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Spatiotemporal soil erosion assessment using RUSLE model on geospatial platform for Maharashtra state

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ABSTRACT

Soil erosion is one of the most serious problems arising from agricultural intensification, desertification, deforestation, landform degradation and other anthropogenic activities. The soil erosion assessment is essential in planning conservation activities. The erosion modeling can provide a quantitative approach to estimate soil erosion. The present study was focused to estimate the vulnerability of soil loss by using revised universal soil loss equation (RUSLE) for the state of Maharashtra, India. The parameters of RUSLE model were estimated using geospatial technology. For the years 2000 and 2011, the estimated R factor were found to be varying from 220.21 to 1496.84 (MJ-mm $ha^{-1}hr^{-1}yr^{-1}$) and 301.51 to 1509.6 (MJ-mm $ha^{-1}hr^{-1}yr^{-1}$), while the average K factor was observed to be 0.007 and 0.107, respectively. The slope-length factor was varying from 0.029 to 45344.024. The results of the study showed that 80% area of Maharashtra were having the soil erosion rate in the range of 0-10 (t $ha^{-1}yr^{-1}$) but the corresponding area had been declined by about 3.23% in the period of 2000 to 2011. The area having soil erosion vulnerability greater than 40.0 (t $ha^{-1}yr^{-1}$) had increased by about 32% in period of 11 years, which lies in the western coastal part and to some extent in the Northern coastal part of Maharashtra. The average soil erosion rate had increased by about 9% in the eleven years period, which needs very careful attention for appropriate soil and water conservation measures. The results of this study can certainly aid in implementation of soil management and conservation practices to reduce the soil erosion in the study region.

1. INTRODUCTION

Erosion is a natural and a geological phenomenon, which results from the transportation of soil particles by water or wind. Land degradation, especially in agricultural land due to soil erosion, is a worldwide known phenomenon that leads to the loss of nutrient-rich surface soil with high increased in surface-runoff and decreased availability of water to roots of plants. The total land area subjected to human-induced soil degradation is estimated to about 2 billion hectares. Out of the 2 billion hectares, it is estimated that the water erosion has degraded about 1100 M ha of land and nearly 550 M ha of area is affected by wind erosion (Saha, 2003).

The erosion process is affected by numerous variables, both man-made (urbanisation and mining) and natural (floods and rainstorms) (Koirala *et al.,* 2019; Das *et al.,* 2021a). Estimating these parameters are essential for understanding their unique impacts and determining the critical sub-watershed in order to design effective conservation and sustainable management actions to prevent erosion.

The erosion has a greater effect on siltation of reservoirs and the agricultural sector. The primary success of any soil conservation program is estimating soil loss and identifying critical areas for implementation of effective management practice (Das *et al.,* 2021b). The government has taken many actions for rectifying and preventing the problem, but the situation is still not very good. Although soil erosion has been a continuous and non-linear process, determining its impact on the environment is challenging (Sujatha *et al.,* 2018). Several complicated biophysical advancements (in terms of modelling) have been made to address this non-linearity.

Soil erosion can be measured using various approaches. Physical or experimental / laboratory scale models are commonly used in these procedures. Physical-based models were primarily employed in the water erosion prediction project (WEPP), the european soil erosion model (EURO SEM), and the limburg soil erosion model (LISEM). Because these approaches are based on real-life procedures, they necessitate a huge number of input parameters and extensive processing. As a result, simulating these for a specific location, necessitates data on observed sediment loss, which is unavailable for ungauged watersheds in many developing and underdeveloped countries. On the other hand, empirical models such as universal soil loss equation (USLE) and the revised universal soil loss equation (RUSLE) present an option to connect soil loss to numerous physical components that are generally easy to calculate / estimate.

Unlike USLE, which has several drawbacks such as point size soil loss estimation and is mainly used on agricultural lands, RUSLE has the advantage of combining remote sensing (RS) and geographic information systems (GIS) to assess the risk of possible soil erosion at a spatial scale. Because of its simplicity and low data requirements, soil erosion community widely recognised this empirical approach. Rainfall erosivity (R), soil erodibility (K), slope length and gradient (LS), crop management (C), and conservation practise (P) elements, as well as GIS information layers, can be linked in the ArcGIS platform to assess the collective impact on average annual soil loss.

Many researchers have applied RUSLE model for the soil erosion assessment. Prasannakumar *et al.* (2011) has estimated the soil loss using RUSLE within a small mountainous sub-watershed in Kerala. Ganasri *et al.* (2016) have performed GIS - based RUSLE methodology to identify the spatial distribution of different erosion prone areas in the Nethravathi basin. The researcher's work is mainly confined or has been focused on a watershed and basin basis. However, for the successful implementation and management of the project, it is also required to estimate the soil loss for an administrative boundary. In this study, the Maharasthra administrative boundary has been considered for the erosion estimation so that the state government can implement the mitigation steps and examine the proper functioning of the conservation structures. To address the above problems, the present research has been planned to estimate the spatio-temporal variation of soil erosion by the RUSLE model on the geospatial platform for the year 2000 and 2011 in the state.

2. MATERIALS AND METHODS

The Maharashtra state is located between 16N to 22N latitudes and 72.8E to 80.89E longitudes. It is spread over an area of 307,713 km^2. The location map of the study area is shown in Fig. 1. Seven soil groups have been identified in the study area based on the classification system of ICAR, National Bureau of Soil Survey and Land Use Planning (ICAR, NBSS&LUP), Nagpur.

The soil classes are sandy-clay-loam, clay-loam, silty, silty-loam, loamy, sandy and clayey, as shown in Fig. 3. The area is mainly composed of clay (53.6%) followed by loamy (44.2%), clayey loam (0.93%), silt loam (0.90%), sandy clay loam (0.18%), silt (0.12%) and sandy (0.033%). The topography of Maharashtra is quite level. In the western part mountain range, high altitude acts as a ridge that diverts the water flow in two different directions east (Bay of Bengal) and west (Arabian Sea) as can be seen in the DEM map in Fig. 2.

