Malaysian Journal
Of Civil
Engineering

QUANTITATIFICATION OF SOIL EROSION USING CAUSATIVE FACTORS IN THE GIS ENVIRONMENT FOR SYLHET DISTRICT, BANGLADESH

Rafiqul Bari[a]*, Md. Altaf Hossain[a], Md. Jahir Alam[b], Tanvir Islam[a]

[a]Department of Agricultural Construction and Environmental Engineering, Faculty of Agricultural Engineering and Technology, Sylhet Agricultural University, Alurtol Road, Sylhet- 3100, Bangladesh
[b]Department of Civil and Environmental Engineering, Shahjalal University of Science and Technology, 3114 University Ave, Sylhet, Bangladesh

Article history
Received
09 November 2021
Received in revised form
28 February 2022
Accepted
08 March 2022
Published online
31 March 2022

Corresponding author
rbkaet12@gmail.com

Abstract

The aim of this study was to enumerate the potential soil erosion in the Sylhet district of Bangladesh using the Revised Universal Soil Loss Equation (RUSLE) approach in the software-based windows. Using the rainfall erosivity factor (R), the soil erodibility factor (K), the cover management factor (C), the topographic factor (LS) and the support practices factor (P), the RUSLE formula quantified the possible soil loss rate. The soil erosion rate was classified into six classes based on the erosion severity. The result shows that the annual soil deterioration rate differs from 0 to 799.67 t/ha/year. However, almost about 97.71% of the total surface area is under low potential (54.1%) and moderate (43.61%) erosion risk. Rather about 2.29% area of Sylhet district was under average, high, very high and critic erosion risk. Result indicates that the north-eastern and central zone are highly vulnerable to soil erosion due to steep slope and P factor.

Keywords: Soil Erosion, DEM, Quantitative Calculation, RUSLE, GIS and Remote Sensing

1.0 INTRODUCTION

Soil erosion is the removal and washing away of the top surface soil by the water flow, raindrops and wind (Ritter, 2011). Water flow and raindrops are among the most widespread causes of soil loss around the world, posing a significant danger to agriculture's long-term stability and sustainable potential, as well as terrestrial habitats (Cerdan et al., 2010; Islam et al., 2015; Lal, 2004; Pimentel, 2006; Pimentel and Burgess, 2013).

Soil degradation causes the depletion of fertile agricultural soil and water pollution both directly and indirectly (Yang et al., 2003). Loss in crop productivity, loss of organic matter, dam siltation, water contamination, and a decrease of water storage capacity are all negative effects of soil degradation (Bakker et al., 2004, 2005; Boardman and Poesen, 2006). All of these concerns may contribute to fundamental social problems including land rejection and rural population decline (Bakker et al., 2005).

At present days, soil erosion is closely interconnected with excessive farming, deforestation, irregular grazing in the slopy area, excessive rainfall and unplanned urbanization (Reusing et al., 2000; Terranova et al., 2009; Valentin et al., 2005; Yang et al., 2003). Owing to soil erosion, around 12 to 15 t/ha/year of soil is being lost which indicates the loss of topsoil approximately 0.90–0.95 mm per year (FAO and ITPS, 2015).

Achieving food security is the foremost goal of Bangladesh (Parvin and Ahsan, 2013). The condition of food insecurity is more serious in Bangladesh due to overpopulation (Shaheen and Islam, 2012). Food supply must rise by 70% between 2005 and 2050 to achieve global food safety (ELD Initiative, 2015). Approximately 99.7% of the foodstuff of human beings is derived from land, and food security for an ever-growing population mostly relies on the productivity and quality of soils (Pimentel, 2006). So proper steps to control soil erosion have become a major issue in achieving sustainable agriculture (Cerdà et al., 2009; Montgomery, 2007).

It is clear from the previous studies that it is possible to estimate soil erosion using both Physical based models and empirical models. But physical-based models provide a wide range of work environments for temporal and spatial scenarios of soil erosion, simulating these models is difficult due to a lack of information (Bhattarai and Dutta, 2007). In order to qualitative analysis to predict soil erosion of watershed, the Revised Universal Soil Loss Equation (RUSLE) are now widely used due to less data requirement (Bhattarai and Dutta, 2007; Zhang et al., 2009). The Universal Soil Loss Equation (USLE) and the Modified Universal Soil Loss Equation (MUSLE) are also used in the qualitative analysis of soil erosion.

