Geospatial approach in mapping soil erodibility using CartoDEM – A case study in hilly watershed of Lower Himalayan Range

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Soil erodibility is one of the most important factors used in spatial soil erosion risk assessment. Soil information derived from soil map is used to generate soil erodibility factor map. Soil maps are not available at appropriate scale. In general, soil maps at small scale are used in deriving soil erodibility map that largely generalized spatial variability and it largely ignores the spatial variability since soil map units are discrete polygons. The present study was attempted to generate soil erodibilty map using terrain indices derived from DTM and surface soil sample data. Soil variability in the hilly landscape is largely controlled by topography represented by DTM. The CartoDEM (30 m) was used to derive terrain indices such as terrain wetness index (TWI), stream power index (SPI), sediment transport index (STI) and slope parameters. A total of 95 surface soil samples were collected to compute soil erodibility factor (K) values. The K values ranged from 0.23 to 0.81 t ha^{-1}R^{-1} in the watershed. Correlation analysis among K-factor and terrain parameters showed highest correlation of soil erodibilty with TWI (r^2 = 0.561) followed by slope (r^2 = 0.33). A multiple linear regression model was developed to derive soil erodibilty using terrain parameters. A set of 20 soil sample points were used to assess the accuracy of the model. The coefficient of determination (r^2) and RMSE were computed to be 0.76 and 0.07 t ha^{-1}R^{-1} respectively. The proposed methodology is quite useful in generating soil erodibilty factor map using digital elevation model (DEM) for any hilly terrain areas. The equation/model need to be established for the particular hilly terrain under the study. The developed model was used to generate spatial soil erodibility factor (K) map of the watershed in the lower Himalayan range.

1. Introduction

Soil erosion is a major land degradation process in the mountain and hilly regions (Dabral *et al.* 2008). It has increased due to inappropriate LU/LC and unscientific management practices followed in the hilly regions. The Himalayan region is facing highest erosion rates in the world (Ismail and Ravichandran 2008), attributed to its topography and vegetation cover (Jain *et al.* 2001). Soil erosion is estimated employing various empirical and process-based models (Jetten *et al.* 2003). Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) and Revised USLE (Renard *et al.* 1997) are the widely used empirical models. These models compute soil erosion by integrating rain erosivity factor (R), soil erodibility factor (K), slope length factor (L), slope steepness factor (S), cover management factor (C) and support practice factor (P) (Wang *et al.* 2001). Soil erodibility factor is one of the main factors governing soil erosion. It expresses the susceptibility of soil towards erosion and measures

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the contribution of soil types. Commonly, it is computed using mathematical equation (Wischmeier and Smith 1978) accounting the soil texture, soil organic matter, soil structure and permeability of the soil. Topography largely governed the spatial variability of the soil properties (Lal 2001) in hilly watershed. Digital Elevation Models (DEMs) are commonly used to represent topography and also in extracting topographical parameters. In recent years, availability of freely downloadable DEMs in various resolutions such as CartoDEM (30 m), SRTM (30, 90 m) and ASTER (30 m), has increased its utility to characterize the terrain parameters and terrain indices at various spatial resolutions to cater the needs of various mapping scales. CartoDEM (30 m) has planimetric accuracy of 15 m and vertical accuracy of 8 m (Krishnamurthy *et al.* 2008). When it was compared to SRTM DEM over Indian landmass, 90% of the pixels of CartoDEM reported were within ±8 m difference. The drainage delineation showed better accuracy and clear demarcation of catchment ridgeline and more reliable flow-path prediction in comparison with ASTER (Muralikrishnan *et al.* 2013).

Soil maps are in general used by several researchers/ users to compute the soil erodibility factor in soil erosion assessment (Behera *et al.* 2005; Jiang 2013; Tirkey *et al.* 2013). In the absence of appropriate scale of soil map, users face the difficulty in preparing soil erodibility map and thus soil erosion assessment is highly underestimated. Soil maps are basically represented by discrete polygons. They fail to represent continuous variability in soil and thus the soil erodibility. Secondly, soil maps available at small scales fail to capture the variation in soil erodibility at the larger scale. Several studies were carried out to assess soil erosion at micro and sub-watershed scales (1:50,000 scale) using these small scale soil maps (Shi *et al.* 2002; Park *et al.* 2011). Researchers in these studies had derived vegetation cover (C) and management practice factor (P) maps from land use/land cover map prepared at a scale of 1:50,000 and topographic (LS) factor (slope steepness and slope length factor) map using DEM of 30 m spatial resolution. But the soil erodibility factor map was derived from soil map of small scales (1:250,000 or 1:500,000) and integrated them using erosion models to compute soil erosion which is inappropriate due to large variation in their scales. In small scale soil map, soil erodibility factor (soil-K) values are represented by few soil map units in the watershed. Thus, the spatial variation of soil-K factor, which is considered to be the most important data layer in soil erosion modelling and assessment, is largely masked. Unavailability of the soil maps at larger scale is a major bottleneck in soil erosion studies and watershed planning since the spatial variability of the soil erodibility is not well represented in the area.

