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Feasibility Study of USLE and MUSLE Models in Estimation of Soil Erosion in Data Scare Situation – A Case Study of Coastal Region

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Abstract: Soil degradation has reached alarming proportions in many parts of the world, especially in the tropics and sub-tropics because of its over-exploitation. A large area suffers from soil erosion, which in turn, reduces productivity. It is necessary to adopt scientific and proper planning to execute conservation work, in order to protect land as well as to meet the increasing demand of food. Assessment of soil erosion is expensive and intensively long exercise. Also, its estimation and accuracy depend upon availability of various types of data. The present study of Ratnagiri district in Konkan region of India uses the Universal Soil Loss Equation (USLE) and Modified Universal Soil Loss Equation (MUSLE) to predict soil erosion using geospatial technology. Rainfall and soil characteristics data were analysed for erosivity and erodibility factors. Topographic and crop cover factors data were obtained through analysis using geospatial tools. Run-off data was not available for any basin of Ratnagiri district. So, rational method and SCS-CN method were used to get required run-off parameters from available data sets. Based on these input data, soil loss of Ratnagiri district by USLE model was found as 43.61 t ha^{-1} yr^{-1} and sediment yield by MUSLE model was 33.45 t ha^{-1} yr^{-1}. Sediment yield was more than 70% of total soil loss which is on higher side by 20% for Konkan region but follows the run-off percentage trend. So, MUSLE model can be used with caution of overestimation in data-scare situations in heavy rainfall, hilly region of lateritic soil, wherever run-off gauging stations are not available.

Keywords: *Soil erosion, USLE, MUSLE, sediment yield*

Introduction

Soil erosion continues to be a global constraint to economic development. Soil degradation by accelerated erosion is a serious problem and will remain so during the 21^{st} century. The severity and economic and environmental impacts of erosion are debatable (Lal 2001). Soil erosion on cultivated lands is a matter of high concern since it is considered to be one of the most critical forms of degradation (Montgomery 2007). Globally, more than 50% of pasture lands and about 80% of agricultural lands suffer from soil erosion (Bhattacharyya *et al*. 2007). Maharashtra is placed among the top five states of the country in terms of area affected by soil erosion. Annually, about 773.5 M tonnes soil is eroded in Maharashtra, and 94% of that erosion is water induced (Durbude 2015). Soil erosion reduces not only the storage capacity of the downstream reservoirs but also deteriorates the productivity of the watershed (Jose *et al*. 2015; Singh and Panda 2017).

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Proper estimation of soil erosion at local levels with suitable modelling technique based on available data is necessary for development of conservation plan. Konkan region of Maharashtra, located in the Western Ghats, boasts of being one of the 34 world biodiversity hotspots (Chitale *et al*. 2015). This region also experiences huge loss of soil through run-off due to extreme weather conditions. Further, Ratnagiri district of Konkan region is an ecologically sensitive zone wherein natural resources need to be protected with maximum care. However, the hilly terrain of Sahyadri ranges hinders data availability or accessibility. Therefore, application of Remote Sensing (RS) and Geographic Information System (GIS) is one of the most suitable alternate techniques for accurate soil loss estimations and regional level planning.

The combined use of geospatial technology and erosion models, such as USLE and MUSLE, has been established to be an effective approach for estimating the magnitude and spatial distribution of erosion (Shinde *et al*. 2011; Alewell *et al*. 2019). The USLE (Wischmeier and Smith 1978) was developed for estimation of the annual soil loss from the plots with help of climatic, soil, topographic, crop and management parameters. In the USLE model, there is no direct consideration of run-off, although erosion depends on sediment being discharged with flow and varies with run-off and sediment concentration (Kinnell 2005). It has been observed that delivery ratios to determine sediment yield from soil loss equation can be predicted but that vary considerably due to the variation in rainfall distribution over time from year to year. As a result of uncertainty in the delivery ratio, MUSLE (Williams and Berndt 1977) was proposed with the replacement of the rainfall factor with a run-off factor. Particularly, this model is intended to estimate the sediment yield on a single storm basis for the outlet of the watershed based on run-off data, as latter is the best indicator for sediment yield prediction (ASCE 1970; Bhattarai and Dutta 2008). MUSLE increases sediment yield prediction accuracy and also, it eliminates the need for sediment delivery ratios, provided sufficient run-off data is available. In absence of run-off data, run-off parameter of MUSLE obtained by indirect method from rainfall and other characteristics can be used. But, it may hamper the accuracy of sediment yield. So, it is essential to compare both the models in data-scare situation. In this context, the present study was undertaken to estimate soil loss and sediment yield in Ratnagiri district with help of USLE and MUSLE model.

