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Unveiling the Wrath of Erosion: Assessing the Impacts of Soil Erosion on the Coastal Region of Bangladesh

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RUSLE, Geographical information system, Land cover, Topography, Bangladesh.

Abstract

Study on soil erosion in the coastal region of Bangladesh is crucial due to its severe environmental and socio-economic impacts. Understanding erosion patterns, identifying vulnerable areas, and developing effective conservation strategies are essential to safeguard agricultural productivity, preserve coastal ecosystems, and protect the livelihoods of coastal communities. This study focuses on soil erosion in the low-lying, flood-prone coastal regions of Bangladesh. The Revised Universal Soil Loss Equation (RUSLE) technique was used to calculate soil erosion rates. The southern section of the study area, characterized by high rainfall erosivity (R) and soil erodibility (K), exhibited the highest erosion rates at 1446 t/ha/year. The region experiences significantly higher rainfall erosivity than other parts of the world. Cox's Bazar, Chittagong, Feni, and Patuakhali receive over 3000 mm/yr of precipitation, while Teknaf and Hatiya surpass 4000 mm/yr. The vulnerability of the soft, sand-rich topsoil to water-driven gully and rill erosion contributes to the high erodibility factor. Conversely, the northwest and low-lying marshy areas exhibit low erosion rates due to the flat terrain and deposition of eroded soil mass from the hinterland. The hilly areas of Chittagong, Teknaf, and Cox's Bazar experience above-average erosion rates. Effective soil conservation and management strategies are essential for reducing soil erosion in Bangladesh's coastal regions, considering local environmental conditions such as precipitation and soil type. The findings of this research provide valuable insights for future studies and policies on soil erosion management in the coastal districts of Bangladesh. By guiding efficient conservation efforts, this information can help mitigate the adverse impacts of soil erosion on the environment and economy.

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1. Introduction

Soil erosion poses significant challenges worldwide, leading to land degradation, infrastructure damage, and environmental deterioration (Angima *et al.*, 2003; Singh *et al.*, 2017). It affects agricultural productivity, contributes to sedimentation in water bodies, and leads to economic losses and environmental degradation. Effective soil conservation measures are essential to mitigate these impacts and sustainably manage the land and water resources (Zuazo & Pleguezuelo, 2009). Human-induced activities, such as agriculture, deforestation, and urbanization, play a crucial role in driving soil erosion in the region, compounding the problem and amplifying its consequences (Erkossa *et al.*, 2015; Mekonnen *et al.*, 2016). Unsustainable land use practices and the removal of vegetation cover increase surface runoff and soil vulnerability to erosion. In Bangladesh, a country with one of the longest coastlines globally, soil erosion is a major concern, with both direct and indirect impacts on soil quality and water pollution (Yang *et al.*, 2003). Soil erosion in Bangladesh's coastal regions has far-reaching environmental implications, including loss of biodiversity, destruction of natural habitats, and altered sediment dynamics (Shamsuddoha & Chowdhury, 2007). These consequences impact local ecosystems and wider coastal areas, including mangroves and marine ecosystems, which are vital for coastal protection and fisheries.

The coastal area of Bangladesh, situated along the Bay of Bengal, boasts diverse geomorphology and active natural processes that shape distinctive landscapes (Dewan *et al.*, 2017). However, this delicate equilibrium is increasingly disrupted due to various factors, rendering the region highly susceptible to soil erosion. The interaction of rivers, tidal impacts, sediment movement, and other environmental elements leads to a fragile balance, perturbed by human activities such as deforestation, incorrect land use, and intensive agriculture, exacerbating soil erosion challenges (Wada, 2020). Consequently, the coastal region faces severe environmental threats due to soil erosion, with significant implications for agriculture, livelihoods, and the overall well-being of coastal communities (Islam *et al.*, 2021). The geographical location and climate of the coastline contribute significantly to the heightened vulnerability of the region to soil erosion. The convergence of the Ganges, Brahmaputra, and Meghna rivers in a vast deltaic plain, along with low elevation, heavy rainfall, and the prevalence of cyclones and high tides, all contribute to significant soil erosion rates, estimated between 30 to 40 tons per hectare per year (Islam *et al.*, 2015). As one of the most populous and commercially significant areas in the nation, soil erosion in the study regions emerges as a pressing environmental issue.

Soil erosion represents a critical threat to human security and sustainable development, as it impacts agricultural productivity, water quality, and human health (Lal, 1998). To develop effective erosion management and environmental protection strategies, accurate estimates of the annual rate of soil loss are crucial. However, obtaining these estimates requires considering the complex interplay of ecological, biotic, and abiotic factors that influence soil erodibility, emphasizing the need for a multi-factor approach for estimation (Ostovari *et al.*, 2017). According to the literature, multiple models are used to calculate the annual rate of soil erosion. These models include the Revised Universal Soil Loss Equation (RUSLE) and Soil and Water Assessment Tool (SWAT). These models take into account various factors impacting soil erosion rates, allowing researchers to obtain accurate estimates and better understand the complexities of soil erosion in different regions. Renard *et al.* (1991) introduced the RUSLE, a comprehensive model addressing factors impacting soil erosion rates. However, quantifying soil loss in Bangladesh's densely populated coastal regions, where approximately 35 million people reside, remains challenging due to the complexities of field approaches in a riverine setting (Ahmad, 2019). Comprehensive studies integrating field measurements, geospatial analysis, and data modeling are necessary for accurate estimates and effective mitigation of soil erosion consequences (Hateffard *et al.*, 2021). Soil erosion presents a severe environmental challenge in the coastal region, particularly affecting agriculture, providing numerous people with jobs and income (Hasan *et al.*, 2018). Reduced soil fertility and diminished crop yields are immediate consequences of soil erosion (Khan *et al.*, 2015), while broader impacts include river and wetland sedimentation, biodiversity loss, and water quality deterioration, hampering sustainable development (Sarker *et al.*, 2012). To address these challenges, soil conservation measures, such as physical structures and conservation agricultural methods, have been implemented (Bari *et al.*, 2022). However, their effectiveness remains debatable, underscoring the need for further research and tailored erosion management strategies that suit the unique context of coastal region. This study aims to conduct a comprehensive literature analysis on coastal erosion, employing remote sensing, GIS technology, and soil erosion models like RUSLE to provide accurate rate estimates and identify priority areas for erosion management.

