

# Estimation of Soil Erosion and Identification of Critical Areas for Soil Conservation Measures using RS and GIS-based Universal Soil Loss Equation

Deepesh Machiwal · Pratibha Katara ·  
H. K. Mittal

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**Abstract** Present study aimed at estimating soil erosion potential and identification of critical areas for soil conservation measures in an ungauged catchment situated in Aravalli hills of Udaipur district, Rajasthan (India). Also, impact of rainfall on soil erosion is evaluated. The soil erosion is estimated for 10 year period (2001–2010) by Universal Soil Loss Equation (USLE) model using Geographical information system (GIS) and remote sensing techniques for every 12 m × 12 m area. Thematic maps of six USLE model parameters, i.e., rainfall erosivity (*R*-factor), soil erodibility (*K*-factor), slope length (*L*-factor), slope steepness (*S*-factor), crop and management (*C*-factor), and support practice (*P*-factor), were prepared in GIS platform. The *R*-factor ranged from 1,522.93 to 10,225.88 MJ mm ha<sup>-1</sup> h<sup>-1</sup> year<sup>-1</sup> in the years 2006 and 2008, respectively, when the annual rainfall was 984.3 and 572.2 mm, and number of rainy days were 58 and 47, respectively. The *K*-factor was highest for fine loam soil covering 56 % area, while the lowest value was for coarse loamy sand in 22 % area. The lowest value of the *L*-factor (0.736) was in accordance with the high slopes nearby catchment boundary; whereas the highest value (0.832) was for almost zero slopes in 34 % area nearby waterbodies. Opposite to the *L*-factor, the *S*-factor values were high (>4) for the higher slopes nearby catchment boundary and the lowest values for the zero slopes. The *C*-factor value in 170.36 km<sup>2</sup> or 48.91 % of the area is 0.1 while the value is zero for waterbodies and builtup lands. The *P*-factor value in 250.36 km<sup>2</sup> or 71.87 % of the area is 0.8. The mean annual soil erosion in the major portion of the catchment (231.13 km<sup>2</sup> or 66.38 %) exceeds 10 t ha<sup>-1</sup> year<sup>-1</sup> indicating high to very severe soil erosion conditions prevailing in the catchment. It is apparent that vast quantities of the soil are getting eroded from the catchment, and the annual rainfall amount and rainfall intensity have the profound effect on the soil erosion potential. This study emphasizes that USLE model coupled with GIS and remote sensing techniques are promising and cost-effective tools for mapping critical areas of soil erosion in ungauged catchments especially in developing countries.

**Keywords** Geographical information system · Remote sensing · Soil erosion · Ungauged catchment · Universal soil loss equation model

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D. Machiwal (✉)  
Central Arid Zone Research Institute, Regional Research Station,  
Bhuj 370 105, Gujarat, India  
e-mail: dmachiwal@rediffmail.com

P. Katara · H. K. Mittal  
SWE Department, College of Technology and Engineering,  
MPUAT, Udaipur 313 001, Rajasthan, India  
e-mail: pratibhakatara@gmail.com

H. K. Mittal  
e-mail: hemant.mittal@yahoo.com

## Introduction

The continuous erosion of the soil by various agents is a severe problem throughout the world. The total geographical area of India is 328 million hectares, of which 69 million ha are critically degraded, while 106 million ha are severely eroded [19, 33]. It has been estimated that 5,334 million tonnes of soil is being eroded and removed annually in the country because of various agents of destruction [31, 35, 38]. Nearly 10 % of the soil detached annually is being deposited in surface reservoirs resulting in a loss of about

2 % of storage capacity annually [24, 36, 42]. The nutrient losses in this way are much greater than the quantity that is presently used in the country. Out of 16 rivers of the world, which experience severe erosion and carry heavy sediment load, three rivers namely Ganga, Brahmaputra and Kosi occupy 2nd, 3rd and 4th position, respectively. Over and above many of the reservoirs in India are losing their capacity at the rate of 0.2–1 % annually. Thus, there is an urgent need to plan appropriate strategies for conserving and managing the vital soil resources at catchment level [28].

Quantification of soil erosion potential is essential for studies of reservoir sedimentation, river morphology, planning soil conservation strategies, water quality modeling and design of efficient erosion control structures on catchment or basin scale [23]. Practical field methods of determining soil erosion have the disadvantage of requiring a lot of resources apart from micro-plot studies under a controlled system [16]. Measurement of soil erosion through gauging stations is very limited in India due to lack of adequate funds [17]. In the recent years, the Universal Soil Loss Equation (USLE) model developed by Wischmeier and Smith [51] coupled with geographic information systems (GIS) is gaining wide acceptance among the researchers for estimating soil erosion [4, 13, 15, 27, 34, 35, 37, 41, 43, 47]. Most of the past studies estimated the soil loss for 200 m × 200 m area, which may not be adequate for identifying sites for soil conservation measures. Besides all such studies were carried out either in northern or eastern parts of India; only few of them focused on western part of the country.

