__Original Research Article__

Assessment of soil erosion within the Gayathripuzha River Basin using RUSLE model and GIS tools

ABSTRACT

Soil erosion, worsened by the 2018 floods in Kerala, has wide-ranging effects on society, economy, and nature. To address this, it is essential to know the nature and quantity of soil erosion and create specific strategies for soil conservation. This research paper thoroughly examines the susceptibility of soil erosion in the Gayathripuzha river basin, encompassing a wide area of around 961 km². Employing the Revised Universal Soil Loss Equation (RUSLE), this investigation assesses the influential factors affecting soil erosion, which comprise rainfall (R Factor), soil erodibility (K Factor), topography (LS Factor), land usage (C Factor), and the impact of conservation measures (P Factor). Employing Geographic Information System (GIS) tools like ArcGIS 10.8 Desktop and integrating data from multiple sources including rain gauge stations, soilgrids.org, Bhuvan, and Sentinel-2 imagery, the study was conducted. The average annual soil erosion measurement ranges from 0 to 133.18 t ha^{-1} yr^{-1} within the research site. The research found that soil erosion varied greatly across the study area. Regions with slopes over 50% had much higher erosion rates, while most of the study area had low erosion levels. Notably, the intensity of soil erosion demonstrated a positive correlation with slope percentage, with areas classified as bare ground demonstrating the highest erosion rates. These findings emphasize the necessity for targeted and comprehensive conservation strategies tailored to the diverse landscape of the region to effectively manage soil erosion and mitigate its adverse impacts.

Keywords: ArcGIS; GIS; K factor; RUSLE; R factor; Soil; Soil erosion

1. INTRODUCTION

Soil erosion, a natural phenomenon intensified by human intervention, refers to the gradual degradation of the earth's topsoil. It occurs due to various factors such as wind, water, and disturbances caused by human activities [1]. It is influenced by various elements like slope steepness, climate, land use, land cover, and ecological events such as forest fires [2]. This phenomenon has wide-ranging consequences, affecting ecosystems, agriculture, and overall environmental well-being[3]. Soil erosion within river basins significantly influences environmental dynamics, impacting ecosystems, water sources, and human activities in crucial ways [4]. Comprehending the mechanisms and trends of soil erosion is vital for sustainable management of land and water resources, particularly in expansive landscapes where the intricate interplay between soil, water, and topography unfolds.

Assessment of soil erosion is a global concern for land use planners, particularly in the context of planning sustainable development for a region. In India, around 91% of the entire land area is impacted by soil erosion, with potential rates varying from less than 5 to 40 t ha-1 yr-1 and among this 50% area requires intensive soil conservation practices [5].

Researchers globally have employed a diverse range of approaches, encompassing physical models, empirical models, statistical models, and process-based models, to forecast soil erosion. Despite the advancement of various physical and conceptual models, the Universal Soil Loss Equation (USLE), and its modified versions like the Modified Universal Soil Loss Equation (MUSLE) or the Revised Universal Soil Loss Equation (RUSLE) remain the most widely used empirical models globally for predicting and managing erosion [6]. These models have been extensively tested in numerous agricultural watersheds worldwide [7].

The RUSLE model is formulated to forecast the long-term average annual soil loss (A) transported by runoff from particular field slopes under defined cropping and management systems, including rangeland areas. The RUSLE equation maintains the same factors as the USLE equation, but its computations are more complex compared to those of the USLE. The process is made easier through the use of a computer program and involves analysing research data that were unavailable when the USLE equation (introduced by Wischmeier and Smith in 1965 and 1978)[8] was developed [9]. It serves as a comprehensive model to estimate average annual soil loss, encompassing factors like rainfall erosivity, soil erodibility, topography, land cover, and conservation practices. RUSLE proposed in the early 1990s, has become a widely utilized tool in the fields of soil science, agriculture, and environmental management for assessing and mitigating soil erosion. It has been widely utilized to predict annual soil loss averages by integrating improved techniques for calculating soil erosion factors in both agricultural and forest watersheds [10].

RUSLE has gained extensive global usage for predicting soil loss and developing effective soil erosion management strategies. Its widespread application is attributed to its user-friendly implementation and compatibility with GIS. Various studies, including those conducted by Dabral et al. (2008)[11], Jain et al. (2010)[12], Jasrotia and Singh (2006) [13], Millward and Mersey (1999)[14], Pandey et al. (2009)[15] and Shivhare et al. (2018) [16] have utilized RUSLE to assess soil erosion. The calculation of soil erosion rates with RUSLE equation can be carried out using the Spatial Analyst extension in ArcGIS.

Soil erosion in the Western Ghats region has been assessed by numerous researchers using the RUSLE approach (Prasannakumar et al. 2011a) [17], (Prasannakumar et al. 2011 b) [18],and (Thomas et al., 2018b) [19]. Recently, a substantial portion of the Western Ghats Region has undergone conversion into land for cultivating tea, coffee, rubber, palm, and other crops, or has been cleared for livestock grazing and road construction. The mountain slopes in Kerala are experiencing a severe issue with soil erosion [20]. In August 2018, Kerala witnessed one of the deadliest natural disasters in the last century, characterized by widespread waterlogging in low-lying areas and significant landslides in hilly regions, resulting in the loss of hundreds of lives. This catastrophic event was triggered by exceptionally heavy rainfall. In this context, the Gayathripuzha river basin, characterized by its susceptibility to erosion, serves as a focal point for a comprehensive analysis.

The study has two main objectives: firstly, to estimate soil loss within the Gayathripuzha river basin and identify land use categories particularly prone to erosion, and secondly, to develop suitable strategies for soil conservation and management specific to the ecosystems of the Gayathripuzha river basin.