Standard soil maps are prepared by soil surveyor and it provide comprehensive information of soils through systematic examination, description, classification and mapping of soils of an area. It provides soil information of typical pedons with several physico-chemical properties of soils and its taxonomic classification. Therefore, standard soil maps are expensive to prepare and time consuming. At present, soil map of the country prepared at 1:250,000 scale and published at 1:500,000 by National Bureau of Soil Survey & Land Use Planning (NBSS & LUP) is available to the users (Bhattacharyya *et al.* 2009). They are used for assessing soils at regional or state levels with generalized soil information (Manchanda *et al.* 2002). Large scale soil maps are not available for the entire country. In the absence of large scale or detail map, researcher use the small scale of soil map prepared by NBSS & LUP to derive soil erodibility factor map for erosion study. But these maps are useful only at regional scale study. Preparing soil erodibility map require information of surface soils which can be easily generated by collecting surface soil samples and analyzing basic soil characteristics of soil texture, soil organic matter, soil structure and permeability of soils (Wischmeier and Smith 1978). Thus, there is high need to map soil erodibility factor at appropriate scale to meet the requirement of soil erosion assessment for watershed planning and management. Availability of DEM at varying spatial resolution (10–90 m) facilitated the characterization of terrain parameters at various scales. The characterization and investigation of the spatial distribution of soils and their properties through soil survey, is advancing due to the increasing need to gather knowledge about soils. The conventional soil mapping is costly and time consuming. Therefore, researchers are focusing on digital techniques (McBratney *et al.* 2003; Hengl 2007) in mapping soil properties. Digital soil mapping is, thus, a paradigm in progress although remarkable achievements have already been made (Lagacherie *et al.* 2007; Hartemink *et al.* 2008). Digital soil mapping involves quantitative prediction of soils and their properties using some observed soil data and auxiliary data on all or some of the soil forming factors (Dobos *et al.* 2006). Spatial distribution of soils is dictated by five major factors, among which the influence of topography is so strong that it can be used solely to predict the spatial distribution of soils in many landscapes. Topography influences endogenic and exogenic soil forming factors and processes, and plays a crucial role in the spatial distribution of soils and their properties (Schaetzl and Anderson 2005).

Field soil survey is the primary method of acquiring soil properties and is normally done with point samples, obtained either systematically or randomly. The point data are usually interpolated to produce soil maps. Various interpolation methods have been used to generate soil maps (Voltz *et al.* 1997). The accuracy of the map depends upon the soil sampling density and distribution of the original data points (McBratney *et al.* 2000). Several researchers have used statistical models to map soil properties such as soil moisture distribution (Wu *et al.* 2007), soil carbon maps (Luca *et al.* 2007), and soil drainage (Bell *et al.* 1994).

The present study has attempted the use of DEM in mapping soil erodibility factor map of the hilly watershed. It establishes relationship of terrain parameters with soil erodibility to generate spatial variability soil erodibility.

2. Study area

A hilly watershed, located between latitude 30°25′–30°30′N and longitude 77°45′–78°0′E, lies in lesser Himalaya in Dehradun district was selected for the study (figure 1). The total geographical area is 805 ha. The climate is characterized as humid and subtropical. The mean annual temperature ranges from 15.8°C in winter to 33.3°C in summer. The mean annual rainfall received is 2051 mm (1983–2008) and 70% of it is received during the monsoon season (June–September) in which July and August are highest rainfall receiving months. Geology of watershed gives the evidence of pre-Cambrian rocks of lesser Himalaya. The lesser Himalayas consist of granite, quartzite, phyillite and pebbles, etc. Soils are sandy loam and sandy clay loam in texture. The forest, crop land and scrub are the major land use/land cover classes. The main cropping season is the monsoon (kharif) and the winter (rabi). Paddy (Oryza sativa) and maize (Zea mays) are grown in the kharif season whereas wheat (Triticum aestivum) is cultivated during the rabi season. Sal trees (*Shorea robusta*) are the dominant tree species in the forest land.