Soil erosion in coastal areas has far-reaching ecological consequences, particularly for the region's diverse ecosystems and biodiversity. The erosion process disrupts and degrades vital habitats such as mangroves, wetlands, and estuaries, which serve as essential breeding grounds, shelter, and sustenance sources for numerous terrestrial and aquatic species. As eroded soil and associated pollutants enter nearby water bodies, water quality deteriorates, adversely affecting aquatic life and triggering problems like algal blooms and oxygen depletion. Additionally, the physical changes caused by erosion can alter the dynamics of coastal regions, influencing the distribution of species that rely on specific features like nesting sites or feeding areas. These impacts can lead to population declines and even species extinctions, ultimately reducing the overall biodiversity of the coastal ecosystem. Furthermore, the loss of habitats can disrupt the natural migration patterns of various species. Soil erosion in these areas not only threatens the natural world but also increases the vulnerability of coastal communities to extreme weather events and flooding. Hence, comprehensive research and conservation efforts are essential to mitigate these ecological consequences and preserve the fragile balance of coastal ecosystems.

This study offers a novel and comprehensive approach to studying soil erosion in coastal regions, addressing a critical environmental challenge. The research findings hold significant contributions to science and society. It will advance our understanding of soil erosion processes, guide the formulation of tailored erosion management strategies, and inform informed policymaking for environmental protection. By fostering community resilience and promoting sustainable land management practices, the research project aims to safeguard the well-being of coastal populations and the fragile ecosystems they depend on, making a meaningful contribution to combat soil erosion and foster environmental protection in the coastal zone of Bangladesh.

2. Material and Methods

2.1 Study Area

Soil erosion poses a significant concern in the coastal regions of Bangladesh due to the frequent occurrence of severe weather events, such as cyclones and tidal surges (Bari *et al*., 2022). The southern part of Bangladesh includes various districts, covering approximately one-third of the country's total land area (Parvin *et al.*, 2017). The studied area comprises 19 coastal districts (Figure 1), characterized by high rainfall intensity, increasing flooding frequency, and sediment transport in rivers and coastal regions. This tropical environment, with coordinates between 21° to 23° N and 89° to 93° E, is home to about 35 million people, constituting around 29% of the country's total population (Ahmad, 2019).

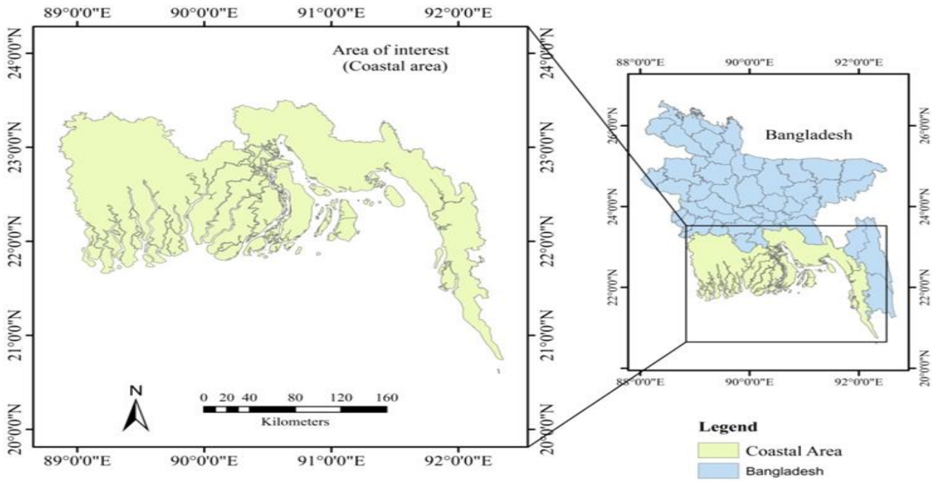

Figure 1: The study area is situated in the coastal districts of Bangladesh

The region experiences an average annual rainfall of 1,368.10 mm (Islam *et al.*, 2021). The soil in this area primarily consists of alluvial silt, which is easily eroded due to its unconsolidated, sandy texture (Huq & Shoaib, 2013). Geologically, the coastline of Bangladesh can be described by two primary units: the Holocene alluvial plain and the Pleistocene Madhupur Clay (Mukherjee *et al.*, 2009). The vulnerability of this coastal region to soil erosion necessitates comprehensive studies and effective erosion management strategies to protect the livelihoods and well-being of its coastal communities.

2.2 Data Sources

Soil erosion forecasting in the coastal regions of Bangladesh utilizes the RUSLE model, which considers multiple interrelated parameters. i.e., rainfall erosivity, soil erodibility, slope length, slope steepness, cover management, and conservation practices (Teng *et al.*, 2016). Utilizing Geographic Information System (GIS) methods, these factors can be visualized across time and space (Mostafavi *et al.*, 2013). For this investigation, the modified RUSLE model was selected for its compatibility with ArcGIS v. 10.5 and its ability to work with limited input data.