Materials and Methods

Study area

Ratnagiri is a coastal district of Maharashtra state, situated in the western coast of India extending from 16°25′ to 18°05′ N latitude and 73°00′ to 73°50′ E longitude (Fig. 1). The total geographical area of Ratnagiri district is 8,377 Km^2 with average annual rainfall of 3,591 mm. Daily rainfall data from 1984 to 2011 used to compute rainfall erosivity factor and peak run-off rate for five rain gauge stations (*Hedvi, Karak, Poynar, Dapoli and Wakavali)* of study area was collected from Water Resource Department, Government of Maharashtra, Nashik and Department of Agronomy Dr. BSKKV, Dapoli.

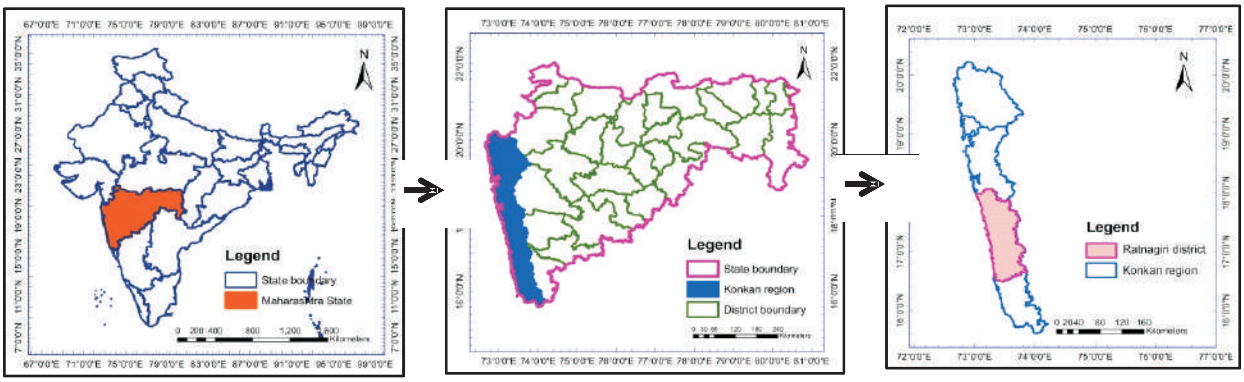

Fig. 1. Location map of study area

Universal Soil Loss Equation (USLE)

The USLE was proposed for estimating sheet and rill erosion losses from cultivated fields. This empirical equation, based on a large mass of field data, computes sheet and rill erosion as annual average soil loss (t $ha^{-1}yr^{-1}$) using the values representing the four major types of factors affecting erosion (Renard *et al.* 1997). These factors are climatic, soil, topographic, land use and management. In the present study an attempt has been made to estimate the actual soil loss in study area through Universal Soil Loss Equation (USLE) and by the integrated analysis of spatial data in GIS.

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

where, A is computed soil loss (t ha^{-1} yr^{-1}), R is the rainfall erosivity factor (MJ $mm^{-1}ha^{-1}hr^{-1}yr^{-1}$), K is the soil erodibility factor (t ha $hr^{-1}ha^{-1}MJmm^{-1}$), L is the slope length factor (m), S is the slope steepness factor, C is the crop cover management factor, and P is the conservation practice factor.

