Soil erosion estimation by RUSLE model using GIS and remote sensing techniques: A case study of the tertiary hilly regions in Bangladesh from 2017 to 2021

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Abstract Soil erosion is one of the major environmental threats in Bangladesh, especially in the tertiary hilly regions located in the northeastern and southeastern parts of the country. The revised universal soil loss equation (RUSLE), combined with Geographic Information System, is a reliable methodology to estimate the potential soil loss in an area. This research aimed to use the RUSLE model to estimate the soil erosion in the tertiary hill tracts of Bangladesh from 2017 to 2021. The erosivity factor was determined from the annual average precipitation, and erodibility factor was estimated from FAO soil database. The elevation model was used to analyze slope length steepness factors, while land use land cover was used to compute cover management factor. Lastly, land use and elevation were integrated to estimate the support practice factor. Results revealed that the potential mean annual soil loss in 2017, 2019, and 2021 was 68.77, 69.84, and 83.7 ton ha^{-1} year^{-1} from northeastern and 101.72, 107.83, and 114.04 ton ha^{-1} year^{-1} from southeastern region, respectively. Although total annual rainfall was high in 2017, soil loss was found higher in 2021 which indicates the impact of land use change on erosion. This investigation will help the policymakers to identify the erosion-vulnerable areas in the hill tracts that require immediate soil conservation practices. Additionally, there is no latest field-based data available for the country for the validation, and hence, it is recommended to conduct field-based studies for validating the model-derived results and creating a reliable soil erosion database for the country.

Introduction

Soil erosion is a worldwide serious geo-environmental issue because it is severely threatening the agricultural sector (Robinson et al., 2017), ecological balance (Owens & Collins, 2006), and other natural resources (Borrelli et al., 2017; Kefi et al., 2011; Pimentel, 2006) in this era. This natural phenomenon results from the detachment of soil particles by the force of water or wind and their transportation to elsewhere. This process is influenced by different biophysical and environmental factors, including rainfall intensity, soil type, terrain, land cover, and interactions among them. The most important terrain factors affecting the mechanism of erosion are slope length, steepness, and shape. The runoff increases with the slope steepness

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and infiltration rate decreases (Ganasri & Ramesh, 2016). Without these, anthropogenic activities such as conversion of forests to agricultural lands and faulty agricultural practices are also responsible for increasing soil loss (Negese, 2021; Sun et al., 2020). Intensification of soil erosion process is also leading to a significant loss of fertile topsoil, river siltation, flash flooding, etc. The fear of soil loss, especially the removal of fertile topsoil, is linked to mass starvation, and this process has been revised very recently (Kaiser, 2004).

Singh and Panda (2017) estimated that approximately 85% of land accretion happens because of soil erosion and reduces crop productivity by 17% by affecting soil fertility severely. Studies have been conducted to help the local governments to adopt soil conservation and management policies to minimize soil erosion (Wang & Su, 2020; Xu et al., 2020). Clarifying the entire occurring processes associated with soil erosion can be a fundamental basis of preparing scientific as well as adopting reasonable actions to control soil erosion (Alewell et al., 2019; Tamene et al., 2017). In addition to this, the adaptation of soil and water conservation measures is now necessary to quantify the effects of soil loss, particularly in hilly and mountainous regions, which are highly vulnerable to erosion (Chen et al., 2019). This is why it is urgent to conduct precise and regional-based research on soil erosion in hilly and mountainous areas (Tian et al., 2020).

Soil erosion model has been developed to assess the potential loss of soil and predict soil erosion intensity for the future at the regional scale (Behera et al., 2020; Biddoccu et al., 2020). Several erosion models exist with different complexity levels, but empirical models (Liu et al., 2002; Wischmeier & Smith, 1978) and physics-based models (Morgan et al., 1998) have proved to be effective in assessing soil erosion. Physical-based models, like water erosion prediction project (WEPP) developed by Nearing et al. (1989), are limited to covering larger or regional scales because of the requirement of a large amount of precise data. Revised universal soil loss equation (RUSLE), on the other hand, is an empirical-statistical model that can be used to estimate the soil loss at a larger scale (Renard et al., 1997), and it provides a relatively reliable and highly accurate result (Farhan & Nawaiseh, 2015). Meanwhile, due to its increased use, the RUSLE model can be integrated with remote sensing and geographic information system (GIS) techniques to cover a large region for estimating

potential annual soil loss precisely (Behera et al., 2020; Islam et al., 2020) because, in the combined process, estimation of soil loss is performed at cell-by-cell basis (Prasannakumar et al., 2011). However, the main problem of these developed models is the validation due to the scarcity of the available data to compare the estimation of the model results and the actual magnitude of soil loss (Lazzari et al., 2015).

In Bangladesh, soil erosion has become a rising concern because of the increasing demand for food and pressure on arable lands. Still, more than 45% of Bangladeshi is directly or indirectly employed in the agricultural sector (Bangladesh Finance Bureau, 2014) with rice being the most cultivated crop. But the conventional tillage system associated with rice cultivation has been found degradative to soil aggregates (Shoumik & Islam, 2022). Deininger et al. (2011) estimated that approximately 6 million hectares of land may be converted into agricultural lands each year up to 2030 to tackle the growing food demand. The southeastern and northeastern hilly regions of the country are the most vulnerable areas to water erosion. Hasan and Alam (2006) reported that around 75% of the total hilly regions are at high erosion risk, while 20% and 5% of the total areas are at moderate and low risk, respectively. The most destructive agricultural practice in this region is shifting cultivation, which is damaging the soil's health. Traditionally, shifting cultivation was clearing the primary forest lands and planting crops for up to two seasons. Then the farmers moved to another area and left the previous plot fallows for a minimum of 10 years, which allowed the soil to replenish the nutrients (Nath et al., 2005). Intercropping was another cropping system that was considered a sustainable economic and environmental option. However, in recent years, shifting cultivation has been changed from the traditional practices to meet the population growth and food pressure.

The tertiary hill tracts of Bangladesh have ecological and socio-political significance because of their biodiversity and geographic position. Also, the area contains over 40% of the total forest cover of the total country. Due to the recently abrupt land use/cover changes, geopolitical issues (Khan & Shoumik, 2022), and forced migration, the southeastern region is experiencing severe soil loss. Hence, quantification and studying the dynamics of soil erosion considering the entire hilly region of both northeastern and

southeastern parts are necessary because very few previous studies have been conducted in these regions on soil erosion, particularly on the changes in annual soil erosion rate. Farhad et al. (2022) conducted a research on soil erosion quantification in only the Cox's Bazar district and geopolitical refugee camp, but it is necessary to study the magnitude of soil loss considering the entire tertiary hilly region in different years due to its importance. Therefore, this research was conducted to study the potential annual loss of soil using the RUSLE model in the tertiary hilly regions of Bangladesh from 2017 to 2021.

Materials and methods

Study area

Hills occupy approximately 15,000 km^2 area of the total Bangladesh, and Chittagong hill tract that is located in the southeastern region occupies around 13,191 km^2, while a small area is located at the northeastern region. The northeastern part of the country is considered relatively cooler than the other areas. The annual rainfall is approximately 3500–4500 mm in this region. During the summer, the average maximum daily temperature is 30℃. The southeastern part of the country receives around 3000 mm of annual precipitation, but in some areas (e.g., Cox's Bazar), it may exceed 4000 mm. During the summer, the average maximum temperature reaches more than 31℃. These hill soils are considered brown hill soils with sedimentary rocks. These soils can be characterized by slight or almost no leaching of iron and clay. The upper horizon always remains decalcified, and the texture varies from silty loam to sandy loam with an organic matter of < 1.5% in grassland and 2–5% in forested areas (SRDI, 1986). The elevation of this area ranges between and 992 m (Fig. 1). The primary limitations of these regions are steep slopes, moderate to high soil erodibility, heavy rainfall, and low soil fertility status. According to Shaheed (1995), 75% of the hill tracts are very highly susceptible to erosion, while 20% are highly susceptible to erosion, and 5% are moderately susceptible to erosion. Islam et al. (2017) reported that the southeastern region suffered two major landslides after 2000s, one in 2007 and another in 2017. Soil erosion and landslides in these hilly regions cause a massive siltation in the rivers or valleys.