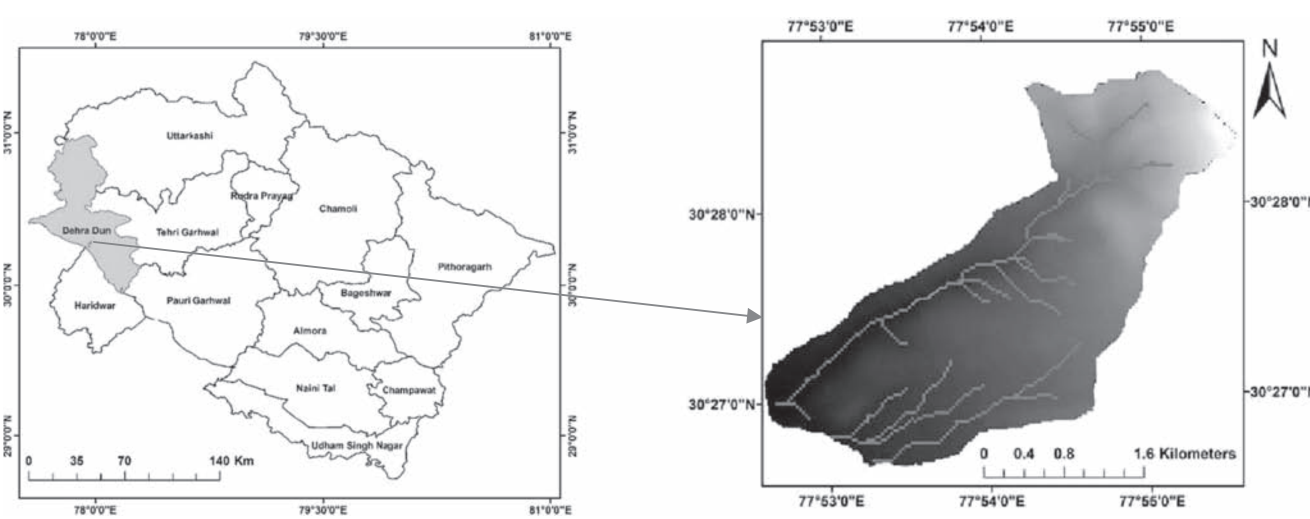
3. Methodology

3.1 *Soil sampling and soil analysis*

Preparing a comprehensive sampling plan is an important step prior to sampling, in order to carry out a precise and accurate sampling. Toposheet 53F/15 and Google Earth image were used to prepare a grid sampling plan in order to ensure that samples could be taken systematically and were well distributed. Grid sampling in addition to transect sampling was done with grid size of 250 m × 250 m (±20 m) at a depth of 0–15 cm in the months of April–May, 2011. A total of 95 sample locations were identified to collect the soil samples (figure 2). The soil properties such as gravel percentage and soil structure were recorded during field work in order to account for the soil permeability and soil structure class. Soil samples were collected and analysed for soil texture (sand, silt, clay) using Bouyoucos hydrometer method (Gee and Bauder 1986) while the organic carbon was measured using Walkley & Black method (Page *et al.* 1992).

3.2 *Data and software used*

Cartosat-1 DEM (www.bhuvan.nrsc.gov.in) having the spatial resolution of 30 m was used to generate



(a) (b)

Figure 1. Study area **(a)** Dehradun District, Uttarakhand state and **(b)** watershed.