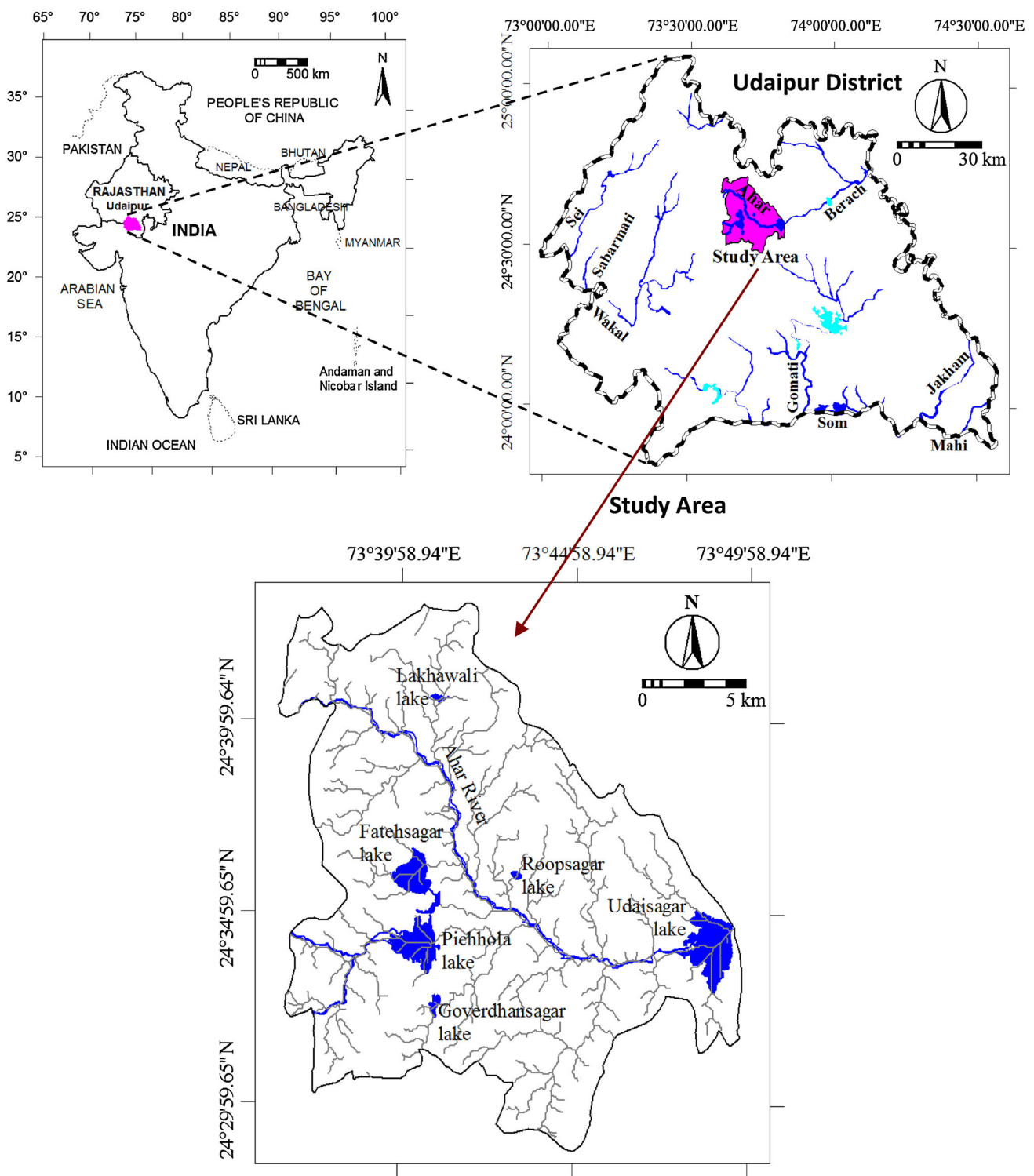
Ahar River catchment is situated in undulating topographic terrain of Aravalli hills of Rajasthan (India). The entire catchment is surrounded by hilly tract with an overall topographical gradient in the direction of major drainage system formed by the Ahar River. Whenever the catchment receives short duration and high intensity rainfall storms, enormous amount of surface runoff is generated due to presence of ‘hard-rock’ subsurface formations, hilly-tract and steep slopes (Machiwal et al. [22]). The high overland flow velocities carry vast quantity of soil from the catchment area, which ultimately gets deposited into Udaisagar lake at the outlet of the catchment. Thus, the eroded soil not only reduces effective soil depth in agricultural fields, but also diminishes the storage capacity of one of the major lakes in the catchment. Records of the soil erosion/sediment loss are not available for the catchment and only a few studies have been undertaken in this direction, e.g. Machiwal et al. [23]. Looking at the soil erosion problems existing in the catchment, the present study is undertaken to estimate soil erosion by Universal Soil Loss Equation using GIS and remote sensing techniques for every 12 m × 12 m area. This study also evaluates effect of rainfall variability on the amount of soil erosion based on ten-year data.

## Materials and Methods

### Study Area Description

Ahar River catchment (study area) is situated in Udaipur district of Rajasthan state, India (Fig. 1). The study area partly incorporates two administrative blocks of Udaipur district called *Girwa* and *Badgaon* with a total aerial extent of 348.23 km<sup>2</sup>. The area lies between 73°36'51" to 73°49'46"E longitude and 24°28'49" to 24°42'56"N latitude. The general slope of the catchment is from northwest to southeast direction. The catchment is mainly drained by Ahar River, which enters the catchment from northwest and flows towards southeast having a course of 30 km up to Udaisagar Lake. Several seasonal tributaries join the Ahar River on the course forming a generalized dendritic drainage pattern. The Ahar and all its tributaries are basically seasonal rivers, which flows during rainy season. The climate of the study area is sub-humid to semi-arid conditions. Ten-year (2001–2010) mean annual rainfall of the study area is 620.89 mm, of which about 95 % rainfall is received during monsoon season, i.e. June to September months. Geology of the hard-rock study catchment consists of gneiss, schist, phyllite-schist and the combination of these rock formations.

The lakes and rivers form the major sources of surface water resources in the catchment. There is no perennial river flowing in the area, while the main seasonal river is Ahar. Two other seasonal rivers are Kotra and Amarjok river. Hence, in absence of any perennial river in the Ahar River catchment, the river water does not remain available to fulfil drinking and irrigation demands throughout the year. The Ahar River, entering the catchment from the northeast portion and flowing towards Udaisagar lake in the southeast portion, creates drainage system of the entire catchment. Thus, the Ahar River carries significant quantities of runoff water generated during rainy season through its well-defined network of drainage lines (Fig. 1). In general, the Ahar River also transports considerable amount of eroded soils, nutrients, and pollutants. There exist a total of six lakes in the catchment namely Fatehsagar, Pichhola, Udaisagar, Lakhawali, Goverdhansagar and Roopsagar. Among the six lakes, three lakes, i.e. Fatehsagar, Pichhola and Udaisagar, have relatively large storage capacities as compared to rest of the lakes. All the lakes are artificially-constructed, and most of their storage capacity is filled up by the runoff water drained from the surrounding catchments. It is experienced that the storage capacity of the lakes is being reduced due to deposition of large quantities of the soil eroded and transported from their catchment areas. The water level of the lakes fluctuates greatly, and very often, the lakes dry up entirely during drought seasons.



**Fig. 1** Location map of the study area showing drainage lines of the catchment

The major groundwater resources in the catchment occur under unconfined conditions, and the underlying aquifer is observed to be hydraulically connected beneath the surface [21]. The groundwater levels in the area

respond fairly well to rainfall events [20]. The main groundwater extraction mechanism existing in the catchment are dug well, tubewell, handpump and stepwell.

## Spatial Database Using GIS and Remote Sensing

In this study, daily rainfall data of 10 year period (2001–2010) for single raingauge station of the Ahar River catchment were collected from Agro-meteorological Observatory located in College of Technology and Engineering, Udaipur, Rajasthan. As the raingauge station existing in the study area does not have any other raingauge station in vicinity, spatial distribution of rainfall was considered uniform all over the study area. Digital soil map of the study area was prepared from the soil map of Udaipur district collected in hardcopy from National Bureau of Soil Survey & Land Use Planning, Regional Research Station, Udaipur [12]. The GIS-based land use/land cover map of the catchment was developed from satellite imagery (IRS-P4, LISS III) of February 8, 2004 collected from the Indian Institute of Remote Sensing, Dehradun, Uttaranchal, India. Topography of the study area was extracted from Shuttle Radar Topographic Mission data (elevations obtained during February 2000) downloaded from the US Geological Survey website [46]. The catchment boundary was delineated in GIS by using Universal Transverse Mercator (UTM) projection system with Ellipsoid as Everest India 1956 and Datum as Indian (India Nepal). The GIS analysis, processes and operations were performed by using Integrated Land and Water Information System [11] software (version 3.2).

## Universal Soil Loss Equation Model

The Universal Soil Loss Equation (USLE) model was used in this study to estimate the average annual soil loss ( $t\ ha^{-1}\ year^{-1}$ ). The USLE model was developed based on 40 years experimental field observations of Agricultural Research Service of the United States Department of Agriculture [32] and presently, it is the most-widely used soil erosion assessment model. The USLE model is considered as an index method associating factors that represent how climate, soil, topography, and land use affect rill and inter-rill soil erosion caused by raindrop impact and surface runoff [6–8, 22]. The USLE model determines the soil loss for a given area as a product of six key factors whose values at a particular location can be expressed numerically. The soil loss can be computed by using the following USLE model expressed as [51]:

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

where, A is the average annual soil loss ( $t\ ha^{-1}\ year^{-1}$ ); R is the rainfall erosivity factor ( $MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}$ ); K is the soil erodibility factor ( $tonnes\ ha\ h\ ha^{-1}\ MJ^{-1}\ mm^{-1}$ ); L is the slope length (dimensionless); S is the steepness factor (dimensionless); C is the cover and management factor (dimensionless); and P is the support practice factor (dimensionless).