Modified Universal Soil Loss Equation

Accurate prediction of sediment yield from watersheds is important from land use, management, and environmental standpoints. Modified Universal Soil Loss Equation (MUSLE), was developed to aid in this prediction (Williams 1975) by replacing the rainfall energy factor of the USLE (Wischmeier and Smith 1960) with a run-off energy factor. The energy factor in MUSLE is a function of the product of the run-off volume and the peak run-off rate for an individual storm. MUSLE has certain advantages over USLE (Williams 1981), especially in simulating sediment yield from a watershed. The advantages include application to individual storms, elimination of the need for sediment delivery ratios because the run-off factor reflects energy used in sediment transport as well as in sediment detachment and greater accuracy because run-off accounts for sediment yield variation better than rainfall.

In fact, the Hydraulics Division, American Society of Civil Engineers (Sedimentation Task Committee 1970) has stated that run-off is the best single indicator of sediment yield. To date, initial results with MUSLE have been encouraging (Djoukbala 2018) wherever, run-off parameter data *viz.* run-off volume and peak run-off rate are available, but additional testing is necessary to fully document the equation's utility in specific land resource areas and under different land management conditions. In present study, run-off data was not available; so, attempt was made to generate run-off data with the help of available rainfall data. Based on rainfall characteristics and other relevant information, peak run-off rate and run-off depth were estimated by rational method and SCS-CN method respectively. Ratnagiri district was divided into 13 basins and run-off parameters were estimated for each basin as per procedure given below. These were used to estimate the sediment yield in study area through Modified Universal Soil Loss Equation (MUSLE) by applying the integrated analysis of spatial data in GIS.

$$Y = 11.8*(Q*Q_{peak})^{0.56} * K * LS * C * P \ldots\ldots\ldots(2)$$

Peak run-off rate (q_{peak})

Daily rainfall data from 1984 to 2011 of 5 stations in the study area were used to compute peak run-off rate (q_{peak}, m^3 s^{-1}) using rational method (Eq. 3).

$$Q_{peak} = \frac{C*I*A}{360} \ldots\ldots\ldots(3)$$

where, C is run-off coefficient, I is rainfall intensity (mm hr^{-1}) and A is watershed area (ha). Run-off coefficient is the fraction of rainfall converting into surface run-off. It is defined as the ratio of the run-off and rainfall. It depends on land use and land types (Suresh 2012). For present study, different values of C were shown in table 1 depending upon land use and soil types for Ratnagiri district.

Table 1. Values of C for use in rational formula

Land use and topography	Soil type	
	Loam	Sandy loam
Forest land		
(a) Flat	0.30	0.10
(b) Hilly	0.50	0.30
Agriculture land		
(b) Flat	0.50	0.30
(c) Rolling	0.60	0.40
(c) Hilly	0.70	0.52

Run-off volume (Q, m^3)-SCS Curve Number Model

In hydrological modelling, the estimation of run-off is the most important aspect. The most commonly and widely used empirical method is the Soil Conservation Service-Curve Number Method (Soil Conservation Service 1972) developed by United States of Department of Agriculture and Soil Conservation Service (USDA-SCS) to estimate surface run-off. It computes storm wise direct run-off (depth) or rainfall excess. This method is based on potential retention capacity (S) of watershed. I_a is the initial loss of rain water by interception, infiltration through the soil, depression storage *etc.* This method assumes that the ratio of direct run-off (surface run-off) (Q) to the rainfall depth minus the initial losses ($P-I_a$) is equal to the ratio of actual retention of rainfall to the S, *i.e.*

$$\frac{Q}{P - I} = \frac{P-Q-I_a}{S} \quad ....(4)$$

To simplify the above equation (10), it is assumed that I_a is the fraction of potential retention (S). Let, I_a= 0.3S for Indian condition (Suresh 2012), then

$$Q= \frac{(P-0.3S)^2}{P + 0.7S} \quad ....(5)$$

By using this equation (equation. 5), the value of Q has been calculated for Ratnagiri district of 13 basins. The retention capacity (S) of the watershed was calculated by using curve number, as defined (Latha *et al.* 2012), given as,

$$CN= \frac{2540}{25.4+S} \quad ....(6)$$

In which CN is the curve number. The values of curve number (Suresh 2012) for different land use conditions and hydrologic soil groups (HSG) are shown in table 2. Then weighted CN was calculated for Ratnagiri district.