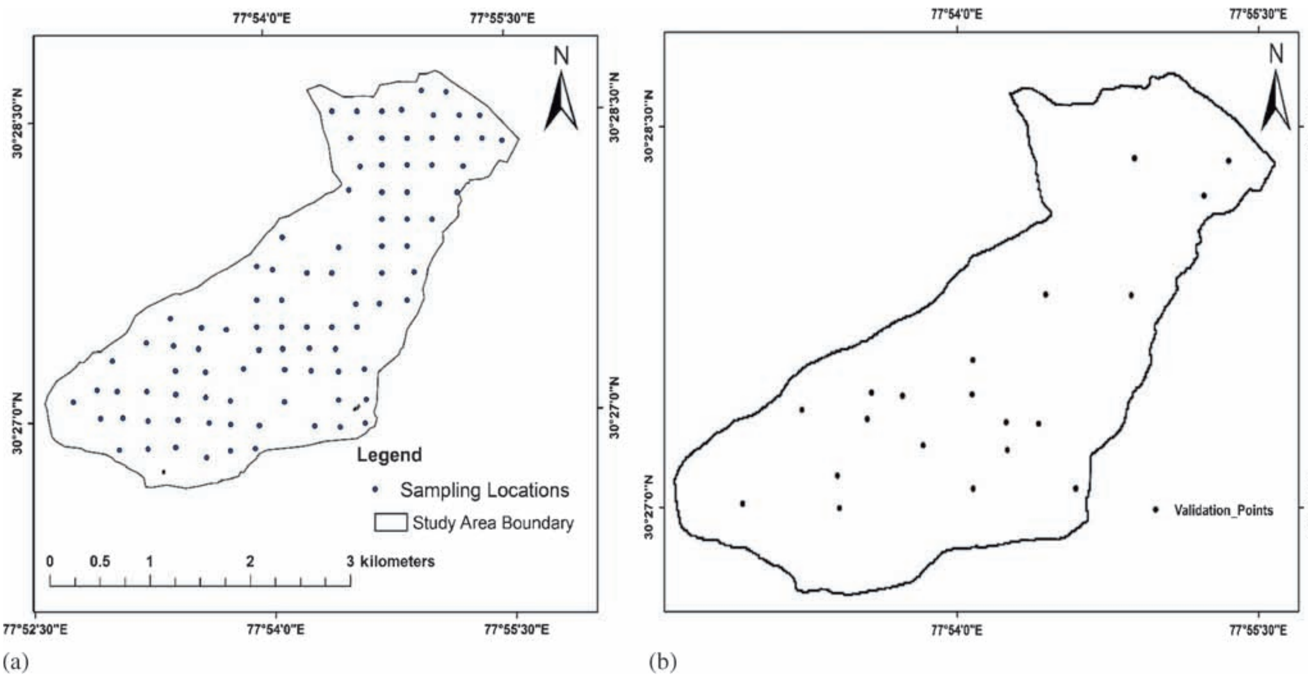


Figure 2. **(a)** Soil sampling locations in the watershed. **(b)** Distribution of soil sample sites used for validation.

topographic (slope length and steepness) parameters. Muralikrishnan *et al.* (2013) compared CartoDEM to SRTM over Indian landmass and reported vertical accuracies within ±8 m difference. ArcMap ver. 10.1 software was used to derive the terrain parameters. SPSS 20 software was used for developing multiple linear regression equations.

3.3 *Deriving terrain parameters*

Terrain parameters derived from digital elevation model (DEM) are classified as primary and secondary terrain parameters. Primary attributes that are computed directly from the DEM and secondary or compound attributes that involve combinations of primary attributes and constitute physically based or empirically derived indices that can characterize the spatial variability of specific processes occurring in the landscape. Primary attributes include slope, aspect, plan and profile curvature, flow-path length, and upslope contributing area (Wilson and Gallant 2000). Secondary terrain parameters are computed from two or more primary attributes such as slope and upslope contributing area. They offer an opportunity to describe pattern as a function of process and quantify the role played by topography in redistributing water in the landscape. These attributes may affect soil characteristics as the pedogenesis of the soil catena is affected by the way water moves through the environment in many landscapes), distribution and abundance of soil water, susceptibility of landscapes to erosion by water, and the distribution and abundance of flora and fauna.

Cartosat DEM was used in the study to compute primary terrain parameter (slope) and terrain based indices such as: terrain wetness index (TWI), stream power index (SPI) and sediment transport index (STI) as secondary terrain parameters using GIS software ArcGIS ver. 10.1. These terrain parameters are discussed as below:

3.3.1 *Slope*

Slope is calculated by finding the ratio of the 'vertical change' to the 'horizontal change' between (any) two distinct points on a line. Sometimes the ratio is expressed as a quotient (rise over run), giving the same number for every two distinct points on the same line. It describes both the direction and the steepness of the line. More is the slope, more it will be prone to erosion. It is expressed in per cent or degree. It was calculated in degree using GIS software as given in equation (1):

$$\text{Slope in percent} = \frac{\text{Vertical change } (m)}{\text{Horizontal distance } (m)} * 100 = \frac{\Delta y}{\Delta x} * 100 \quad (1)$$

$$\text{Slope in degree} = \tan^{-1}\left(\frac{\text{Slope in percent}}{100}\right)$$

3.3.2 *Terrain wetness index (TWI)*

The TWI index is based on the assumption that topography controls the movement of water in the landscape. It quantifies the control of local topography on hydrological processes and is considered primarily responsible for variation in soil process in the hilly landscape. TWI index has been extensively used to characterize the spatial distribution and extent of zones of saturation and variable source areas for runoff generation (Beven and Kirkby 1979). It was computed as:

$$\mathrm{TWI} = \mathrm{Ln}\frac{(A_S * \text{Pixel area})}{\mathrm{Tan}((S * \pi)/180))} \tag{2}$$

A_s is the upslope contributing area per unit width of contour line (m^2/m) and S is the slope gradient in degrees.

3.3.3 *Stream power index (SPI)*

Stream power is the time rate of energy expenditure and has been used extensively in studies of erosion, sediment transport, and geomorphology as a measure of the erosive power of flowing water. Moore *et al.* (1991) concluded that threshold values of these indices are likely to vary from place to place because of differences in soil properties.

SPI is a measure of the erosive power of water and can be used to identify suitable locations for soil conservation measures so as to reduce the effect of concentrated surface runoff. It was calculated using the following equation described by Moore *et al.* (1993):

$$\mathrm{SPI} = \mathrm{Ln}\left(\frac{A_s}{S}\right). \tag{3}$$

3.3.4 *Sediment transport index (STI)*

This STI index calculates a spatially distributed sediment transport capacity and may be better suited to landscape assessments of erosion than the original empirical equation because it explicitly accounts for flow convergence and divergence (Moore and Wilson 1992). STI accounts for the effect of topography on erosion. It characterizes the process of erosion and deposition. It is computed using the equation described by Moore *et al.* (1993):

$$\mathrm{STI} = \left(\frac{A_s}{22.13}\right)^{0.6}\left(\frac{\sin\beta}{0.0896}\right)^{1.3} \tag{4}$$

This was derived from unit stream power theory and is equivalent to the length–slope factor in the Revised Universal Soil Loss Equation in certain circumstances. Another form of this equation is sometimes used to predict locations of net erosion and net deposition areas.