The state is covered with seventeen types of land use and land cover (LU/LC). LU/LC map for the years 2000 and

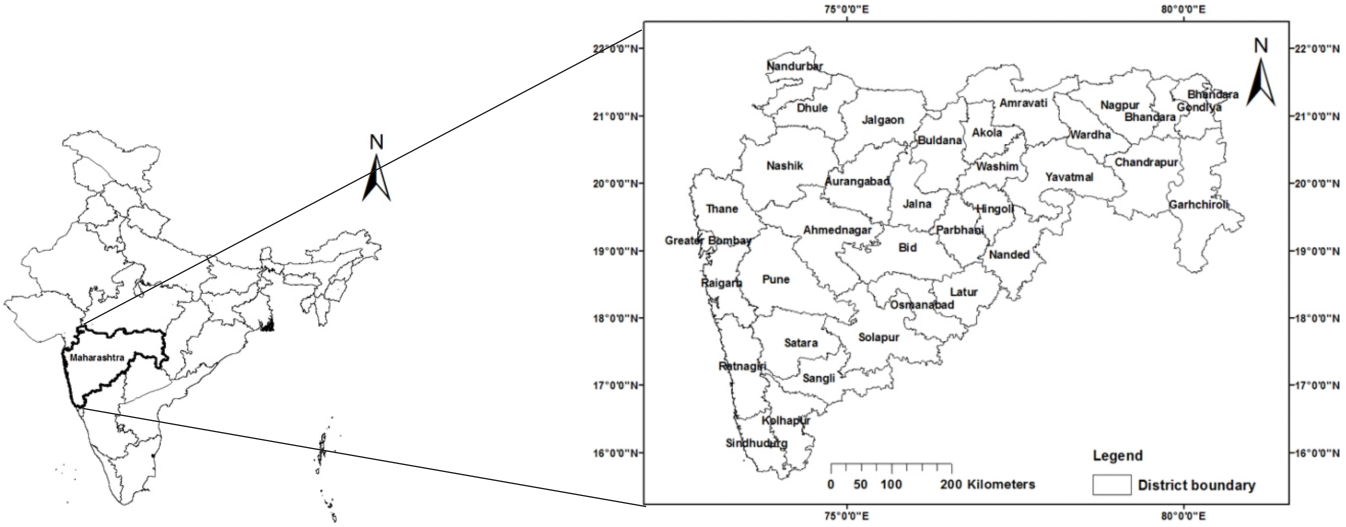

Fig. 1. Location map of study area

2011 were collected from https://earthdata.nasa.gov/learn/user-resources/lcluc-information on the scale of 1:250,000, as shown in Fig's 4 and 5, respectively. The percentage of area under different classes in the years 2000 and 2011 are listed in the Table 1.

The datasets used in this paper are daily rainfall gridded data from 1991 to 2011, provided by India Meteorological Department (IMD), soil map from ICAR-NBSS&LUP, Nagpur, digital elevation model (DEM) 90 m from shuttle radar topography mission (SRTM) (www.srtm.csi.cgiar.org), LU/LC for the year 2000 and 2011 from https://earthdata.nasa.gov/learn/user-resources/lcluc-information and normalized differential vegetation index (NDVI) from moderate resolution imaging spectroradiometer (MODIS) 16 days composites version 6 (250 m) (https://modis.gsfc.