It is noted here that there is a wide range of significantly advanced studies of soil erosion using remote sensing and geographic information system (GIS) (Demirci and Karaburun, 2012; Feng et al., 2010; Pan and Wen, 2014). GIS provides an opportunity to incorporate all variables like soil condition, gradient, and terrestrial usage by splitting the whole area into small grid cells for detailed analysis (Bhattarai and Dutta, 2007). To forecast soil erosion at the watershed level, several studies were conducted using a combination of RUSLE and GIS environments (Ghosal and Bhattacharya, 2020; Kouli et al., 2009; Meghraoui et al., 2017; Terranova et al., 2009; Tiruneh and Ayalew, 2015).

This investigation was accomplished with the local rainfall data, Digital Elevation Map (DEM) data, soil texture data, and Landsat 8 data according to the RUSLE model using ArcGIS.

1.1 Study Area

This study was conducted in the Sylhet district. It is the north-western region of Bangladesh, which is situated between 24º32' North latitude and 91º52' East longitude (Hossain et al., 2011). It is located on the bank of the Surma river having a population of over 0.5 million. It covers an area of about 3452.07 km^2(Figure 1). Tea estates, rain forests, and river valleys are the main features of the Sylhet district. It is also famous for its freshwater bodies. Lots of haors are located in this area (Chowdhury et al., 2016). Sylhet is 21 meters above the mean sea level.

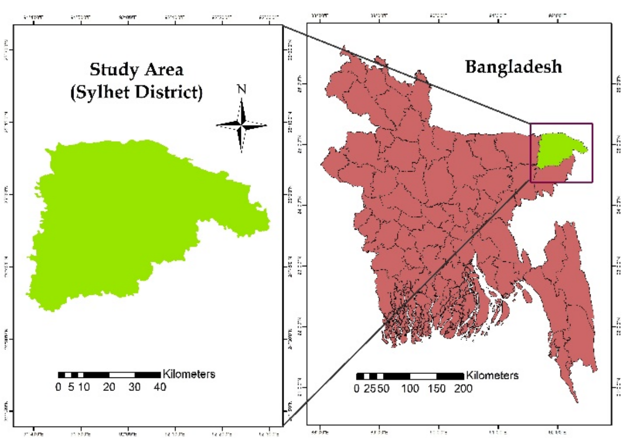

Figure 1 Study area map

The wet season from April to October and then almost every day is hot and humid, with torrential rainfall and gusty winds. The summers here have a lot of rainfall, while the winters have relatively little rainfall. The foggy surroundings are very dry during the winter from November to February. The annual temperature on average in the Sylhet region is 23.6°C. The estimated mean yearly precipitation is 3854.2 mm and the humidity is 68,92 percent (Islam et al., 2015). Therefore, As Sylhet has a huge hilly region, is selected based on its topographical character (Eshika et al., 2017). The main river of the Sylhet district is Surma. Khusiyara, Piyain, Ghorai are also notable rivers in this region. Sylhet district is divided into thirteen Upazilas such as Balaganj, Bishwanath, Beanibazar, Companyganj, Dakshin Surma, Fenchuganj, Golapganj, Guainghat, Osmaninagar, Jaintiapur, Kanaighat, Sylhet Sadar, and Zakiganj. Sylhet is one of the major tea, oil, and gas-producing areas in Bangladesh. Agriculture is the primary source of livelihood for the people of this region. Other non-agricultural activities carried out by the residents of that region include manufacturing, trade, transportation and telecommunications, service, renovation, religious service, rent and remittance, and others. Sylhet is one of the most prominent cultural and spiritual centers in Bangladesh. The ancient traditional music of the district includes Mursidi, Marfati, Lai Haroaba dance, Manipuri dance, Kumari dance, Jhum dance, etc. The major transport systems used in the Sylhet district are motorcycles, rickshaws, CNGs, taxis, mini-buses, and other vehicles.