2. MATERIAL AND METHODS

2.1 Study Area

The Gayathripuzha river, a tributary of the Bharathapuzha, is located in Palakkad district of Kerala, India. It begins its course in the Anamalai hills, flowing through Kollengode, Nenmara, Alathur, Padur, and Pazhayannur before ultimately merging with the Bharathapuzha at Mayannur. It lies between 10°27'0" N, 76°21'30" E to 10°45'0" N, 76°51'30" E with an area of approximately 961 km^2. The south-eastern section of the Gayathripuzha river basin contains a small portion of the Nelliyampathy forest reserve, while its southwestern side borders the PeechiVazhani wildlife sanctuary and Chimmony wildlife sanctuary. Most of the Gayathripuzha river basin consists of flat plains used for paddy fields, with elevated terrain only present in the area it shares with the reserve forest. Several surface water bodies, Mangalam dam, Pothundy dam, Chuliyar dam, and Meenkara dam, are included within its boundary. The study area is depicted in Figure 1.

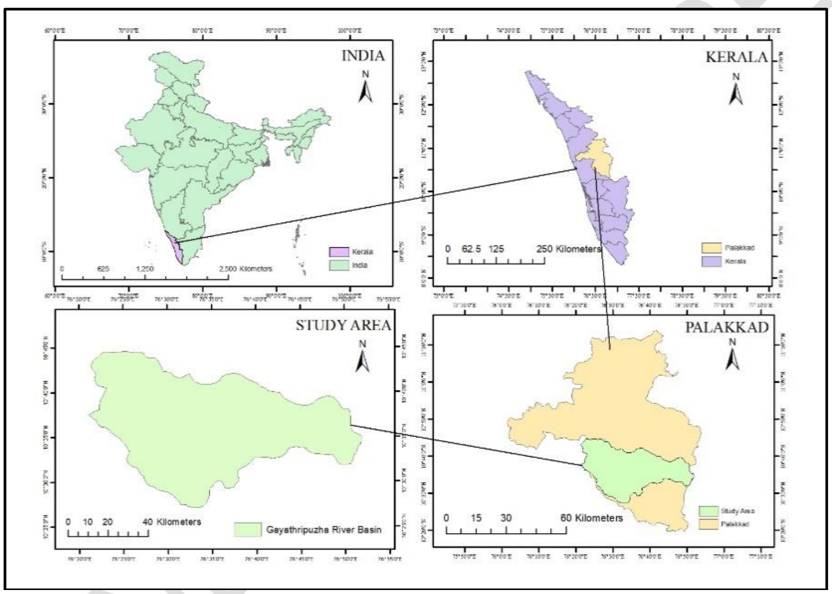

Figure 1. Map depicting the study area.

2.2 Software

The primary tool employed in this research is ArcMap 10.8, which constitutes a part of the ArcGIS (Geographic Information System) software suite developed by ESRI (Environmental Systems Research Institute). The study extensively utilizes ArcGIS for tasks related to data management, analysis, and visualization.

2.3 Model

In this study, the RUSLE model was utilized to estimate soil erosion. RUSLE offers a comprehensive approach to predict average annual soil loss, considering factors such as rainfall erosivity, soil erodibility, topography, land cover, and conservation methods.

Both USLE and RUSLE calculate the average annual erosion using equation (1) given by [9].

$$\boldsymbol{A} = \boldsymbol{R} \times \boldsymbol{K} \times \boldsymbol{LS} \times \boldsymbol{C} \times \boldsymbol{P} \quad (1)$$

where:

A is the estimated average annual soil loss, t ha^{-1} y^{-1}

R represents the rainfall-runoff erosivity factor, which quantifies the potential of rainfall to cause soil erosion. MJ mm ha^{-1} h^{-1} y^{-1}

K is the soil erodibility factor, signifies the vulnerability of a specific soil type to erosion. t ha h ha^{-1} MJ^{-1} mm^{-1}

LS combines the slope-length (L) and slope-steepness (S) factors, considering the topography's impact on erosion.

C is the cover and management factor, reflecting the influence of vegetation cover and land management practices on erosion.

P represents the support practice factor, accounting for the effect of erosion control measures or conservation practices.

2.4 Data Sources

Daily rainfall data spanning the years 2014 to 2022 for the Alathur, Kollengode, Chittur, and Ottappalam rain gauge stations was acquired from the Meteorological Centre in Thiruvananthapuram, a division of the Indian Meteorological Department. This data is meant for calculating the average annual rainfall in the designated areas. To ascertain the K factor for the Gayathripuzha Basin, soil grid data were acquired from soilgrids.org, a platform providing comprehensive global soil information through detailed property maps of high resolution. The specific layers needed for calculating the K factor, including sand (g/kg), silt (g/kg), clay content (g/kg), and soil organic carbon (dg/kg), were downloaded from soilgrids. Benchmarks of soils in Kerala were referenced from the book published by Soil Survey Organization of Agriculture (S.C. Unit) Department, Government of Kerala (2007). The LS factor in soil erosion assessment takes into account topographical influences by integrating both slope-length (L) and slope steepness (S) factors. To calculate these factors and generate flow direction and flow accumulation maps, it is crucial to have a Digital Elevation Model (DEM) of the designated area. The necessary DEM data was acquired from the Bhuvan website, the Indian Geo Platform operated by ISRO. The specific dataset obtained is the Cartosat-1:DEM - Version-3R1, accessible through the Bhuvan Store. The prerequisite for determining the C factor involves obtaining a Land use map. This map was downloaded from the ESRI Sentinel-2 website, specifically selecting the necessary area tile for the year 2022. The P factor map was created utilizing the slope percentage map acquired during the generation of the LS factor map.