3.4 *Computing soil erodibility (K) factor*

The soil erodibility factor (K) value was computed for the soil samples collected from 95 locations during the field survey using equation (5) (Wischmeier and Smith 1978).

$$100K = 2.1 * 10^{-4} * M^{1.14} * (12 - OM) + 3.25 * (S - 2) + 2.5 * (P - 3) \tag{5}$$

where K = soil erodibility factor in t.h/MJ.mm; M = (% very fine sand + % silt) × (100 − % clay); OM = Percentage of organic matter; S = Code according to the soil structure (very fine granular = 1, fine granular = 2, coarse granular = 3, lattice or massive = 4); P = Code according to the permeability/drainage class (fast = 1, fast to moderately fast = 2, moderately fast = 3, moderately fast to slow = 4, slow = 5, very slow = 6).

3.5 *Generating soil erodibility factor map*

Geographic locations of soil sampling sites were stored as point map. The point map was overlaid on terrain parameters and the focal mean value of TWI, SPI, STI and slope for all soil sampling sites was extracted defining 3 × 3 pixel window using ArcGIS. The values of TWI, SPI and slope corresponding to the each sample were then extracted and saved in the excel sheet. Linear regression equations were developed for the K values with TWI, SPI and slope as the independent variables. The variables which showed high correlation coefficient with the K value were selected for developing multiple linear regression equation. The brief methodology is described in figure 3. The equation was then implemented to generate the soil erodibility map.

3.6 *Accuracy assessment*

The soil erodibility factor map was generated based on the equation developed using 75 samples out of 95 samples and remaining 20 samples were used for validation purpose (figure 2b). The coefficient of determination (r^2) and root mean square error (RMSE) were computed to assess the accuracy.

4. Results and discussion

4.1 *Terrain characterization*

The elevation in the watershed ranged from 610 to 1374 m whereas the slope varied from 1 to 98% (table 1). The watershed is dominantly covered by natural forest cover (56.4%), followed by cropland (29.34%) and scrub land (14.22%). The soils in the watershed are sandy loam to loamy in texture. Soil texture analysis revealed that sand particles in surface soil varies from 40 to 89% whereas silt particles from 12 to 43%. The clay content in the surface soils varies from 8 to 30%. Organic matter in surface soil varies from 0.87 to 4.86%. The soil pH ranged from 5.4 to 6.8. Slope analysis revealed that 54.3% area had very steep to steep slope (>35%) while 26.7% and 19% area had moderate and gentle slope, respectively (figure 4d). The TWI values ranged from 4.8 to 16.3 (figure 4a). In the flat and broad summit areas of hilly landscape, the TWI has higher values than the TWI of the nearing sloping land, indicating potential area of accumulation of surface runoff water favouring deposition of clay content and organic matter and high moisture contents. Lower values of TWI indicate area of washing of fine material and organic matter. Low TWI value corresponds to the area with higher slope and low soil moisture content and *vice versa* (Qin *et al.* 2006; Ma *et al.* 2010). Spatial distributions of TWI can reasonably indicate the spatial pattern of soil distribution controlled by topography in the hilly landscape. Crave and Gascuel-Odoux (1997) reported that the soil characteristics were strongly linked with the dispersal (or downslope) control by topography. SPI values in the watershed ranged from −1.3 to 9.77 (figure 4b). The area with high SPI indicates the area of high susceptibility to the erosive power of runoff and soil erosion. STI values ranged from 0 to 168 (figure 4c). The higher STI denotes the area with more sediment transport than those with lower STI values.

4.2 *Soil erodibility (K) factor value*

Soil erodibility was calculated for 95 surface soil samples representing various land use/land cover. The average percentage of sand, silt and clay in soils of watershed was 51, 32 and 17, respectively. The soil erodibility values for the soil samples ranged from 0.3 to 0.6 t $ha^{-1}R^{-1}$. The area (9.3%) with higher K value (>0.64) showed higher susceptibility of soils to erosion (table 4). The K values were analysed in relation to slope of the watershed and it was found that soils in higher slopes were highly susceptible to erosion since they contained low organic matter and had poor structural development. It was also revealed that the areas of moderate to gentle slopes contained more organic carbon (1.5–2.8%) along with a good soil structure (fine granular) whereas, areas with steep to very steep slope contained less organic carbon (0.5–1.5%) with fair soil structure.