2.0 METHODOLOGY

The RUSLE model estimates soil damage for watershed in Geographic Information System (GIS) windows using the combined equation of geophysical and land cover factors. It is widely used to predict long term rates of soil erosion subjected to a raindrop, water flow and general agricultural practice (Renard et al., 1997) and a widely used model for soil removal from topsoil in a tropical environment (Bhandari et al., 2015; Bhattarai and Dutta, 2007). It can determine erosion rates based on the properties of the watersheds as well as their spatial distribution under specified metrological conditions (Angima et al., 2003). The RUSLE has been the most widely utilized scientific model in the world due to its ease of use and reliability with GIS as it can combine empirical and predictive models (Xu et al., 2008).

Soil erosion within each pixel is estimated using the RUSLE model considering the following parameters (Renard et al., 1997)

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

Here A = the computed spatial average soil loss over a period (t/ha/year), R = the rainfall runoff erosivity factor (MJ mm/ha.h.year), K = the soil erodibility factor (t h/ MJ mm), LS = slope length and steepness factor (dimensionless), C = the cover management factor (dimensionless, within the 0 to 1.5), and P = the conservation practice factor (dimensionless, within 0 to 1). The C and P values are unitless.

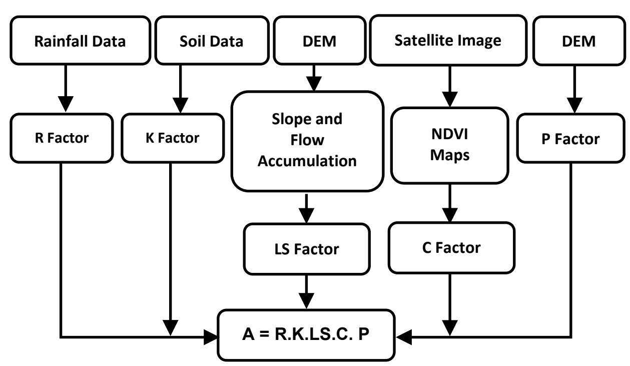

Figure 2 Steps of the working procedure

The RUSLE parameters were evaluated using time series precipitation data of the past 59 years, textural characteristics of soil data, spatial distribution of digital elevation model (DEM) and geometrically corrected satellite data in the sections below. The flowchart in Figure 2 summarized all the investigation processes detailed.

2.1 Rainfall Erosivity Factor (R)

The rainfall erosivity factor (R) describes the intensity of raindrops to cause erosion and is a function of the total energy of rainstorms (Dahal, 2020). It is the capacity of rain to induce erosion in a given soil if no cover exists. The R factor is related to overall precipitation as well as the kinetic of rain particles that hit the surface. It is influenced by both strength and size of rain particles. (Beskow et al., 2009). For sub-tropical environments such as Sylhet, the R factor was measured using the following equation which provides erosion index values of area (Dahal, 2020; Mandal et al., 2015).

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

Here P means average annual precipitation

2.2 Soil Erodibility Factor (K)

Soil erodibility is an important assessment index of the resistance of soil to being separated, flushed, or moved by the erosion force of rainfall and other eroding agents. It refers to whether the soil is readily eroded or not (Demirci and Karaburun, 2012; Koirala et al., 2019; Liu et al., 2020). It is correlated to soil physical qualities such as texture, structure, organic content, and permeability. To measure soil erodibility, a generally nomograph developed by Wisuneirer was used. However, due to the lack of access to certainly required datasets such as soil permeability and soil structure, K values were estimated in this study from the percentage of silt, sand, clay, organic content in soil samples using the following equations, which had been successfully used in many studies (Bou-Imajjane and Belfoul, 2020; Gourfi and Daoudi, 2019).

