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Integration of GIS and remote sensing with RUSLE model for estimation of soil erosion

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Abstract
Soil erosion, a major environmental hazard caused mostly by natural forces but exacerbated by human activities, requires appropriate management measures. Soil erosion in the Upper Krishna subbasin, Maharashtra state, India, which encompasses 5422.20 km^2, was examined utilizing a rigorous methodology that includes the RUSLE (Revised Universal Soil Loss Equation), Remote Sensing data, and GIS (Geographic Information System) technologies. The spatial variation of annual soil loss erosion was determined by combining raster-derived parameters in a GIS environment. Using ArcGIS 10.3.1, thematic layers were created, including maps of the rainfall erosivity factor, soil erodibility factor, slope length and steepness factor, cover and management factor, and support and conservation practice factor. The analysis further reveals that the Upper Krishna sub-basin experiences an annual average soil loss of approximately 23,663 tons for total watershed area, as per the RUSLE model. In comparison to other areas, the western portion of the study area was projected to have higher annual soil erosion, ranging from 100 t/ha/yr to 200 t/ha/yr. Because of the higher slope and significant rainfall, the western hill portion of the basin was also anticipated to have very high annual soil erosion (>200 t/ha/yr). The eastern and central portions of the research area, which include the majority of the agricultural land, were assessed to have low to low annual soil erosion (0 to 50 t/ha/yr).

Keywords: Soil erosion, RUSLE, GIS, remote sensing, upper Krishna

Introduction

An important environmental and socioeconomic problem is soil erosion, a natural process made worse by human activity. The average rate of soil erosion worldwide is 12 to 15 t/ha/yr (Ashiagbor *et al.*, 2013) [1]. Soil degradation, agriculture, river sedimentation, reservoir siltation, floods, and landslide hazards are all significantly impacted by soil erosion in India. Soil erosion affects over 130 million hectares, or 45% of India's total land area (Kothyari, 1996) [10]. Because of erosion, the state of Maharashtra loses over 773.5 million tonnes of soil annually (Shejale *et al.*, 2022) [15]. In many regions of the world, erosion could increase in the future due to significant climate change that alters the hydrologic cycle.

Numerous models with differing levels of complexity are available for estimating soil loss from water erosion. These models fall into three main categories: physical-based, conceptual (partially empirical or mixed), and empirical. Examples for the first two groups include the empirical Universal Soil Loss Equation (USLE) and its modifications, such as the Modified Universal Soil Loss Equation (MUSLE), the Revised Universal Soil Loss Equation (RUSLE), and some more comprehensive models, such as ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation), MODANSW (Modified ANSWERS), and CREAMS (Chemicals, Runoff, Erosion from Agricultural Management Systems).

Wischmeier and Smith developed the USLE, one of the most frequently used and recognized empirical models for assessing soil loss, in 1978. Renard and Freimund (1991) [12] first proposed RUSLE, which was then expanded to incorporate new research results and experimental data, improving our comprehension of erosion processes. To increase the equation's accuracy and applicability, several elements have been refined while maintaining the equation's basic structure. Among these changes are an improved smoothing of the R iso-erodent map and a new R-factor with filling of data gaps. Additionally, a seasonal approach for the soil erodibility factor (K) and the impacts of rainfall on ponded water have been taken into account.

In order to better reflect the interaction between rill and inter-rill erosion, the modified equation takes into account parameters related to both slope length (L) and steepness (S). The updated C factor represents a continuous function that incorporates multiple elements, including previous land use, surface cover, crop canopy, surface roughness, and soil moisture. This improved method uses sub-factors to evaluate the cover-management factor. Additionally, the model adds new conservation-practice values, broadening the P-factor's application to rangeland, contouring, strip-cropping, and terracing situations (Renard *et al.*, 1991) [12]

The RUSLE has been used in numerous research to quantify soil erosion and pinpoint erosion hotspots in different parts of India and globally (Jiang *et al.*, 2015; Getu *et al.*, 2022). Estimating soil erosion and its spatial distribution on a greater scale is both feasible and economical when the RUSLE is integrated with GIS and remote sensing techniques (Chatterjee *et al.*, 2014; Jiang *et al.*, 2015; Kashiwar *et al.*, 2021) [3, 7, 9]. For instant, Thapa (2020) used the RUSLE model to investigate soil erosion in Nepal's Dolakha District. The study calculated that steep slopes cause severe erosion rates of 80 t/ha/yr in about 5.01% of the area, while high to severe erosion rates range from 10 Mg/ha/yr to 80 Mg/ha/yr in about 10% of the region. Moderate to low levels of erosion were seen in the remaining 15-70% of the area. In Punjab, India, Sharma *et al.* (2022) [14] used both RUSLE and GIS to analyze soil erosion in the Sutlej sub-basin. Only 0.75% of the region had very significant erosion, according to their findings. In a semi-arid area in Maharashtra, Maury *et al.* (2019) [11] used RUSLE and GIS to conduct a thorough mapping of soil erosion. About 4.3 and 2.4% of the region, respectively, were at high and severe risk of soil loss, according to this study.