The USLE model in conjunction with GIS technique is used to estimate the average annual soil loss and its distribution in the study area for 10 years (2001–2010). The entire catchment area was discretized into small grid or cells of  $12\ m \times 12\ m$  size. The raster maps of all factors of the USLE model (including L-factor and S-factor maps developed from 90 m resolution DEM) were resampled by using ILWIS software to one common georeference ( $12\ m$  pixel size) such that the all maps could be combined in GIS. The approach of discretizing the catchment into grids is recommended and followed in many studies in the past [1, 9, 12, 13, 19, 35, 48].

## Factors Used for Soil Erosion Assessment

Estimation of soil erosion by USLE model requires estimates of six factors appearing in Eq. 1. The rainfall erosivity factor (R-factor) is defined as the product of total storm energy and maximum 30 min intensity divided by 100 for numerical convenience, known as the  $EI_{30}$  index [49, 50]. The  $EI_{30}$  index method is developed by evaluating correlations between soil erosion and a number of rainfall parameters [49]. The annual R-factor is computed as sum of  $EI_{30}$  values for individual storms during a year. In absence of rainfall intensity records, as is the case with present study, monthly rainfall data can be used to calculate R-factor annually using the following relationship developed by Wischmeier and Smith [51].

$$R = \sum_{i=1}^{12} 1.735 \times 10^{\left\{1.5 \log_{10} \left(\frac{P_i^2}{P}\right) - 0.08188\right\}} \quad (2)$$

where, R is the rainfall erosivity factor in  $MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}$ ,  $P_i$  is the monthly rainfall in mm, and P is the annual rainfall in mm. There is only one raingauge station, therefore, one R-factor value was considered for the whole catchment in a year.

The K-factor, termed as ‘soil erodibility factor’, is the integrated effect of processes that regulate rainfall acceptance and resistance of soil to particle detachment and transportation. The K-factor is an empirical measure of soil erodibility and is a function of soil intrinsic properties. The main soil properties affecting the K-factor are soil texture, amount of fine sand in addition to the usual sand, silt and clay percentages used to describe soil texture, organic matter, soil structure, and permeability of soil profile. The K-factor can be computed by empirical method [39], nomograph [52] or K-value triangle based on soil texture [29]. The empirical method requires several parameters for each soil type, which were not easily available for all soil types in the study catchment. Hence, in this study, it is attempted to compile texture, depth, permeability, and then K-factor values were selected from Schwab et al. [40] by

carefully examining the soil texture of the study area (Fig. 2). The values were adjusted according to local experiences and available literature.

The slope length and steepness factor or *LS*-factor is a product of two separate factors: slope length (*L*) and steepness (*S*). The slope length is defined as the horizontal distance from the point of origin of overland flow to either the point where the slope decreases sufficiently for deposition to begin or the point where runoff water enters a well-defined channel [51]. The *LS*-factor is the most difficult parameter of USLE model to compute [39], and several methods have been devised to compute the *LS* from complex topographic terrain [3, 5, 10, 26, 30]. In this study, *L* and *S* factors were calculated separately by using SRTM (Shuttle Radar Topographic Mission) DEM with resolution of 3 arc-second (or 90 m pixel size) as shown in Fig. 3. The SRTM DEM dataset were ‘finished’ meaning that ‘sink holes’ had been removed. The *L*-factor was estimated by technique proposed by McCool et al. [25] using the following relationship.

$$L = \left( \frac{\lambda}{22.13} \right)^m \tag{3}$$

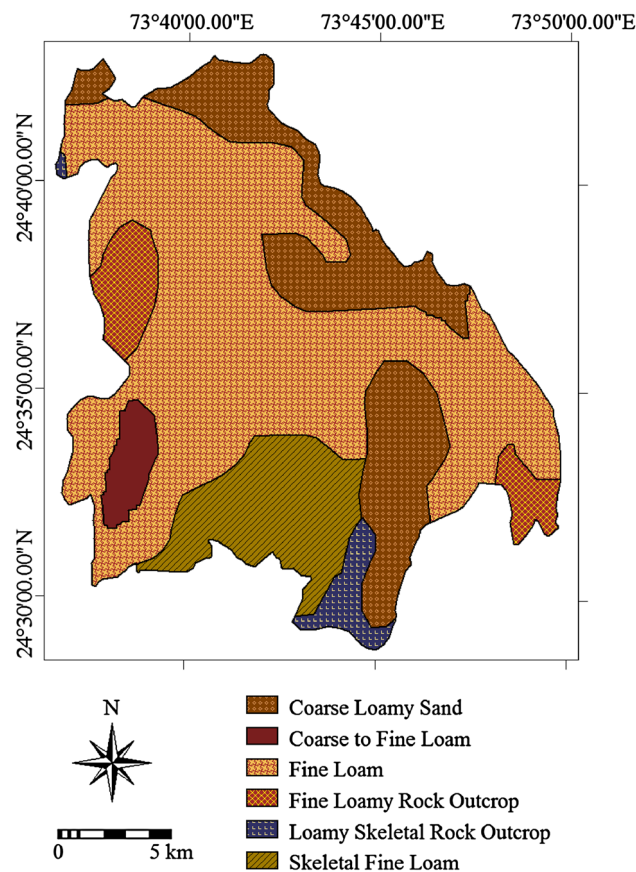


Fig. 2 Soil map of the catchment

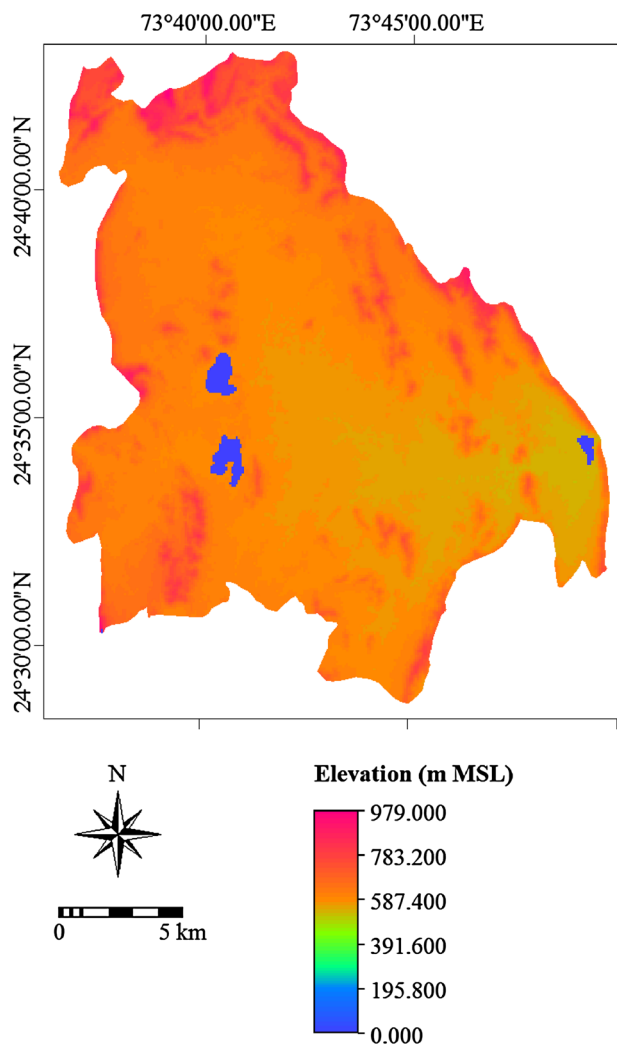


Fig. 3 Digital elevation model obtained from Shuttle Radar Topography Mission

where, *L* is the slope length factor (unit less);  $\lambda$  is the field slope length (m); *m* is the dimensionless exponent that depends on slope steepness, being 0.5 for slopes exceeding 5 %, 0.4 for 4 % slopes and 0.3 for slopes less than 3 %.

