Integrated Use of Remote Sensing and GIS in estimating Soil Erosion in the Tukvar Tea Plantation Area, Darjeeling, India by RUSLE Modelling

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Abstract

Soil erosion is one of the major threats to food security and agricultural sustainability worldwide. Numerous factors including relief, slope, land use, land cover, rainfall pattern, soil texture, conservation techniques and anthropogenic factors, combine to cause soil erosion. The enormity and spatial distribution of soil erosion should be known for effectively assessing and mapping erosion-prone areas.

In the hill region, soil loss is a significant component in decreasing stability and persistent loss causes landslides. So in order to study this, various soil erosion models have come up amongst which RUSLE has been adopted by many researchers. The goal of the current study is to forecast the projected soil loss in Tukvar tea plantations of the Darjeeling district. This study will provide an estimate of the amount and rate of erosion in the Darjeeling district's Tukvar tea plantations. This study revealed that the leading factors to soil erosion are slope factors and rainfall erosivity. The geo-coded reference of the geographic extent of soil erosion-prone areas will be useful for micro-level planning and will serve as a useful tool for managing and conserving soil.

Keywords: Soil Erosion, GIS and Remote Sensing, RUSLE, Tukvar Tea Plantation, Darjeeling

Introduction

Soil erosion is a complex dynamic process that normally refers to the detachment, carrying an accumulation of the top fertile soil under the influences of natural and anthropogenic processes. Soil texture, rainfall amount, slope length, steepness climate, soil, topography and vegetation are the basic natural factors that caused soil erosion[4]. The rate of soil erosion, however, can be accelerated by human interferences such as land use modifications, deforestation, agricultural operations, construction activities, overgrazing, rapid urbanization, mining and lots of other developmental activities like the construction of roads and other anthropogenic factors hastening these natural processes[25].

Next to population growth, soil erosion is the world's second biggest issue[17]. In mountainous areas, soil erosion is significantly more severe and vulnerable to soil loss from steep slopes and deforestation[24] and creates a number of risks that contribute to land degradation[2,24]. In this context, the Himalayan Mountains, Northeastern States and the Western Ghats, which together make up 45% (130 million ha) of the total geographic area, have the highest rate of soil erosion in Asia, with a rate of 74 tons per acre per year[18]. India's overall land area is thought to be eroding by 53%[15]. In India, 800 ha of agricultural land is lost to water erosion each year, eroding approximately 5,334 million tons of soil at a rate of 16.4 t/ha/yr[8].

With possible soil erosion rates ranging from 5 to 40 t ha^{-1} yr^{-1} in India, 91% of the country's total geographic area comes into one of five erosion categories, necessitating a variety of soil conservation techniques,[22] thus posing a threat to the soil productivity and soil fertility[10]. In India, major soil erosion is also caused by ravines, gullies, shifting agriculture, farmed wastelands, sandy areas, deserts and waterlogging. Considering this point, soil erosion has become more severe in recent years[9] in mountainous areas posing a threat to the entire Himalayan region[20].

However, it is difficult to measure or predict erosion in a precise manner due to the complexity of the variables involved in the erosion process[26]. To identify places vulnerable to severe erosion and implement effective land management programs, it is crucial to quantify soil loss and estimate risk. The field-based methods for quantifying soil loss take a long time and a deficient sampling plot could reduce the accuracy of the area actually subjected to soil erosion. To estimate soil loss at various scales, a wide variety of soil erosion models (physical and empirical) has been developed since the 1930s[5]. These models vary in terms of complexity, the processes they take into account and the data they need to be used.

However, there are several aspects that influence the choice of the best model including the intended purpose, the features of the catchment, the accessibility of the input data and others[19]. In order to assess and describe erosion in terms of parameters such as rainfall erosivity index, soil erodibility, topography and management techniques, among others, soil loss models typically aim to transform physical laws and landscape processes into mathematical connections[12].

Due to their straightforward and reliable model structure as well as their GIS compatibility, the USLE and RUSLE models stand out among the others for their extraordinary global acceptability for the prediction of soil loss at various spatial scales.

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Soil loss from water erosion is a major concern in the rough mountainous regions of eastern Himalayas where tea cultivation has a long history. The region is extremely vulnerable to various hillslope processes due to the rugged and steeply sloping topography, heavy rainfall and increased overland flow due to terrain modification for developmental and agricultural needs. Water erosion is essentially the main source of land degradation in mountainous areas[11]. A variety of opposing spheres may be observed in the tea gardens located in various altitudinal regions, from high altitude to middle altitude to low altitude, making it an attractive habitat to explore[1].