The equation of soil erodibility factor is stated as

$$K = A \times B \times C \times D \times 0.1317 \qquad (3)$$

Here, $A = [0.2 + 0.3\exp(-0.0256\ \text{Sand}\ (1 - \frac{\text{Silt}}{100}))]$

$$B = \left(\frac{\text{Silt}}{\text{Clay+Silt}}\right)^{0.3}$$

$$C = [1.0 - (\frac{0.25 \times OC}{OC + \exp[(3.72 - 2.95 \times OC)]})]$$

$$D = [1.0 - \frac{0.70\ SN1}{SN1 + \exp[(5.41 + 22.9\ SN1)]}]$$

OC = Organic Carbon and $SN1 = 1 - \frac{\text{Sand}}{100}$

2.3 Topographic Factor (LS)

There is a significant relationship between the accumulation of water and the slope of the area. These two factors increase the detachment and transport capacities of soil evaluated using the topographic factor (LS) which was used in the RUSLE algorithm (Renard et al., 1997). It's also termed as sediment transport capacity index, which is used to measure erosion caused as a result of its effect on surface runoff speed (Conforti et al., 2016). It describes how the slope angle affects the erosion of the surface (Lu et al., 2004). This parameter is made up of the slope steepness (S) and the slope-length factor (L), those are calculated using the DEM in the ArcGIS. An equation developed by (Wischmeier and Smith, 1978) was used by (Bizuwerk et al., 1999; Bou-Imajjane and Belfoul, 2020) to measure the topographic component.

$$LS = (\frac{L}{22.13})^m + (0.065 + 0.045S + 0.0065S2 + 0.0065S^2) \qquad (4)$$

Here, L indicates Flow Accumulation × Cell Size, L indicates the length of the slope (m) and S indicates the slope of the gradient (%). The range of m value based on the slope is presented in Table 1 (Wischmeier and Smith, 1978).

Table 1 m values based on slope

Value of m	Slope (%)
0.2	< 1
0.3	1-3
0.4	3-5
0.5	> 5

2.4 Support Practice Factor (P)

The factor which refers to the ratio of soil loss with upslope and downslope tillage is the Support practice Factor (P). It is related to the adaptation of suitable conservation measures like contour bunding, terrace farming, contour cultivation, by rows of crops planted up and down the slope (Pulido and Bocco, 2014). It helps to reduce topsoil loss due to water flow, which is regulated by drainage patterns, runoff volume, and flow force on the soil surface (Panagos et al., 2015). This factor is defined as the relationship between slope and agricultural practices. Due to the lack of these datasets, this study used a method followed by (Bou-Imajjane and Belfoul, 2020; Dahal, 2020; Koirala et al., 2019). This approach was tested in the same setting where the P factor is related with the change of slopes. The P factor values vary from 0 to1, with 0 indicating areas with anthropic erosion tolerance and 1 indicating area with steep slopes with no anthropic Support Practice (Table 2).

Table 2 P factor values depending on the percentage of slope (Koirala et al., 2019)

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

2.5 Cover Management Factor (C)

Soil surface cover includes soil canopy and crop type on surface or vegetation cover. Cover management factor increases penetration as a result effect of precipitation decreases. For getting optimal C factor, computation of Normalized Difference vegetation Index was conducted from Landsat 8 image-based on Near Infrared (NIR) and Red (R) bands. The NDVI refers photosynthetic status of vegetation. The C factors in the study area encompass land use which induces different kinds of land such as forest, agriculture, wastelands, etc. The cover management factor distinguishes between plan type and density (Wischmeier and Smith, 1978). C factor 1 means more soil erosion due to less vegetation coverage. The C factor value varies from 0 to approximately 1. If the value of the C factor is 1 then there is less vegetation coverage and more soil erosion, on the other hand, the value of the C-factor is 0 indicates more vegetation coverage and less soil erosion (Atoma et al., 2020).

The C factor map based on the NDVI of the Landsat OLI image in this analysis is obtained. The radiometric and atmospheric correction of the satellite image had been undertaken prior to the NDVI calculation. The C values for each grid were derived using the following equation.

$$\mathrm{C} = 0.431 - 0.805 \times \mathrm{NDVI} \tag{5}$$

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}} \tag{6}$$

3.0 RESULTS AND DISCUSSION

The soil erosion was assessed spatially by integrating the rasters of R, K, LS, C and P factors in the GIS platform. Soil conservation measures without quantifying soil erosion led to failure. So, quantitative analysis of soil erosion and its special variation can act a significant role in the implementation of conservation measures. Here soil erosion can be occurred due to human activities, wind and climate change along with water. But human-induced soil erosion is 10 to 15 times quicker than any other natural way of soil depletion (Wilkinson and McElroy, 2007). According to classification based on the study conducted by Reddy et al (2016) more than 80 t/ha/year is considered as extremely severe.