Remote sensing and GIS are being used extensively these days to estimate soil erosion and identify regions that are vulnerable to water erosion. When combined with GIS and remote sensing methods, a hydrological model has enormous promise for determining soil loss, locating hotspots for erosion, and detecting the spatial spread of erosion. It is now feasible to predict erosion from a wide area in a shorter amount of time due to remote sensing and GIS applications. To assess soil loss due to water erosion, a digital elevation model (DEM) can be used to extract topographical features such slope of watershed, flow direction and accumulation, and drainage network.

By reducing the possible loss of soil, the basin area can be managed properly. This study's primary goal is to estimate soil erosion in the Upper Krishna sub-basin of Maharashtra State, India, by integrating remote sensing and GIS with the RUSLE model.

Materials and Methods

Upper Krishna basin having area of 5422.20 km^2 is situated in Satara district of Maharashtra state (Fig. 1) is selected for this study which is located between 17° 07 45" N 18° 03' 07" N latitude and 73° 34' 38" E to 74° 18' 42"E longitude. The altitude of the basin ranges from 1435 to 532 m.s.1. The mean annual rainfall of the basin is 1600 mm. June through September are the wet months for crop production since they get over 85% of the annual rainfall, with July and August receiving the highest amounts and the rest of the months November to February relatively considered as dry months.

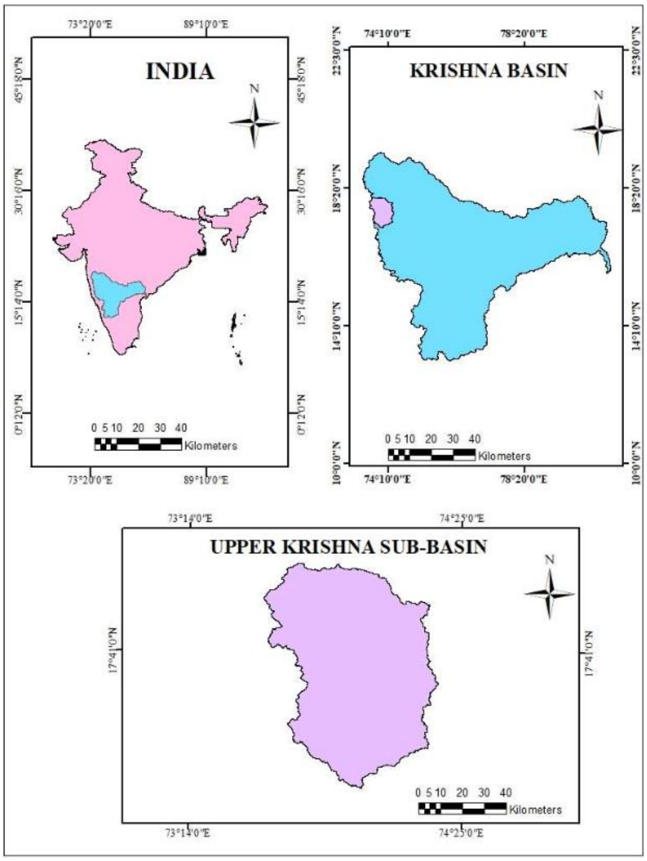

Fig 1: Location map of study area

Data collection

Slope and steepness factors were prepared using ASTER GDEM. The soil erodibility factor (K) was calculated using information on soil texture and organic carbon content from the soil map. The Support practice factor (P) was estimated using the Land Use Land Cover Map (LULC) map. Google Earth Engine created the LULC map (GEE). A map of the Normalized Difference Vegetation Index (NDVI) was created from a 30 m resolution Landsat 8 image (OLI TIRS). The research area's cover and management factors were computed using the NDVI map. In order to estimate the rainfall erosivity factor (R), annual rainfall was calculated using rainfall data from 12 stations within the study area from 1989 to 2018.

Table 1: Data source for the study

Sr. No.	Data	Source	Description
1.	DEM	https://earthexplorer.usgs.gov/	ASTER GDEM (30 m resolution)
2.	Soil map	National Bureau of Soil Survey and Land Use Planning, Nagpur	Soil texture and organic carbon
3.	Land use Land cover	https://earthengine.google.com	Landsat 8 image (OLI TIRS, 30 m resolution)
4.	Rainfall data	Hydrological Data User Group, Nasik	Daily rainfall data of 12 rain gauge stations (1989-2019)

Revised Universal Soil Loss Equation

The revised form of the USLE (Wischmeier and Smith 1978) is the RUSLE (Renard, 1997) [13]. The average annual soil erosion was calculated using the formula below:

$$A = R * K * LS * C * P \qquad (1)$$

Where,
A = soil erosion, t/ha/yr,
R = rainfall-runoff erosivity factor, MJ-mm/ha/h/yr,
K = soil erodibility factor, t.h/MJ/mm,
LS = slope length and steepness factor, dimensionless
C = cover and management factor, dimensionless and
P = Support and conservation practice factor, dimensionless.