2.5 Soil Erosion Estimation

2.5.1 Rainfall-Runoff Erosivity Factor (R)

The Gayathripuzha basin encompasses two primary rain gauge stations, Alathur and Kollengode. However, for a more comprehensive analysis, two additional stations, Chittur and Ottappalam, near but outside the basin, have been taken into consideration. The calculation of the R factor involves incorporating rainfall data from 2014 to 2022 to determine the average annual rainfall. The equation given byBabu et al., 2004 [21] was used for this purpose as shown in equation (2).

$$R = 81.5 + 0.375 \quad (2)$$

Where A represents the average annual rainfall. It is important to note that this equation is applicable within the range of average annual rainfall values from 340 to 3500 mm. The R factor map was generated using the Inverse Distance Weighted (IDW) tool available in the Arc Toolbox.

2.5.2 Soil Erodibility Factor (K)

To estimate the K Factor for the Gayathripuzha Basin, the regression equation suggested by Foster and Wischmeier (1974) [22] was employed, utilizing erosivity factor values obtained from the nomograph. The equation (3) is given by:

$$\mathbf{K} = \frac{2.1 \times 10^{-4}(12 - \mathrm{O.M.})\mathbf{M}^{1.14} + 3.25(\mathbf{s} - 2) + (\mathbf{p} - 3)}{759.4} \quad (3)$$

Where, K represents the soil erodibility (t ha h ha^{-1} MJ^{-1} mm^{-1}), OM the percentage organic matter, p the soil permeability code, s the soil structure code, and M a function of soil primary particle size fraction, as in equation (4).

$$\mathbf{M} = (\%\mathbf{silt} + \%\mathbf{very\ fine\ sand}) * (\mathbf{100} - \%\mathbf{clay}) \quad (4)$$

The specific layers needed for estimating the K factor were downloaded and customization options such as depth, mean or uncertainty values, and a 2×2-degree tile based on longitude and latitude were selected for the analysis. Upon downloading the data, it was integrated into ArcGIS and extracted based on the boundaries of the Gayathripuzha river basin. Soil permeability (p) and soil structure (s) codes were referred from *Benchmark soils in Kerala* [23].

2.5.3Slope Length and Slope Steepness Factor (LS)

The L factor and S factor are typically assessed in conjunction. The LS factors consist of two components: L, which represents the slope length factor accounting for the effect of slope length on erosion, and S, which represents the slope steepness factor addressing the influence of slope steepness on erosion. These two factors work in tandem to evaluate the combined effect of slope characteristics on erosive processes. DEM was downloaded and utilized to account for topographical influences on soil erosion through the slope-length factor (L) and slope steepness factor (S), which collectively constituted the LS factor.

The slope-length factor (L) for the slope length λ (in metres) is determined using the following equations (5, 6, and 7)given by [9]:

$$L = \left(\frac{\lambda}{22.13}\right)^m \quad (5)$$

Where, 22.13 = the RUSLE unit plot length (in metres) and m = a variable slope length exponent. The slope length exponent, denoted as m, was computed asequations (6).

$$\mathrm{m} = \beta / (1 + \beta) \quad (6)$$

$$\beta = (sin\,\theta/0.0896)/\,[3.0(sin\,\theta)^{0.8} + .56] \quad (7)$$

Where, θ is the slope angle

The slope steepness factor (S) is determined based on the following equations (8 and 9) given by [9]:

$$S = 10.8\sin\theta + 0.03 \qquad S < 9\%\ (i.e. \tan\theta < 0.09)(8)$$

$$S = (\sin\theta/sin5.143)^{0.6} S \geq 9\%\ (i.e. \tan\theta \geq 0.09)(9)$$

The equations were adapted into formats suitable for utilization in the raster calculator of ArcGIS. Flow, flow direction, and flow accumulation operations were executed, and the flow accumulation raster was employed to derive the L Factor. To obtain the S factor, Slope map is generated from the Digital Elevation Model (DEM) in both degree and percentage formats. The degree format is then converted to radians, as ArcGIS exclusively interprets angles in radians. The LS Factor map in raster format was generated by multiplying the L Factor and S Factor maps.

2.5.4 Cover Management Factor (C)

The land use map essential for estimating the C factor was obtained from the ESRI Sentinel-2 website by selecting the relevant area tile for the year 2022. The land cover map is imported into ArcMap and clipped to match the study area.

Table 1. 'C' factor values corresponding to Land Use

Land Use	**Sub Land Use**	**C Factor**
Agriculture	Current Fallow	0.6
	Kharif + Rabi(Double Cropped)	0.6
	Kharif Crop	0.5
	Plantations	0.5
Built Up	Commercial	0.2
	Industrial	0.2
	Towns/Cities	0.2
	Villages(Rural)	0.2
Forest	Scrub Forest	0.02
Others	Prosophis	0.15
	Quarry	0.15
Waste Land	Land with Scrub	0.95
	Land without Scrub	0.8
Water bodies	Canal	0
	Lakes/ponds	0

	Reservoirs	0
	River	0

Following a review of multiple research papers [6], [24] and [25], C values associated with each land use were acquired. The selected C values are primarily based on[10**]** and these values are integrated into the attribute table of the Land use map and transformed into a raster format. The C values used in the study are shown in Table 1.

2.5.5 Conservation Practice Factor (P)

The P factor, representing the influence of conservation practices and land management on soil erosion, considers the effectiveness of measures like contour ploughing, cover crops, and terracing. It is a factor without dimension which ranges from zero to one, with zero indicating a high level of soil conservation and one indicating no soil conservation practices.

In the research, the P factor map was generated using the slope percentage map obtained during LS factor map creation. Based on land use and slope percentage within a field, Wischmeier and Smith (1978) [10] introduced P factor values. These values vary depending on particular land use practices and slope degrees. To generate the P Factor map, the classified slope map is linked spatially to the land-use map, and P values are allocated based on the information provided in the table. Table 2 provides the P factor values corresponding to land use and slope.