Table 2. CN values for different land use categories for Ratnagiri district

Land use	Area (ha)	CN	HSG	Weighted CN
Agriculture	120437.4	76	A	65
Forest	299097.6	48		
Built up	213621.4	77		
Fallow	201678.8	71		

Results and Discussion

Rainfall erosivity factor (R)

R is long term annual average of the product of event rainfall kinetic energy and the maximum intensity in 30 minutes in mm per hour (Wischmeier and Smith 1978). In the present study the daily precipitation data of 28 years for five stations of Ratnagiri district was used to estimate erosivity index. Erosivity index of Wakavali station of Dapoli was calculated by EI_{30} method (Nandgude *et al*. 2013). Due to scarcity of rainfall intensity data of study area, in the present study the daily precipitation and EI_{30} data of Wakavali station were used for regression analysis and regression equation was obtained for computing the daily erosivity index from trend line of graph. The following equation implies the correlation between daily Erosivity Index and daily rainfall.

$$Y = aX^{b} \quad \text{.................................(7)}$$

where, Y is daily erosivity index and X is daily precipitation. The equation found was a power function with a and b as constants. The coefficient of determination obtained was 0.7624 with value of 'a' as 0.3339 and that of 'b' as 1.50. It was observed that average annual erosivity for Hedvi, Karak, Poynar, Dapoli and Wakavali stations were 10001, 10837, 9734, 10285 and 10,117 MJ mm $ha^{-1}hr^{-1}yr^{-1}$ respectively. These values were assigned to respective polygons in these polygons to get R factor map. Using these annual erosivity values R-map of study area was prepared (Fig. 2). Erosivity of Ratnagiri district is very high due to very high intensity and amount of rainfall, which makes it one of the major factors influencing soil erosion of the district.

Soil erodibility factor (K)

The soil erodibility factor, K, relates to the rate at which different soils erode due to inherent soil properties. The K factor was computed for each soil type of study area with the help of data obtained from soil analysis regarding soil texture, structure, permeability and organic matter content. An algebraic approximation of the monograph that includes soil parameters such as texture, structure, permeability and organic matter content is proposed by the equation (Renard *et al*. 1997; Wischmeier and Smith 1978),

$$K = \{[2.1*10^{-4}M^{1.14}(12-a) + 3.25\,(b-2) + 2.5\,(c-3)]/100\}*0.1317 \quad \text{............... (8)}$$

where, K= soil erodibility factor (t ha hr $ha^{-1}MJ^{-1}mm^{-1}$), b= structure of the soil, M= (% silt + 0.7 * % sand) * (100 - % clay), c= permeability of the soil, a= organic matter content (a=organic carbon * 1.724).

These K factor values were assigned to the different location of study area in ArcGIS 10.2 to get soil erodibility (K) map (Fig. 3). The value of K factor for different locations of Ratnagiri district were found in the range of 0.0346 to 0.0636 t ha hr ha^{-1} MJ^{-1} mm^{-1}. A higher soil erodibility value was observed in patches, and the values increased towards the coastal side.