Rainfall Erosivity Factor (R)

The rainfall erosivity factor (R), which measures the effect of raindrops, reflects the quantity and rate of runoff related to the rain. The rainfall distribution throughout the basin area was used to compute the R factor. The Inverse Distance Weighted (IDW) interpolation method in ArcToolbox was used to create the rainfall map. Since rainfall is irregularly distributed in area and time and is essential to the dynamics of soil erosion, it is imperative to analyze it. Thus, the updated equation (Eq.2) provided by Babu *et al.* (2004) for the Indian framework was utilized to overcome this issue.

$$R = 81.5 + 0.380\, P_a \qquad (2)$$

Where,

R = Annual rainfall erosivity index, MJ.mm/ha/yr, and

P_a = Annual rainfall, mm.

Soil Erodibility Factor (K)

This factor indicates the soil's susceptibility to erosion. The land and soil characteristics, soil texture, organic matter content, and unsaturated hydraulic conductivity are the primary determinants. Using the soil map and the following formula, K factors were determined for various soil taxanomy (Das *et al.*, 2021).

$$K = \frac{2.1 * 10^{-4}\,(12 - \mathrm{OM})M^{1.14} + 3.25\,(s - 2) + 2.5\,(p - 3)}{759.4} \qquad (3)$$

Where,
K = soil erodibility, t/h/MJ/mm,
OM = percentage organic matter,%,
s = soil structure code,
p = soil permeability code, and,
M = function of the primary particle size fraction and given by;

$$M = (\%\ \text{Silt} + \%\ \text{Very fine sand}) \times (100\%\ \text{clay}) \qquad (4)$$

Slope length and steepness factor (LS)

It shows the proportion of soil loss at a place under given conditions compared to standard conditions. Slope length and steepness layer were created for the purpose of generating topographic factor (LS) using the following equation (Kashiwar, 2021) [9];

$$LS = Power(flow\,accumulation * \frac{cell\ size}{22.13}, 0.4) * Power(\frac{\sin(slope\,0.01745)}{0.09}, 1.4) * 1.4 \qquad (5)$$

where,
LS = combined slope-length and slope-steepness factor,
Flow Accumulation = accumulated upslope contributing area for a specific cell,
Cell Size = size of the grid cell and
Sin slope = sin of slope angle in degrees.

Cover and Management factor (C)

The effectiveness of crop and soil management techniques in preventing soil loss is assessed using this factor. Since they are regarded as unprotected barren terrain, higher C factor values suggest greater susceptibility to soil erosion. In this work, the normalized difference vegetation index (NDVI) was computed using the ArcGIS map algebra toolset on Landsat 8 satellite images (30 m spatial resolution). The NDVI and equation (6) were used to determine the C factor. This equation has been effectively applied by numerous researchers to determine the regional distribution of the C factor (Vatandalar and Yavuz 2017).

$$C = \frac{(-NDVI + 1)}{2} \qquad (6)$$

Where,
C = cover and management factor, and,
NDVI = normalized difference vegetation index

Support and Conservation Practice Factor (P)

The support practice (P) factor indicates the rate of soil erosion as a result of agricultural practices (Wischmeier and Smith, 1978; Renard *et al.*, 1997) [13]. It explains how different support techniques, such terracing, stone walls, and contour farming, affect soil loss overall at a particular location. The P factor map has been estimated using the study's land use and land cover data. In general, low P values show that conservation methods are successful in reducing soil erosion, while higher values point to less-than-ideal conservation strategies.

Fig. 2 Shows the flowchart of methodology for estimation of soil erosion using RUSLE.