Data acquisition

In this study, 30 years data of each meteorological station located in the studied area was obtained from the Bangladesh Meteorological Department (BMD). There were total of 9 meteorological stations (Fig. 1), and the obtained data were used to determine the erosivity of the rainfall in the area. The digital elevation, which was used to estimate the slope length, slope steepness, and conservation support practice factor, was downloaded from the official website of USGS (https://earthexplorer.usgs.gov). Land use and cover were required to determine the cover and management factor in the study area. Land use and land cover (LULC) data from Sentinel-2 with a 10-m resolution was downloaded from ESRI website (https://livingatlas.arcgis.com/landcover). The vector database of the soil in the region was obtained from the Harmonized World Soil Database (https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/) as suggested by Fischer et al. (2008).

Soil erosion estimation using RUSLE model

The revised universal soil loss equation (RUSLE), developed by Renard et al. (1997), is an empirical model to estimate soil erosion from a specific area. Scientists confirmed its applicability in all those continents that have water erosion problems (Laflen & Moldenhauer, 2003). It is an improved version of USLE, which was developed by Wischmeier and Smith (1978). However, RUSLE is now one of the universally accepted and most widely applied models to estimate potential annual soil loss. RUSLE can be expressed as the following equation (Eq. 1):

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

Here, A = potential annual soil loss (ton ha^{-1} year^{-1}), R = rainfall-runoff erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K = soil erodibility factor (ton h MJ^{-1} mm^{-1}), LS = slope length and slope steepness factor, C = cover and management factor, and P = conservation support practice factor. The major limitation of this model is that it only considers sheet and rill erosion but not gully erosion, which is actually the major erosion in many regions. In this study, the potential annual soil loss was determined at a cell size of 0.5 m × 0.5 m for studying the erosion at finer scale in ArcGIS 10.4.1.
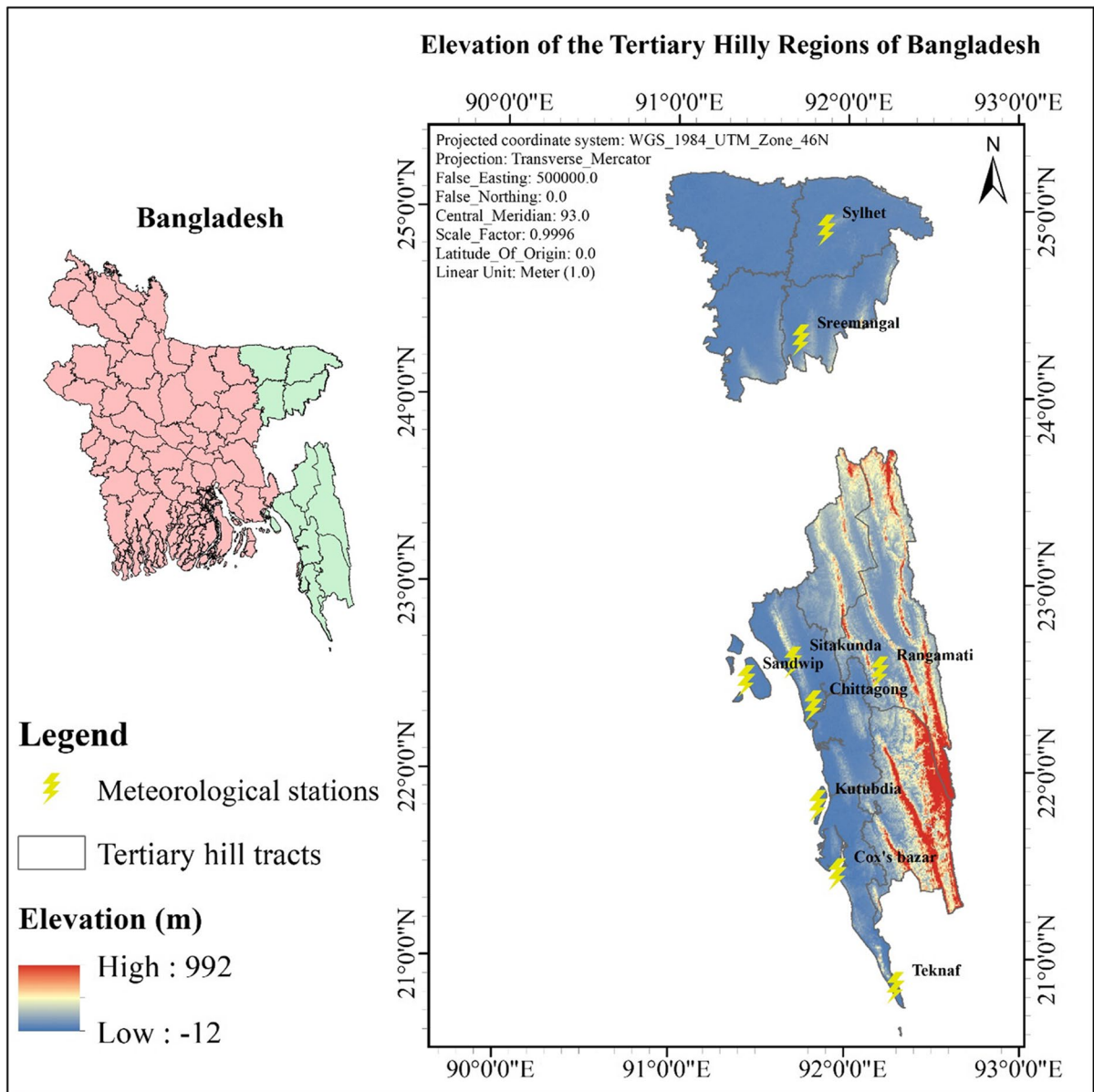
Fig. 1 Elevation and location of the meteorological stations in the study area

Rainfall erosivity factor (R)

Rainfall erosivity factor (*R*) demonstrates the kinetic energy of rainfall that has an impact on soil erosion (Ghosal & Bhattacharya, 2020), and this is an annual measurement of both erosive force and intensity of rainfall (Goldman et al., 1986). This factor represents the soil erosion processes, which induce splash, sheet, and rill erosion on soil erosion (Renard et al., 1991). It is computed from the continuous and detailed rainfall data, including kinetic energy of the rainstorms and the maximum 30-min rainfall intensity of a region (Wischmeier & Smith, 1978). However, because of the lack of sufficient data on 30-min rainfall intensity and kinetic energy, the empirical equation suggested by Babu et al. (2004) was followed. For calculating *R* factor from the continuous precipitation data available from 1981 to 2021 was used. Since Bangladesh has

a subtropical humid climate, Eq. (2), developed and used by Babu et al. (2004) and Saha et al. (2022) in the similar climate, was followed,

$$R = 81.5 + 0.375 \times r \qquad (2)$$

Here, R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}) and r = annual average rainfall (mm year^{-1}) when $340 \leq r \leq 3500$ mm.

Soil erodibility factor (K)

Soil erodibility factor (K) dictates the vulnerability of soil to be eroded by raindrops or runoff. It is affected by various soil inherent properties, including soil texture, particle size, organic matter content, permeability, and structure (Auerswald et al., 2014; Wang et al., 2013). K factor is significantly related to the presence of silt (%) in soil. The equation (Eq. 3) proposed by Wischmeier and Smith (1978) was used to estimate the erodibility (K) factor:

$$K = [2.1 \times 10^{-4} \times M^{1.14} \times (12 - OM) \\ + 3.25(S - 2) + 2.5(P - 3)]/100 \qquad (3)$$

Here, M is [silt (%) + very fine sand (%)] × [100 – clay (%)], OM is organic matter (%), S is structure code, and P indicates permeability code. The structural code (S) and permeability code (P) are subdivided into four and five classes, respectively (Table 1).

Generally, clay and sandy soils have low erodibility (K) value indicating resistant to soil erosion. Clay particles are resistant to detachment, while sand particles form macropores that increase infiltration rate and reduce runoff. Silty soil, on the other hand, has moderate to high K value because silt particles are easy to moderately detachable and transported (Ganasri & Ramesh, 2016; Wischmeier & Smith, 1978).