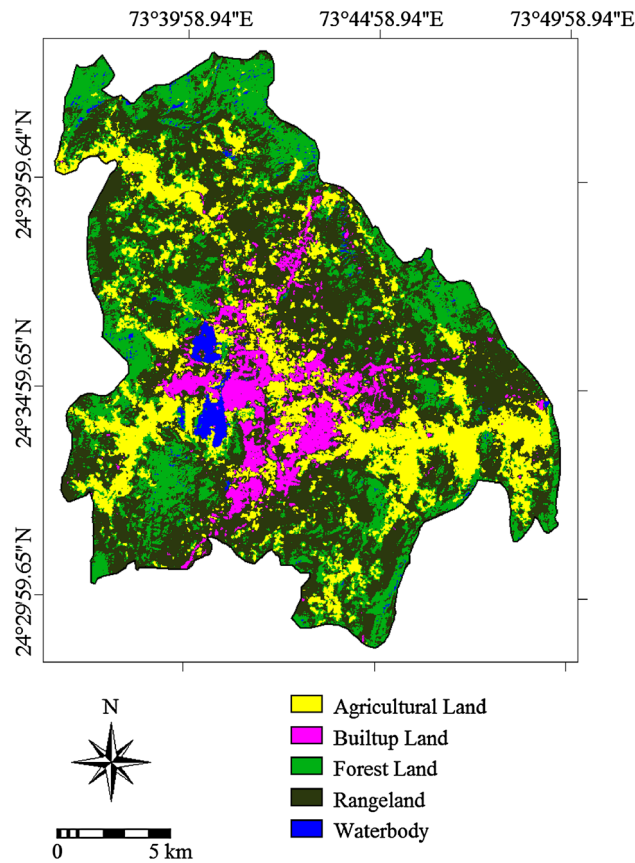
The slope steepness *S*-factor was derived for slope length longer than 4 m using the following equations [25].

$$S = 10.8 \sin\theta + 0.03, \quad s < 9 \% \tag{4}$$

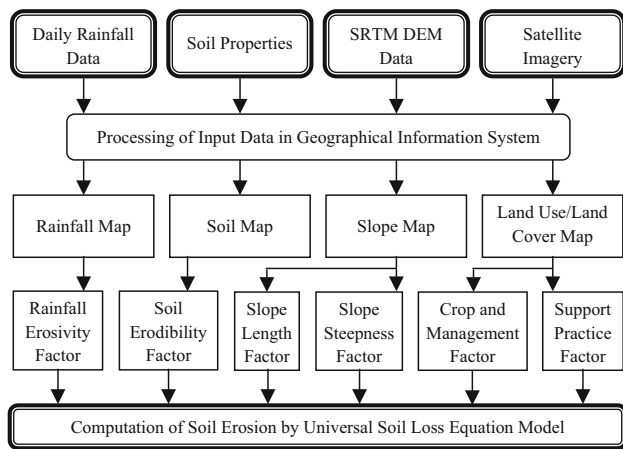
$$S = 16.8 \sin\theta - 0.05, \quad s \geq 9 \% \tag{5}$$

where, *S* is the slope steepness factor (unit less); and  $\theta$  is the slope angle (degree).

The GIS-based slope map for the study catchment was generated by applying two differential gradient filters ( $\frac{\partial}{\partial x}$  and  $\frac{\partial}{\partial y}$ ) on the DEM by using ILWIS software. Then, *L*-factor was computed from Eq. 3 with field slope length ( $\lambda$ ) value as 90 m, and *S*-factor was estimated from Eqs. 4



**Fig. 4** Land use/land cover map of the catchment



**Fig. 5** Flowchart depicting methodology for estimating soil erosion potential by USLE model coupled with GIS and remote sensing techniques

and 5 in GIS environment using slope map of the catchment.

The crop and management factor (*C*-factor) has marked effect on soil erosion and runoff by different type of vegetation and cropping systems. The *C*-factor is described

**Table 1** Annual rainfall erosivity factor values for 10 year period

Year	Annual rainfall (mm)	<i>R</i> -factor (MJ mm ha <sup>-1</sup> h <sup>-1</sup> )
2001	531.20	2,335.02
2002	363.30	1,811.47
2003	497.40	1,717.54
2004	601.00	2,816.63
2005	885.20	3,712.98
2006	984.30	10,225.88
2007	494.30	2,218.69
2008	572.20	1,522.93
2009	489.60	1,827.86
2010	790.40	4,459.41
Average	620.89	3264.84

as is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow land [51]. The effectiveness order of different vegetation and cropping systems is undisturbed forests > dense grass > forage crops (legumes and grasses) > small grains (wheat, oats, etc.) > row crops (corn, soybean, potatoes) [2]. For the study area, satellite imagery was used to classify the land use/land cover (LULC) into suitable classes for assigning the *C*-factor values. The LULC map shown in Fig. 4 was prepared by multispectral supervised classification of satellite image (IRS-P6 LISS III of February 8, 2004). The process was completed by following training stage, classification stage, and accuracy assessment stage [23]. The support practice factor (*P*-factor) is defined as the ratio of soil loss with a specific support practice to the corresponding soil loss with up and down cultivation [51]. The lower the *P* value, the more effective the conservation practice is deemed to be at reducing soil erosion. In absence of any support practices, the *P*-factor is 1.0 (highest). In this study, the *P*-factor values are calculated using the LULC map.

A flowchart depicting step-by-step methodology for estimating the soil erosion by USLE model using GIS and remote sensing techniques is shown in Fig. 5.

**Table 2** *K*-factor values for different soil texture classes

Soil texture	<i>K</i> -factor
Coarse loamy sand	0.07
Coarse to fine loam	0.15
Fine loam	0.17
Fine loamy rock outcrop	0.11
Loamy skeletal rocky outcrop	0.10
Skeletal fine loam	0.13

## Results and Discussion

### Distributed USLE Model Factors

Distributed maps of the factors influencing the process of soil erosion used in USLE model namely rainfall erosivity, soil erodibility, slope length, steepness, crop and management, and support practice factors were prepared in GIS platform, and are described ahead.

#### Rainfall Erosivity Factor

The estimated annual values of the rainfall erosivity factor (*R*-factor) for ten-year period (2001–2010) are given in Table 1. The *R*-factor values are found to be in the range of 1,522.93–10,225.88 MJ mm ha<sup>-1</sup> h<sup>-1</sup> year<sup>-1</sup> over the period 2001–2010. The average *R*-factor value was observed to be 3,264.84 MJ mm ha<sup>-1</sup> h<sup>-1</sup> year<sup>-1</sup> (Table 1). The highest value of the *R*-factor (10,225.88 MJ mm ha<sup>-1</sup> h<sup>-1</sup> year<sup>-1</sup>) was observed in the year 2006 when the total rainfall and rainy days were 984.3 mm and 58 days, respectively. The lowest value of the *R*-factor was found to be 1,522.93 MJ mm ha<sup>-1</sup> h<sup>-1</sup> year<sup>-1</sup> in the year 2008 when the total annual rainfall and rainy days were 572.2 mm and

47 days, respectively. In the study catchment, only single raingauge station exists, and hence, the *R*-factor value for a year was considered to be uniformly distributed over the space for individual 10 years.