For the purpose of developing regional land management programs for the preservation of soil resources, a quantitative assessment of soil loss may also be used[25]. This present study was conducted in hilly tea-growing tracts of the Tukvar tea plantation in Darjeeling so as to understand the soil loss in the said study.

Material and Methods

Study area: Tukvar tea garden was established in the year 1852. It is located at an altitude of 1500 to 6500 feet above sea level. It comprises of five divisions covering an area of 436.72 hectares and spreads over 20 to 22 square kilometers and lies between longitudes 88°16' 3" E and latitudes 27° 4' 43"N (Fig. 1). It is bordered by Sikkim in the north, Badamtam Tea Garden and Barnesberg tea garden in the south. The area experiences a tropical humid climate and receives rainfall from monsoons (June–September) which account for more than 85% of the annual rainfall. The annual mean maximum temperature is 14.9 °C while the mean minimum temperature is 8.9 °C with monthly mean temperatures ranging from 6 to 18 °C.

In Darjeeling, seven soil series are found and the said study area falls under 3 series i.e. Ramman, Chota Mangwa and Barbung series. These soil series are found in the very deep slope of the Himalayas The soil in these series consists of coarse-loamy, mixed, thermic types with gneiss, granite gneiss and schist as the parent material[14].

Data Source: Topo sheet number 78 $\frac{A}{4}$ and $\frac{A}{8}$ were used to delineate the study area. Landsat 8 satellite imagery acquired on 7 March 2018 Path: 139 Row**:** 41, United States Geographical Survey (USGS) and was used in this study for preparing land use Land cover map. Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model(DEM) with a 30 m resolution was used to generate slope, flow direction and flow accumulation in the watershed. The Digital soil map of the World (DSMW) was acquired to spawn the soil texture of the study area. Rainfall data from 1997-2014 has been extracted from the tea garden authority. The spatial data were analyzed using Arc GIS 10.0 software.

RUSLE Modeling and Data Dispensation: The RUSLE model was used to estimate the average annual soil loss as a combined function of rainfall-runoff erosivity, soil erodability, slope length, steepness factor, cover and management and conservation support-practices factor (Fig. 2)[5]. It was developed as an empirical model. The equation is expressed as

$$A = R \times K \times LS \times C \times P$$

where A = predicted average annual soil loss per unit area [ton·ha^{-1}·year^{-1}], R = rainfall-runoff erosivity factor (rainfall and snowmelt) in [MJ mm·ha^{-1}·hr^{-1}·year^{-1}], K = soil erodibility factor [ton·ha·hr·ha−1·MJ^{-1}·mm^{-1}], LS = slope length-steepness factor (dimensionless), C = cover-management factor (ratio of soil loss from a specified area with specified cover and Management to that from the same area in tilled continuous fallow) (dimensionless) and P = conservation support practice factor (dimensionless).