Slope length (L) and slope steepness (S) factor

The slope length and slope steepness factors demonstrate the role of terrain on soil erosion in RUSLE (Qiu et al., 2018; Tian et al., 2020). Increased slope length and steepness result in higher loss of soil because of the cumulative increase in the velocity and the amount of runoff (Ghosal & Bhattacharya, 2020). The slope length has a significant effect on

Table 1 Soil structure and permeability code (Wischmeier et al., 1971)

Soil properties	Remark
Structural code (S)	1 = very fine granular 2 = fine granular 3 = moderate to coarse granular 4 = massive clay
Permeability code (P)	1 = rapid to moderate 2 = moderate 3 = moderate to slow 4 = slow 5 = very slow

soil erosion. It is the distance from the origination point of the overland flow to that particular point where either the slope reduces to such an extent that the deposition starts or the runoff water enters into a channel. When slope length increases, the soil erosion also increases. Slope steepness (S) factor is the role of slope gradient in soil erosion. Steeper slope is responsible for higher soil loss. In this study, Moore and Burch (1986) equations (Eqs. (4)–(7)) was used to determine L and S factors.

$$L\ factor = \left(\frac{flow\ accumulation \times cell\ size}{22.13}\right)^{m} \qquad (4)$$

Here, flow accumulation was determined using "Hydrology" toolbox of "Spatial Analyst Toolset" in ArcGIS, and m is a universal constant, which depends on slope percentage (Eq. 5).

$$m = \begin{cases} 0.3, \ when\ slope(\%)\ is \leq 3\% \\ 0.4, when\ slope(\%)\ is \leq 4\% \\ 0.5, when\ slope(\%)\ is \geq 5\% \end{cases} \qquad (5)$$

$$S\ factor = \left(\frac{sin\beta}{0.0896}\right)^{n} \times Z \qquad (6)$$

$$\beta = \left(3.14 \times \frac{\theta}{180}\right) \qquad (7)$$

Here, β = the angle of slope (in rad.), Z = rilling factor with a value of 1.62, and n = a coefficient factor with a value of 1.3 (Moore & Burch, 1986).

After calculating L and S factors separately, Eq. (8) was used to calculate LS factor.

$$LS = L \times S \qquad (8)$$

Hrabalíková and Janeček (2017) showed that Moore's equation provides an acceptable value, which complies the measured data. However, they suggested conducting a comparison study between Moore's and original Wischmeier and Smith's (1978) equations in different hillslopes of various lengths and shapes.

Cover and management factor (C)

From the ESRI land use/cover data, five major land covers were identified, and they were water bodies, agricultural lands, forest areas, urban areas, and bare lands. The C factor indicates the ratio of soil loss magnitude from a land with a particular land cover to the corresponding soil loss magnitude from a fallow land (Morgan, 2005; Wischmeier & Smith, 1978). This factor is the most sensitive as it changes with the land use patterns. Hence, scientists consider this factor for developing and establishing a conservation plan immediately (Gelagay & Minale, 2016). C-value for each land use/cover was assigned based on different research works (Table 2).

Conservation support practice factor (P)

Support practice (P) factor is the ratio of soil erosion under a particular conservation practice to the soil loss in downslope or upslope cultivation (Wischmeier & Smith, 1978). The P factor is used to analyze the condition of existing conservation practice in an area. The P factor of a region is calculated using the slope of that region, and if there no conservation practices are adopted, then P-value is considered 1, and if there are good conservation practices, then the value is assigned 0. Wischmeier and Smith (1978) categorized the land uses into two major classes—agricultural lands and other lands. The agricultural lands were further subdivided into six slope classes, and each of those classes had different P values (Table 3). It is because many management or conservation support practices are dependent on the slope of an area.

Results and discussions

Rainfall erosivity factor (R)

The average annual rainfall (Fig. 2) indicated that the annual average rainfall (mm) ranged between 2300 and 3500 mm. In 2017, 2019, and 2021, there were not any significant changes in the distribution of average annual precipitation in these regions. In all the years, the far northeastern and southeastern regions received the highest amount of rainfall compared to the other parts of the studied area. The rainfall erosivity factor (R) also showed a similar distribution pattern of average annual rainfall (Fig. 3). Rainfall erosivity factor ranged between 900 and 1500 MJ mm ha^{-1} h^{-1} year^{-1} from 2017 to 2021. The highest R factor was found in those areas that received higher average annual rainfall. The northeastern and southeastern areas had the R factor of 1301–1500 M J mm ha^{-1} h^{-1} year^{-1}, while the central region had the R factor of 900–1100 MJ mm ha^{-1} h^{-1} year^{-1}, and the distribution was almost similar in 2017, 2019, and 2021. R value is dependent on the rainfall, and hence, areas receiving a higher amount of rain had a higher R value. Shinde et al. (2010) reported that daily rainfall can be a better indicator for studying seasonal distribution of rainfall erosivity factor and for estimating seasonal soil loss. However, average annual rainfall can provide a result with better regional consistency.

Table 2 C-factor values for different land uses/covers (Ganasri & Ramesh, 2016; Gelagay & Minale, 2016)

Land use land cover	C-factor value
Water bodies	0
Agricultural lands	0.63
Forest areas	0.01
Urban/Built-up areas	0
Bare lands	1

Table 3 P value of different land uses with respect to different slope (%) classes (Wischmeier & Smith, 1978)

Land use land cover	Slope (%)	P-factor values
Agricultural lands	0–5	0.1
	5–10	0.12
	10–20	0.14
	20–30	0.19
	30–50	0.25
	>50	0.33
Other lands	All	1

**Fig. 2** Average annual rainfall (mm) in 2017, 2019, and 2021
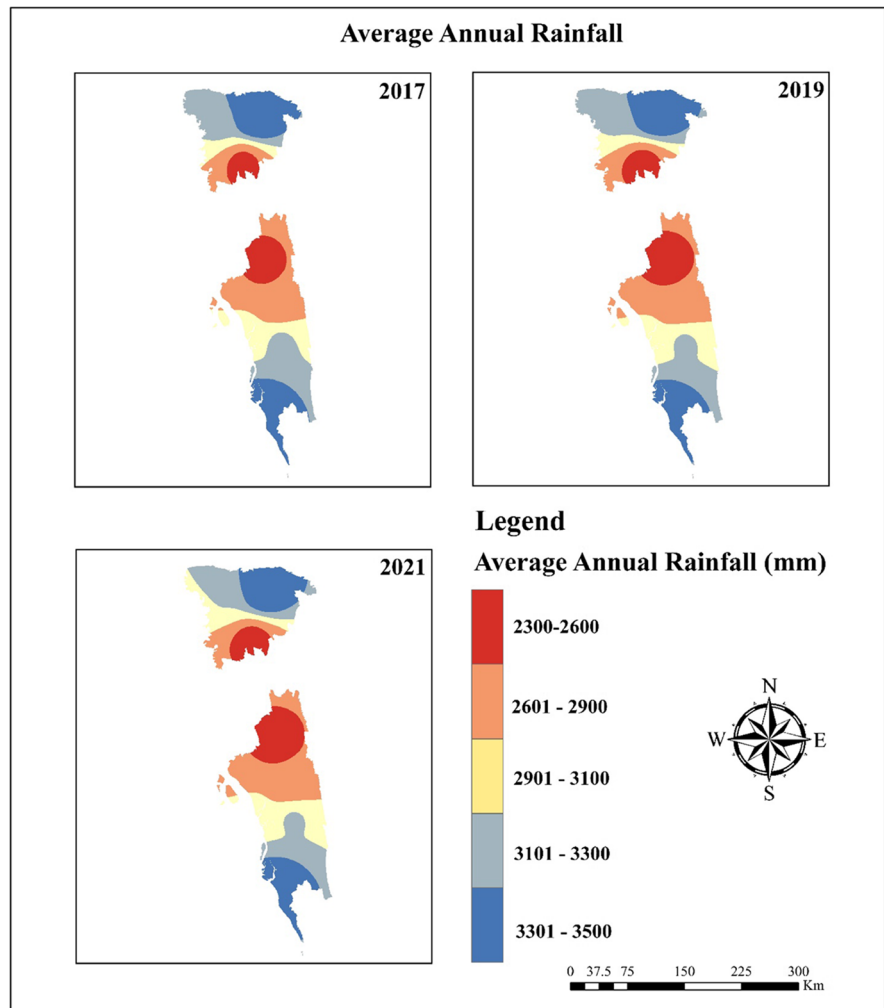
Soil erodibility factor (K)