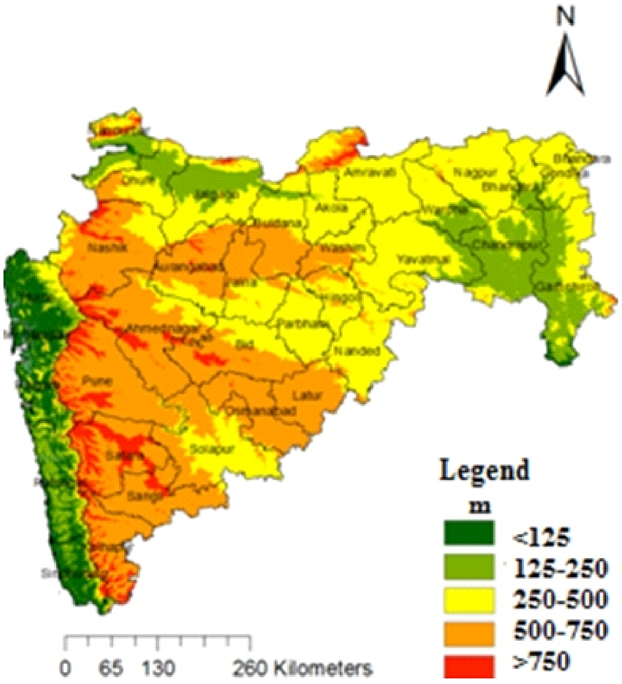

Fig. 2. DEM

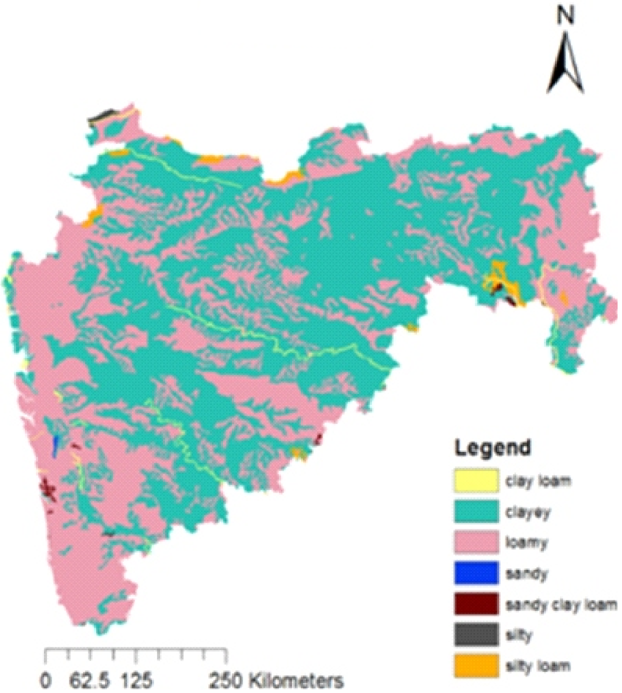

Fig. 3. Soil map

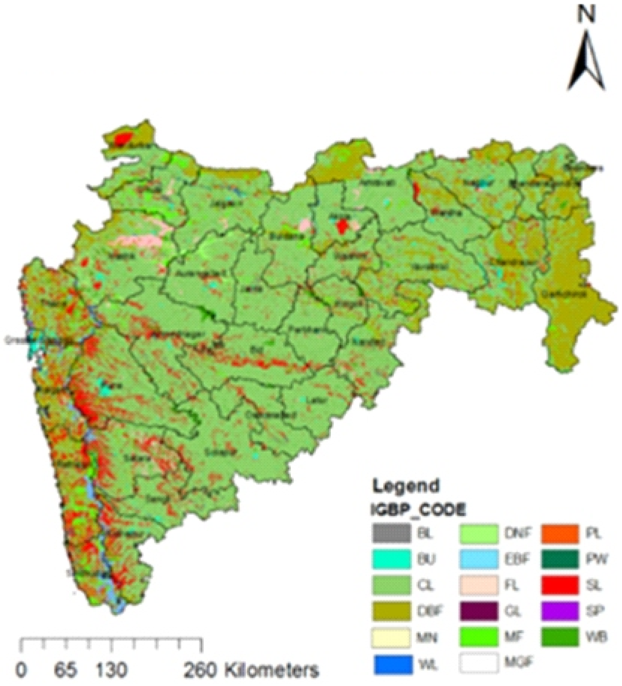

Fig. 4. LU/LC map (2000)

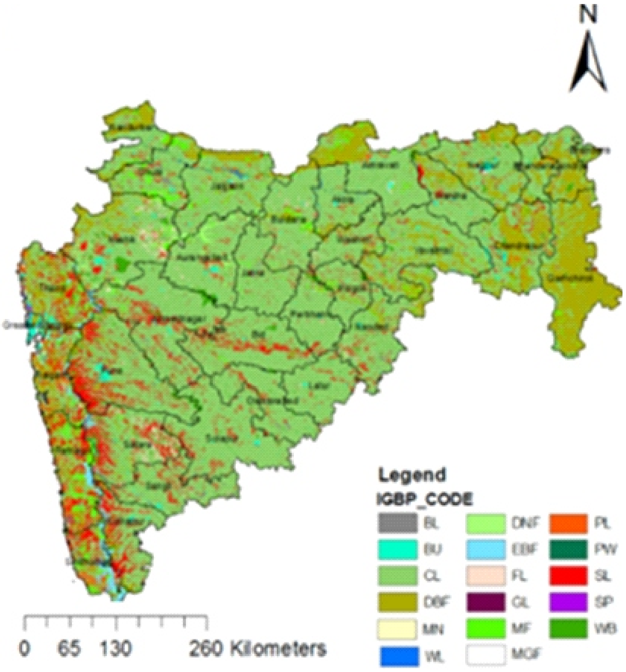

Fig. 5. LU/LC map (2011)

Table: 1
Land use and land cover class area percentage variation from 2000-2011

S.No.	Class (code)	Area % (2000)	Area % (2011)	Area % change
1.	Barren land (BL)	0.487	0.499	2.46
2.	Built up (BU)	0.942	1.040	10.40
3.	Cultivated land (CL)	66.993	67.798	1.20
4.	Deciduous broad leaf forest (DBF)	13.819	13.444	-2.71
5.	Evergreen broad leaf forest (EBF)	1.014	0.953	-6.02
6.	Fallow land (FL)	1.501	0.871	-41.97
7.	Grass land (GL)	0.001	0.0016	23.07
8.	Mixed-forest (MF)	2.539	2.741	7.95
9.	Mining (MN)	0.003	0.003513	2.04
10.	Mangrove's forest (MGF)	0.101	0.107	5.94
11.	Plantation (PL)	0.901	0.930	3.22
12.	Permanent wetland (PW)	0.016	0.0162	1.25
13.	Shrub land (SL)	8.079	7.878	-2.48
14.	Water bodies (WB)	2.982	3.106	4.16
15.	Wetland (WL)	0.147	0.141	-4.08
16.	Deciduous needle leaf forest (DNF)	0.448	0.447	-0.22
17.	Salt-pans (SP)	0.023	0.022	2.46

nasa.gov/data/dataprod/mod13.php). The IMD gridded data is quite good in use due to its easily availability for longer historical time series at grid level. The same has been used by many researchers (Singh *et al.,* 2021) has used IMD rainfall gridded data for drought severity assessment in south Bihar region (Singh *et al.,* 2021) has used successfully the rainfall data for rainfall variability assessment, using entropy method in Uttarahand region.

The RUSLE (Renard, 1997) is an improved form of USLE (Wischmeier and Smith 1965, 1978). The assumption in RUSLE that underlies is that the detachment and deposition are controlled by flow sediment content. The eroded material (instead of source limited) is limited by the flow carrying capacity. The complete flowchart for preparing the soil erosion map has been shown in Fig. 6. It was used to estimate average annual soil erosion potential (eq. 1).

$$A = R * K * L * S * C * P \qquad ...(1)$$

Where, A = soil loss (t ha^{-1}yr^{-1}), R = rainfall-runoff erosivity factor (MJ-mm ha^{-1}hr^{-1}yr^{-1}), K = soil erodibility factor (t ha^{-1} h ha^{-1}MJ-mm), L = slope length factor, S = slope steepness factor, C = cover-management factor and P = conservation practice factor.