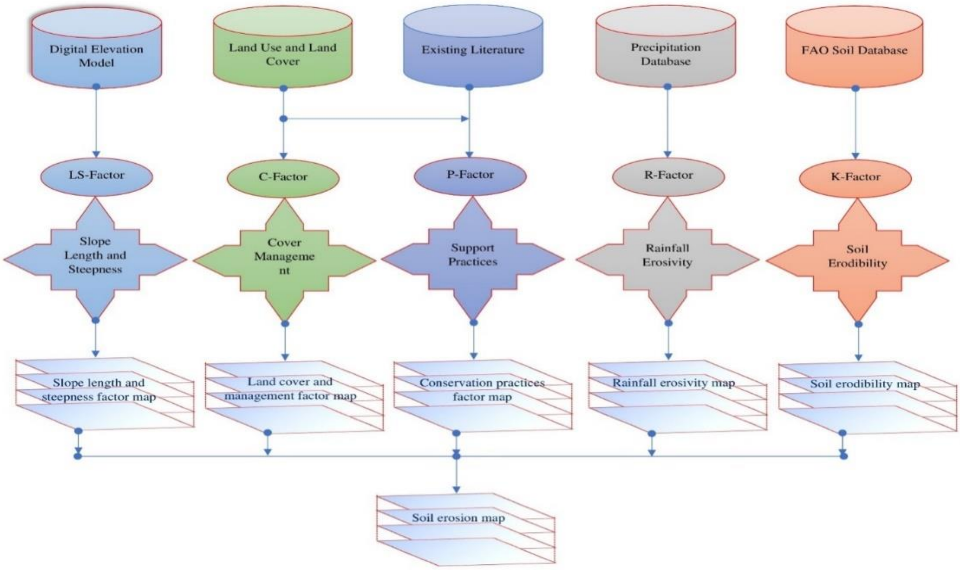

Figure 2: The methodological flowchart employed for estimating soil erosion usedthe RUSLE model

The estimation and mapping of soil erosion were conducted in 2020, utilizing public geospatial data sets. The mean monthly rainfall data for 2020 was obtained from the Bangladesh Agricultural Research Council (BARC), which was used to calculate the annual rainfall (Bangladesh Agricultural Research Council, 2020). Food and Agriculture Organization(2020) provided the soil map used in the study. A digital elevation model (DEM) was extracted from https://search.asf.alaska.edu/ with a resolution of 12.5 to determine the slope length and gradient m. This integrated approach allows for accurate and efficient soil erosion assessment, providing valuable insights into the vulnerability of the coastal region and supporting the development of targeted erosion management strategies to safeguard the environment and livelihoods of coastal communities.

2.3 Spatial Modeling

Considering factors such as data availability, regional and temporal scale, and practical limitations, the Revised Universal Soil Loss Equation (RUSLE) model was selected as the preferred approach for this study. The RUSLE model has gained popularity due to its simplicity, minimal data requirements, and high accuracy (Ghosal & Bhattacharya, 2020; Renard *et al.*, 1991). Using geospatial datasets and tools, the RUSLE facilitates efficient and comprehensive evaluations across various geographical scales, streamlining data acquisition, processing, and application (Gelagay *et al.*, 2016; Serbaji *et al.*, 2023). Empirically, the RUSLE is represented as Equation (1) (Renard *et al.*, 1991):

$$A = K \times R \times C \times LS \times P \tag{1}$$

Where, Equation (1) represents the soil loss (A) as a result of the interaction of various factors: soil erodibility (K), rainfall erosivity (R), cover management (C), slope length and steepness (LS), and conservation practices (P).

2.3.1 Rainfall Erosivity Factor (R)

The quantity that quantifies the erosive potential of raindrops is known as the rainfall erosivity factor (R), which is influenced by the total energy of the storm (Dahal, 2020). The power of raindrops to induce erosion makes this factor significant. Elevated rainfall erosivity in certain coastal regions threatens water quality by increasing sediment runoff, impacting aquatic ecosystems and aquaculture. It also necessitates costly maintenance of navigation infrastructure and highlights the importance of erosion control and sustainable land practices for resilience and community well-being. Soil erosion occurs when the ground is not sufficiently covered, and the R factor is linked to the total rainfall and the impact speed of raindrops on the ground (Beskow *et al.*, 2009). Additionally, the size and intensity of raindrops play a role in determining the R-factor. It is important to note that the R-factor varies geographically, with areas having higher values experiencing more erosion (Farhan *et al.*, 2013). The R-value for flat terrains with low inclination or slope degree is generally low, indicating lower erosivity, while areas with higher R-values are more susceptible to erosion. The R-value is calculated using rainfall energy (E) multiplied by the maximum 30-minute intensity, considering slope conditions and other climatic factors (Brown & Foster, 1987). To determine the R factor for the coastal zone, the study utilized Equation (2), which provides erosion index values for the region, as studied by Dahal (2020) and Mandal *et al.* (2015). By understanding and quantifying the R-factor, valuable insights into the erosive potential of rainfall in the coastal zone can be obtained, aiding in implementing erosion control measures and sustainable land management practices.

$$R = 38.5 + 0.35P \quad (2)$$

Where,Equation (2) represents a simple form of the rainfall erosivity factor (*R*) calculation, where *P* denotes the total annual precipitation (rainfall) in millimeters.

2.3.2 Soil Erodibility Factor (K)

Soil erodibility is a crucial factor that quantifies how soil particles are eroded from their underlying rock, influenced by natural and human-induced factors like rainfall, wind, sediment movement, and runoff (Zuazo & Pleguezuelo, 2009). While silt and clay particles are commonly associated with soil erosion, sand particles are also susceptible due to their cohesive nature near the source. Direct data from runoff plots measurement was used to calculate the erodibility factor (*K*). Williams's soil texture categorizations and organic matter contents were employed in this study to determine the *K* factor, considering data on particle size distribution, organic matter content, and soil texture to compute corresponding *K* values for different soil types (Williams *et al*., 1990). Erodibility ratings range from 0 to 1, where lower values indicate less water erosion and higher values signify more water erosion. For this study, the equation proposed by Williams *et al*. (1990), Equation (3)was utilized to determine the *K* factor, enabling a comprehensive understanding of soil erodibility in the coastal zone and supporting effective erosion control and land management strategies.

$$K_{usle} = f_{scand} \times f_{cl-si} \times f_{orgc} \times f_{hisand} \quad (3)$$

Where, f_{scand} accounts for the cohesive behavior of sand particles near the source, f_{cl-si}considers the difference between clay and silt contents in the soil, f_{orgc} reflects the influence of organic matter content, and f_{hisand} represents the interaction between sand particles and other soil components.