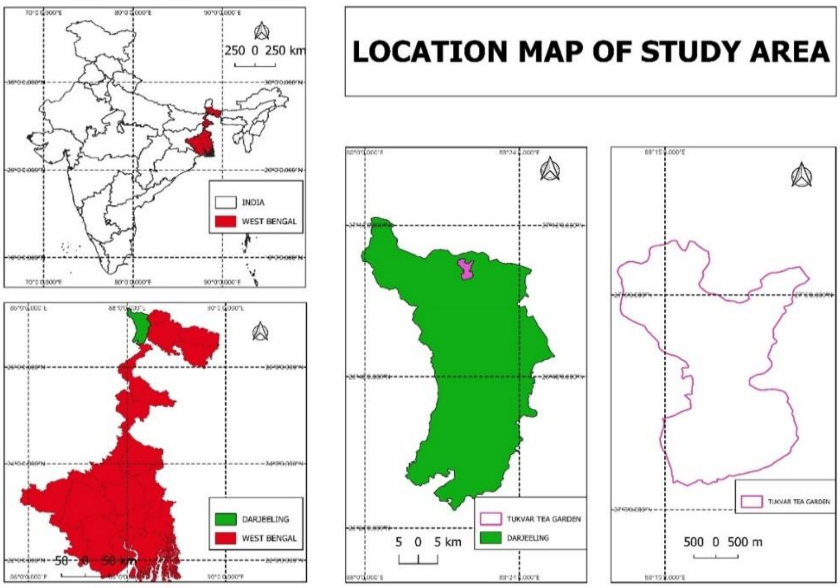

Figure 1: Study Site

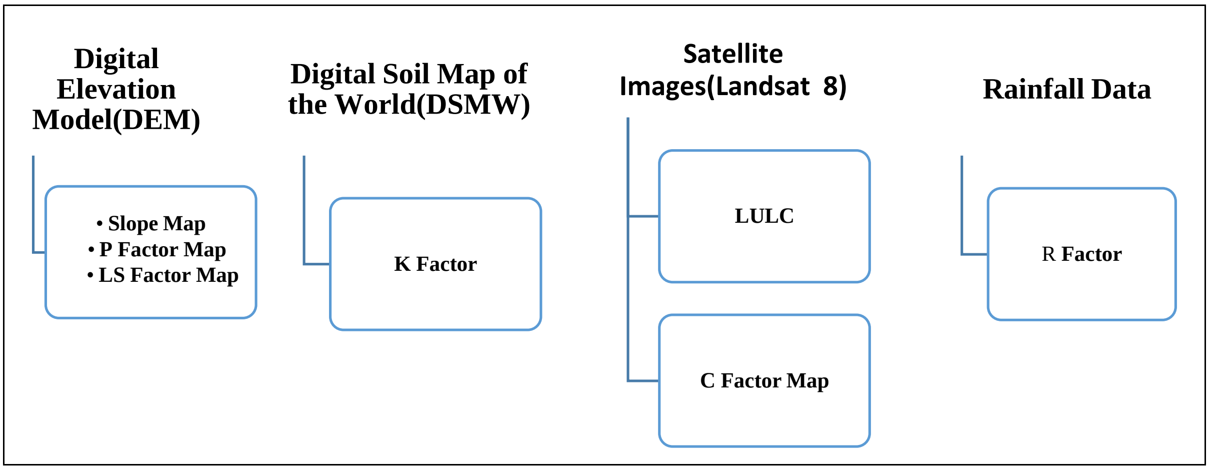

Figure 2: Methodology Flow Chart

R factor (rainfall erosivity factor): The R factor is a measure of the erosive force of specific rainfall. It quantitatively expresses the erosivity of local average annual rainfall. R-factor computation requires long-term data on rainfall amounts and intensities. Since the rainfall intensity of the study area could not be estimated in the absence of a recording-type rain gauge, well-established empirical equations using total rainfall (monthly, seasonal, or annual) are widely employed[3]. R factor was estimated using the rainfall data of the past 18 years (1997-2014) obtained from Tukvar tea garden factory records.

$R = 81.5+0.375*A \ (340 \leq A \leq 3500\text{mm})$

where A is Average Annual Rainfall (mm).

K Factor (Soil Erodibility factor): K factor was estimated with the help of soil texture (% of Sand, Silt and Clay in topsoil) and soil organic matter. The soil texture data were derived from the Digital soil map of the World (DSMW, FAO). Williams KUSLE equation was used for estimating the K:

$$K_{USLE} = K_W = f_{csand} \cdot f_{cl\text{-}si} \cdot f_{orgc} \cdot f_{hisand}$$

where f_{csand} is a factor that lowers the K indicator in soils with high coarse-sand content and higher for soils with little sand, $f_{cl\text{-}si}$ gives low soil erodibility factors for soils with high clay-to-silt ratios, f_{orgc} reduces K values in soils with high organic carbon content and f_{hisand} lowers K values for soils with extremely high sand content

LS Factor (Slope length and steepness factor): Soil erosion of an area depends upon slope length (L) and steepness of the slope(S). The steeper is the slope, larger will be the soil erosion and vice versa. Taking this factor into account, RUSLE helps in computing the effect of slope steepness on the loss of soil. SRTM digital elevation model with 30 m resolution was used to compute the LS factor followed by the method used by Mitasova et al[13].

LS = (Flow Accumulation*Grid Size/22.13) 0.6 (Sin[Slope]*0.01745/0.0896)1.3

where LS is the slope length-slope steepness factor, cell size is the size of a grid cell (for this study 30 m) and sin slope is the slope degree value in sin.

C Factor (Crop Cover Factor): The c factor represents the effects of crop cover on soil erosion. In the study, the C factor was developed from the land use land cover (LULC) prepared from the satellite image (Landsat 8). The land use/land cover map was re-classified based on C factor values using tools in ArcGIS 10.0, which was assigned C factor values based on Wischmeier and Smith[28].