Table 2. Variation of the P Factor in relation to land use and slope

Land use	Land slope	P factor
Agriculture	0-5	0.10
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
	>100	0.35
All other land use		1.00

2.5.6 Soil Erosion Estimation

The assessment of the average annual soil loss in the Gayathripuzha river basin involved integrating five factors from the RUSLE model: rainfall erosivity (R), soil erodibility (K), topography (LS), land cover (C), and conservation practice (P). This consolidation of maps was achieved using the raster calculator in ArcMap. All factor maps shared a consistent cell size of 30x30 and were defined by transverse Mercator projection and WGS_1984_UTM_43N coordinate system. The methodology flow chart is depicted in Figure 2.

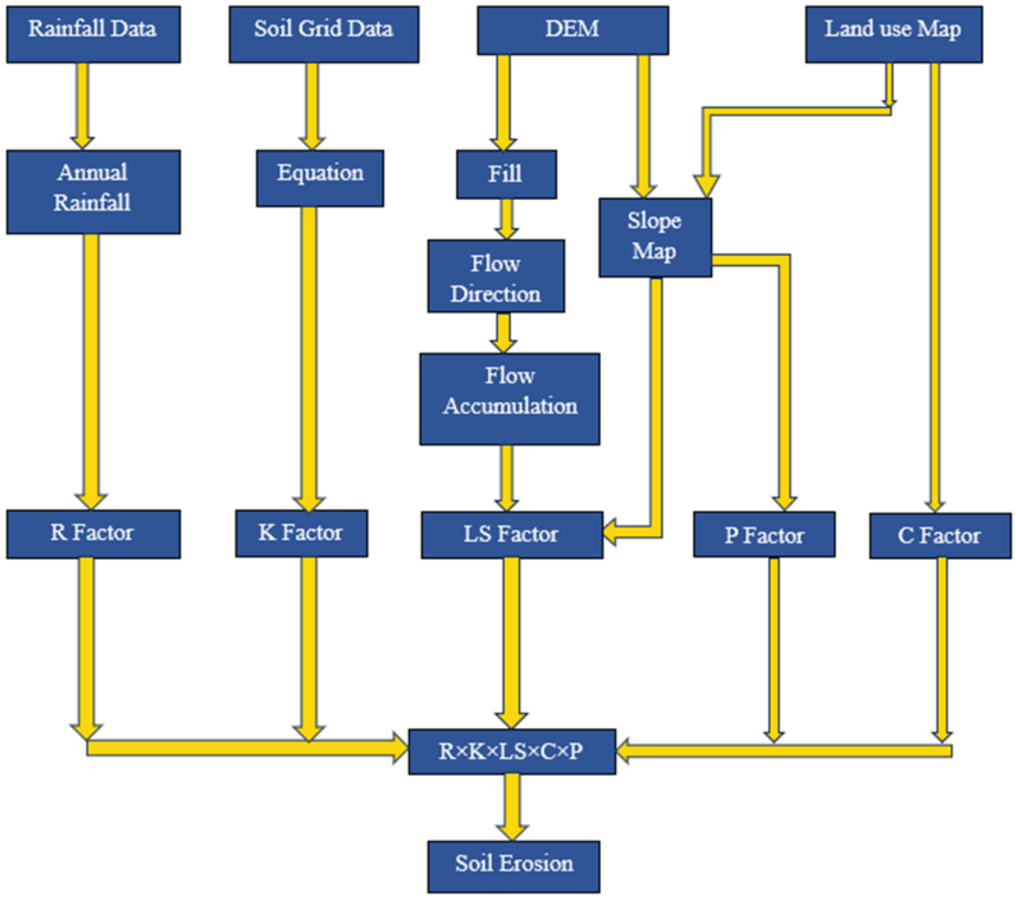

Figure 2. Methodology flowchart.

3. RESULTS AND DISCUSSION

The resulting spatial distribution maps provided a detailed understanding of vulnerable areas, aiding policymakers and land stewards towards effective conservation approaches.

3.1 Rainfall-Runoff Erosivity Factor (R)

Rainfall erosivity refers to the energy generated by the force of raindrops and the resulting flow rate. The R-factor, an average index over multiple years, quantifies the kinetic energy and force of rainfall. It serves to characterize the influence of rainfall on sheet and rill erosion. Rainfall erosivity holds significant importance due to its role as the primary catalyst for erosion, directly affecting the detachment of soil particles. The average rainfall data from four rain gauge stations was considered for estimation of R factor. Of this rain gauge stations, Ottappalam has higher R value and Chittur has lowest R value.

The following Table 3 provides the latitude, longitude, and corresponding R factor for each rain gauge station within the Gayathripuzha river basin.

Table 3. Latitude, Longitude and R Factor of Rain gauge stations

Place	Latitude	Longitude	R Factor
Alathur	10.63	76.55	833.6293
Chittur	10.7	76.73	699.3875
Kollengode	10.62	76.72	792.8709
Ottappalam	10.78	76.38	1246.5920

In the assessment of the R-factor based on rainfall data, it was observed a range of values spanning from 746.031 to 1222.35 MJ mm ha^{-1} h^{-1} y^{-1} with a mean of 863.168 MJ mm ha^{-1} h^{-1} yr^{-1}, where higher R value indicates increased rainfall to contribute to soil erosion. The results highlight the dynamic nature of rainfall erosivity over the study period under consideration. Figure 3 shows the R Factor Map. It was already reported that [26] the Palakkad District has the highest proportion of land area, with 50.62% falling within the R factor range of 1000-1250, and 25.66% within the range of 750-1000. R factor values in the study area falls in the same range.