$$f_{scand} = \left(0.2 + 0.3 \cdot exp\left[-0.256 \cdot m_s \cdot \left(1 - \frac{m_{silt}}{100}\right)\right]\right) (4)$$

$$f_{cl-si} = \left(\frac{m_{silt}}{m_c + m_{silt}}\right)^{0.3} (5)$$

$$f_{orgc} = \left(1 - \frac{0.25 \cdot orgc}{orgc + exp[3.72 - 2.95 \cdot orgc]}\right) (6)$$

$$f_{hisand} = \left(1 - \frac{0.7\cdot\left(1-\frac{m_s}{100}\right)}{\left(1-\frac{m_s}{100}\right)+exp\left[-5.51+22.9\cdot\left(1-\frac{m_s}{100}\right)\right]}\right) (7)$$

The K values, calculated using the Williams formula, are summarized in Table 1. These values are influenced by different soil components, such as the sand fraction (m_s), silt fraction (m_{silt}), clay fraction (m_c), and organic carbon (SOC) content (expressed as a percentage). The Williams formula's implementation allows for a comprehensive understanding of soil erodibility in the studied region, enabling targeted erosion control and land management strategies based on the spatial distribution of K values.

Table 1: Soil erodibility factor (K) was calculated using Williams's equation

FAO soil unit symbol (Soil acronym)	*K* factor value (ton.ha.hr $ha^{-1}MJ^{-1}mm^{-1}$)
GE	0.12
BD	0.13
AF	0.14
JC	0.17
OD	0.14
JE	0.13

2.3.3 Crop and Management Factor (C)

The crop management factor (C) was evaluated by taking into account the existing land use and land cover patterns to assess their impact on soil erosion due to agricultural practices (Panagos *et al.*, 2015). The rate of C represents the proportion of soil loss from croplands under specific conditions compared to the same amount of soil loss from uncultivated areas (Wischmeier & Smith, 1978). Larger C-factor values indicate little or no cover effect, exacerbating erosion risks, while lower values indicate a denser cover effect, leading to reduced erosion (Erencin, 2000). The factors used in cover management were determined by averaging data from existing research, considering crop cover and soil type as essential elements influencing this factor, making it the second most crucial factor in controlling erosion (Farhan *et al.*, 2013). Land cover patterns were available, and specific values were assigned to each land cover category based on its utilization in the study region, as presented in Table 2, showcasing information gathered from the literature research on various land types and their corresponding C values. This analysis allows for a comprehensive understanding of erosion risks in the study area and facilitates the development of targeted erosion control strategies based on land use patterns and their influence on soil erosion.

Table 2: Land cover classes and their corresponding cover management factors (*C*) were determined based on the literature

Land cover class	*C* factor value
Bare land	1.000
Rainfed cropland	0.350
Herbaceous cover	0.050
Mosaic cropland	0.350
Mosaic natural vegetation	0.050
Tree cover	0.010
Mosaic tree and shrub	0.014
Shrub land	0.014
Shrub evergreen	0.013
Grassland	0.015
Sparse vegetation	0.050
Shrub or herbaceous cover	0.010
Urban area	0.500
Bare area	1.000
Post flooding cropland	0.050
Mosaic herbaceous cover	0.012
Water body	0.000

2.3.4 Slope Length and Steepness Factor (LS)

The RUSLE *LS* factor is a crucial component that integrates the effects of both slope (*S*) and slope length (*L*) in a given topography. Calculation of the *LS* factor involves considering various factors like flow direction, flow accumulation, and soil topography (Bircher *et al.*, 2019). Slope length refers to the distance from the point where overland flow starts to concentrate in a selected channel. Different researchers have developed formulas specific to the physical characteristics of a location to estimate the *LS* factor, and widely-used GIS software like ArcGIS, SAGA GIS, GRASS, IDRISI, and others already incorporate algorithms for computing it (Bircher *et al.*, 2019; Hrabalíková *et al.*, 2017). For the coastal region in this study, the *LS* factor was obtained using Equation (8) presented by Moore and Burch (1986), and the slope length and steepness map were generated from the DEM of the study area.

$$LS = POW(flow\ accumulation \times cell\ size/22.13)^{0.4} \times (sin\ slope/0.0896)^{1.3} \quad (8)$$

2.3.5 Support Practice Factor (P)

The *P*-factor plays a crucial role in evaluating the effectiveness of various maintenance strategies in reducing annual soil erosion rates (Fu *et al.*, 2011). It quantifies the soil loss reduction achieved through practices such as contouring, strip cropping, and terracing on sloped areas compared to conventional straight row cultivation methods (Renard, 1997). This factor also reflects the overall rate of soil loss relative to different agricultural regions on a broader scale (Gelagay *et al.*, 2016). Table 3 provides the *P*-factor values for different cultivation methods and slope conditions, aiding decision-making in erosion control measures (Pesaran *et al.*, 1999). The *P*-factor ranges from 0 to 1, representing the effectiveness of erosion control practices (Didoné *et al.*, 2021). Within coastal zones, various agricultural support activities, including contour farmland and fish farmlands, are implemented to address erosion challenges and maintain soil health.

Table 3 The support practice factor varies depending on the slope

Slope (%)	*P* factor
0.0 to 7.0	0.55
7.0 to 11.3	0.60
11.3 to 17.6	0.80
17.6 to 26.8	0.90
>26.8	1.00

3. Results and Discussion

3.1 Assessment of Soil Erosion Factors

(i) Rainfall erosivity factor (*R*): The *R* quantifies the impact of long-term rainfall on soil erosion (Dahal, 2020). By analyzing data from 11 coastal rain gauge stations, the study captured the geographical distribution of this factor across the region. The erosivity factors associated with precipitation varied between 665.7 MJ mm/ha.h.year to 1944.95 MJ mm/ha.h.year (Farhan *et al.*, 2013). The *R* factor was most pronounced in the south and east, where higher erosivity is attributed to the influence of elevated rainfall (Dahal, 2020). In contrast, the northern and western coastal areas exhibited lower *R* factors due to reduced rainfall (Farhan *et al.*, 2013). This information aids in understanding the potential severity of soil erosion based on long-term precipitation patterns.The Table displaying the location, yearly precipitation, and erosivity of rainfall computed using the Dahal (2020) and Mandal *et al.* (2015) method is presented as Table 3 for the rain gauge stations in the study area.