The rainfall erosivity factor (R) reflects the effect of rainfall intensity on soil erosion. It requires continuous precipitation data to calculate (Wischmeier and Smith, 1978). The spatial distribution of average annual precipitation (P) in the study area is estimated using 'Kriging' method of interpolation. In the interpolation process, 10 years of average annual rainfall data for all districts in the study area were considered. In the raster calculator of ArcGIS 10.1 software environment, The R-factor was calculated by using the eq. 2 (Singh *et al.,* 1981).

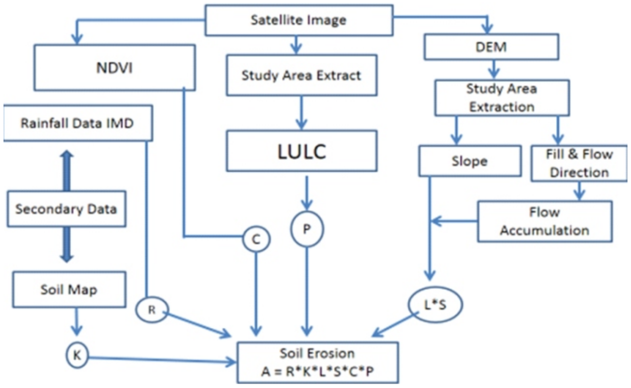

Fig. 6. RUSLE model flowchart

$$R_a = 81.5 + 0.380 * P_a \qquad ...(2)$$

Where, R_a = rainfall erositivity factor (MJ-mm ha^{-1}hr^{-1} yr^{-1}) and P_a = average annual rainfall (mm). Soil erodibility factor (K) represents the susceptibility of soils or surface materials to get detach, transport and erode for a particular rainfall input as measured under a standard condition (Kim, 2006). Normally nomograph is used to determine K factor for a soil, based on its texture, organic matter content, soil structure, and permeability (Wischmeier and Smith, 1978). 'K' factor map was prepared in raster calculator, using the soil map and the regression eq. 3 for the nomograph by Wischmeier *et al.* (1971).

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

Where, K = soil erodibility (t ha^{-1} h ha^{-1} MJ-mm), OM = percentage organic matter, p = soil permeability code, s = soil structure code, M = (% silt + % sand) × (100 − % clay).

Topographic factor (LS) represents a ratio of soil loss under given condition to that with the standard conditions at a site. Topographical factor constitutes two factors which are slope length (L) and slope steepness (S). The soil loss per unit area increases when the slope length increases or the slope gets steeper. The effects of slope steepness have a greater impact on soil loss than slope length. Das *et al.* (2021c) has prepared the slope length factor (L) using the eq. 4 and the same has been applied in the current research work.

$$L = (\lambda / 22.13)^m = (\text{Flow accumulation} * \text{Grid size} / 22.13)^m \quad ...(4)$$

Where, 22.13 = the RUSLE unit plot length, m = a variable slope-length exponent and λ = (Flow accumulation * Grid size). The λ is the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases enough so that depositions begins or runoff becomes concentrated in a defined channel (McCool *et al.,* 1987).

The slope-length exponent m is calculated as:

$$m = \beta / (1 + \beta) \quad ...(5)$$

Where, $\beta = (\sin\theta / 0.0896) / (3.0 * (\sin\theta)\ 0.8 + 0.56)$ and θ = slope angle in radians, (McCool *et al.,* 1987). The slope steepness factor (S) map was derived by applying the conditional equations on slope map of the study area using eq's 6 and 7 (McCool, 1987, 1993). Finally, the L-Factor and S-factor map was processed in the Arc environment to create the L * S factor map.

$$S\ (\text{Slope steepness factor}) = 10.8 * \sin\theta + 0.03;\ \text{if ' } \tan\theta < 9\% \quad ...(6)$$

$$S = (\sin\theta / \sin 5.143)^{(0.6)};\ \text{if } \tan\theta \geq 9\% \quad ...(7)$$

Where, θ = slope angle (radians). Cover management factor (C) is the ratio of soil loss from an area with specified cover and management to that of an identical area in tilled continuous fallow is termed as the cover-management factor C.

The use of vegetation indices in order to extract vegetation parameters for erosion models has been described by De Jong (1994). Based on Jong work NDVI map can be analysed to formulate the two linear regression equations between NDVI and C factor as shown in eq's 8 and 9. The C-factor map is prepared using the conditional function in the raster calculator in ArcGIS 10.1 platform.

$$C = 0 \text{ if NDVI} \leq 0 \quad ...(8)$$

$$C = -(1/\text{NDVI max}) * (\text{NDVI}) + 1);\ \text{if NDVI} > 0 \quad ...(9)$$

The conservation practice factor (P) represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope. The factor accounts for control practices that reduce the erosion potential of the runoff by their influence on drainage patterns, runoff concentration, runoff velocity, and hydraulic forces exerted by runoff on soil. The value of P factor ranges from 0 to 1. The value approaching 0 indicates good conservation practice and 1 indicates poor conservation practice. The values of conservation practice factor, P for different land management practices were tabulated by Haan *et al.* (1994). All the created parameter maps were processed to generate the final water soil erosion map in ArcGIS 10.1 platform using the eq. 10.

$$\text{Soil erosion} = \text{Factor R} * \text{Factor K} * \text{Factor LS} * \text{Factor C} * \text{Factor P} \quad ...(10)$$