#### Soil Erodibility Factor

The soil erodibility factor (*K*-factor) values were assigned based on the soil texture according to information available in literature and local experiences (Table 2). The spatial distribution of the *K*-factor in the study area is shown in Fig. 6 and proportion of area under different *K*-factor classes is given in Table 3. Soils high in clay content have low *K*-factor values, varying from 0.05 to 0.15, because the clayey soils are highly resistant to detachment of soil particles. The medium-textured soils, such as silt loam soils, have moderate *K*-factor values, whereas soils with high silt content are the most erodible among all types of soils. It is seen from Fig. 6 that the *K*-factor ranged from 0.07 to 0.17 in the catchment. The large part of the area, i.e. 194.33 km<sup>2</sup> (56 % of the total area) covered with fine loam soil has the highest *K*-factor value (0.17) and 75.69 km<sup>2</sup>

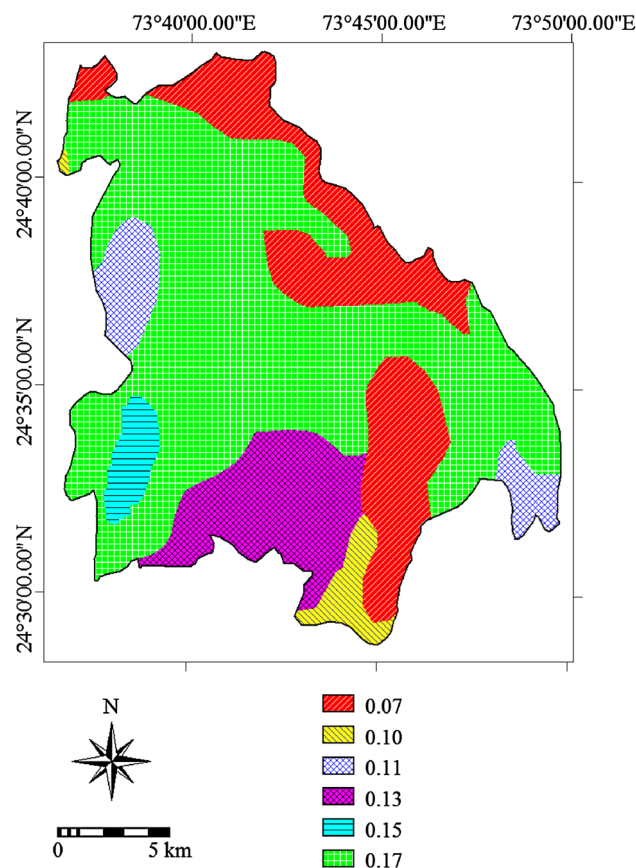
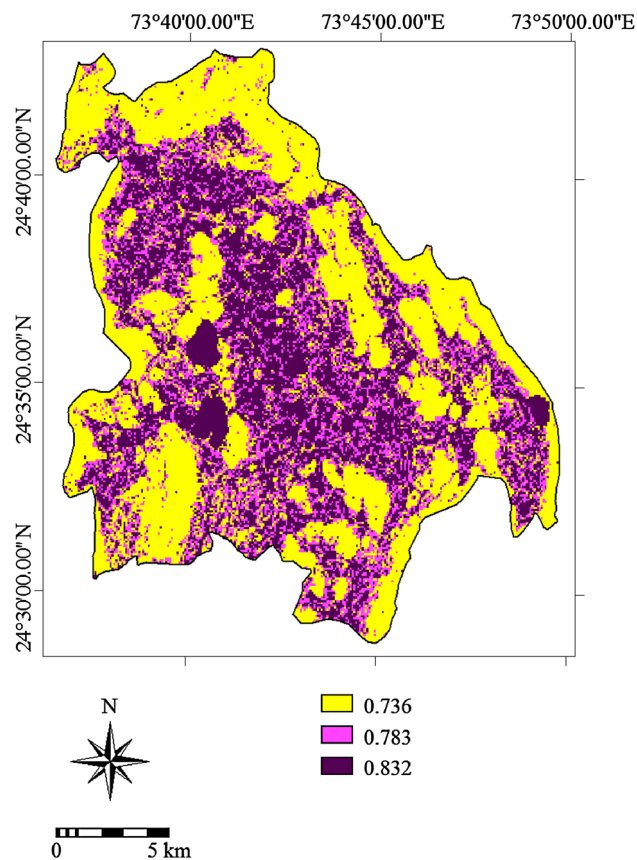


Fig. 6 Spatially-distributed soil erodibility factor over the catchment

Table 3 Area covered under different classes of USLE factors

Name of factor	Class	Aerial extent	
		km <sup>2</sup>	%
Soil erodibility	0.07	75.69	21.73
	0.1	9.25	2.66
	0.11	19.20	5.51
	0.13	41.03	11.78
	0.15	8.84	2.54
	0.17	194.33	55.79
Slope length (L)	0.736	153.04	43.93
	0.783	76.12	21.85
	0.832	119.18	34.21
Slope steepness (S)	0–0.25	56.90	16
	0.25–0.50	118.29	34
	0.50–4.0	124.45	36
	>4.0	48.61	14
Combined <i>LS</i> -factor	0–0.25	88.28	25.35
	0.25–1.0	160.14	45.99
	1.0–3.0	52.36	15.04
	>0.3	47.46	13.63
Crop and management	0	29.19	8.38
	0.05	80.00	22.97
	0.1	170.36	48.91
	0.3	68.79	19.75
Support practice	0	29.19	8.38
	0.6	68.79	19.75
	0.8	250.36	71.87



**Fig. 7** Spatial distribution of slope length factor over the catchment

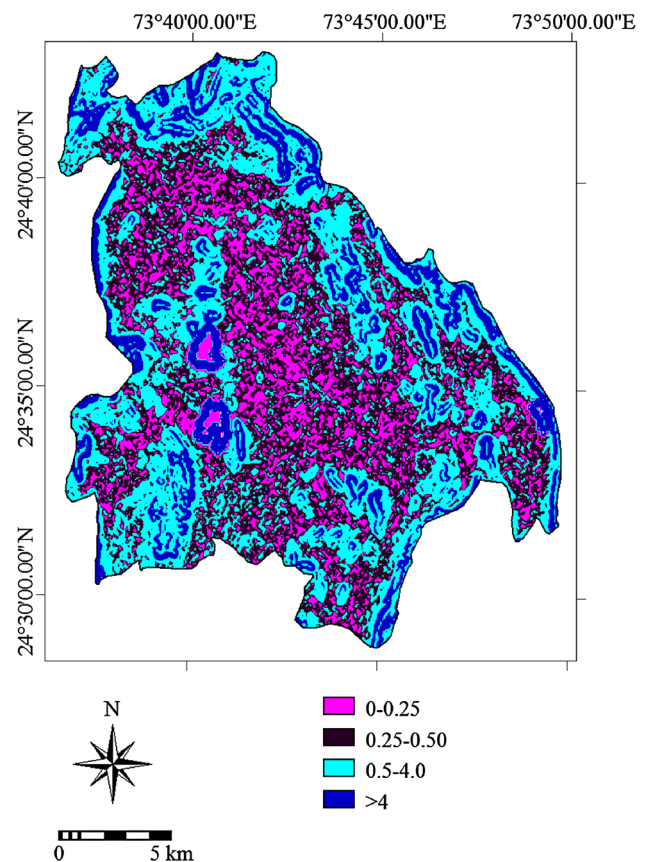
(22 %) covered by coarse loamy sand is with the lowest  $K$ -factor value of 0.07 (Table 3). Besides, the lowest proportion of the area, i.e. 8.84 km<sup>2</sup> (about 2.5 %), has the  $K$ -factor value of 0.15.