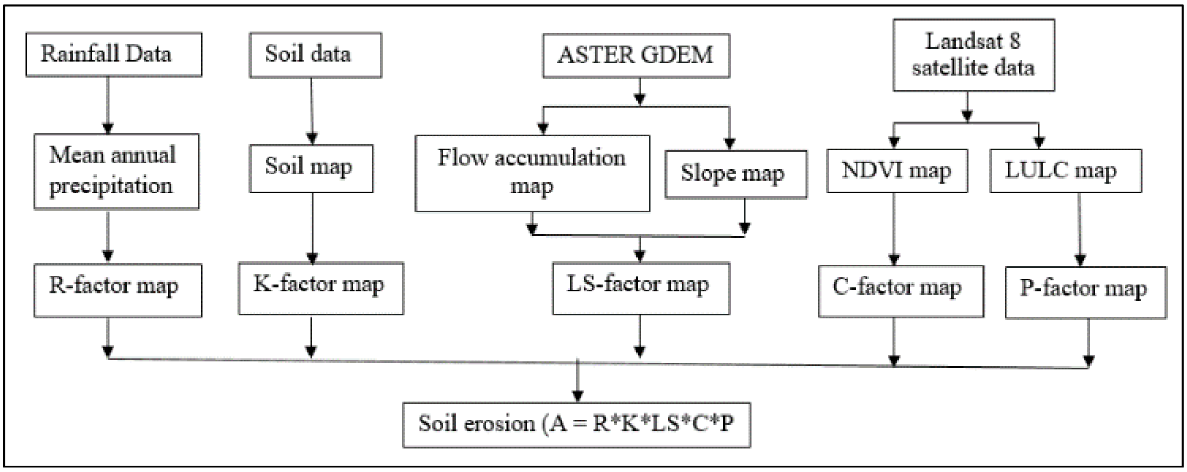

Fig 2: Flowchart of methodology for estimation of soil erosion

Results and Discussion

RUSLE parameters

1. Rainfall Erosivity Factor (R)

The rainfall map was created using daily rainfall data from 12 stations over a 30-year period (1989-2018) (Fig.3). The watershed receives an average of 87.993 mm to 5465.54 mm of rainfall annually. According to Figure 4, the predicted R-factor values varied from 114. 937 to 2158.41 MJ.mm/ha/h/yr. The western part of the basin received more rainfall than the eastern part. The erosive power is most noticeable in the western portion of the watershed, where hills dominate. The distribution of rainfall and the erosivity factor are positively correlated; when rainfall decreases, the watershed's erosive power also decreases (Fig. 3 and Fig. 4)

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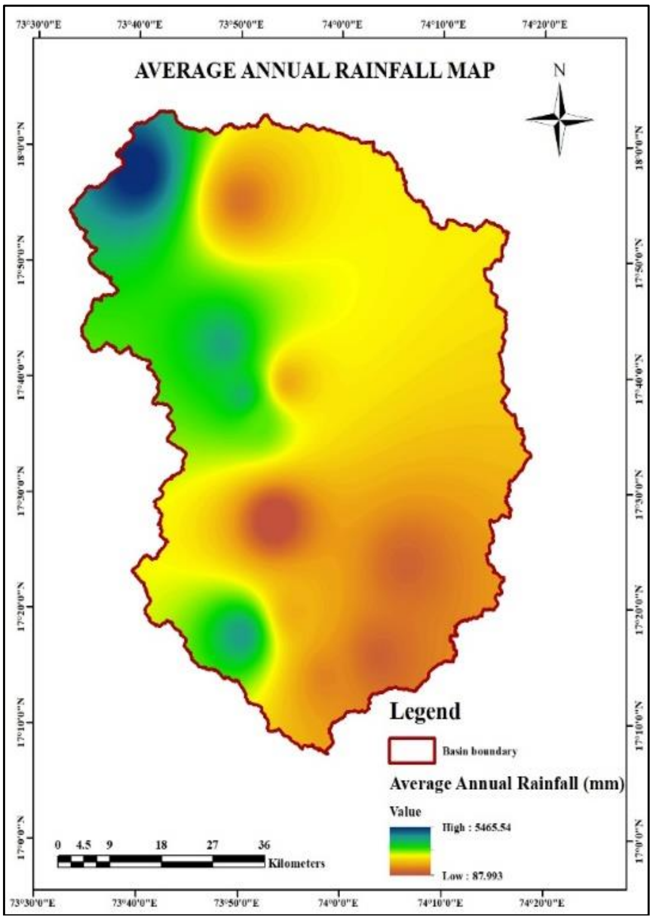

Fig 3: Rainfall map of study area

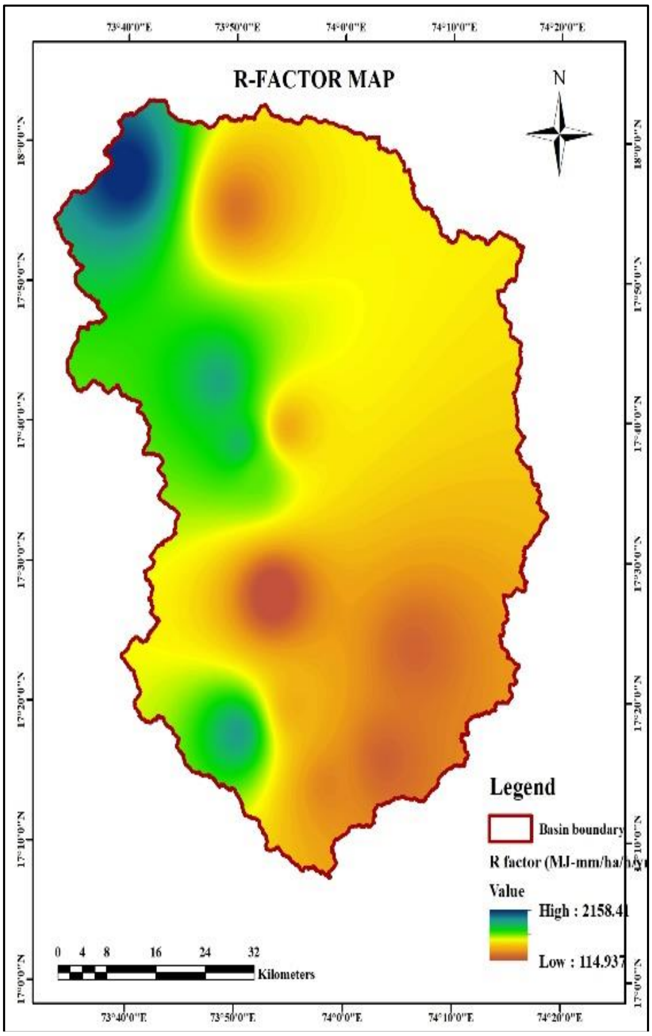

Fig 4: R-factor map of study area

2. Soil Erodibility factor (K)

There are five distinct soil taxonomy types found in the Upper Krishna sub-basin: Lithic Ustorthents, Typic Chromusterts, Typic Ustorthents, Typic Ustropets, and Udic Rhodustalfs (Fig. 5). According to Figure 6, the K values varied from 0.2067 to 0.2759 t.h/MJ/mm. The research area contains clay, clay loam, and loam-textured soils.