Soil erodibility map was prepared by using the soil erodibility factor (K) equation developed by Wischmeier and Smith (1978) (Fig. 4). Soil particles, organic matter content, soil structure, and permeability were included for determining K factor. The figure also reveals the dominant soil type in the study area. Across the entire region, the major soil types were acrisols, cambisols, gleysols, and fluvisols. Both southeastern and northeastern regions had acrisols, gleysols, and cambisols. However, the southeastern had an extra soil type, named fluvisols. Each of these soil types has different sand, silt, clay, organic matter content, structure, and permeability. According to the estimation, the K values ranged from 0.01 to 0.43

(0 is for the water bodies that have no erodibility value). The northeastern hills had the K values between 0.01 and 0.38, while the southeastern hills had the K values between 0 and 0.43. Acrisols was the least susceptible to soil erosion followed by gleysols and cambisols, while fluvisols was the most susceptible soil type in the study area. Fluvisols was found in the Sandwip Island, which is a separate island in the southeastern area. Soil erodibility factor (K) in this island ranged between 0.39 and 0.43. It might be due to the formation by the deposition of sand and silt and the lack of organic matter content and weaker soil structure. The lower organic matter (%) in this island was also confirmed by Hasan et al. (2020). Higher K values indicate that those regions are very susceptible to soil erosion.

**Fig. 3** Rainfall erosivity factor (*R*) in 2017, 2019, and 2021
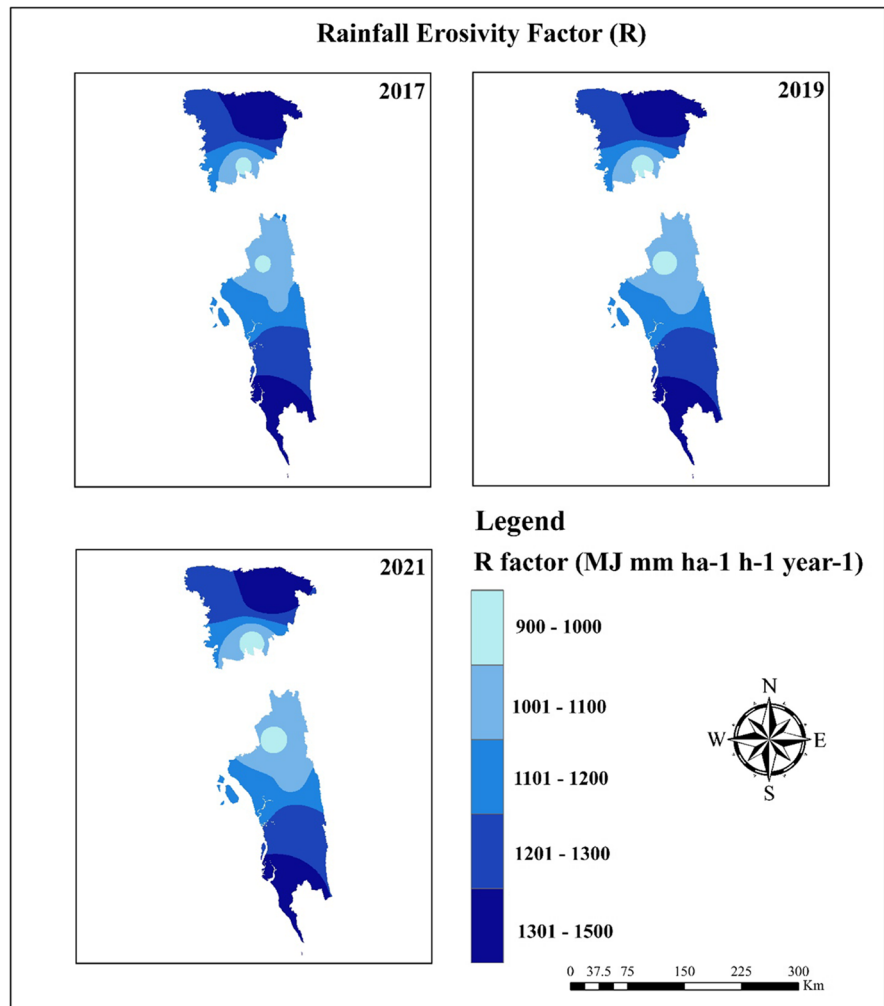
Slope length (L) and slope steepness (S) factor

The estimation of slope length (*L*), slope steepness (*S*), and their combination *LS* factor (Fig. 5) clarifies that the *L* factor ranged between 0 and 1.9. The *L* factor can be defined as the distance from a particular point of origin of overland flow to a specific point, where either slope gradient (*S*) reduces to a level that the deposition starts or the runoff water enters into a defined channel (Wischmeier & Smith, 1978). The predomination of low *L* factor across the study area indicates that the distance is quite low. Slope steepness (*S*) factor in the study area ranged between 0 and 30.7, and the value was found higher across the southeastern region, while the northern area had lower value. The *LS* factor ranged between 0 and 17, and its distribution was similar to *L* factor across the area. The most predominant *LS* value was between 0 and 0.59, while 0.6 to 17 was scattered over the hilly regions.

Das et al. (2022) reported that in Moore and Burch (1986) method, the slope length (*L*) factor depends on flow accumulation, and hence, the magnitude increases near the channels. Their study area fell near our study area, and that was also a hilly region. They found a higher *LS* value near the stream line. Ganasri and Ramesh (2016) also followed the Moore and Burch's equation and showed that the *LS* factor increases with slope and flow accumulation. Das et al. (2022) confirmed that *LS* factor calculated by this method will estimate higher soil loss near the streamline. However, if the method is applied to the entire catchment area, the final soil erosion estimation might be different (Hrabalíková & Janeček, 2017).

Fig. 4 Soil erodibility factor (*K*) in 2017, 2019, and 2021
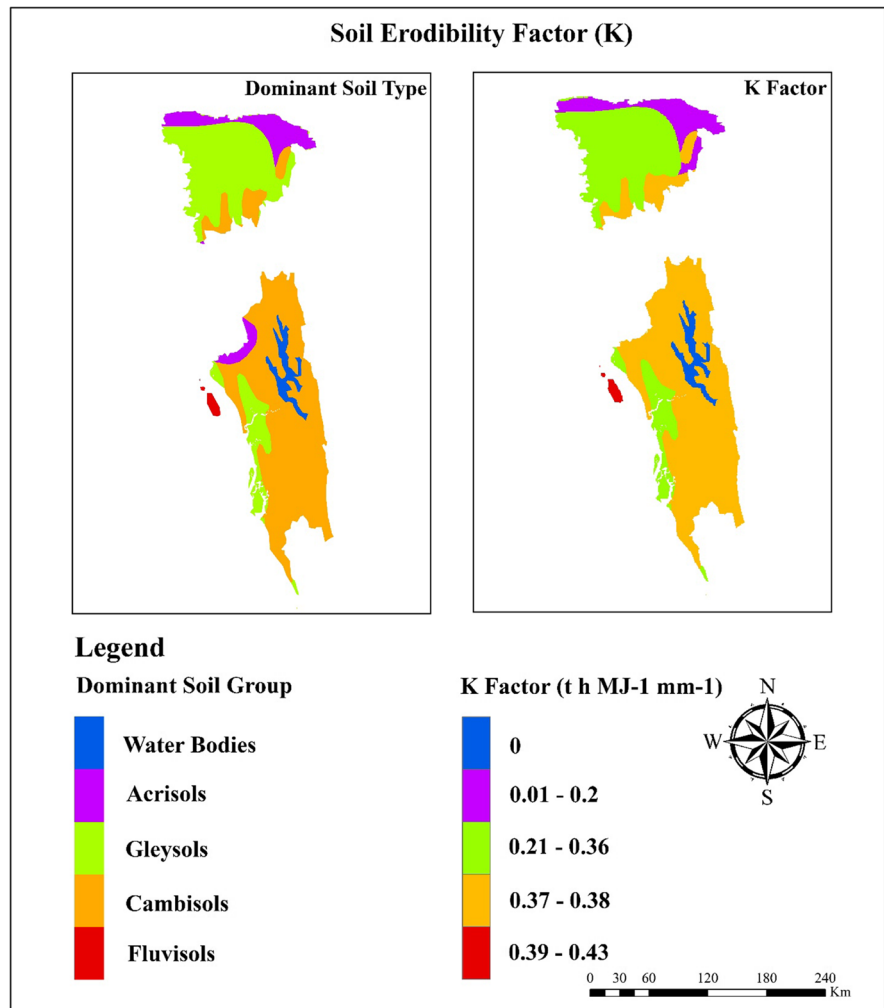