Table: 2
Conservation practice factor for different land management practices

S.No.	Class name	Practice factor (P)	Organic matter (OM)
1.	Barren land (BL)	0	0
2.	Built up (BU)	0	0
3.	Cultivated land (CL)	0.9	2
4.	Deciduous broad leaf forest (DBF)	1	4
5.	Evergreen broad leaf forest (EBF)	1	4
6.	Fallow land (FL)	0.1	0.5
7.	Grass land (GL)	0.5	2
8.	Mixed-forest (MF)	1	2
9.	Mining (MN)	0	0.5
10.	Mangrove's forest (MGF)	1	2
11.	Plantation (PL)	0.8	2
12.	Permanent wetland (PW)	0.1	4
13.	Shrub land (SL)	0.5	0.5
14.	Water bodies (WB)	0	0.5
15.	Wetland (WL)	0	0.5
16.	Deciduous needle leaf forest (DNF)	1	2
17.	Salt-pans (SP)	0	0.5

Source: Haan et al. (1994)

3. RESULTS AND DISCUSSIONS

It was observed that the highest rainfall occurred as 3724.59 mm and 3758.15 mm, while the minimum as 366.021 mm and 578.963 mm in the year 2000 and 2011 as shown in Fig's 7 and 8, respectively. The southern part of the study area received highest rainfall and the lowest rainfall occurred in the central part of the study area. The rainfall erosivity factor (R) map was prepared from the rainfall map. The estimated R factor varied from 220.208 to 1496.84 (MJ-mm $ha^{-1}hr^{-1}$) in 2000 and 301.508 to 1509.6 (MJ-mm $ha^{-1}hr^{-1}$) in 2011 as shown in Fig's 9 and 10, respectively. The soil erodibility factor (K) map was prepared by processing the soil map based on the analytical relationship as a function of soil texture, provided by Wischmeier and Smith (1978). The values of K-factor were found to be ranging from 0.007 (t MJ^{-1}mm) to 0.107 (t MJ^{-1}mm) as shown in Fig. 11. The lower value of K-factor was associated with the soils having low permeability, low antecedent moisture content. Topographic factor (LS) varied from 0.029 to 45344.03.

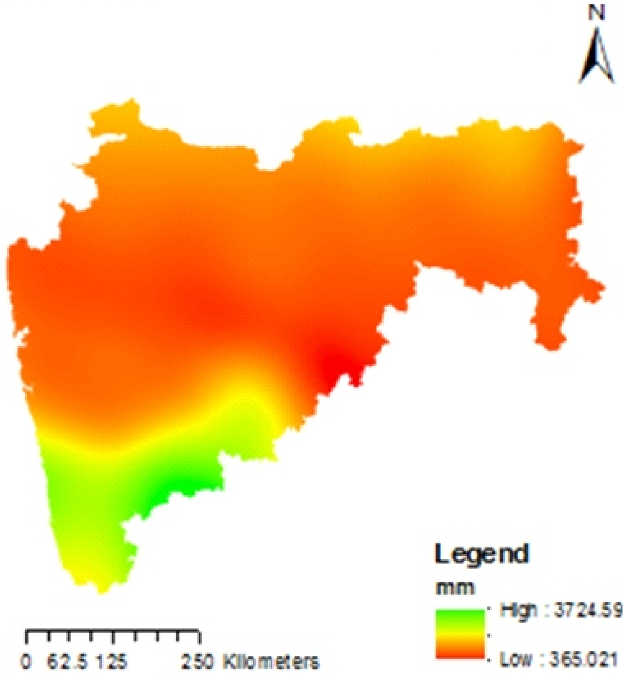

Fig. 7. Average annual rainfall (mm) 2000

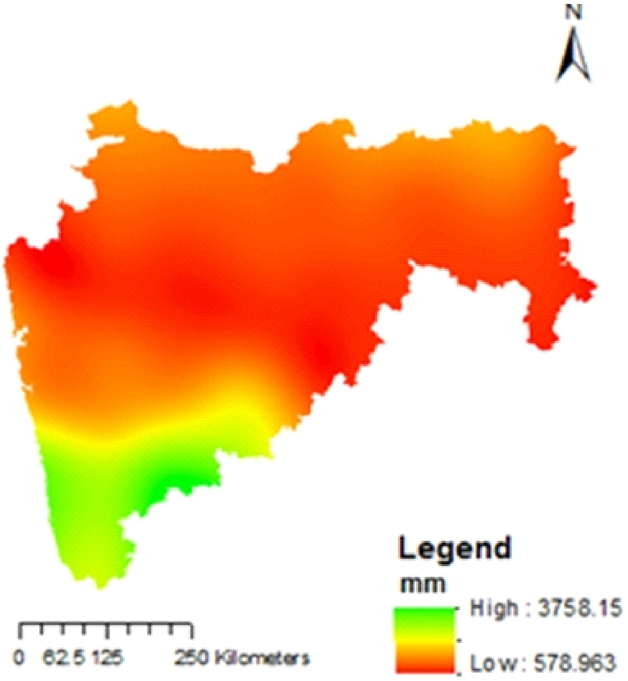

Fig. 8. Average annual rainfall (mm) 2011

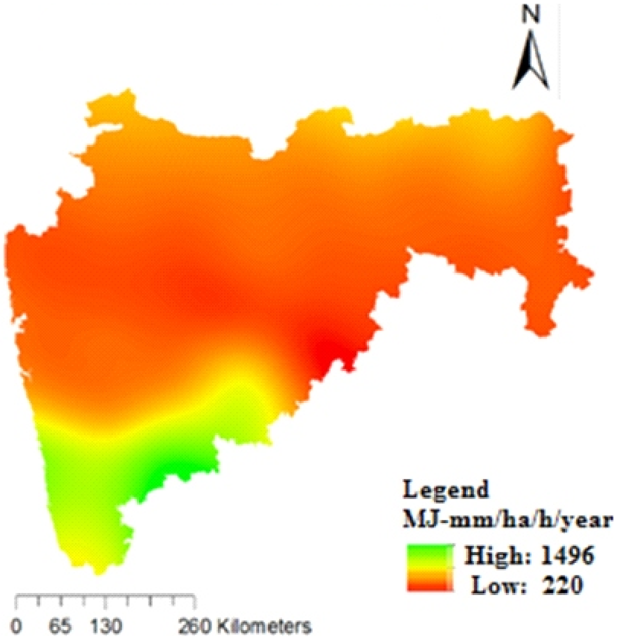

Fig. 9. R-factor map (2000)