Table 4: Rain gauge stations with their annual precipitation (mm) and rainfall erosivity

Rain gaugestation	Latitude in degree	Longitude in degree	Annual precipitation (mm)	Rainfall erosivity MJ mm ha^{-1} hr^{-1} yr^{-1}
Barisal	23.72	90.37	2407	880.95
Bhola	22.68	90.65	2649	965.65
Feni	23.03	91.42	3099	1123.15
Chittagong	22.22	91.8	3719	1340.15
Cox's bazar	21.45	91.97	3300	1193.51
Teknaf	20.87	92.3	5447	1944.95
Jessore	23.2	89.33	1867	691.95
Satkhira	22.72	89.08	1792	665.7
Khulna	22.78	89.53	2317	849.45
Patuakhali	22.33	90.33	3098	1122.8
Hatiya	22.45	92	4360	1564.5

(ii) Soil erodibility factor (*K*): The *K* characterizes the soil's susceptibility to particle displacement and runoff conveyance (Bou-imajjane *et al.*, 2020; Tiruneh *et al.*, 2015). Variations in soil composition, organic content, and coherency of soil particles influence the *K* factor. The study determined *K* values ranging from 0.03352 t h/ MJ mm to 0.17488 t h/ MJ mm (Almeida *et al.*, 2013; Buttafuoco *et al.*, 2012). Higher *K* values were associated with areas having soil with lower cohesiveness, such as sandy and loose surface soils (Bou-imajjane *et al.*, 2020). These regions are prone to water-induced erosion, with increased vulnerability to gullies and rills (Bou-imajjane *et al.*, 2020). In contrast, low-lying marshy areas exhibited minimal soil erodibility due to their flat topography and the accumulation of eroded soil material from surrounding lands (Buttafuoco *et al.*, 2012).

iii) Topographic factor (*LS*): The *LS* integrates the effects of *L* and *S* in a region (Desmet *et al.*, 1996). This composite measure is determined using DEM data, considering factors such as flow direction and flow accumulation (Hrabalíková *et al.*, 2017). The *LS* values varied from -285.26 to +253, with the smallest values observed in flatland areas and increasing with altitude (Hrabalíková *et al.*, 2017). Regions with longer slope lengths and steeper slopes experience faster soil erosion rates due to the accumulation of raindrops downslope (Desmet *et al.*, 1996). The *LS* factor helps in understanding the role of topography in soil erosion and assists in identifying areas with higher erosion potential.

(iv) Cover management factor (*C*): The *C* evaluates the impact of different land use and land cover patterns on soil erosion (Wischmeier & Smith, 1978). It reflects the reduction in soil loss achieved through agricultural practices like contouring and strip cropping compared to conventional cultivation methods (Shin, 1999). The study employed values from existing research to determine *C* factors for various cultivation methods and slope conditions (Shin, 1999). Areas with high *C* factor values are more susceptible to erosion, while those with lower values exhibit a dense cover effect, resulting in less erosion (Erencin, 2000). Understanding the *C* factor aids in assessing the impact of agricultural practices on soil conservation and erosion control (Wischmeier & Smith, 1978).

(v) Support practice factor (*P*): The *P* assesses the effectiveness of different agricultural practices, such as contour farming and terracing, in controlling soil erosion (Renard, 1997). The ratio of natural soil exhaustion to plow loss determines the *P* value (Shin, 1999). The study derived *P* values from existing literature and found that they ranged from 0.27 to 0.5 (Shin, 1999). Higher *P* values indicate better protection from wind and water erosion, while lower values imply a flat area where additional erosion control measures are unnecessary. The *P* factor assists in understanding the suitability of ploughing in undulated terrains and helps in decision-making for erosion control practices (Matthews, 1991).

Figure. 3 illustrates the soil erosion factors used to calculate the potential soil erosion map for the study area. Each factor plays a crucial role in determining the rate and severity of soil erosion across the coastal region. By integrating these factors through RUSLE model in ArcGIS v. 10.5, the map provides valuable insights into the spatial distribution of soil erosion and helps identify areas at higher risk of erosion. The research findings can inform targeted erosion management strategies to promote sustainable land use and conservation in the study area.