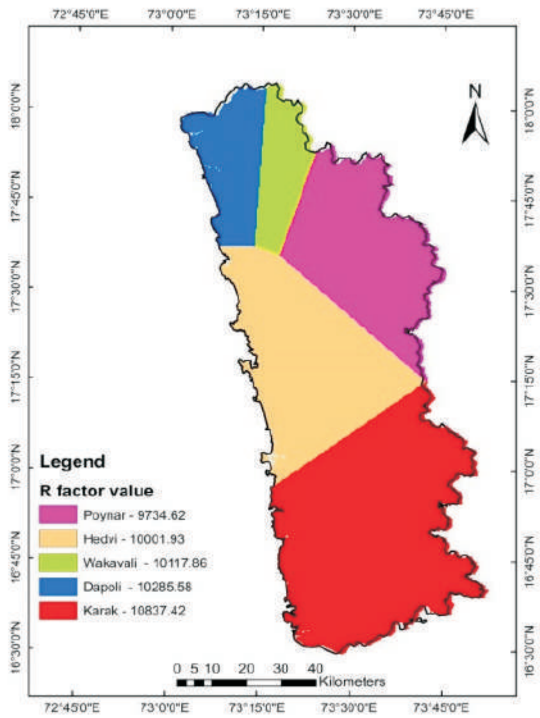

Fig. 2. Rainfall Erosivity map of Ratnagiri district

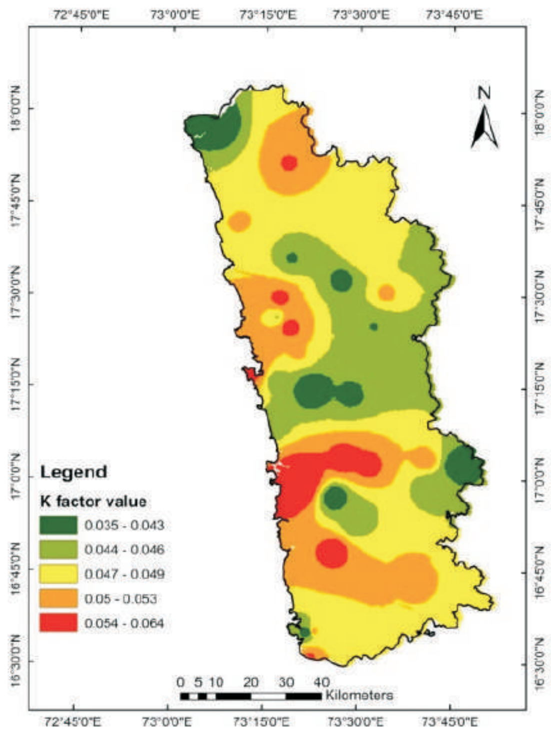

Fig. 3. Soil erodibility map of Ratnagiri district

Topographic factor (LS)

Topographic factor (LS) in USLE accounts for the effect of topography on sheet and rill erosion. The two parameters that constitute the topographic factor are slope gradient (S) and slope length factor (L) and can be estimated from a digital elevation model (DEM).

The relationship between the slope steepness in percentages (Sp) and slope length in meters (L) were used to generate slope length map. It is given by

$$L = 0.4 * Sp + 40 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where, L = Slope length in meters and Sp = Slope steepness in percentage. By applying this equation the resultant map was prepared for slope length.

Although L and S factors were determined separately, the procedure has been further simplified by combining the L and S factors together and considering the two as a single topographic factor (LS) (Wischmeier and Smith 1965). Combined LS factor layer was generated as

I. For slopes up to 21%, the equation modified (Wischmeier and Smith 1978) was used which is,

$$LS1 = (L / 22.1) *(65.41 \sin^2\theta + 4.56 \sin\theta + 0.065) \ldots (10)$$

where, LS1 is the slope length and gradient factor and θ is angle of the slope.

II. For slope steepness of 21 % or more, the equation used, which is given by

$$LS2 = (L / 22.1)^{0.7} * (6.432 * \sin(\theta^{0.79}) *\cos(\theta)) \ldots (11)$$

where, LS2 is the slope length and gradient factor, θ is angle of the slope and L is slope length in meters. Digital elevation model (DEM) of the study area was prepared using SRTM data. A slope map was created from the DEM, based on the slope map, slope length (L) and slope gradient (S) maps and finally a layer of LS factor was generated for Ratnagiri district (Fig. 4). The values of LS factor for study area was found in the range of 1.953 to 4.393. Major portion of Ratnagiri district was covered by LS factor ranging between 2 to 3 (85.42%), followed by 1 to 2 (14.25%) and 3 to 4 (0.34%). Very small portion of the study area was covered by LS factor more than 4 (0.001%).

Crop cover and management factor (C)

The C factor is related to the land use and land cover. The cover and management factor (C) reflects the effect of cropping and management practices on soil erosion rates. The land use and land cover map of study area was used for analysing the C-value. LANDSAT-7 images (ftp.glcf.umd.edu, Path No. 147, Row No. 48 and 49) were used for preparation of land use land cover map. Crop cover data of study area was collected from the District Superintending Agriculture Office, Ratnagiri, Maharashtra to obtain the crop cover management factor (C). The land use/cover classification of the study area was carried out using supervised classification (maximum likelihood classification). Classification was carried out for five land use classes: forest, barren land, built up land, agricultural land and water body. Each class is then assigned C factor value (Table 3) as suggested by Rasool *et al*. (2014), based on these values; C factor map of study area was prepared (Fig 5).