P Factor (Conservation Practice factor): The P factor represents the effect of various conservation and support practices being taken up in the study area on soil erosion. The various practices normally reduce the amount and rate of runoff water by influencing drainage patterns, runoff concentration, runoff velocity and hydraulic forces exerted by runoff on soil, eventually reducing soil erosion[7].

Table 1 shows the support practice factor according to the cultivating methods and slope. The P value ranges from 0 to 1 where 0 represents a very good manmade erosion resistance facility and 1 represents no manmade erosion resistance facility[16].

Results and Discussion

R factor: Rainfall erosivity is the major factor of RUSLE which is responsible for soil erosion over an area. It indicates the potential ability of a storm event to erode soil at a particular location. The R factor is estimated by the total annual or seasonal rainfall erosivity of individual erosive storms. However, the lack of data on rainfall intensity and the number of storms have constrained the implementation of the original R equation of RUSLE[5]. R-value is greatly affected by the volume, intensity, duration and pattern of rainfall. Large numbers of R factors indicate more erosive weather conditions[18]. The R factor value was estimated to be 884.62MJ mm $ha^{-1}h^{-1}$ (Tukvar) (Table 2) and as it had a single value, no map was generated and the same was used as a value along with other factors.

Table 1
P Factor

Support Practice Factor according to the Types of Cultivation and Slope			
Slope (%)	**Contouring**	**Strip Cropping**	**Terracing**
0.0-7.0	0.55	0.27	0.10
7.0-11.3	0.60	0.30	0.12
11.3-17.6	0.80	0.40	0.16
17.6-26.8	0.90	0.45	0.18
>26.8	1.00	0.50	0.20

These findings were in line with the previous finding done by Elangovan et al[6] where the R factor value varied from 704-2849MJ mm $ha^{-1}h^{-1}$ and also in one of the studies carried out in Western Rajasthan where the R-value ranged between 250-above 1250MJ mm $ha^{-1}h^{-1}$[23]. Varied R-values have been estimated from several past studies

Table 2
R factor

R=81.5+0.375*A
R=884.62MJ mm ha-^{1}h^{-1}

Since the area is relatively small, it can be assumed that the rainfall characteristics are nearly uniform for the watershed[26]. In this regard, the R-value for Dudhawa Catchment always showed that the R factor can vary in the same watershed with different rain gauge stations [21].

K factor: The soil erodibility factor depends on the physicochemical properties of texture, organic matter content, the permeability of the soil and soil structure[7]. Different soil types normally have different structures which influence the intensity of soil erosion. The soil erodibility K-value indicates the vulnerability and susceptibility of a certain type of soil to detachment by erosion. The higher is the erodibility value, the soil is more erosive and will suffer when the soils are exposed to the same intensity of rainfall, splash, or surface flow.

In this study, the soil texture was clay soil where the estimated K value showed 0.0524 (Table 3). Generally, soils become low erodible if the silt content is low, regardless of the corresponding high content in the sand and clay fractions[18]. This indicates that the area is very less susceptible to soil erosion.

LS factor: The LS factor represents the effect of topography on soil erosion expressed in terms of slope length (L) and slope steepness (S). To a very common understanding, steeper is the slope, higher will be the runoff and its velocity and vice versa. LS factor was generated from the DEM using the flow accumulation, flow direction and slope map. The slope showed a more or less moderate slope with an inclination of 30 degrees and a steep slope with an inclination of 55 degrees (Fig. 3a) where LS factor values ranged from 0 (low) to 327.064 (high). These results were opposite to the result derived from earlier studies in the Kallar watershed of Tamil Nadu where LS ranged between 0- 69[18]. This is due to the fact that the said study area lies in the mountain belt where the slopes are steep as compared to the area of plain topography.

C Factor: The C factor represents mainly the effects of plant cover on the surface of the Earth. It can be explained by the ratio of soil loss from a certain land use. It expresses the relation between erosion on bare soil and erosion under cultivation and is based on plant cover, production level and cropping techniques. The soil under vegetation cover prevents soil erosion by a considerable amount by reducing the direct impact of raindrops on the surface of the Earth. The C Factor also helps in carrying out conservation plans, crop rotation plans and other such management schemes. The Land use land cover of the study sites is shown in fig. 3c. The land use land cover pattern of both the sites is similar to the C factor ranging from 0.008-1. A higher C factor indicates no cover effect and vice versa.

P Factor: The erosion control practice factor was derived from the DEM of the study area. The values were assigned from the previous study taken by Parveen and Kumar[16]. The P value ranged from 0.55 to 1 (Fig. 3b).