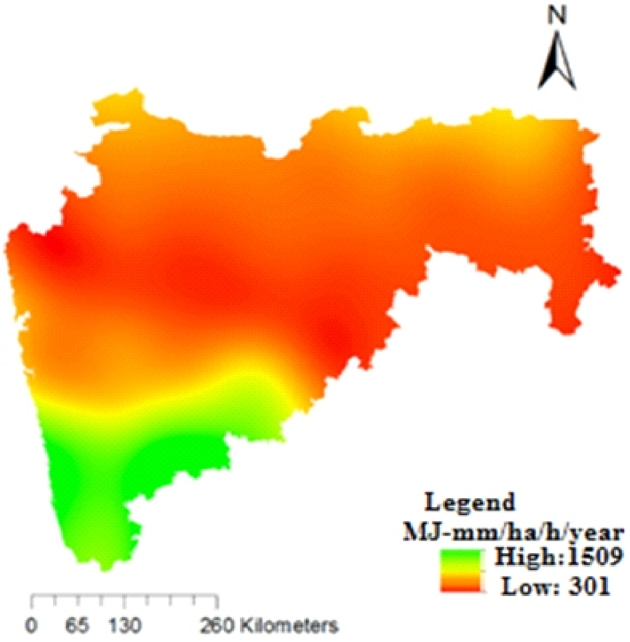

Fig. 10. R-factor map (2011)

The area was more dominated in the range of 0.029 to 1, as shown in Fig. 12. The cover management factor (C) map was prepared by processing the NDVI map for 2000 and 2011, as shown in Fig's 13 and 14, respectively. The zone having higher values of C factor indicate relatively lesser vegetation and *vice-versa*. The conservation practice factor (P) was prepared by processing the LU/LC map using the ratings for different land management practices given by Haan *et al.* (1994), for the year 2000 and 2011, as shown in Fig's 15 and 16, respectively. The factor varies from 0 to 1. The zone having higher values of P-factor indicates a relatively high density of vegetation and *vice-versa*.

Singh *et al.* (1992) has classified soil erosion rate in India into six classes as 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 (above 80 t ha^{-1}yr^{-1}). The present study was classified into five classes in view of