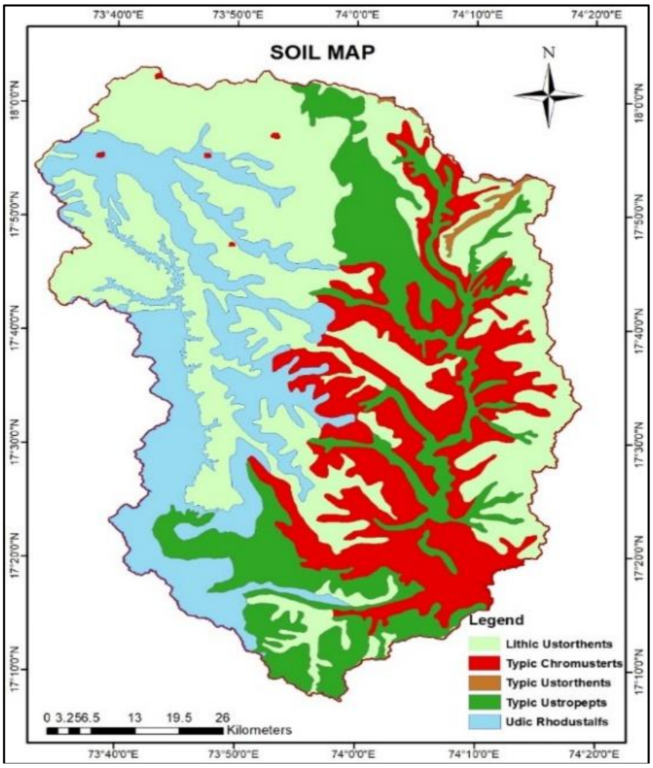

Fig 5: Soil map of study area

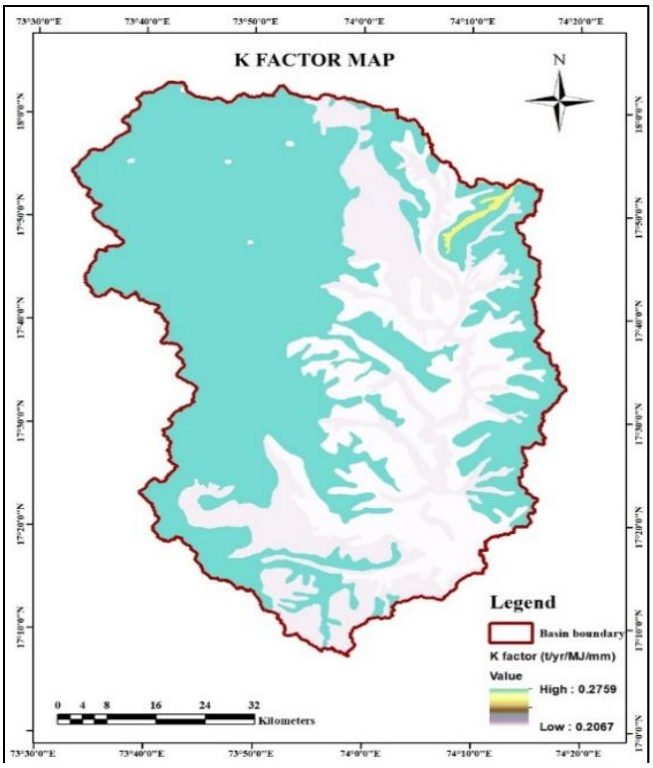

Fig 6: K-factor map of study area

3. Slope length and steepness factor (LS)

Based on flow accumulation and slope (degree), the study area's slope length and steepness factor map was created. 0 to 66.040 is the range of the basin slope (Fig. 7). The study area's topographic factor ranges from 0 to 114.298 (Fig. 8). High slope length and steepness values tend to accelerate soil erosion since they directly increase the erosive force of water. On the other hand, when LS are low, erosion is probably going to decrease. The western portions of the research area have a steeper slope. Additionally, areas with a high potential for runoff and, consequently, a high rate of soil erosion are identified by the slope map. The LS-factor values are higher in the basin's western region. A comprehensive investigation of all soil loss factors indicates that the LS-factor significantly influences the estimation of total soil loss in the study area.