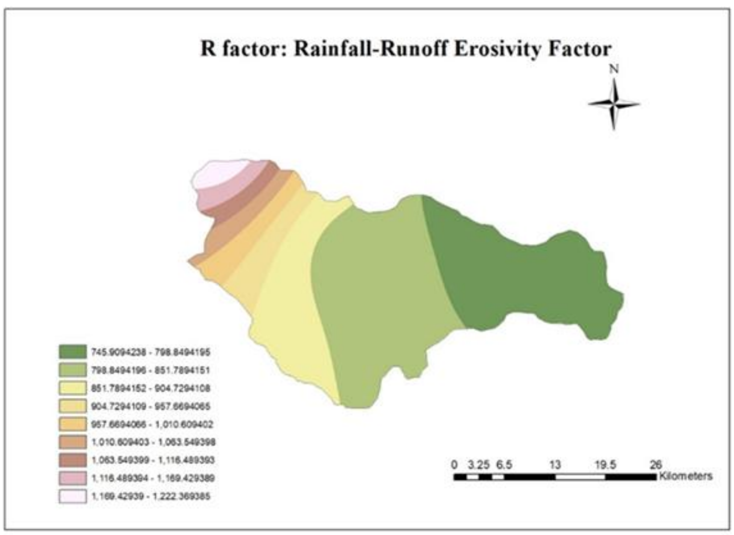

Figure 3. Rainfall-runoff erosivity factor (R Factor) Map

3.2 Soil Erodibility Factor (K)

The soil erodibility factor, often denoted as the K-factor, serves as a numerical representation of a soil's inherent susceptibility to erosion. In essence, the K-factor provides a measure of how prone a specific soil is to erosion, considering factors like particle detachment and transport under the influence of precipitation and runoff. The study area being analyzed demonstrates a variety of K factor values, ranging from 0.029 to a lower value of 0.0072 t ha h ha^{-1} MJ^{-1} mm^{-1}.This variation implies differing degrees of erodibility within the region, with some soils being more resistant to erosion (lower K values) and others more susceptible (higher K values) By examining the outcomes, it is evident that the K factor is lower in regions with high clay content, and conversely, higher in areas with lower clay content. The K factor values give us important information about how likely the soil is to erode. K Factor Map is shown in Figure 4.

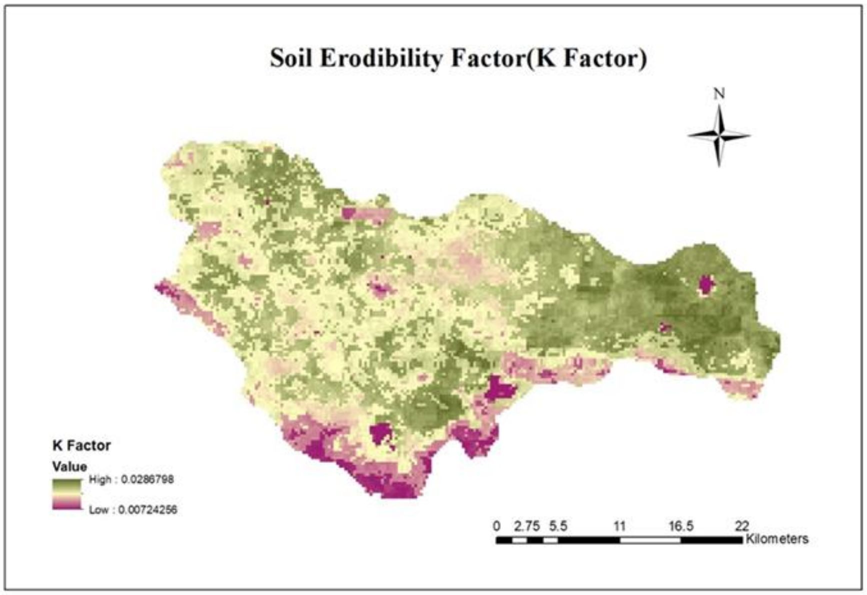

Figure 4. Soil Erodibility (K Factor) Map.

3.3 Slope Length and Slope Steepness Factor (LS)

The LS factor quantifies the extent to which both the length and steepness of a slope contribute to the likelihood of soil erosion. Higher LS values generally imply a greater risk of erosion. When using the RUSLE equation, a higher LS factor suggests that the combination of slope length and steepness increases the vulnerability of a particular area to soil erosion, and erosion estimates will be higher in such locations. The LS factor for the Gayathripuzha river basin varies between 0 and 9.66 with a mean of 0.911 (Figure 5). Areas with high LS values are typically found in regions with elevated terrain and steep slopes. This observation is supported by the slope map generated during the estimation of the S Factor (Figure 6), where regions with higher slope percentages correspond to higher LS values. This relationship can be observed by comparing both Figure 5 and Figure 6.

The Table 4 illustrates the slope percentages within the study area alongside the corresponding land area. It indicates that only a small portion of the highland ecosystems are present in the region under consideration.

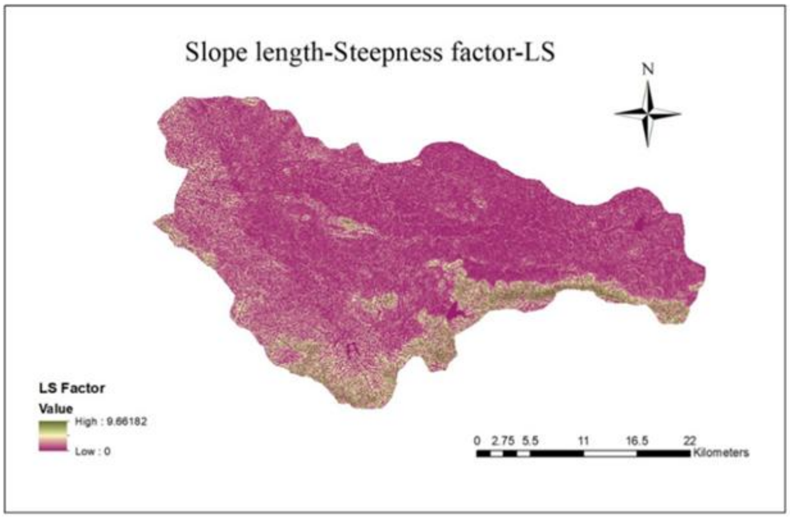

Figure 5. Slope Length and Slope Steepness Factor (LS).