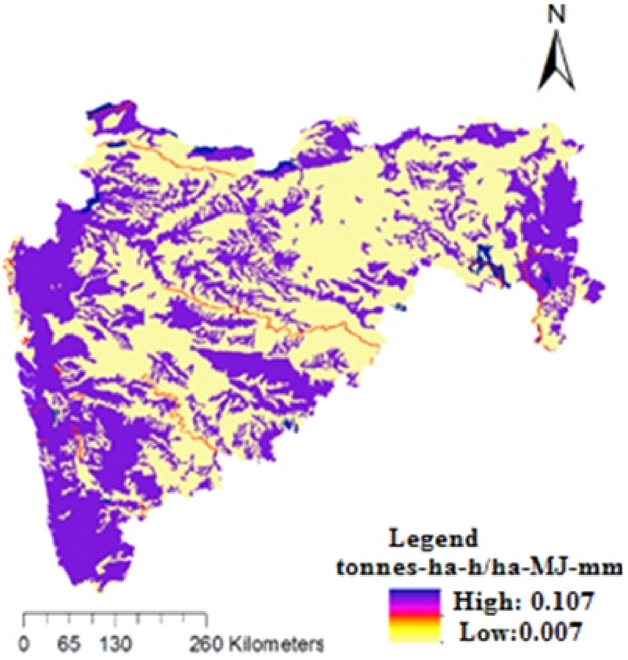

Fig. 11. K-factor map

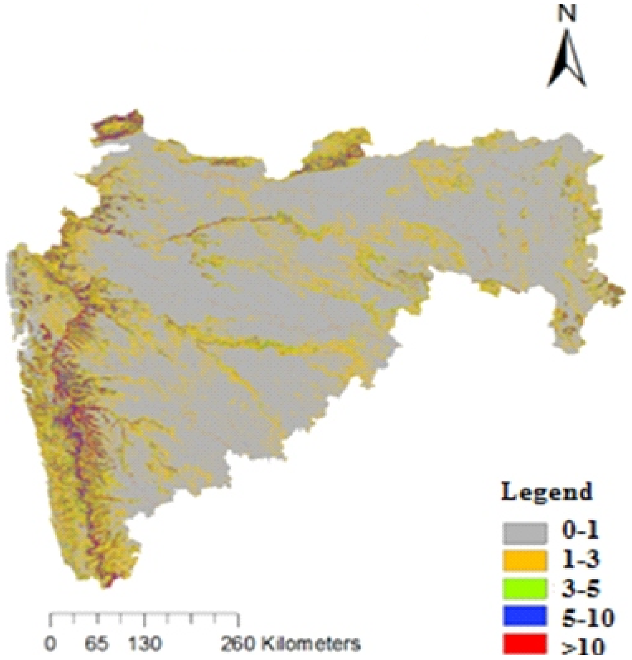

Fig. 12. LS-factor map

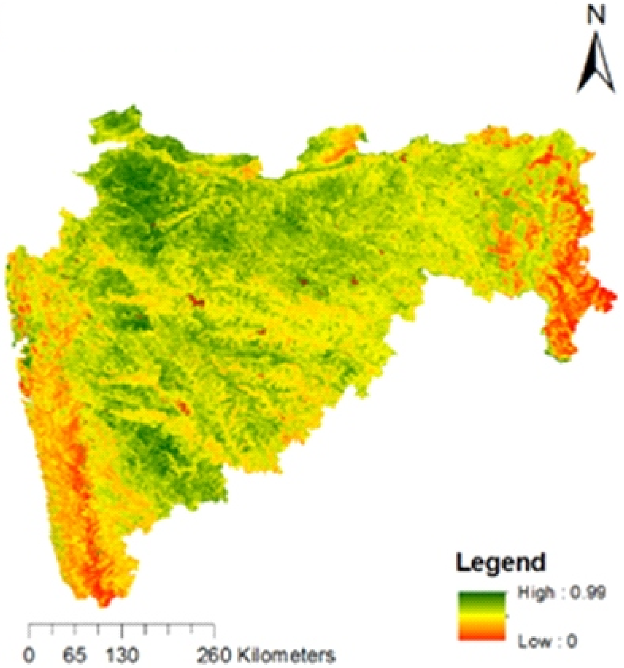

Fig. 13. C-factor map 2000

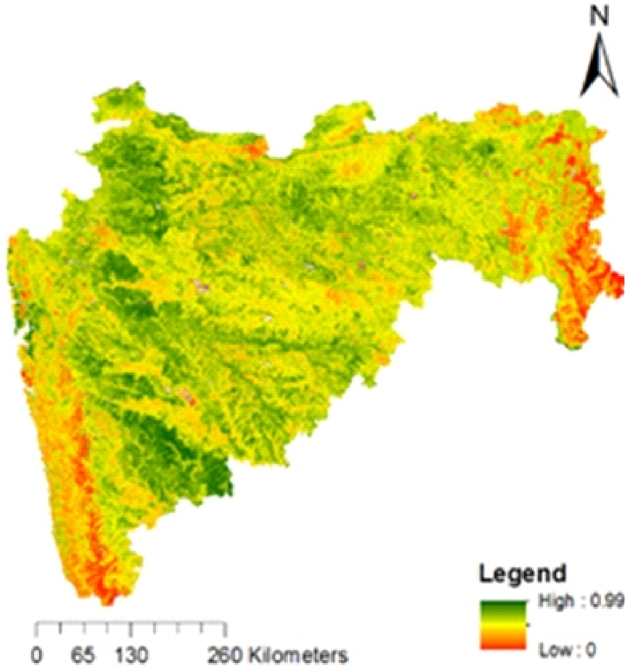

Fig. 14. C-factor map 2011

this classification and the study area situation. As the percentage of slight and very severe is very less and so have been merged with the near class, while the very high (20-40) has been further sub-classified as 20-30 t ha^{-1}yr^{-1} and 30-40 t ha^{-1}yr^{-1}, to have the clear picture of the situation. In the soil erosion map of Maharashtra (2000 and 2011), a wide area was covered with the soil erosion rate (0-10 t ha^{-1}yr^{-1}) about 80%. The minimum soil erosion rate had declined from 2000 to 2011 by 3.23%. The area having severe erosion rate (greater than 40 t ha^{-1}yr^{-1}) had been increased by about 32% in the eleven years gap and lies in the western coastal part (*i.e.* in the districts of Raigarh, Ratnagiri, Sindudurg, Kolhapur, Pune, Satara etc.) and some area of northern coastal part (*i.e.* in the districts of Nasik, Nandurbar, Jalgaon, Amravati, Buldana) as shown in Fig' 17 and 18. The similar results have been concluded by Maji *et al.* (2010), the highly water erosion affected districts in the state are: Ahmednagar, Nashik, Pune, Sangli, Raigad, Solapur, and Ratnagiri. The

