4B3E1b08) should adopt soil and water conservation measures to minimize soil loss caused by erosion (Fig. 3).

The study conclusively demonstrated the effectiveness of integrating the Revised Universal Soil Loss Equation (RUSLE) with GIS techniques to estimate spatial soil erosion across the micro-catchment area. The predicted erosion rates ranged from 0 to 0.31 t ha^{-1} yr^{-1}, culminating in a total annual soil loss of 151.59 tons over 489 hectares. This quantification was driven by key RUSLE parameters: rainfall-runoff erosivity (R) was calculated at 109.9 MJ mm ha^{-1} yr^{-1}, while soil erodibility (K) varied up to 0.67 depending on soil texture and structure. The topographic factor (LS) reached values as high as 0.21, reflecting slope-induced vulnerability and the cover management factor (C) ranged from 0 to 0.15, indicating spatial variability in vegetation density and land use intensity. Support practice values (P) between 0.55 and 0.6 suggested moderate implementation of conservation measures such as bunding or contour farming. The spatial heterogeneity of erosion susceptibility was evident, with erosion hotspots aligning with steeper slopes, sparse vegetation and poorly managed agricultural zones. This integrated modeling approach provided high-resolution insights essential for targeted soil and water conservation planning, emphasizing the interplay of climatic, edaphic, topographic, vegetative and management factors in sustainable watershed development.

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