Cover management factor (C)

The major land use/cover types of the tertiary hilly areas in Bangladesh are forests, bare lands, urban areas, agricultural lands, and water bodies. The southern region is comprised mostly of forested areas, while the northern hilly part is covered by agricultural lands (Fig. 6). It is clear that between 2017 and 2021, water bodies and forested lands have been reduced by 41.7% and 7.9%, while agricultural lands, urban areas, and bare lands have been increased by 19.3%, 53.9%, and 88.2%, respectively (Table 4).

Northeastern part of Bangladesh has international importance because of its wetlands, subtropical forested areas, and tea gardens. Masum and Hasan (2020) and Rai et al. (2017) showed that this part of the country had been undergoing a massive urbanization by destroying forest areas and water bodies from 1987 to 2007, and Hassan (2017) reported that the urbanization rate is the highest in this part compared to the other areas in Bangladesh. Chowdhury et al. (2018) conducted an experiment in the Halda watershed, one of the largest watersheds in the southern region, and found that the water bodies and vegetation cover significantly decreased but agricultural lands increased from 1978 to 2017. According to our findings, the vegetation cover and water bodies in these two parts of the country are still decreasing, while agricultural lands and urban areas are increasing.

C factor dictates the influence of different management practices on soil loss and ranges between 0 (for well protected lands) and 1 (for barren lands). According to the LULC of the study area, there were five dominant land uses in the tertiary hills. The *C* factor in our study area ranged from 0 to 1. Here, 0 and 1, respectively, indicates

Fig. 5 Slope length (*L*) slope steepness (*S*) factor in the tertiary hilly region of Bangladesh
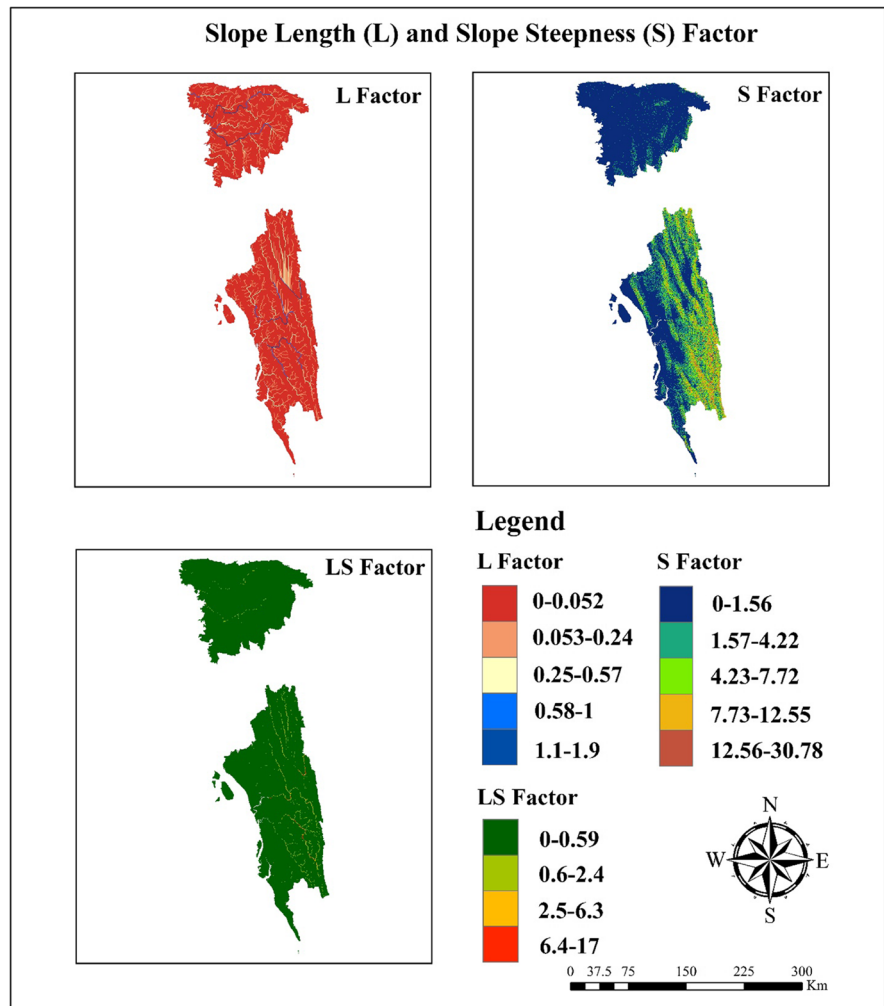

water bodies and bare lands (Fig. 7). The figure clarifies that since 2017, the *C* factor is changing in the northeastern region of Bangladesh, while the change is not noticeable in the Chittagong hill tracts. Most part of the Sylhet division is covered with agricultural fields with little forested areas, and this could be the reason for higher *C* factor value in that region. On the other hand, in Chittagong hilly areas, the agricultural lands were less than the forest, and this is why this part had a lower *C* factor value. Forests or densely vegetated cover reduces the destructive impact of intensive rain on soil.

Conservation practice factor (P)

The conservation practice (*P*) factor map (Fig. 8) for the tertiary hilly regions in Bangladesh from 2017, 2019, and 2021 represents that the *P* factor value

ranged between 0 and 1. According to the *P*-factor value classification, there are two main classes of *P*—(i) 0–0.33 indicating agricultural croplands under different slopes and (ii) 1 indicating other land uses with no conservation practices. The lands containing forest and urban areas, water bodies, and shrubs were assigned a *P* value of 1 regardless their slope. On the other hand, the *P* values in the agricultural lands were assigned based on the six slope classes as represented in Table 3. The figure reveals that in all the 3 years, lower *P* factor value (0–0.3) was dominant in the northeastern part, while in the southeastern part, higher *P* value dominated because of poor conservation practice in that region. During 2017, the northeastern area was less covered with agricultural lands, which increased in 2019 and 2021. The Chittagong hill tracts did not show any major difference in *P* values from 2017 to 2021.