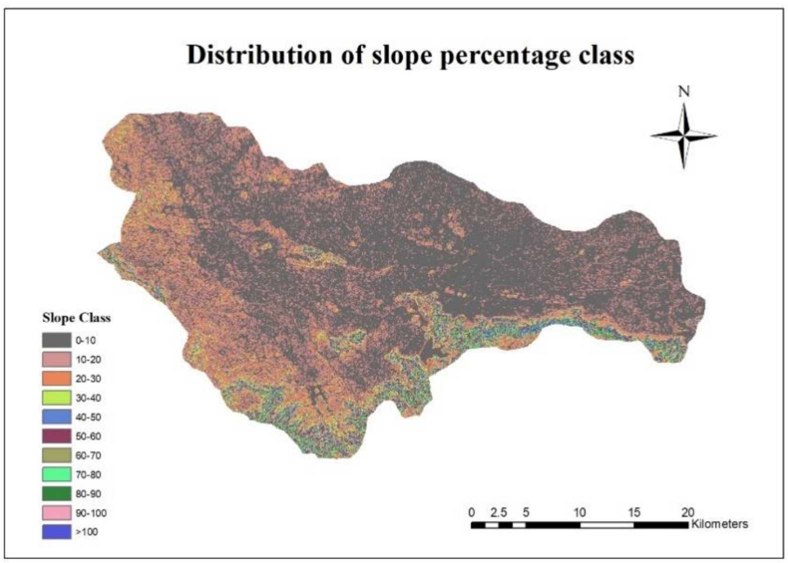

Figure 6. Distribution of Slope percentage class in the study area.

Table 4. The percentage of slope within the research area

Slope Class	Area (in Ha)	Percentage Area (%)
0 to 10	52756.23	55.31
10 to 20	22278.66	23.36
20 to 30	7780.02	8.16

30 to 40	4165.14	4.37
40 to 50	3045.72	3.19
50 to 60	2301.61	2.41
60 to 70	1448.52	1.52
70 to 80	820.00	0.86
80 to 90	401.50	0.42
90 to 100	197.16	0.21
>100	184.68	0.19

3.4 Cover management factor (C)

The crop or land cover management factor (C) evaluates the overall impact of diverse crop covers and land management practices. It evaluates how effectively vegetation protects the soil from the force of raindrops. The C factor represents the comparison of soil loss from cultivated land under specific conditions to that from clean-tilled, continuously fallowed land [10].

The Cover Management Factor (C Factor) map of the study area indicates values ranging from 0 to 0.95. Zero value of C Factor suggests minimal vulnerability to soil erosion, likely due to effective cover or management, while a C Factor of 0.95 suggests a higher vulnerability to erosion, possibly due to insufficient cover or poor management practices. In essence, the values on the map represent the relative impact of land cover and management practices on soil erosion, with lower values indicating better protection against erosion. C factor map is shown in Figure 6. On comparing the Land use map (Figure 7) with the C Factor Map, it is apparent that there is a relationship between Land use and the C Factor. Specifically, forested areas display lower values, while bare ground areas exhibit higher values.

3.5 Conservation Practice Factor (P)

The conservation practice factor (P) signifies the ratio of soil loss under specific supportive practices compared to soil loss under conventional up and downslope tillage methods [9]. It reflects the effectiveness of support practices in mitigating soil loss by modifying the flow characteristics, slope, or trajectory of surface runoff, and by reducing the runoff rate.