#### Slope-Length Factor

The slope length factor ( $L$ -factor) was estimated from Eq. (3) and the spatial distribution of  $L$ -factor in the catchment is shown in Fig. 7. It is seen from Fig. 7 that three classes of the  $L$ -factor, i.e. 0.736, 0.783, and 0.832 exist in the catchment for slopes of  $>5$ , 4, and  $<3$  %, respectively. The lowest value of the  $L$ -factor is observed in 153.04 km<sup>2</sup> (44 %) of the area as seen from Table 3, mainly near boundary of the catchment (Fig. 7) where slopes are relatively high in comparison to other portions with lower slopes. On the contrary, the higher value of the  $L$ -factor is found in 119.18 km<sup>2</sup> (34 %) area mainly nearby waterbodies having almost zero slopes.

#### Steepness Factor

The slope steepness factor ( $S$ -factor) values were computed from Eqs. (4) and (5), and the distribution of the  $S$ -factor over space is depicted in Fig. 8. The  $S$ -factor ranges from 0



**Fig. 8** Spatial distribution of slope steepness factor over the catchment

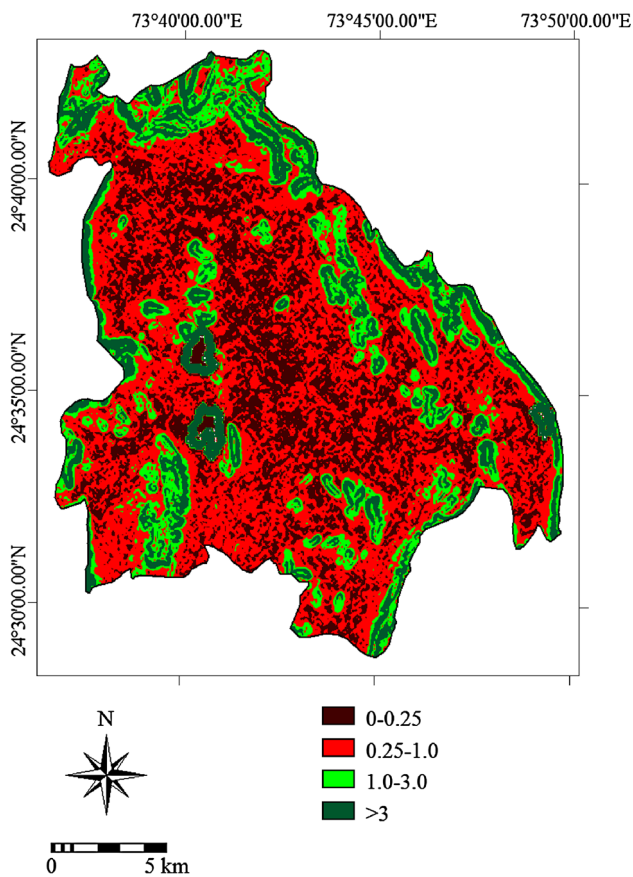
to more than 4 in the catchment. It is revealed that the low values of the  $S$ -factor (0–0.5) are associated with the little slopes in 175.19 km<sup>2</sup> or 50 % of the entire area, whereas the  $S$ -factor value of more than 4 is associated with the high slopes nearby boundary of the catchment in 48.61 km<sup>2</sup> (14 %) of the area. The major portion (124.45 km<sup>2</sup> or 36 %) of the catchment is having  $S$ -factor values in the range of 0.5–4.0 (Table 3). This is followed by the  $S$ -factor values varying from 0.25 to 0.50 covering 118.29 km<sup>2</sup> or 34 % of the catchment area.

The product of  $L$ -factor and  $S$ -factor, resulting in combined  $LS$ -factor, is shown in Fig. 9. It can be seen that the  $LS$ -factor varies from 0 to greater than 3 in the catchment. A large portion of the catchment, i.e. 160.14 km<sup>2</sup> (46 %), depicts  $LS$ -factor values between 0.25 and 1 (Table 3). However, some specific areas (99.82 km<sup>2</sup>) with steep slopes such as slopes along the rivers and along the structure hills present near the boundaries of the catchment, have relatively greater  $LS$ -factor values.

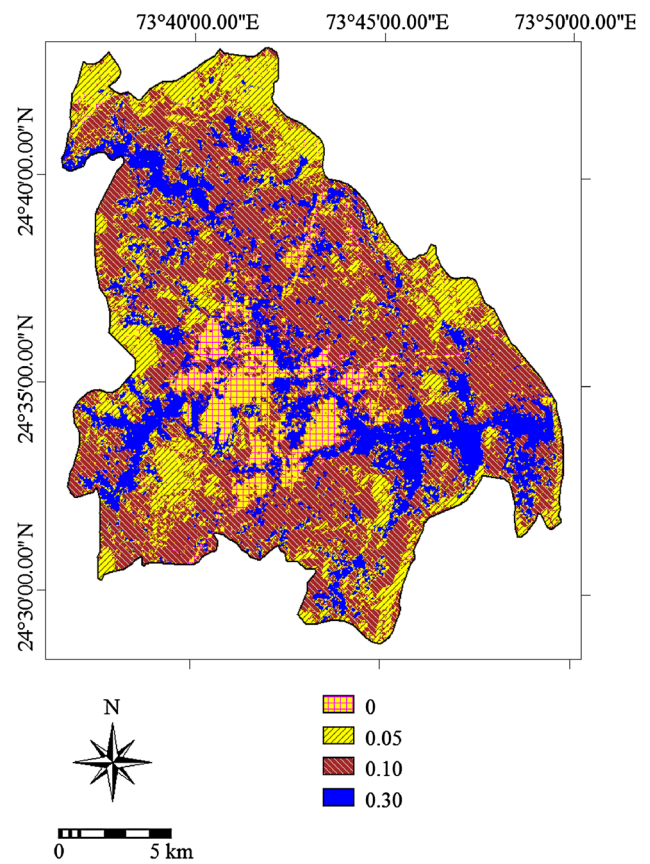
#### Crop Cover and Management Factor

The values of crop cover and management factor ( $C$ -factor) were assigned according to type of land use/land cover