Fig. 6 Land use and land cover (LULC) of the study area in 2017, 2019, and 2021
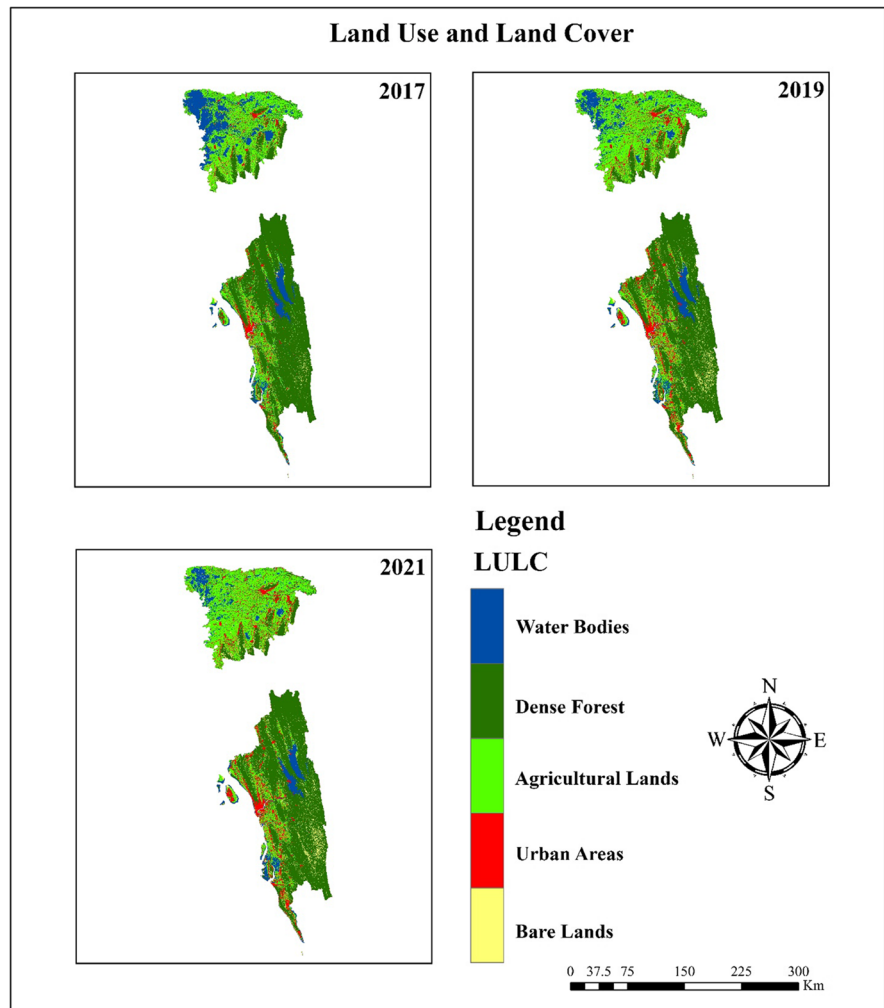
Annual soil loss (A)

All the factors—R, K, LS, C, and P—were multiplied to represent the potential annual soil loss (*A*) in the tertiary hilly regions of Bangladesh at the pixel level

Table 4 Land use and land cover in 2017, 2019, and 2021 in the tertiary hilly regions

LULC	Area (mha)		
	2017	**2019**	**2021**
Water bodies	0.487	0.326	0.284
Forest	1.624	1.507	1.496
Agricultural lands	0.833	0.973	0.994
Urban areas	0.206	0.299	0.317
Bare lands	0.068	0.113	0.128

(Fig. 9), and before the multiplication, the cell size of all the raster files was kept similar. The outcome was classified into seven classes—(i) no erosion (0 ton ha^{-1} year^{-1}), (ii) very low erosion (0.001–0.1 ton ha^{-1} year^{-1}), (iii) low erosion (0.11–1 ton ha^{-1} year^{-1}), (iv) moderate erosion (1.1–10 ton ha^{-1} year^{-1}), (v) high erosion (10.1–100 ton ha^{-1} year^{-1}), (vi) very high erosion (100.1–200 ton ha^{-1} year^{-1}), and (vii) extreme erosion (> 200 ton ha^{-1} year^{-1}).

The total area of Sylhet division (northeast region) is 1.22 mha, and the area affected by no erosion in this area in 2017 was found 0.896 mha, which decreased by 9.6% in 2019. In 2021, the area affected by no erosion was found 0.759 mha. However, the area affected by erosion in this region showed an increasing trend. The erosion-affected area was 0.351 mha, 0.435 mha, and 0.461 mha in 2017, 2019, and 2021, respectively

**Fig. 7** Crop management factor (*C*) in 2017, 2019, and 2021
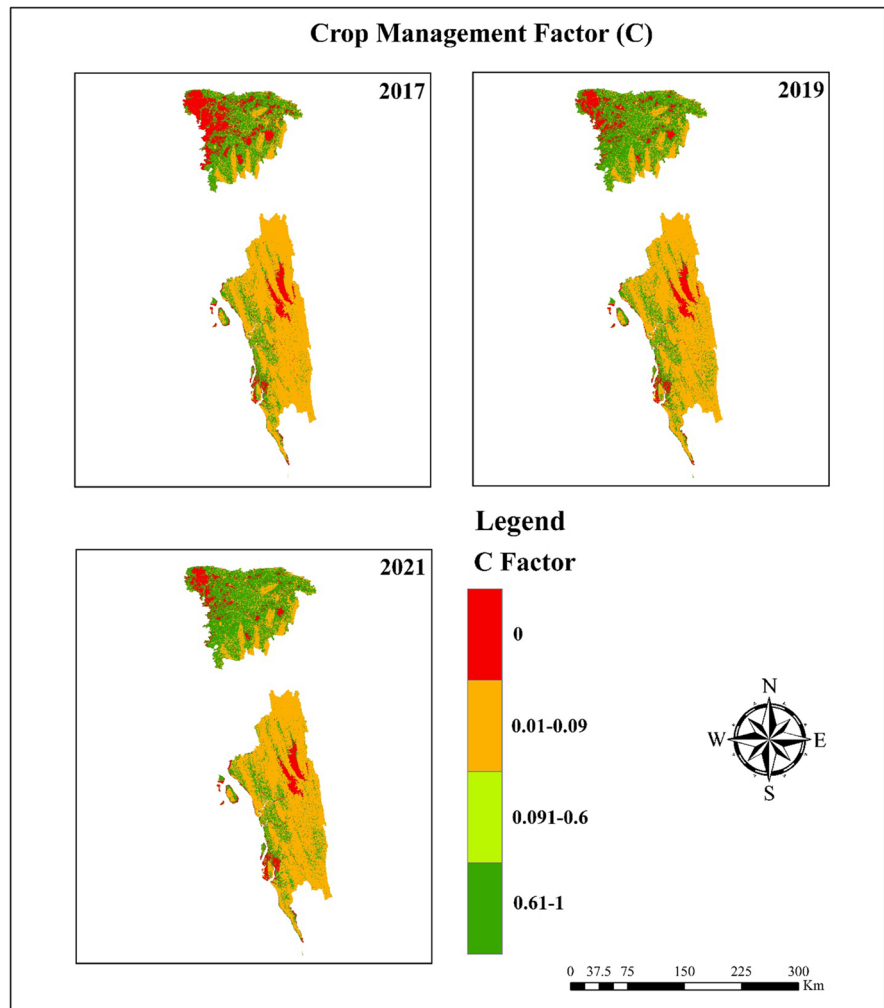
(Fig. 10). On the other hand, in the southeast region, the decreasing or increasing trend was not so significant. The area affected by no erosion was 1.152 mha, 1.15 mha, and 1.149 mha, respectively in 2017, 2019, and 2021, while the area affected by erosion was found 0.769 mha, 0.77 mha, and 0.771 mha in 2017, 2019, and 2021, accordingly.

Total and mean soil loss in the Sylhet and Chittagong hill tracts was estimated in 2017, 2019, and 2021 (Fig. 11). The average soil loss in the studied area was calculated by excluding the water bodies as they do not produce sediments and considering them can cause underestimation of the average magnitude of soil loss. It was found that in 2017 the total soil loss in northeast region was 18,633 ton year^{-1} (mean 68.77 ton ha^{-1} year^{-1}). The magnitude of soil loss notably increased in 2019 in the northeast part. In

this region, the amount of soil loss was found 24,386 ton year^{-1} (mean 69.84 ton ha^{-1} year^{-1}) in 2019 and 26,985 ton year^{-1} (mean 83.7 ton ha^{-1} year^{-1}) in 2021. On the other hand, in the southeast part, the magnitude of soil loss was estimated 51,216 ton year^{-1} (mean 101.72 ton ha^{-1} year^{-1}), 88,603 ton year^{-1} (mean 107.83 ton ha^{-1} year^{-1}), and 88,658 ton year^{-1} (mean 114.04 ton ha^{-1} year^{-1}) in 2017, 2019, and 2021, respectively. Despite a higher total annual rainfall (mm) in 2017, soil erosion was found significantly higher in 2019 and 2021 which is a clear indication of rapid land use change and lack of land cover and conservation support practice in 2019 and 2021.