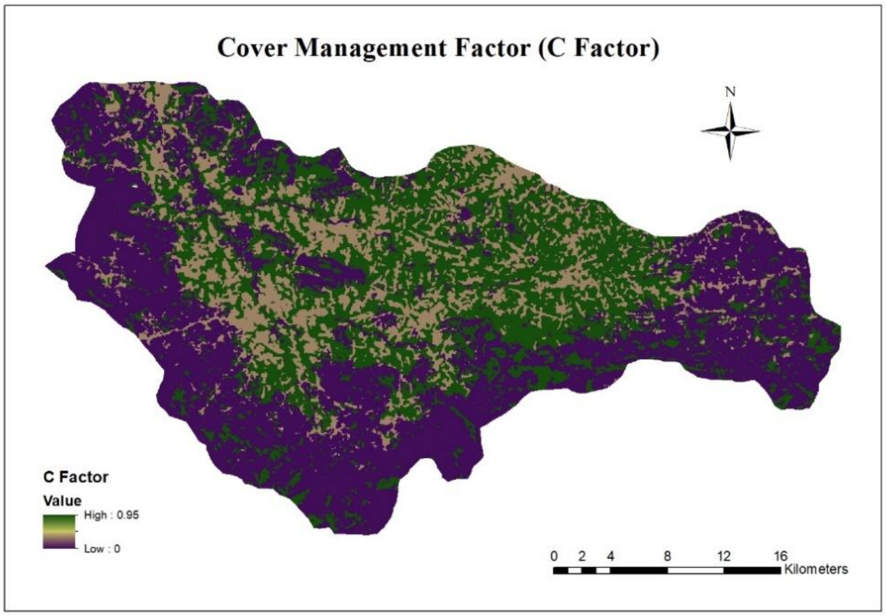

Figure 7. Cover Management Factor (C Factor) map

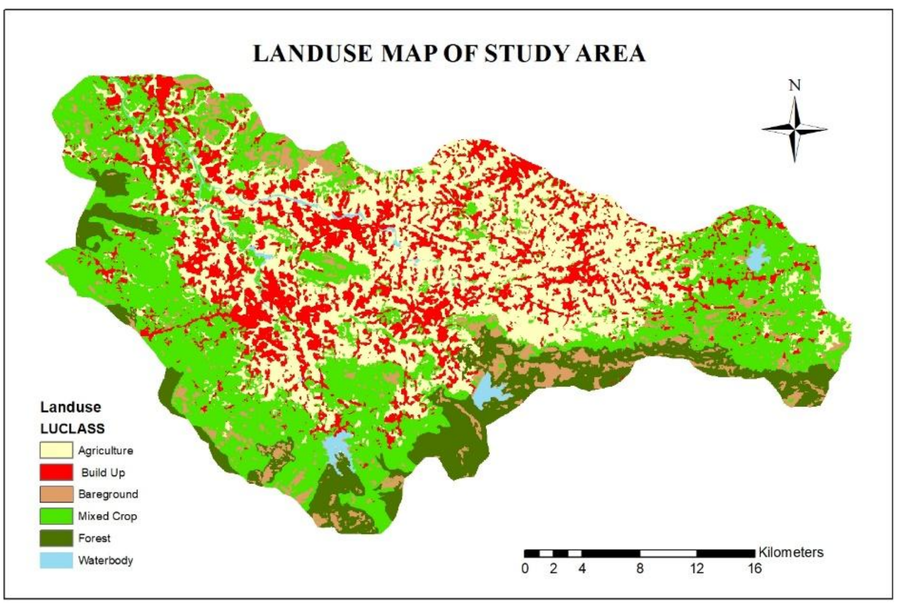

Figure 8. Landuse Map of Gayathripuzha River Basin.

In the study, the conservation practice factor ranges from 0.1 to 1. A lower P factor, such as 0.1, indicates strong soil preservation, suggesting the effective execution of strategies to mitigate erosion. Conversely, as the P factor approaches 1, it signifies a diminishing effectiveness of conservation measures, resulting in an elevated potential for soil erosion. Figure 8 displays the map of the P Factor. The P Factor tends to be lower for agricultural land use, indicating effective conservation practices, and increases with steeper slopes. However, for land uses other than agriculture, the P factor remains constant at 1 regardless of the slope.

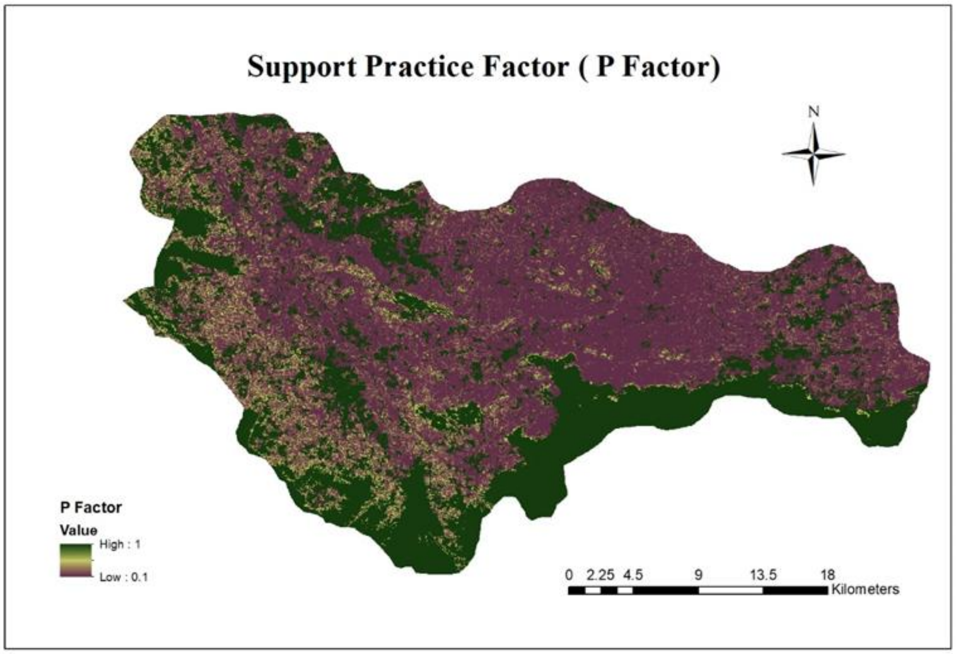

Figure 9. Conservation Practice Factor (P Factor) map.

3.6 Soil Erosion Estimation

The average annual soil erosion measurement ranges from 0 to 133.18 t ha^{-1} y^{-1} within the research site. Specifically, only 5.6% of the entire study area has a slope percentage exceeding 50%, and it is in this particular area that the average erosion rate is notably high. The erosion map is presented in Figure 10. Soil loss class and corresponding area is given in Table 5.

The slope percentage is categorized using the reclassify tool for intervals of 10, and the erosion data is spatially linked with these slope classes. Observing the Table 6, it is evident that the mean erosion increases with higher slope percentages. However, a slight decrease is observed in areas with slope percentages greater than 100, primarily due to the prevalence of rocky terrain.