**Fig. 9** Spatial distribution of combined slope length and steepness factor



**Fig. 10** Spatial distribution of crop management factor

**Table 4** Land use/land cover map under different *C*-factor and *P*-factor values

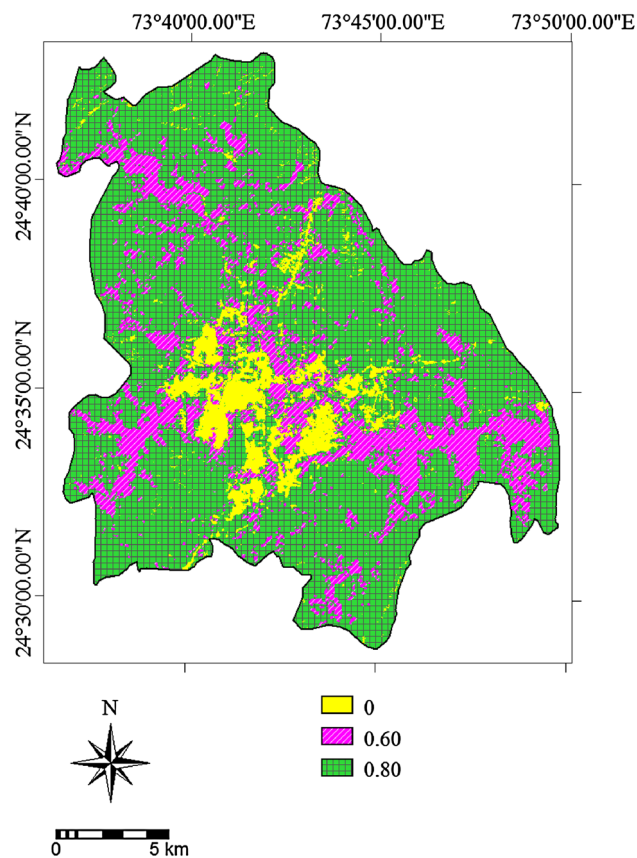
Land use/Land cover	<i>C</i> -factor	<i>P</i> -factor
Agricultural land	0.30	0.60
Builtup land	0	0
Forest land	0.05	0.80
Rangeland	0.10	0.80
Waterbody	0	0

present in the catchment. In this study, the land use/land cover (LULC) map was developed from the satellite imagery as discussed in “Factors Used for Soil Erosion Assessment” section, and the developed LULC map shown in Fig. 4 guided in allocating the *C*-factor values. The LULC map (Fig. 4) classified the catchment into five land use classes namely (i) forest land, (ii) rangeland, (iii) agricultural land, (iv) builtup land, and (v) waterbody. The mean accuracy and reliability of the classified LULC map were 92 and 89 %, respectively. The suitable *C*-factor values to be used in the USLE model were assigned for different LULC patterns as recommended in literature [45]

and based on local experiences (Table 4). It is seen that the highest *C*-factor value of 0.30 was assigned to agricultural land, whereas waterbody and builtup land were assigned 0 value of the *C*-factor. The magnitude and the spatial distribution of the *C*-factor in the catchment are presented in Fig. 10. Aerial extent and percentage proportion of the different *C*-factor classes are provided in Table 3. It is seen from Table 3 that value of the *C*-factor in the major portion of the catchment (170.36 km<sup>2</sup> or 48.91 %) is 0.1, while the *C*-factor value is 0 in 29.19 km<sup>2</sup> (8.38 %) area. The highest *C*-factor value of 0.3 is distributed over 68.79 km<sup>2</sup> (19.75 %) area.

*Support Practice Factor*

In general, no specific or major support/conservation practices are followed in the study catchment. Thus, the values for the *P*-factor were assigned according to the existing land use/land cover (LULC) pattern of the catchment, information available in literature, knowledge and opinion of the local experts, and experiences gained through field visits in the study catchment. While deciding the *P*-factor values for the different LULC classes in the

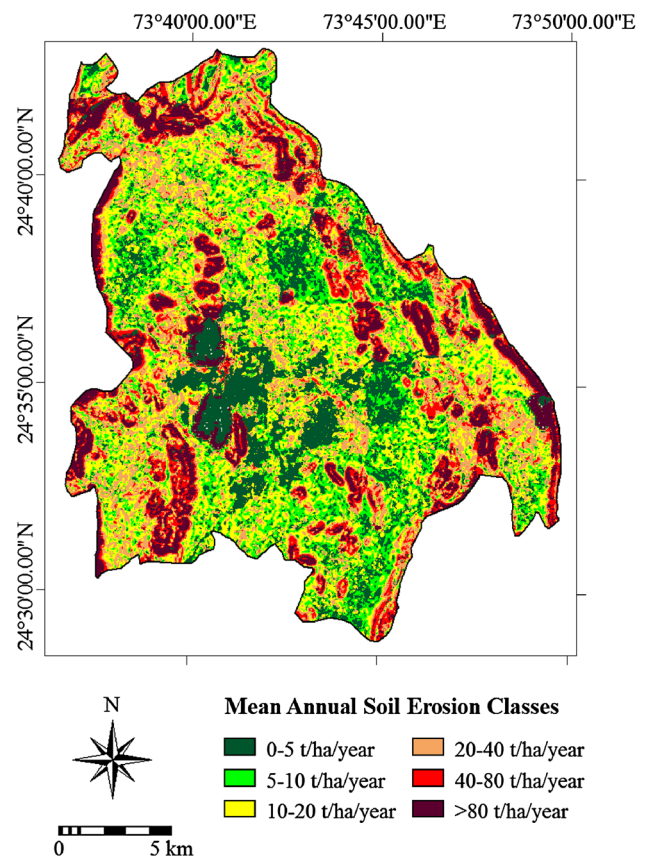


**Fig. 11** Spatial distribution of support practice factor

study area, it was kept in mind that the forest land and rangeland type LULC restrict erosion of the soil up to very less extent compared to other LULC types. Hence, the  $P$ -factor values should be highest for these two LULC types. On the other side, waterbody and builtup land type LULC control the soil erosion effectively (with 0 values of the  $P$ -factor), and agricultural land checks the erosion moderately. The chosen  $P$ -factor values assigned to five LULC classes of the catchment are presented in Table 4 and the spatial distribution of  $P$ -factor is depicted in Fig. 11. It is seen that the highest  $P$ -factor values, i.e. 0.8, is given to forest land and rangeland encompassing 250.36 km<sup>2</sup> (71.87 %) area, while builtup land and waterbody existing in 29.19 km<sup>2</sup> (8.38 %) area are given 0 value of the  $P$ -factor.

#### Spatial Distribution of Soil Loss in Catchment

The spatial distribution of average annual soil loss in the catchment was determined for 10 year period (2001–2010) for 12 m × 12 m size grids/cells following discretization approach by using GIS-based USLE model. The spatially-distributed raster-based maps of the resulted soil erosion estimates were classified into six priority classes, namely



**Fig. 12** Spatially-distributed and classified mean annual soil erosion map of catchment

**Table 5** Area under different classes of mean annual soil erosion

Soil erosion rate (t ha <sup>-1</sup> year <sup>-1</sup> )	Area (km <sup>2</sup> )	Percent area	Soil erosion/priority class
0–5	57.52	16.52	Slight
5–10	59.57	17.11	Moderate
10–20	89.86	25.81	High
20–40	65.19	18.72	Very High
40–80	38.22	10.98	Severe
>80	37.86	10.87	Very Severe

slight, moderate, high, very high, severe, and very severe based on the scheme introduced by Singh et al. [44] for Indian conditions. The classified map of the mean annual soil erosion is shown in Fig. 12. About 57.52 km<sup>2</sup> (16.52 %) of the catchment area is observed to be under slight soil erosion class (Table 5). The areas under moderate, high, very high, severe and very severe soil erosion classes are 17.11, 25.81, 18.72, 10.98, and 10.87 %, respectively (Table 5). It is apparent from Fig. 12 and Table 5 that the soil erosion in 231.13 km<sup>2</sup> (66.38 %) of the total area, covering more than half of the catchment, is