Due to the lack of in situ soil erosion database, we could not validate our estimation. However, Hossain et al. (2023) conducted an investigation on soil erosion in the Cox's Bazar district of the Chittagong division

Fig. 8 Conservation support practice factor (*P*) in 2017, 2019, and 2021
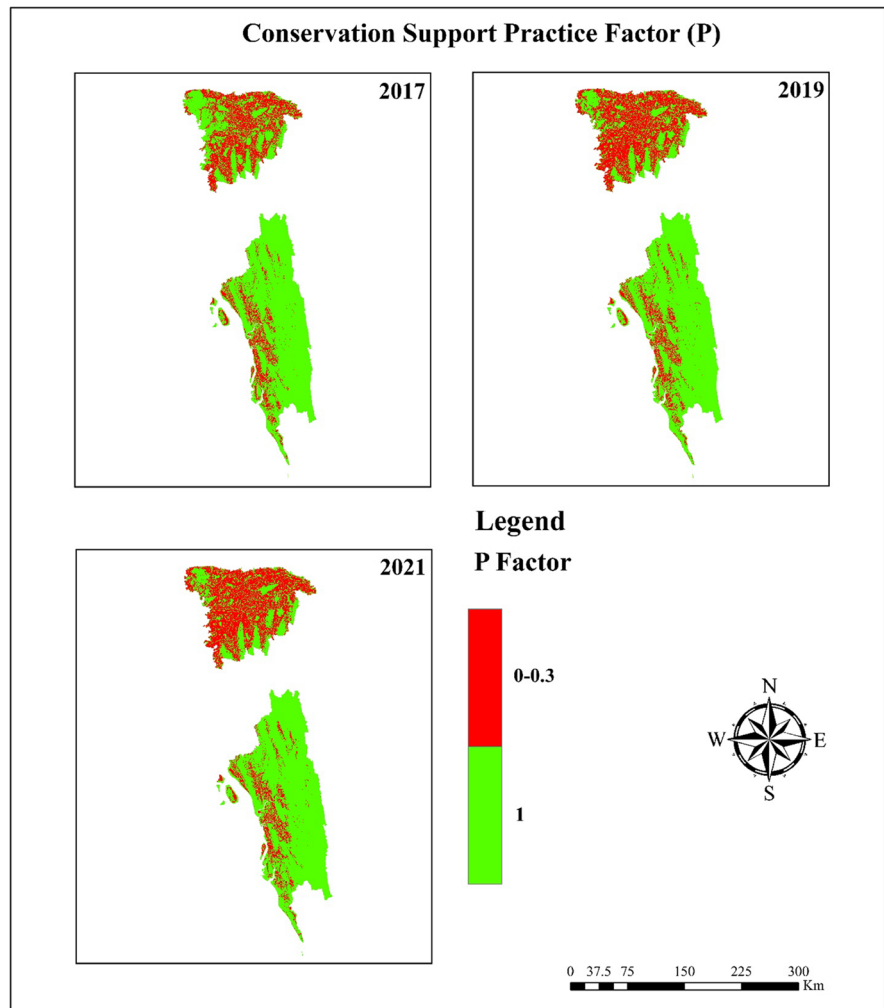
in 2015 and 2020, and they found that the mean soil loss in the studied area was 58.2 and 59 ton ha^{-1} year^{-1} in 2015 and 2020, respectively. On the other hand, in the camp of geopolitical refugees (Rohingya refugees), the soil loss was 59 ton ha^{-1} year^{-1} in 2015 and 78 ton ha^{-1} year^{-1} in 2020. They also confirmed that the higher topography and rugged terrain in this region could be the reason of causing high soil erosion. Our estimation corresponds with their findings. The total and mean soil losses in the southeastern region were high compared to the northeastern hill tracts. Azad (2001) conducted a field-level investigation in six experimental plots in Bandarban district of Chittagong hill tracts and found that the soil loss ranged between 14.25 and 61.42 ton ha^{-1} year^{-1}. Nira (2021) also conducted an experiment considering only the hill tracts of Chittagong and found that the soil erosion in

this part of Bangladesh ranged between 0 and 1436.1 ton ha^{-1} year^{-1} with a mean value of 59.45 ton ha^{-1} year^{-1}. The soil erosion values in these studies fall within the mean value of our estimation for southeastern region. Our mean estimated value is also consistent with standard range (7 to 120 ton ha^{-1} year^{-1}) of soil erosion (Banglapedia: https://en.banglapedia.org/index.php/Soil_Erosion, accessed on November 21, 2022) in Bangladesh. Shoumik and Islam (2020) studied the effects of sand, cow dung, and inorganic fertilizers on soil erosion in coastal area, which is stressed by moderately saline soil. They found that the loss of soil from sand and cow dung–treated plots was, respectively, 23 and 51 ton ha^{-1} year^{-1}, while the loss from control and inorganic fertilizer treated plots was 61 and 64 ton ha^{-1} year^{-1}; however, soil erosion in a specific area is influenced by several environmental factors and

Fig. 9 Potential annual soil loss in the tertiary hilly regions in 2017, 2019, and 2021
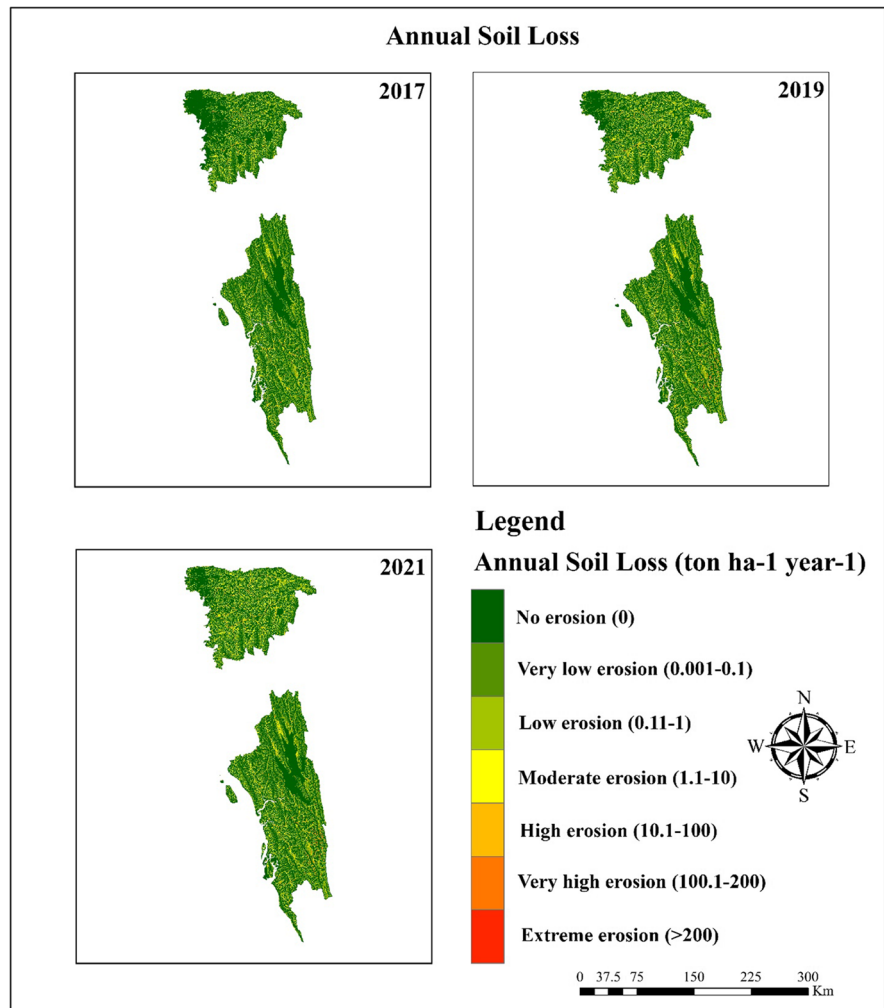
their interactions (Ganasri & Ramesh, 2016). Although *R* and *K* factors on both regions were similar, the *LS* factor could be responsible for higher erosion rate in southeastern part. Also, due to the increase in population in Bangladesh, farmers are moving to hilly regions to start farming practices on the marginal and fragile hill slopes, which were occupied by dense vegetation in the past. Our findings also reveal that the magnitude of soil loss was higher in the bare areas (Figs. 6 and 9) which agrees with the suggestions of Labrière et al. (2015) that in humid tropical climates, soil erosion is more concentrated in the bare lands with a lack of conservation or management practices.