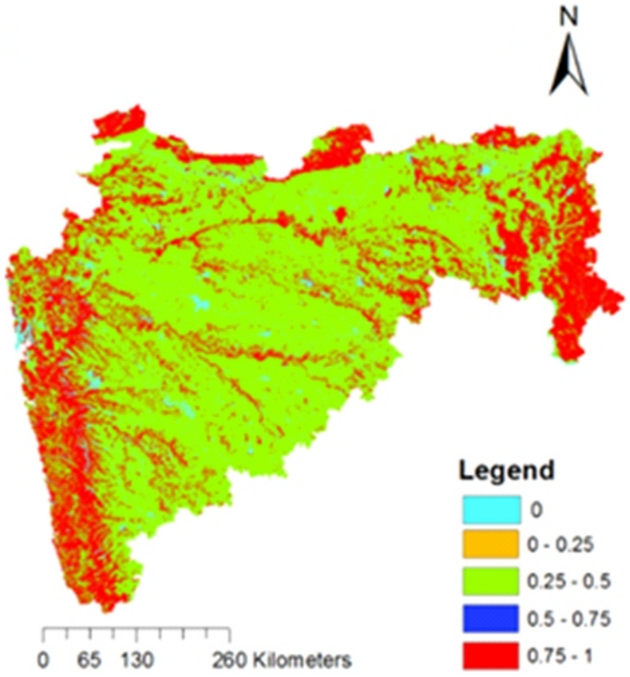

Fig. 15. P-factor map 2000

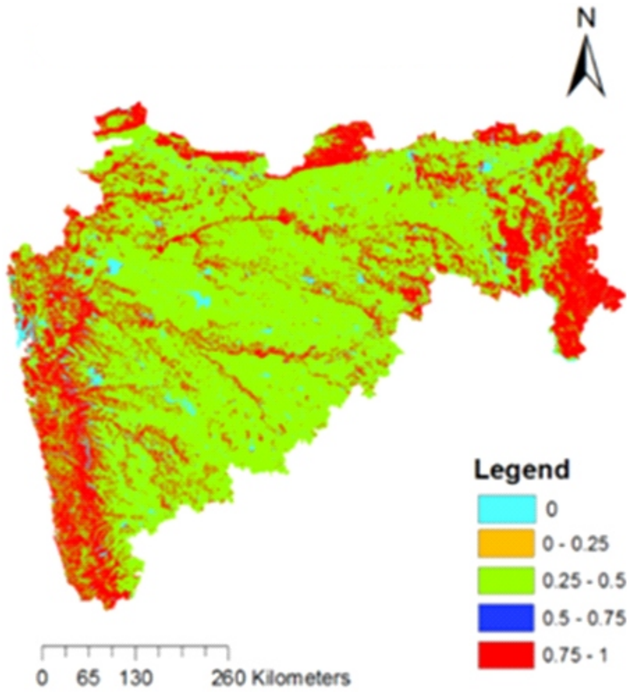

Fig. 16. P-factor map 2011

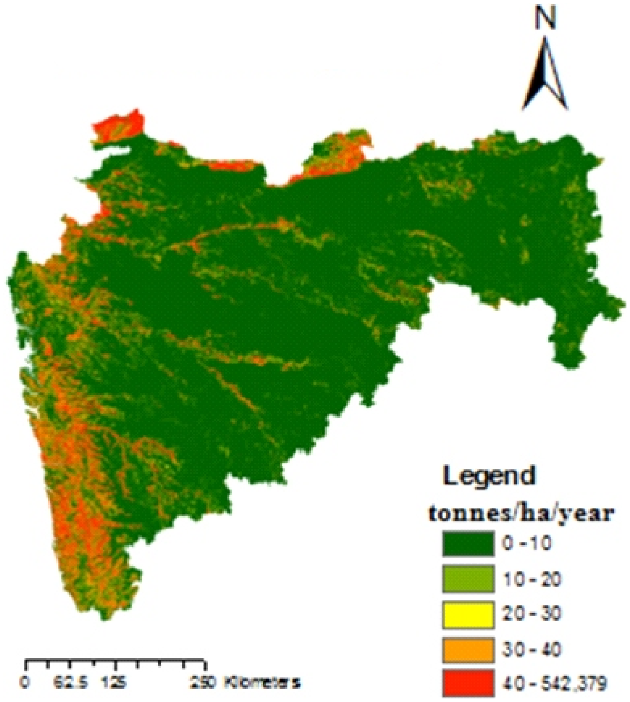

Fig. 17. Soil erosion map 2000

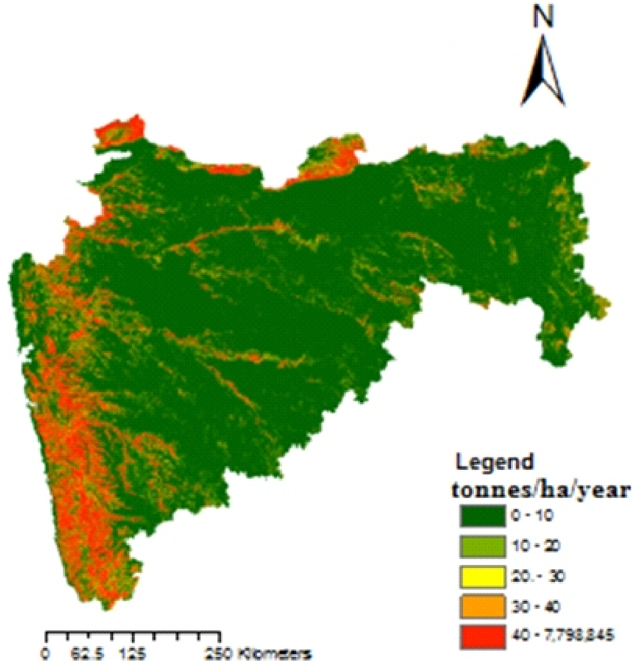

Fig. 18. Soil erosion map 2011

percentage change in soil erosion status of different ranges throughout the study area (Table 3).

The several soil and water conservations structures that can be adopted for erosion control for different return periods were as: field bund can be designed for a return period of 5 years, terrace outlets for 10 years, vegetative waterways for 15 years, small permanent masonry gully control structures for 10-15 years, check dams for 25 years, earthen storage

Table: 3
Soil erosion area (%) and the (%) change from 2000 to 2011

Rate (t ha^{-1}yr^{-1})	Area % (2000)	Area % (2011)	Change (%)
0-10	81.1	78.48	-3.23
10-20	6.41	6.55	2.18
20-30	3.09	3.18	2.92
30-40	1.99	2.03	2.01
Above 40	7.41	9.76	31.72

dam with natural spillways for 25-50 years and storage and diversion dams having spillways for 50-100 years of return periods (Kar *et al.,* 2017). The selection of proper structures for the control of soil loss needs to be further analyzed for sub-watershed wise and finally by ground verification of the status of the actual field conditions.

In addition to the field level characteristics (landholding-size, high field slope, soil-types and high erosion level), the household level features, (age, education level, off-farm income and livestock ownership) also have a significant effect on adoption of these SWC technologies and so need to be analysed for the successful implantation the soil and water conservation measures (Kumar *et al.,* 2021).

4. CONCLUSIONS

This paper presents the application of the empirical soil erosion model, RUSLE, supported by RS and GIS to estimate the average annual soil loss (A) in t $ha^{-1}yr^{-1}$ in the Maharashtra state. The temporal variability of soil-erosion zones for the eleven years gap from 2000 to 2011 had also been computed in the region. The results concluded that the severe erosion rate above 40 (t $ha^{-1}yr^{-1}$) had increased largely in the eleven year gap, which needs to be regionalized district-wise or subwatershed-wise for mitigation plan implementation. This indicates an extreme need for effective soil-water conservation action to be adopted timely. The working structures need to be re-examined for their effective functioning. The erosion was found to be more severe in the eastern and northern part of the study area, indicating its priority for applying soil conservation measures. The soil erosion assessment will provide the necessary information required for designing various soil and water conservation structures like field bund, vegetative waterways, and diversion structures, check dams, gully control structures, etc., on a priority basis. The results of this study concluded that the integration of RUSLE with RS and GIS to estimate soil erosion can distinctly represent the spatio-temporal variation of soil erosion that will provide a clear picture of the situation while planning and adopting proper management practices.

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