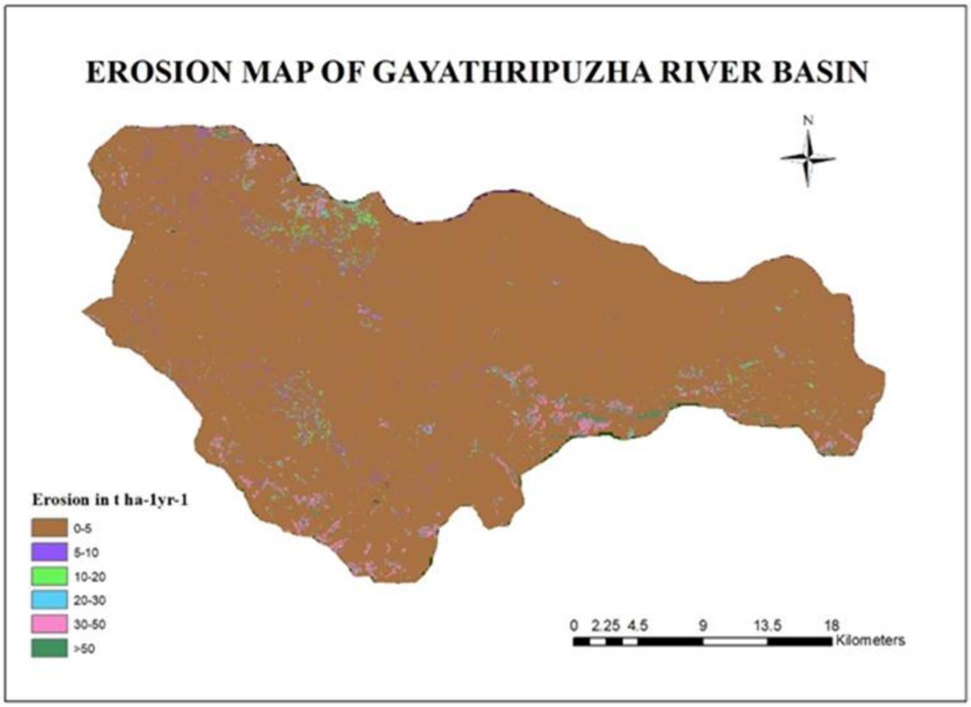

Figure 10. Soil Erosion Map of Gayathripuzha River Basin

Table 5. The distribution of soil loss classes across the study area

Soil Loss ($tha^{-1}y^{-1}$)	Erosion Class	Area (in Ha)	Area (%)
<5	Slight	90551.36	94.94
5 to 10	Moderately Slight	1424.99	1.49
10 to 15	Moderate	423.42	0.44
15 to 20	Moderately Severe	242.14	0.25
20 to 40	Severe	1161.01	1.22
>40	Very Severe	1576.31	1.65

Table 6. The distribution of slope classes across the study area

Slope Class (%)	Area (ha)	Mean Erosion ($tha^{-1}y^{-1}$)
0 to 10	52756.23	0.64
10 to 20	22278.66	1.47
20 to 30	7780.02	2.31
30 to 40	4165.14	3.49
40 to 50	3045.72	5.22
50 to 60	2301.61	9.26
60 to 70	1448.52	14.84

70 to 80	820.00	19.23
80 to 90	401.50	21.77
90 to 100	197.16	22.55
>100	184.68	21.95

Similarly, the spatial integration of land use with erosion yields the following result. Bare ground exhibits the highest erosion due to the absence of any soil cover, leading to an increased impact of erosion agents. Agricultural land use, primarily situated in flat areas and predominantly experiencing deposition rather than erosion, exhibits a lower mean erosion rate.

To mitigate the impact of soil erosion some recommendations can be made based on the observed results, depending on terrain characteristics, land use, and slope. In flat areas with gentle slopes, it is recommended to implement agronomic techniques like intercropping, mulching, and contour terraces. For regions with slopes between 6-7%, graded bunds and vegetated waterways are suggested. In arable lands where slopes exceed 10%, bench terracing is recognized as the most efficient conservation approach as similar to suggestions given by Naidu et al., 2014 [25]. Non-arable lands can be improved through slope stabilization methods such as contour trenching, retaining walls, and gully treatment like check dams.

4. CONCLUSIONS

The comprehensive analysis of various erosion factors, including Rainfall-runoff erosivity (R), Soil Erodibility (K), Slope-length (L), Slope-steepness (S), Cover Management (C), and Conservation Practice (P) factors, has provided detailed understanding into the intricate mechanisms of soil erosion across the study region. The R-factor, derived from rainfall data, showcased a range from 746.031 to 1222.35 MJ mm ha^{-1} h^{-1} y^{-1}, highlighting the diverse kinetic energy and intensity of precipitation over the specified period. This extensive variation underscores the nature of rainfall erosivity, which serves as a primary catalyst for soil erosion. The Soil Erodibility (K-factor) exhibited considerable variability, varying from 0.0072 to 0.0287 t ha h ha^{-1} MJ^{-1} mm^{-1}. This signifies differing degrees of erodibility within the region, with some soils displaying higher resistance to erosion (lower K values) and others being more susceptible (higher K values). The specific K-factor values offer valuable insights into the inherent erosion susceptibility of different soil types, aiding in the targeted comprehension and mitigation of soil erosion across the study area. The LS factor, considering both slope length and steepness, ranged from 0 to 9.66, with higher values indicating a greater vulnerability to erosion. This factor is essential for evaluating the risk of erosion and guiding the implementation of effective erosion control measures. The distribution of slope percentages in the study area further contributes to this understanding, with areas exceeding 50% slope percentage exhibiting elevated erosion rates. Land use analysis revealed distinctive patterns, with bare ground displaying the highest erosion rates, followed by forests. Other land classes, primarily located in plains, exhibited comparatively lower erosion rates. The Cover Management (C) Factor, ranging from 0 to 0.95, provides insights into the degree of soil surface cover and management practices, influencing erosion vulnerability. Similarly, the Conservation Practice (P) Factor, ranging from 0.1 to 1, assesses the efficiency of land management techniques in mitigating erosion.

In the final erosion estimation, the overall soil erosion measurement ranged from 0 to 133.18 t ha^{-1} y^{-1}, with areas having slope percentages exceeding 50% contributing significantly to the elevated erosion rates. These findings collectively emphasize the need for targeted and multifaceted conservation strategies that consider the interplay of rainfall characteristics, soil attributes, landscape features, land cover, and management approaches to effectively address and manage soil erosion within the diverse landscape of the study region.

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