Annual Soil Loss based on RUSLE: The RUSLE model is one of the empirical models predicting soil erosion depending upon various factors of rainfall, soil type, topography, land cover and conservation management practices. In fact, it is one of the most convenient models that can estimate soil loss. The actual soil erosion calculated by RUSLE Modeling was 74564.75 tons/year (Fig. 3d) and in fact this tea garden is being planted after the clearance of the nearby forest area into the plantation area. In the Tukvar tea garden, the annual soil erosion rate is 72t/ha/yr. Heavy torrential rainfall and steep slopes are the main factors for such a huge rate of erosion.

Conclusion

This study has enabled the spatial distribution and determination of RUSLE factors considering rainfall, soil, LULC and slope as parameters with the help of GIS. This method is very simple and cost-effective in assessing erosion risk potential for the remote area where ground-based observation is difficult to access. It is observed that soil erosion in the study site is not more prominent. The soil erosion rate was categorized into 8 classes and it was found that about 80% of the area falls under the low-risk zone.

Table 3
K Factor

	Sand % topsoil	Silt % topsoil	Clay % topsoil	OC % topsoil	f_{csanz}	f_{cl-si}	f_{orgc}	f_{hisand}	K_{USLE}	K FACTOR
Tukvar	31.3	24.8	43.8	3.34	0.20072	2.638011	0.75217006	1	0.398285	0.052454

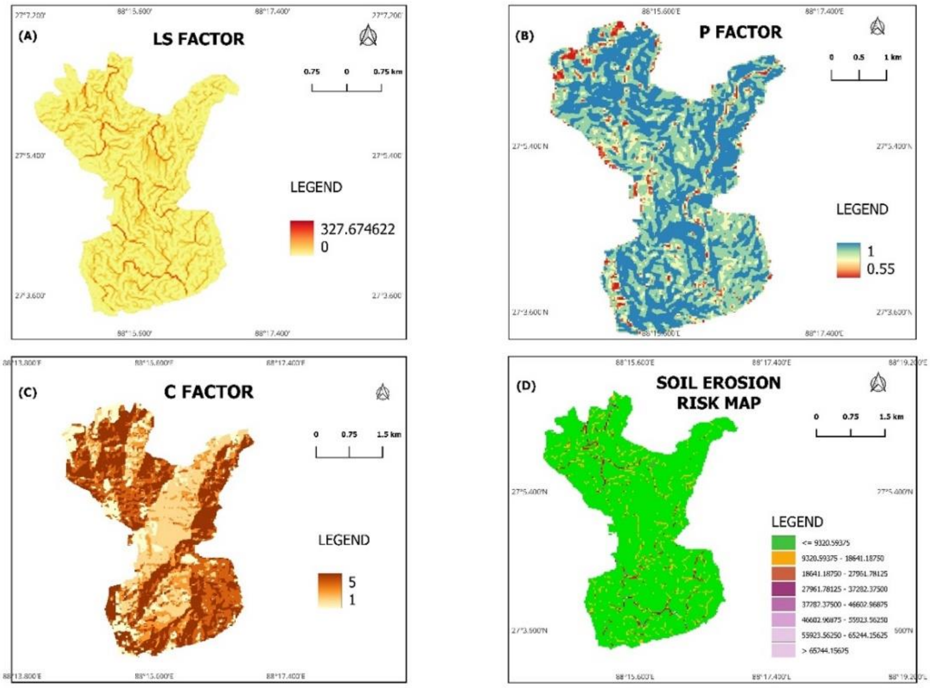

Figure 3: Three-factor map of the study area, (a) Topographic LS factor map, (b) Support practice factor map, (c) cover management factor map and (d) Potential soil erosion map in Tukvar Tea plantation

This is due to the fact that the ground is very less exposed and the ground remained covered by the thick canopy of tea bushes. The output erosion risk map showed that there is some spatial variation in soil erosion severity which has helped out in pointing out the most degradable areas. Taking into account all the factors in RUSLE, R and LS factors play very imperative roles in soil erosion. It is also being seen that the magnitude of erosion also relied upon topography and land use cover.

Another important factor is the rainfall pattern, rainfall variability showed different rates of erosion. So it can be drawn that rainfall factor also plays a very decisive role in soil erosion. Apart from the other factors like conservation practices, soil erodibility and crop cover can be managed by adopting the best management conservation practices to reduce soil erosion. The outcome of this study can help in carrying suitable soil erosion measures in extreme soil erosion risk areas. This study can be applied as an alternative best management practice for soil conservation, soil stabilization etc.

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