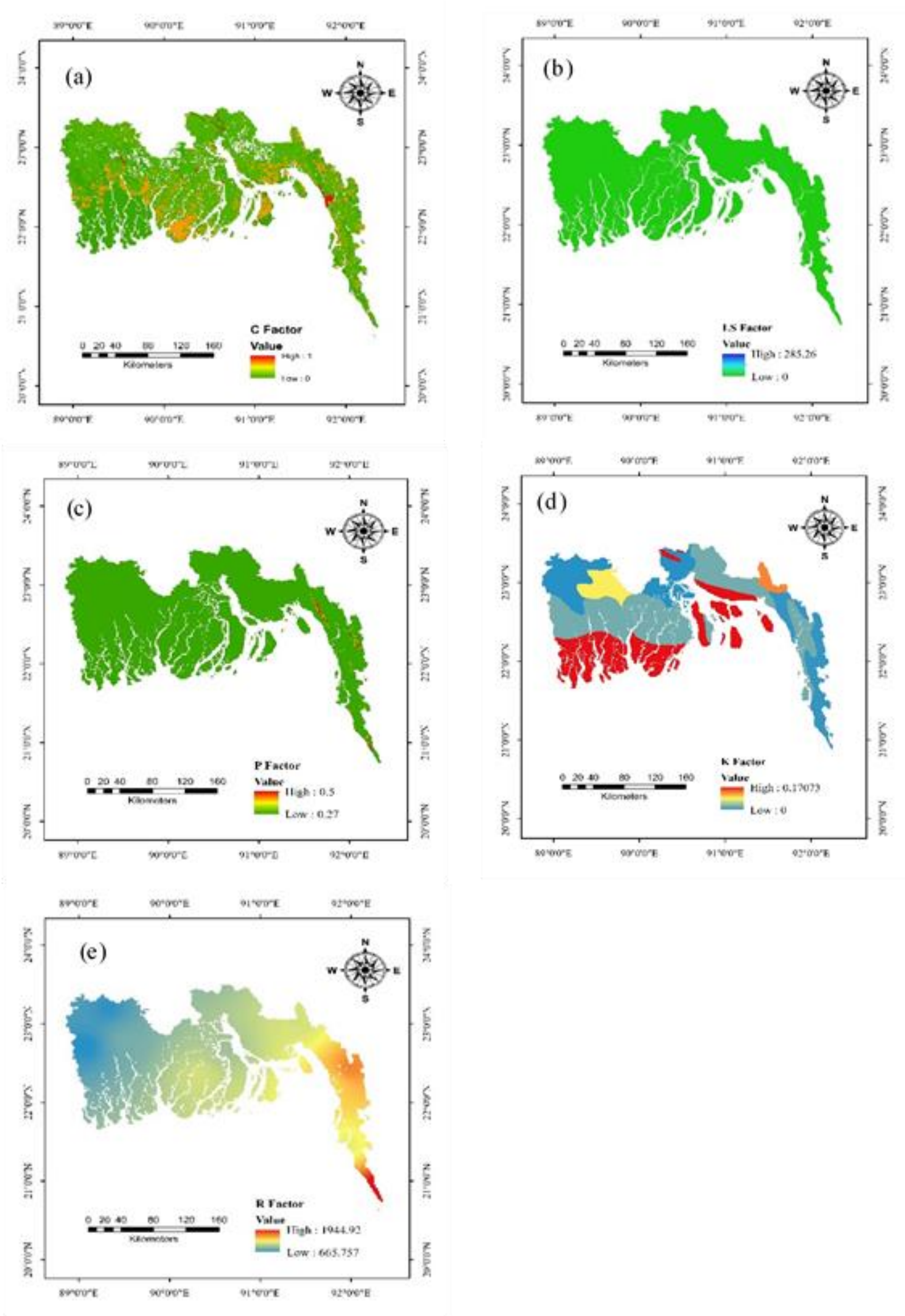

Figure 3: Soil erosion factors: (a) *C* factor, (b) *LS* factor, (c) *P* factor, (d) *K* factor, and (e) *R* factor

3.2 Potential Soil Erosion Map

The potential soil erosion map of the coastal region (Figure 4) was generated by multiplying the factor map in ArcGIS v. 10.5, revealing widespread and varying degrees of soil erosion across the research region. The soil erosion rate for the study area in 2020 was calculated at 1446 t ha^{-1} yr^{-1}. Based on Table 5, the erosion was categorized into five classes: low, medium, high, very high, and severe. Notably, soil erosion was most severe in the southern section of the research area, attributed to the increased erosivity of rainfall (*R*) in that region. Unlike other regions where RUSLE approaches were employed, the *R* factor value here is notably higher due to large-scale precipitation exceeding 4000 mm/yr in districts like Teknaf and Hatiya, and over 3000 mm/yr in Cox's Bazar, Chittagong, Fein, and Patuakhali. Additionally, soil erodibility (measured as *K*) was high, particularly in regions with sandy, loose surface soil that easily creates gullies and rills. Precisely, the high erosion rates observed in the southern section of the study area result from the interplay of two key factors: high rainfall erosivity and soil erodibility. In this region, the prevalence of intense and frequent rainfall events, driven by the monsoon climate and the potential influence of cyclones from the Bay of Bengal, contributes to elevated rainfall erosivity. Additionally, the loose and sandy nature of the soil in coastal areas increases soil erodibility. When these factors combine, the result is a heightened erosive force: intense rainfall impacts the soil directly, causing detachment and transport of soil particles, especially in areas lacking sufficient vegetative cover. The topography of the region, which may include steeper slopes, further amplifies the erosive power of runoff. Recognizing this interaction is pivotal for devising effective erosion control strategies, including afforestation, terracing, and improved soil management, to mitigate the impact of erosion in this vulnerable southern coastal region. Conversely, the Northwest exhibited almost negligible soil erosion, thanks to its flat topography and accumulation of eroded soil material in low-lying marshy areas. The low-lying marshy areas in coastal regions, with their flat terrain and the deposition of eroded soil mass from upstream, offer a natural defense against soil erosion. To leverage these protective features for erosion control, conservation strategies can include mangrove restoration, wetland management, and the promotion of erosion-resistant plant species. Mangrove forests, in particular, play a pivotal role in stabilizing shorelines and providing habitat. These efforts not only enhance erosion control but also contribute to climate resilience by regulating floods and storm surges. Involving local communities in wetland conservation and conducting ongoing research and monitoring are essential components of a comprehensive strategy to safeguard these critical coastal ecosystems

The study identified higher-than-average erosion rates in specific neighborhoods of Chittagong, Teknaf, and Cox's Bazar, primarily due to their elevated topography. The study also categorized soil erosion into five classes, where 94.2 percent of the study area (approximately 28,352 km^2) showed low erosion. Regions with medium, high, very high, and severe erosion accounted for 0.89 percent (267 km^2), 0.73 percent (210 km^2), 0.43 percent (131 km^2), and 3.78 percent (1138 km^2) of the area, respectively. This comprehensive assessment provides valuable insights into the spatial distribution and severity of soil erosion in the coastal region, which can inform targeted erosion management strategies for sustainable land use and conservation.