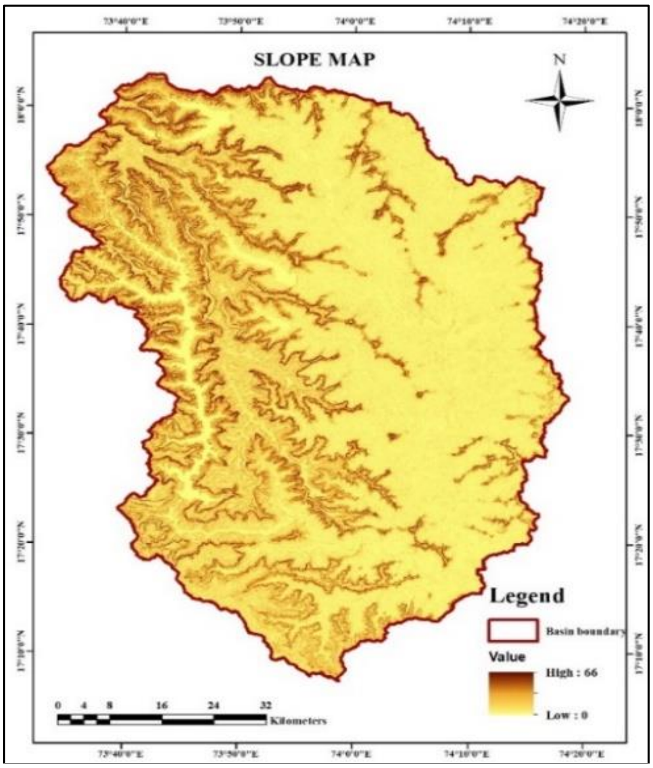

Fig 7: Slope map of study area

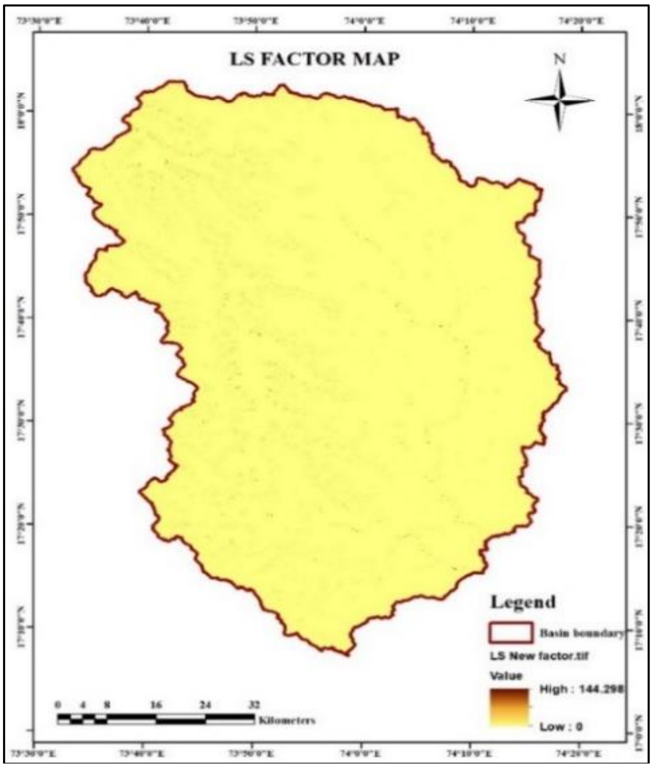

Fig 8: LS-factor map of study area

4. Cover and management factor (C)

The most important factor in determining the C-factor is the NDVI. The research area's NDVI values ranged from-0.28

to 0.53 (Fig. 9). Dense forests are indicated by high NDVI values, while bare surface cover and soil erosion vulnerability are indicated by low values below 0.1. The results showed that the C-factor values were lower in the western part of the study area, which is characterized by the presence of forests (Fig. 10). In the middle and eastern regions of the research area, the C-factor values were greater. Well-protected land has a C-factor value closer to zero, whereas barren land has a value closer to one.