Table 1. *Terrain parameter values in the watershed.*

Terrain parameters	Range	Mean	St. dev.
Elevation	610–1374 m	828	128.87
Slope	1–98%	24	18.77
Terrain wetness index (TWI)	4.8–16.3	8.43	1.47
Sediment power index (SPI)	−1.3 to 9.77	1.89	1.44
Sediment transport index (STI)	0–168	8.44	12.46

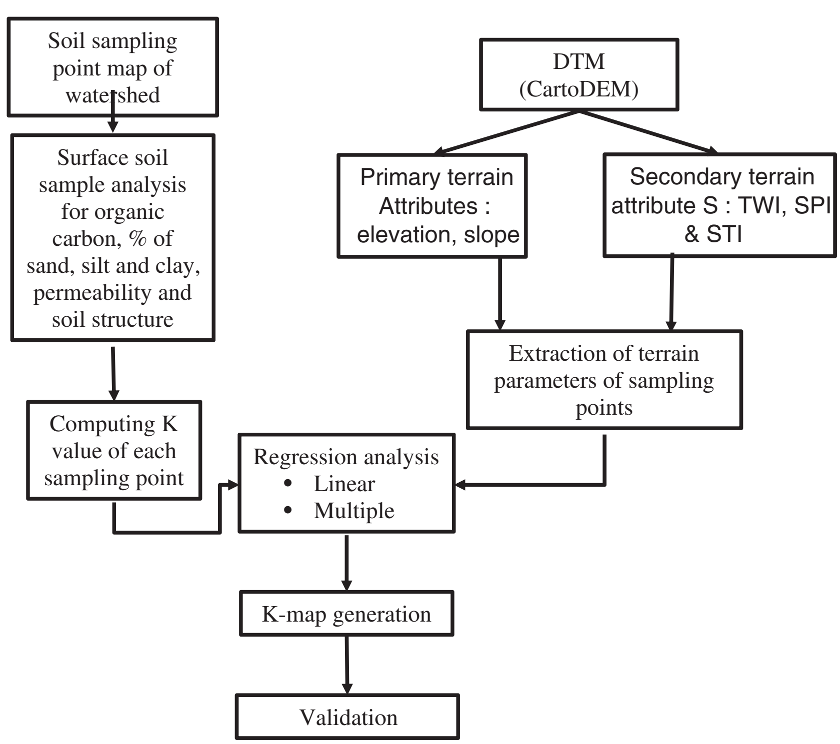


Figure 3. Methodology of mapping soil erodibility (K) factor using terrain attributes.

4.3 *Relationship of terrain parameters with soil erodibility*

The terrain parameters such as slope, TWI, SPI and STI were computed for developing a relationship with soil erodibility values. The linear regression equations were developed. The results unveiled that TWI showed higher correlation ($r^2 = 0.56$) with the K values with a negative trend (figure 5a), i.e., with the increase in moisture, the K values