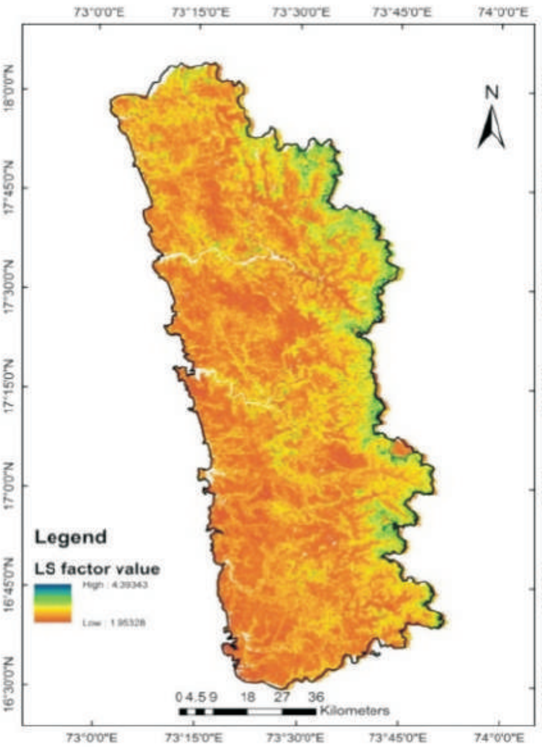

Fig. 4. Topographic factor map of Ratnagiri district.

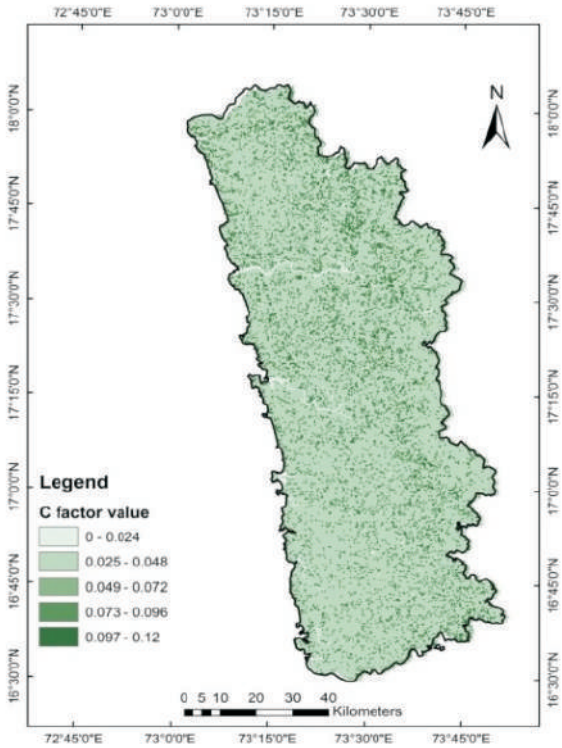

Fig. 5. Crop cover management map of Ratnagiri district.

Table 3. Land use class and C value

Land use class	C value
Forest	0.04
Barren land	0.034
Built up land	0.024
Agricultural land	0.12
Water body	0

Conservation practice factor (P)

The P factor in USLE is defined as the ratio of soil loss with a specific conservation practice to the corresponding soil loss due to up and down practice. It accounts for the practices that reduce the erosion potential of the run-off by their influence on drainage patterns, run-off concentration, run-off velocity, and hydraulic forces exerted by run-off on soil. The supporting mechanical practices include the effects of contouring, strip cropping, or terracing. The P factor depends on the conservation measure applied to the study area. P factor was assigned as 1 for the study area as it was untreated.