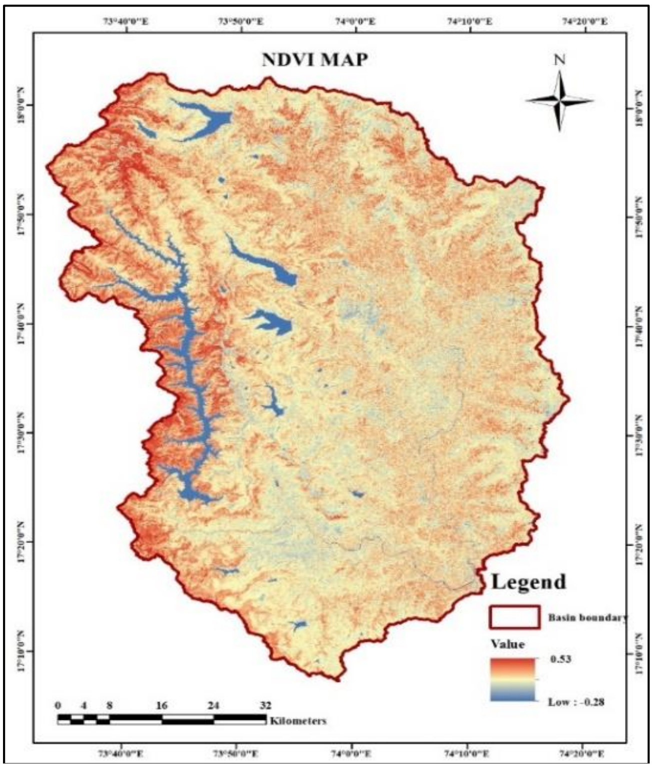

Fig 9: NDVI map of study area

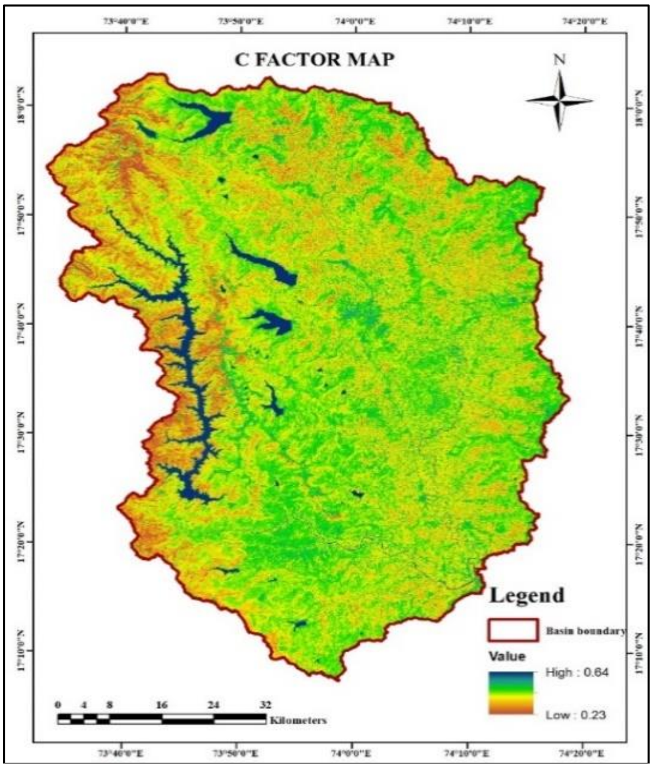

Fig 10: C-factor map of study area

5. Support and conservation practice factor (P)

In comparison to the other basin region, the western side of the research area has a high P-factor and is located in a high elevation (Fig. 12). Since soil loss increases with decreasing P-factor, most of the region's land is highly cultivated and susceptible to erosion. Based on values suggested by Hann *et al.* (1994), P-factor values for various land use and land cover were allocated.