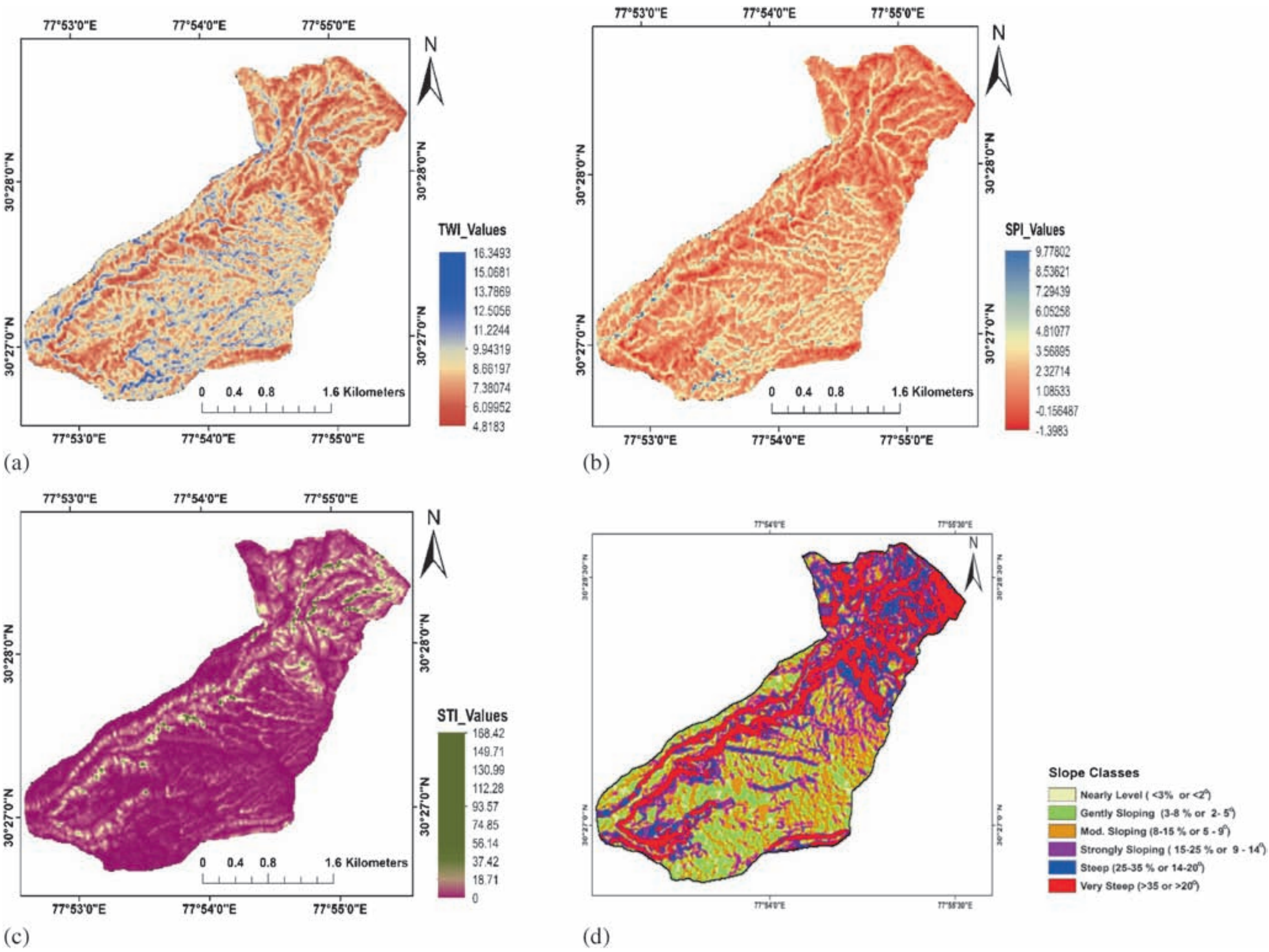


Figure 4. **(a)** Terrain wetness index (TWI), **(b)** stream power index (SPI), **(c)** sediment transport index (STI), and **(d)** slope.

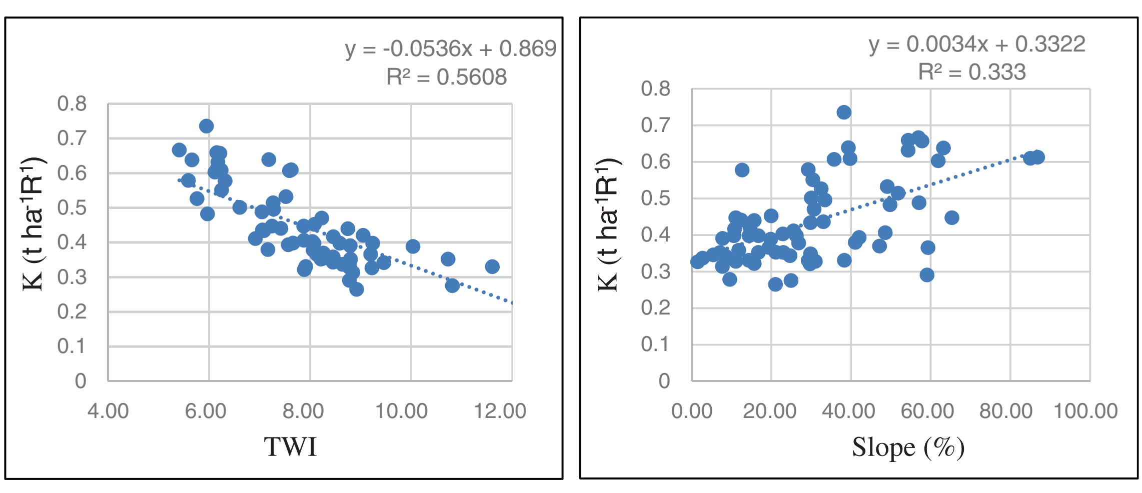


Figure 5. Linear regression of K values with **(a)** TWI and **(b)** slope.

were found to be decreasing. Toy *et al.* (2002) showed high soil erodibility in dried soils than in the wet soils. The relationship of the soil erodibility values was also analysed with SPI and STI. However, no significant relationship was found with these indices. Soil erodibility also depends upon the slope of the landscape and its values vary with respect to increase in slope. The soil erodibility changes with the landscape topography (Christianson 2012). Correlation analysis between the slope and the K values (figure 5b) revealed a positive trend of slope with soil erodibility ($r^2 = 0.34$). Shabani (2010) conducted similar study to see the effect of different slopes on soil erodibility and found that the K value increased with the slope for most of the land uses due to the varying erodibility components such as SOM, texture, structure, and permeability.

4.4 *Multiple linear regression analysis*

Relationship between the terrain parameters and soil erodibilty was established. The terrain parameters with highest correlation (slope and TWI) (table 2), were used to develop multiple linear regression for the hilly watershed. A multiple linear regression equation was developed with the terrain indices:

$$\text{Soil erodibilty } (K) \text{ factor map} = 0.736 + 0.002\text{Slope\_map} - 0.044\text{TWI\_map}$$

The equation was developed using 75 soil sampling points, and reasonably good correlation coefficient ($r^2 = 0.76$) was obtained. 20 sampling points were used for validation. The RMSE value (0.07 t $ha^{-1}R^{-1}$) was quite low suggesting its higher accuracy in mapping of spatial distribution of soil erodibility (K) in the watershed.