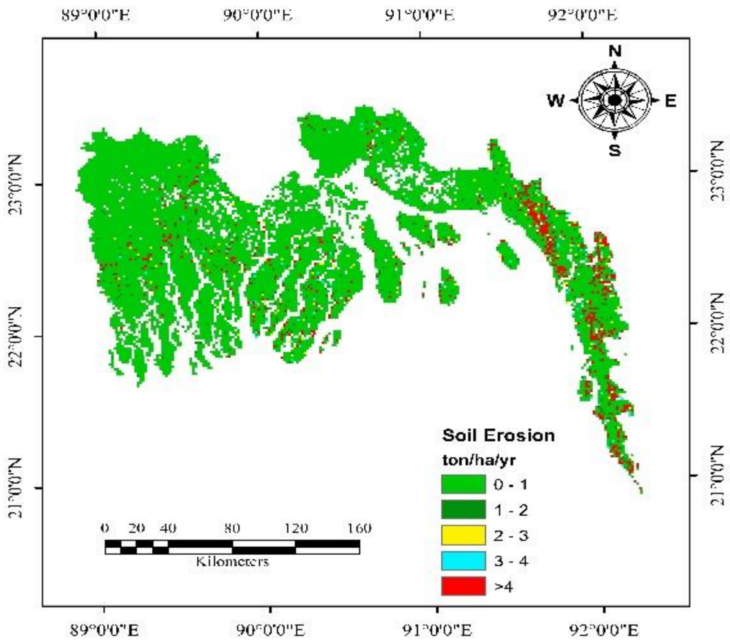

Figure 4: Construction of a potential soil erosion map using ArcGIS v. 10.5 and the RUSLE model.

Table 5: Soil erosion classes and their corresponding affected areas with percentages

Soil erosion class	Area (km^2)	Percentage of area (%)
Low(0-1)	28352	94.20
Medium(1-2)	267	0.89
High(2-3)	220	0.73
Very high(3-4)	131	0.43
Severe(>4)	1138	3.78

3.3 Discussion

The erosion patterns observed in Bangladesh's coastal regions profoundly affect the socio-economic aspects of local communities. High erosion rates disrupt agriculture and aquaculture, diminishing food security and income generation. Loss of livelihoods and forced migration due to erosion compound economic vulnerabilities. Additionally, erosion weakens protective coastal ecosystems, heightening communities' susceptibility to climate change impacts. Addressing erosion through sustainable practices and ecosystem protection is crucial to bolster the resilience and well-being of these coastal communities.The flat terrain and sediment deposition in low-lying marshy areas play pivotal roles in ecosystem dynamics and land use. These areas give rise to vital wetlands, nurturing rich biodiversity and serving as habitats for various species. They facilitate the growth of protective mangrove forests, a buffer against erosion, and a source of livelihoods. As sediments accumulate, previously inundated areas become suitable for agriculture and settlement, albeit with challenges like salinity intrusion. Additionally, these marshy regions are essential for fisheries, offering fertile grounds for fish and crustacean nurseries, contributing significantly to food security and local incomes.

Soil erosion mapping in the coastal region of Bangladesh is a critical endeavor to assess erosion risks and plan effective conservation measures. Utilizing models like the RUSLE, researchers analyze factors such as rainfall erosivity, soil erodibility, topography, and land cover to estimate erosion rates and identify vulnerable areas (Das *et al.*, 2018). The integration of GIS tools enables visualizing erosion patterns and guiding policymakers and land managers in implementing targeted strategies to safeguard agricultural productivity, infrastructure, and the environment against erosion threats in this low-lying and vulnerable coastal landscape (Sourn *et al.*, 2022).

The RUSLE has been extensively utilized worldwide for soil erosion mapping and assessment. Researchers from various countries (Ganasri & Ramesh, 2016; Jahun *et al.*, 2015; Lim *et al.*, 2005) have adapted the model to suit regional conditions, incorporating remote sensing, GIS technologies, and climate change predictions to enhance its accuracy. The integration of spatial analysis techniques and comparisons with other erosion models has also been explored. Additionally, studies have focused on evaluating the effectiveness of conservation practices and land management strategies in reducing soil erosion. Despite its widespread use, uncertainties and limitations associated with RUSLE parameters have been investigated. As the field progresses, ongoing research and global initiatives towards sustainable land management are expected to shape future developments in this area. According to the literature,using the land susceptibility to coastal erosion (LSCE)model provided valuable insights into soil erosion patterns in the Bangladeshi coastal region (Ahmed *et al.*, 2018). The categorization of erosion rates into five levels allows for a comprehensive understanding of the extent and severity of erosion in different areas. By superimposing raster surfaces and considering various input parameters, the LSCE Model provided a detailed spatial analysis of soil erosion across the study area. This information is crucial for developing targeted erosion prevention and management strategies in specific regions that are most vulnerable to erosion. However, it is essential to compare these findings with another study that used the RUSLE model in the Sylhet district (Bari *et al.,* 2022) to highlight differences and similarities. The use of different models may lead to variations in erosion rate estimations and factor values. These differences could be attributed to the unique physical characteristics and environmental conditions of the respective study areas. Understanding these variations helps to identify potential uncertainties in erosion predictions and emphasizes the importance of using multiple models to validate results and enhance accuracy.Despite the valuable insights provided by both the LSCE and RUSLE models, it is crucial to acknowledge the limitations of these models in predicting soil erosion in coastal regions. The RUSLE model, though widely used and valuable for its simplicity, may oversimplify erosion processes and overlook specific mechanisms unique to the coastal study area, such as water-driven gully and rill erosion (Thapa, 2020). Water-driven gully and rill erosion in soft, sand-rich topsoil areas significantly impact local flora and fauna in the coastal regions. It leads to habitat destruction, displacing terrestrial species and disrupting aquatic ecosystems through sedimentation and water quality degradation. This erosion threatens endemic and endangered species, including nesting sea turtles, migratory birds, and river dolphins. Furthermore, changes in plant communities and the potential spread of invasive species can have long-lasting ecological consequences. Preserving these fragile ecosystems and implementing erosion control measures are vital to protect biodiversity and maintain the critical ecological services they provide.Additionally, the accuracy of model outputs heavily relies on site-specific data, which can be challenging to obtain and might introduce inaccuracies (Mandal *et al.,* 2015).

Furthermore, coastal regions are subject to unique factors such as tidal fluctuations, coastal currents, and sediment transport dynamics that the models may not fully account for. The homogenous land management assumption of the RUSLE model might not capture variations in agricultural practices across the diverse coastal landscape, leading to uncertainties in erosion estimations. It is crucial to consider these site-specific factors and adapt the models accordingly to improve the accuracy of soil erosion predictions. Additionally, the models may not explicitly consider the potential impacts of climate change on erosion dynamics. Climate change can significantly influence precipitation patterns, storm intensities, and sea-level rise, all of which can affect erosion rates in coastal regions. Integrating climate change scenarios into erosion models is essential for developing climate-resilient soil conservation strategies.