Average Annual Soil Loss using USLE

All the layers *viz.* R, K, LS, C and P were generated in GIS and were integrated to obtain the product, which gave average annual soil loss of the Ratnagiri district. Classification of soil erosion in study area was done into six classes as slight, moderate, high, very high, severe, and very severe (Singh *et al*. 1992). Estimated average annual soil loss from Ratnagiri district was 43.61 t $ha^{-1}yr^{-1}$ (Fig. 6). It showed that more than 80% of area comes under severe to extremely severe erosion class which is a major cause of concern (Table 4). This calls for urgent soil and water conservation measures in the watershed for the sustainable management of natural resources. However, this soil loss is the displacement of soil from its place of formation. Out of this soil loss not whole gets deposited in sea or reservoir. Though, some portion goes to reservoir and sea in the form of sediment yield and remaining gets deposited at other downstream side location in the watershed. With this soil erosion study, land degradation of specific location can be estimated properly. However, for estimation of soil loss, the stream flow in the form of sediment yield to reservoir and sea, MUSLE may give better accuracy as it considers run-off factor rather than rainfall (Dutta 2016).

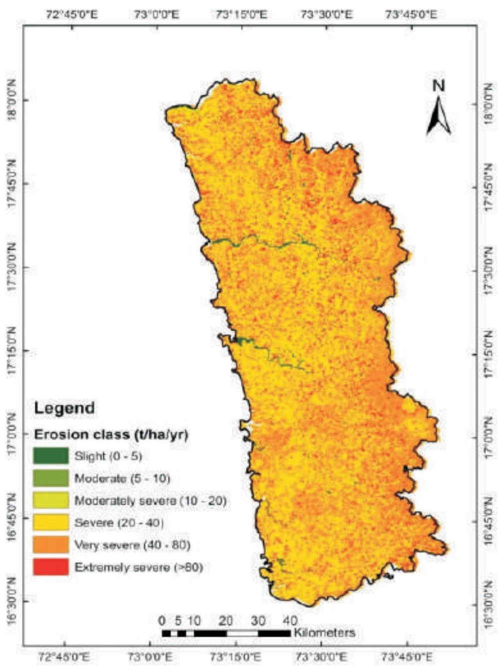

Fig. 6. Average annual soil loss map of Ratnagiri district before conservation measures

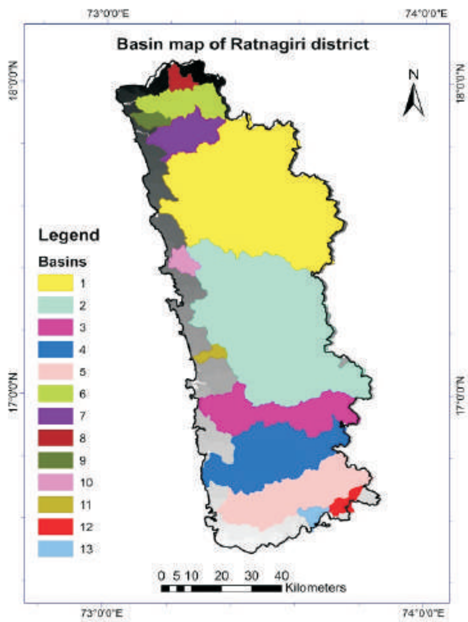

Fig. 7. Basin map of Ratnagiri district

Table 4. Area under different classes of soil erosion

Soil erosion class	Soil loss (t $ha^{-1}yr^{-1}$)	Area (ha)	Per cent area
Slight	0-5	10868.86	1.30
Moderate	5-10	34641.46	4.14
Moderately severe	10-20	95689.16	11.42
Severe	20-40	390953.6	46.67
Very severe	40-80	186843.2	22.31
Extremely severe	>80	118677.4	14.17

Average sediment yield using MUSLE

The study area was divided into 13 basins based on DEM map and drainage characteristics (Fig. 7). As run-off data is not available in any of these basins, run-off parameters of each basin were estimated by rational method and SCS-CN method (Table 5). The average annual sediment yields (t yr^{-1}) were computed by using annual average Q and q_{peak} (based on annual average rainfall data of 1984-2011), K, LS, C and P factors for each basin of Ratnagiri district. Accordingly the sediment yield rates (t $ha^{-1}yr^{-1}$) were also estimated for 13 basins of Ratnagiri district. Total average annual sediment yield from Ratnagiri district was 33.45 t $ha^{-1}yr^{-1}$ (Table 6).