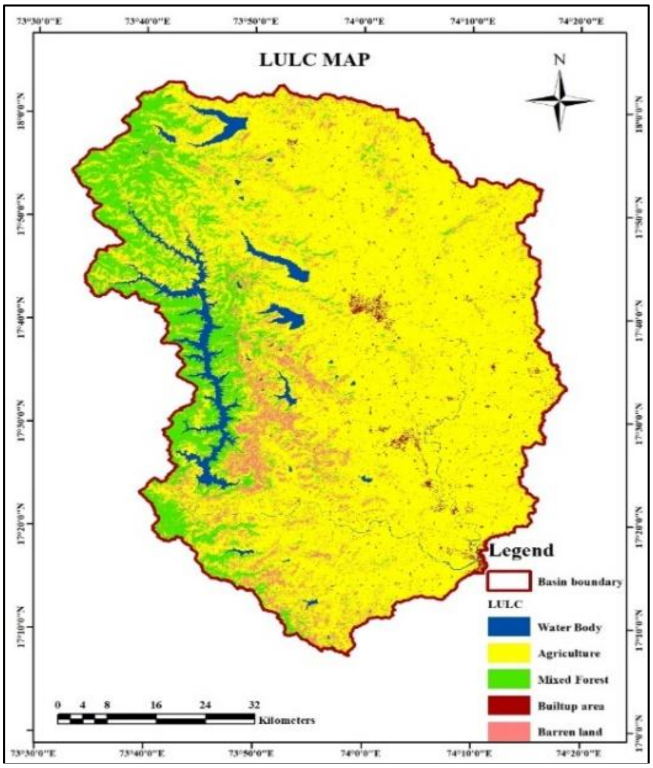

Fig 11: LULC map of study area

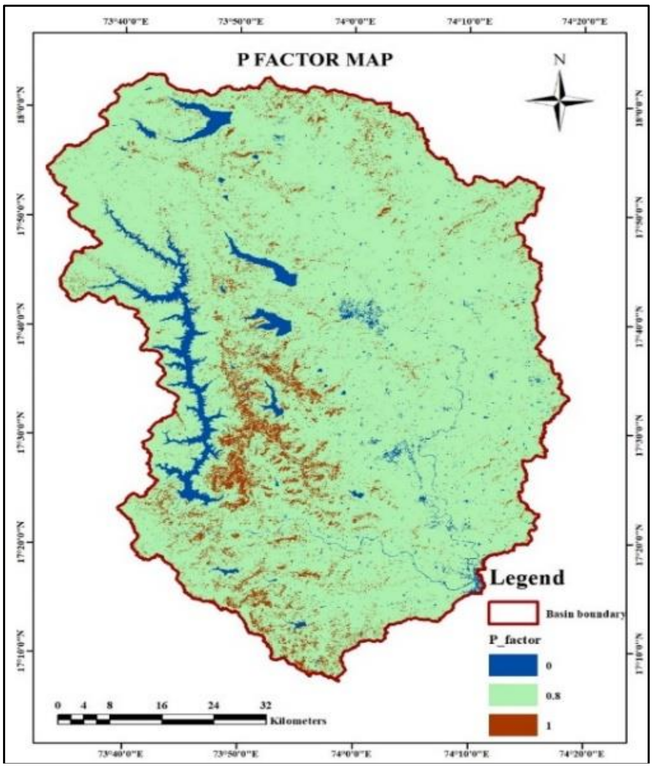

Fig 12: P factor map of study area

Estimation of annual soil erosion

In order to identify locations that are susceptible to soil erosion, the Upper-Krishna sub-basin's annual soil erosion map was estimated using a combination of the GIS and RUSLE model (Fig. 13). The Food and Agriculture Organization (FAO) of the United Nations established a classification system for soil erosion maps, which separated them into five categories: very low (<10 t/ha/yr), low (10-50 t/ha/yr), moderate (50-100 t/ha/yr), high (100-200 t/ha/yr), and very high (>200 t/ha/yr) (FAO, 1979). The analysis further reveals that the Upper Krishna sub-basin experiences an annual average soil loss of approximately 23,663 tons in 5422.20 km^2 area. In comparison to other areas, the western portion of the study area was projected to have higher annual soil erosion, ranging from 100 t/ha/yr to 200 t/ha/yr. Because of the higher slope and significant rainfall, the western hill portion of the basin was also anticipated to have very high annual soil erosion (>200 t/ha/yr). The eastern and central portions of the research area, which include the majority of the agricultural land, were assessed to have very low to low annual soil erosion (0 to 50 t/ha/yr).

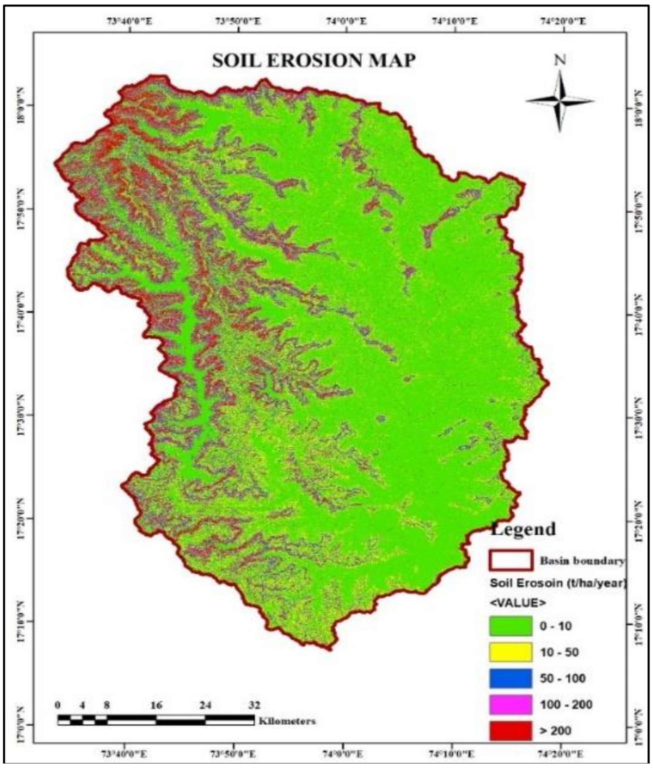

Fig 13: Soil erosion map of study area

Conclusions

This work focuses on estimating soil erosion in the Upper Krishna sub-basin in Maharashtra state, India, using the RUSLE model in conjunction with remote sensing and GIS. According to analysis, the RUSLE model estimates the average annual soil loss is approximately 23,663 tons for total watershed area. Significant differences in soil erosion caused by topography and land use/cover variables are found in the study. The erosion severity map indicated that the western portion of the study region experienced higher annual soil erosion, ranging from 100 to 200 t/ha/yr, in comparison to other areas of the study area. Additionally, the western hill portion of the basin was anticipated to have very high annual soil erosion (>200 t/ha/yr). The eastern and central portions of the study area, which comprise the majority of the agricultural land, have very low to low annual soil erosion estimates, ranging from 0 to 50 t/ha/yr. The rate of soil erosion is higher on steeper slopes than on moderate slopes. Areas with increased rainfall are also worth mentioning. It is necessary to apply suitable soil conservation techniques in these situations. According to this study, GIS is a helpful tool for estimating erosion loss and evaluating soil erosion. The findings can undoubtedly help with the use of conservation and soil management techniques to lessen soil erosion in the Upper Krishna sub-basin, which has a significant area of forest and agricultural land.

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