The developed multiple linear regression equation was implemented in GIS to derive the soil erodibility map by integrating terrain parameter maps. The analysis of soil erodibility map showed that the values in K map ranged from 0.23 to 0.81 t $ha^{-1}R^{-1}$ (figure 6). Study showed that 57% area had the K values between 0.45 and 0.57 t $ha^{-1}R^{-1}$ (table 4). Soil erodibility was analysed with different slope classes and it was revealed that the K values were increasing with the increase in slope. Analysis also showed that for lower slope, the K value is 0.424 t $ha^{-1}R^{-1}$ while for the moderate

Table 2. *Correlation coefficient of soil erodibility factor (K) with terrain parameters.*

Terrain parameters	Correlation coefficient (r^2)
Terrain wetness index (TWI)	0.561
Sediment power index (SPI)	0.069
Slope	0.33
Sediment transport index (STI)	3×10^{-5}

Table 3. *Average soil erodibility factor (K) values in various slope classes.*

Sl. no.	Percent slope	Slope classes	K values
1	0–2	Nearly level	0.424
2	3–6	Gently sloping	0.448
3	7–12	Moderately sloping	0.476
4	13–18	Strongly sloping	0.504
5	19–25	Moderately steep	0.533
6	26–35	Steep	0.564
7	>35	Very steep	0.632

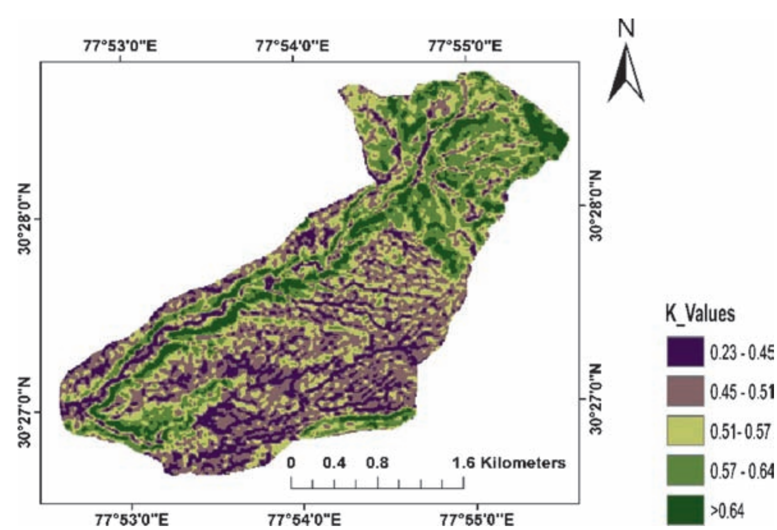


Figure 6. Soil erodibility (K) map.

Table 4. *Aerial extent of soil erodibility (K) values in the watershed.*

Sl. no.	K values	Area (%)
1	0.23–0.45	13.9
2	0.45–0.51	31.1
3	0.51–0.57	26.1
4	0.57–0.64	19.3
5	>0.64	9.3

and steep to very steep slope, the values are 0.533 and 0.632 t $ha^{-1}R^{-1}$, respectively (table 3).

5. Conclusions

The study demonstrated a geospatial approach in mapping soil erodibility in a hilly watershed. DEM derived terrain parameters were used to map spatial variation of soil erodibility (K) in the watershed. Soil erodibility values ranged from 0.23 to 0.81 t $ha^{-1}R^{-1}$ in the watershed. The variables such as TWI ($r^2 = 0.561$) and slope ($r^2 = 0.33$) showed reasonably good correlation with soil erodibility values. These terrain parameters were used to develop multiple linear regression equation to generate soil erodibility map. Analysis of soil erodibility with different slope classes showed that the K values were increasing with the increase in slope. The coefficient of determination ($r^2 = 0.759$) and RMSE (0.07 t $ha^{-1}R^{-1}$) showed higher accuracy of the model. The proposed methodology is quite useful in generating soil erodibilty factor map using digital elevation model (DEM) for any hilly terrain areas. The equation/model need to be established for the particular hilly terrain under the study. Today, the Global DTMs are freely available at varying spatial resolutions (30–90 m) (ASTER-30 m, SRTM-30 and 90 m, CartoDEM-30 m) and can be used to generate at higher resolution to meet the needs of the user to derive terrain parameters at appropriate scale. These DTMs can be used to map soil erodibility at appropriate required scale in the absence of suitable soil map or small scale soil map. It will reduce the dependency on soil map required for preparing soil erodibility map for soil erosion studies.

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