Overall, the study provides valuable insights into soil erosion patterns in the Bangladeshi coastal region and highlights the importance of using different models to validate results. However, it also underscores the need for caution when interpreting the results and acknowledges the limitations of the models. To address these limitations, further research and data collection efforts are required to enhance the accuracy and reliability of erosion predictions in coastal areas. Incorporating site-specific factors and climate change scenarios into erosion models will strengthen the effectiveness of erosion prevention and conservation efforts in coastal districts. Ultimately, such comprehensive research will be instrumental in safeguarding agricultural livelihoods, preserving coastal infrastructure, and ensuring sustainable land use practices in the face of increasing erosion challenges.

The research on soil erosion dynamics in the coastal region carries profound implications for climate change adaptation. This critical connection is evident in the context of rising sea levels, as erosion exacerbates the vulnerability of coastal landscapes and necessitates adaptation strategies to protect infrastructure and communities. Moreover, extreme weather events intensified by climate change, such as heavy rainfall and storms, directly influence erosion dynamics, demanding early warning systems and disaster preparedness measures. Coastal ecosystems affected by erosion, like mangroves and wetlands, are pivotal for climate adaptation due to their role as natural buffers and carbon sinks. Sustainable land use practices informed by erosion research contribute not only to erosion control but also to climate change mitigation. As policymakers formulate climate adaptation strategies, considering erosion dynamics alongside rising sea levels and extreme events is imperative to ensure the resilience of vulnerable coastal regions in the face of climate change.

4. Erosion Mitigation Strategies Align with Sustainable Development Goals

The discovery of high erosion rates in hilly areas of the coastal districts necessitates a comprehensive approach to infrastructure development and land-use planning that aligns with sustainable development goals.Here are some key considerations−(i) Infrastructure resilience: Infrastructure projects in these erosion-prone areas should prioritize resilience. This includes engineering solutions that account for erosion risk, such as reinforced embankments and drainage systems that prevent soil erosion during heavy rainfall events. (ii) Land-use zoning: Land-use planning should involve zoning that recognizes areas prone to erosion and establishes restrictions on certain types of development in high-risk zones. This can help protect both human settlements and natural habitats. (iii) Erosion control measures: Implementing erosion control measures, such as reforestation, terracing, and the use of erosion-resistant vegetation, can help mitigate erosion rates. These strategies align with goals related to environmental conservation and sustainable land management. (iv) Community resilience: Building the resilience of local communities is crucial. This involves education and training on sustainable land use practices, early warning systems for extreme weather events, and the establishment of community-based disaster management initiatives. (v) Sustainable agriculture: Promoting sustainable agricultural practices that reduce soil erosion, such as contour farming and agroforestry, can align with both food security goals and erosion mitigation efforts. (vi) Ecosystem conservation: Prioritizing the conservation of critical ecosystems like mangroves and wetlands can contribute to erosion control while also aligning with goals related to biodiversity conservation and climate resilience. (vii) Data and monitoring: Continuous monitoring of erosion rates, weather patterns, and land-use changes is essential for informed decision-making. This data can inform adaptive management strategies and align with goals related to data-driven development. (viii) Policy integration: Ensuring that erosion mitigation is integrated into broader coastal development policies and strategies is essential for long-term sustainability.

In alignment with Sustainable Development Goals (SDGs), these strategies contribute to several key goals, including SDG 11 (Sustainable Cities and Communities) by promoting resilient infrastructure and land-use planning, SDG 13 (Climate Action) through erosion control and climate resilience, SDG 15 (Life on Land) by conserving ecosystems, and SDG 17 (Partnerships for the Goals) through collaborative efforts between governments, communities, and organizations.Incorporating erosion mitigation into development and land-use planning is essential not only for protecting the environment but also for ensuring the well-being and livelihoods of the coastal communities in these vulnerable areas. Besides, Bangladesh has initiated various policies and initiatives to tackle soil erosion in coastal areas, such as the Bangladesh Delta Plan 2100 and community-based adaptation projects. Research findings can bolster these efforts by providing data-driven insights into erosion patterns and risk areas. They can help fine-tune erosion control measures and support the conservation of crucial ecosystems like mangroves, which act as natural buffers. Additionally, research can inform education and awareness campaigns and facilitate international collaborations to enhance erosion management strategies in the country's vulnerable coastal regions.

5. Conclusion

The study conducted on soil erosion in Bangladesh's coastal regions using the RUSLE method has yielded valuable insights into the severity of the issue and its potential risks to agricultural productivity and ecological balance. The study revealed higher erosion rates in the southern section of the research area, primarily attributed to the presence of soft and loose sand-rich topsoil, coupled with elevated values of rainfall erosivity and soil erodibility factors. Despite its limitations, such as representing extreme rainfall events, the RUSLE method proves useful in predicting erosion patterns and identifying vulnerable areas. The findings highlighted that a small fraction of the coastal zone experiences significant soil erosion, while most of the land area faces moderate erosion rates. This emphasizes the importance of implementing targeted soil conservation management interventions in high-risk areas to effectively mitigate erosion and sustain agricultural activities. Some noteworthy findings of the study include the identification of specific erosion hotspots and the quantification of erosion rates in different land cover types. Moreover, the research demonstrated the potential impacts of soil erosion on agricultural lands, coastal habitats, and water quality in the region. By utilizing the insights from this research and other related studies, policymakers can develop informed strategies for soil conservation and safeguard the long-term viability of coastal ecosystems. Implementing erosion control measures in the identified vulnerable areas and promoting sustainable land use practices are essential steps toward mitigating the adverse effects of soil erosion in Bangladesh's coastal regions. Moreover, ongoing monitoring and further research will be crucial to assess the effectiveness of these interventions and adapt strategies to changing environmental conditions. Ultimately, addressing soil erosion will contribute to the overall resilience and stability of the coastal ecosystem and its socio-economic well-being.

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Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors

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