There can be uncertainties in the estimation of soil erosion models as these models are empirically

based. Soil erosion modeling is solely a representation of the reality, and hence, the estimation may deviate more or less from the real scenario. It has also been recommended to increase the future research works to reduce uncertainties and increasing the accuracy of soil erosion modeling (Alewell et al., 2019). The RUSLE-based models were derived from the globally recognized factors that are responsible for water erosion (Morgan & Nearing 2011; Renard et al., 1997). However, the RUSLE parameters were developed based on the experimental results in the USA under tundra, subarctic, and tropical climatic conditions. Hence, the application of this model in the areas outside the range and to the non-plot-level might not represent an accurate soil loss estimation
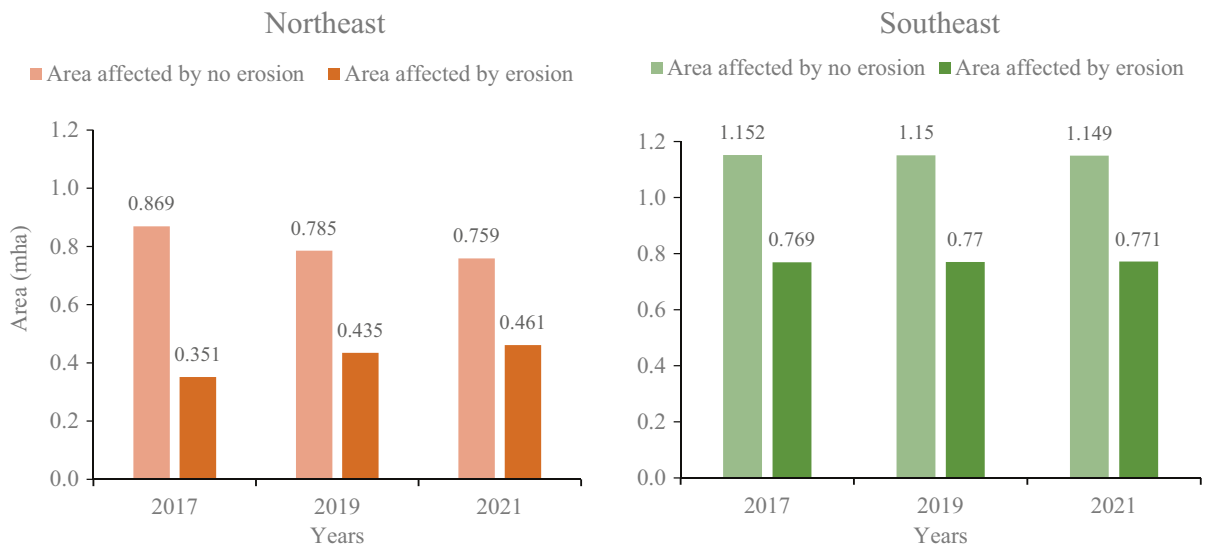
Fig. 10 Total area affected by erosion in the northeast and southeast region in 2017, 2019, and 2021

(Borrelli et al., 2013; Nearing et al., 2000). Soil erosion estimation using empirical-based models has several drawbacks, and many studies lack proper validation due to the lack of regional database (Borrelli et al., 2021). The validation of our soil loss estimation was difficult as there is neither any recent field-level data nor model-derived database on soil erosion for Bangladesh.
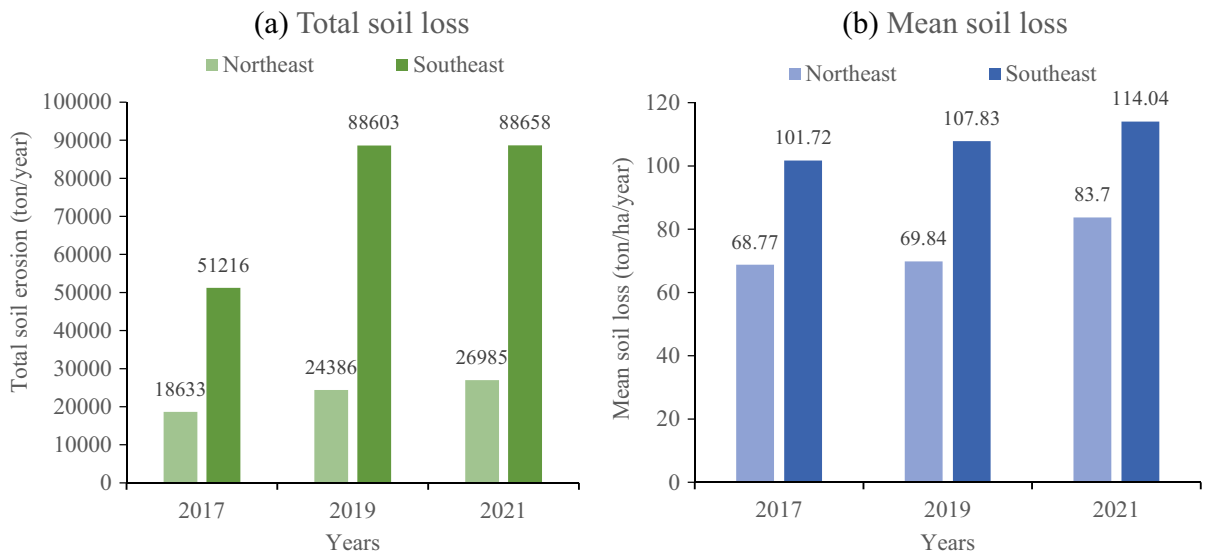

Fig. 11 Soil loss—(**a**) total and (**b**) mean—in the northeast and southeast regions in 2017, 2019, and 2021

Conclusion, limitation, and future recommendation

RUSLE erosion model integrated with GIS can be useful to study soil erosion and identify erosion-vulnerable regions at a larger scale. In this study, RUSLE was used to estimate the potential magnitude of soil loss from 2017 to 2021 in the tertiary hilly regions of Bangladesh which are also the most erosion-prone areas in the country. As a subtropical humid climatic region, the R factor was found high. The erodibility factor (K) ranged between 0 and 0.43. The maximum value of LS factor was 17, and it was found in the Chittagong hill tracts. According to the LULC, the northeastern Sylhet division had more agricultural lands compared to Chittagong. The mean soil loss in the northeastern region was estimated 68.77, 69.85, and 83.7 ton ha^{-1} year^{-1} in 2017, 2019, and 2021, respectively, whereas the loss was accordingly found 101.72, 107.83, and 114.04 ton ha^{-1} year^{-1} in the southeastern region. This increasing trend of soil loss from 2017 indicates the rapid change of land cover in these areas.

This assessment was solely based on the open and freely available database. There was neither any field observation nor a robust soil erosion database or sufficient research works on soil erosion for the country to validate our findings which was the key limitation of this research. Additionally, there was a lack of research data regarding the local agricultural and conservation practices. Even the existing soil erosion data from field observation is too old. Nevertheless, our estimated soil loss value is still consistent with a few scientific works that were conducted on a smaller scale.

Since soil erosion by water is one of the major causes of land degradation in Bangladesh, it is essential to develop a reliable soil erosion database so that the government can take necessary steps to minimize soil erosion and encourage the farmers to adopt conservation practices. A collaboration among the soil scientists can help developing a robust soil erosion estimation model for this country at finer pixels or scales. To validate the model estimation, it is also required to conduct field-level experiments. Borrelli et al. (2021) recommended introducing and developing region- and country-based RUSLE modeling assessments to overcome the drawbacks of the empirical soil loss models, and those new models should be validated by the field-based observations. In Bangladesh, there are almost no latest field-based data on soil erosion and conservation, and hence validating this kind of model is quite difficult. Considering all the potential research gaps on soil erosion, we propose a collaborative research work to (i) develop a new RUSLE model or modify the existing one by considering gully erosion for this climate, (ii) validate the estimation using field-based data, and (iii) create a reliable soil erosion database for identifying vulnerable areas to recommend adopting conservation practices.

Declarations

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