This sediment yield by MUSLE is a part of soil loss estimated by USLE. Run-off is single most influencing parameter for sediment yield prediction (ASCE 1970; Williams 1975), and in the present study measured run-off parameters are replaced by estimated parameters from rainfall data. So, soil loss conversion to sediment yield would also follow the similar trend of rainfall to run-off proportion of the region. In Konkan region, run-off is 68-80% of rainfall (Sawant *et al.* 1997). Accordingly, it was observed that sediment yield by MUSLE was more than 70% of soil loss by USLE model. As per previous studies (Fernandez *et al*. 2003; Vemu and Udaya 2012; Richarde *et al*. 2014) sediment yields were in the range of 30 to 60% of soil erosion loss. So, the sediment yield was overestimated by 15-20% due to absence of measured run-off parameters. So, it is inferred that, even though direct run-off parameters are not available as per requirement of MUSLE model, indirect estimation of run-off parameters for use in MUSLE model overestimate the sediment yield by 15-20%. However, results of study are very encouraging for use in majority of the basins in India as run-off gauging stations are not available in these basins. So, MUSLE model can be used with caution of overestimation in data scare situation in heavy rainfall, hilly region of laterite soil, wherever run-off gauging stations are not available.

Table 5. Run-off volume and peak run-off rate of 13 basins in study area

Basin No.	Basin area, km^2	Q (M^a m^3)	q_{peak} ($T^b m^3 s^{-1}$) (Sandy loam)	q_{peak} ($T^b m^3 s^{-1}$) (Loam)
1	2124.00	3976.73	24.80	41.91
2	2122.00	4462.99	23.90	40.39
3	545.79	1090.66	9.48	16.01
4	727.37	456.33	9.72	16.42
5	625.59	1090.66	8.36	14.13
6	249.00	458.84	3.06	5.16
7	247.00	455.88	3.03	5.12
8	53.83	109.34	0.63	1.07
9	56.84	115.46	0.67	1.13
10	65.60	137.95	0.74	1.25
11	49.67	104.46	0.56	0.95
12	53.32	92.97	0.71	1.20
13	45.35	79.08	0.61	1.02

[a]M = million, [b]T = thousand

Table 6. Basin wise sediment yield in study area

Basin No.	Basin area	Sediment yield	
	km^2	$t\ yr^{-1}$	$t\ ha^{-1}yr^{-1}$
1	2124.00	760045.8	2.66
2	2122.00	806496.7	3.8
3	545.79	213943.3	1.86
4	727.37	68400.4	1.8
5	625.59	177449	3.92
6	249.00	61220.8	2.88
7	247.00	60695.4	2.83
8	53.83	12040.1	2.11
9	56.84	12797.3	2.07
10	65.60	12245.05	2.24
11	49.67	84434.1	2.25
12	53.32	11256.3	2.46
13	45.35	9390.4	2.57
	Total	**2290415**	**33.45**

Conclusion

In the present study, the sediment yield was estimated by Modified Universal Soil Loss Equation (MUSLE) and soil loss was estimated by Universal Soil Loss Equation (USLE). The conversion of soil loss to sediment yield has also followed the similar trend of rainfall to run-off proportion of the region. Accordingly, estimated sediment yield from Ratnagiri district using MUSLE was found as 33.45 $t\ ha^{-1}yr^{-1}$. In Konkan region, run-off is reported to be 68-80% of rainfall. However, in present study it was observed that sediment yield estimated by MUSLE was more than 70% of soil loss estimated by USLE model with similar trend of rainfall to run-off proportion. So, it is inferred that even though direct run-off parameters are not available as per the requirement of MUSLE model, indirect estimation of run-off parameters for use in MUSLE model gives acceptable trend of results with overestimation of the sediment yield by 15-20%. So, results of study are very encouraging for use in majority of the basins in India as run-off gauging stations are not available in these basins. So, MUSLE model can be used with caution of overestimation in data scare situation in heavy rainfall, hilly region of laterite soil, wherever run-off gauging stations are not available.

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