**Table 6** Spatial mean and standard deviation of average annual soil erosion for 10 year period

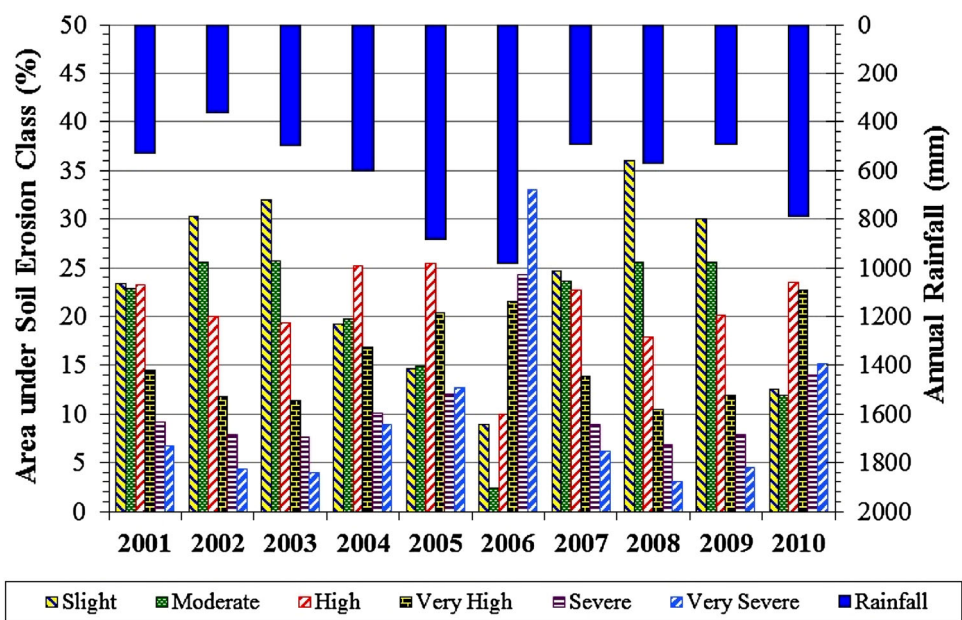
Year	Mean soil erosion (t ha <sup>-1</sup> year <sup>-1</sup> )	Standard deviation (t ha <sup>-1</sup> year <sup>-1</sup> )	Annual rainfall (mm)
2001	74.07	116.70	531.20
2002	57.52	90.58	363.30
2003	54.43	85.80	497.40
2004	89.40	140.81	601.00
2005	117.80	185.59	885.20
2006	324.41	511.10	984.30
2007	70.31	110.84	494.30
2008	48.29	76.09	572.20
2009	58.01	91.38	489.60
2010	141.45	222.90	790.40

already high to very severe conditions accounting for the average annual soil loss of more than 10 t ha<sup>-1</sup> year<sup>-1</sup>. Even the average annual soil loss exceeds the permissible limit (slight soil erosion) of 5 t ha<sup>-1</sup> year<sup>-1</sup> in 290.70 km<sup>2</sup> (83.49 %) of the catchment area. It is revealed from Fig. 9 that the soil erosion is under severe to very severe conditions in portions where hills are present such as catchment boundary. A comparison of Figs. 9 and 12 makes it apparent that the *LS*-factor or steep slopes of hilly terrain is very much crucial for severe soil erosion in the catchment. Hence, huge amounts of soil is getting lost by the process of soil erosion in the major portion of the catchment area, which requires immediate attention to implement soil conservation measures in order to check soil erosion.

### Response of Soil Erosion to Rainfall

The mean and standard deviation of the annual soil loss, occurring from water erosion, estimated by USLE model for ten years (2001–2010) is presented in Table 6 along with annual rainfall values. The large variability of the estimated soil loss over 10 year time scale is largely due to variations in the annual rainfall. The highest amount of mean annual soil loss (324.41 t ha<sup>-1</sup> year<sup>-1</sup>) occurred in the year 2006 when the annual rainfall was also the highest (984.30 mm) for ten-year period. Likewise, the eroded soil quantities were less than 60 t ha<sup>-1</sup> year<sup>-1</sup> in 4 years (2002, 2003, 2008 and 2009) when the amounts of the annual rainfall received in the catchment were less than the mean annual rainfall, i.e. 620.89 mm. Temporal variation of the percentage areas under six soil erosion classes for 10 years is depicted through bar charts in Fig. 13. It is clearly seen from Fig. 13 that the percentage area under the very severe erosion class in 2006 is the maximum (32.99 %) of the 10 years, and at the same time, the slight erosion occurred in the least portion (8.9 %) in the year 2006. Thus, it is apparent that the amount of annual rainfall has profound effect on the occurrence of average annual soil loss occurring in the catchment. It is also revealed that from Fig. 13 that large proportions of areas under slight, moderate and high soil erosion classes, in general, change to areas where very high, severe and very severe soil erosion is experienced. In this study, soil erosion is estimated by using USLE model and the estimated quantities of the soil erosion could not be compared with measured

**Fig. 13** Barcharts showing proportion of areas under six soil erosion classes for 10 years



quantities as the study catchment is ungauged. However, it is recommended that, in future, the estimated amount of soil erosion should be compared with measured soil loss.

## Conclusions

The present study aimed at estimating soil loss potential and identifying critical areas for soil conservation measures in an ungauged catchment of Udaipur, Rajasthan using USLE. The highest and lowest values of rainfall erosivity factor were observed in the years 2006 and 2008 when the annual rainfall (984.3 and 572.2 mm, respectively) was received in 58 and 47 rainy days, respectively. The highest value of soil erodibility (*K*) factor (0.17) was obtained for fine loam soil covering 194.33 km<sup>2</sup> (56 %) of the total catchment area, while the lowest *K*-factor value was computed to be 0.07 for coarse loamy sand spread over 75.69 km<sup>2</sup> (22 %) area. Slope-length (*L*) factor was observed to be the lowest (0.736) in the area nearby catchment boundary having relatively high slopes, whereas the highest *L*-factor value was calculated as 0.832 in 122.26 km<sup>2</sup> (35 %) area nearby waterbodies having zero slopes. Contrary to the *L*-factor, relatively high slope-steepness (*S*) factor values (>4) were found to be associated with high slopes nearby catchment boundary and the low values (*S*-factor ≈ 0–0.5) were observed in 175.19 km<sup>2</sup> (50 %) catchment area having little slopes. The mean annual soil erosion in a large portion of the catchment (231.13 km<sup>2</sup> or 66.38 %) is under high to very severe soil erosion conditions exceeding the soil loss of 10 t ha<sup>-1</sup> year<sup>-1</sup>. The mean annual soil loss in the catchment varied from 48.29 to 324.41 t ha<sup>-1</sup> year<sup>-1</sup> largely depending upon the amount and intensity of annual rainfall. Thus, it is apparent that the huge amount of soil gets eroded from the catchment and the annual rainfall has profound impact on the amount of soil erosion potential. Finally, it is emphasized that the GIS and remote sensing techniques coupled with USLE model are promising and cost-effective tool for estimating the mean annual soil erosion especially in the ungauged catchments of the developing countries. The methodology used in this study is beneficial to identify critical areas of soil erosion in a catchment, which require appropriate planning strategies to conserve soil resources in priority.

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