3.1 Rainfall Erosivity Factor (R)

R factor quantifies the effects of long-term rainfall that influences to erode the soil. The spatial distribution pattern of this factor's map had been generated using the meteorological database of Sylhet Weather Station, as seen in Figure 3. Location wise geographic pattern of the R factor is illustrated in this map. The rainfall erosivity factor values varied from 1120.55 MJ mm/ha.h.year to 1488.55 MJ mm/ha.h.year belongs to Sreemangal. The average value of R was 1435.76 MJ mm/ha.h.year. The area with the greatest significance of the R factor was located in the north-western region of Sylhet. The lower R values are observed at the South-west zone of Sylhet.

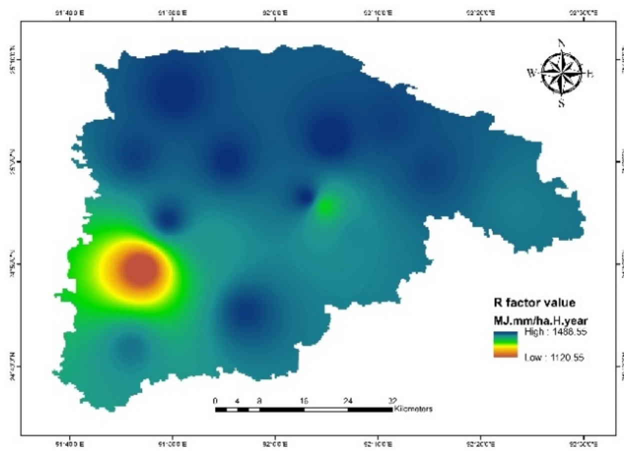

Figure 3 Spatial patterns of R factor in Sylhet District

3.2 Soil Erodibility Factor (K)

Erodibility of the soil is indeed an indication of its inhibitory action on particle displacement and runoff shipment. It is assessed by the coherency of the soil particles and can diverge depending on the existence of living plants, climatic variability, and cultivated methods, the soil's composition as well as its water content (Bou-Imajjane and Belfoul, 2020; Tiruneh and Ayalew, 2015). The K factor reported varying from 0.0147127 t h/ MJ mm to 0.048874 t h/ MJ mm, as seen in Figure 4. The K value which occupies the large portion of the study area is about 0.03352 t h/ MJ mm. It was observed that the erosivity tends to decrease with the topographic variation from hillside to plain area. In this study, the K factor is only linked to the corresponding location's textural properties.

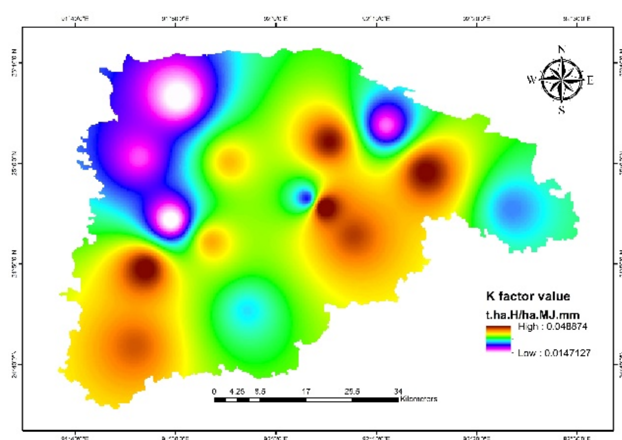

Figure 4 Spatial patterns of K factor in Sylhet District

3.3 Topographic Factor (LS)

The topographic factor (LS) was assessed according to the DEM data of the investigation area. It is the multiplication of flow accumulation, which was also obtained from DEM data and slope gradient. Flatland contains the lower LS values. The LS values get increased according to the elevation. The LS values in this investigation extended from 0 to 67.91 (Figure 5). The largest section of Sylhet occupies a topographic factor value of 0.95. Sylhet is flat with a gentle sloppy area. Only 21.3% of the land has a sloppy area. It refers to overall topographical effects on soil erosion. An increase in slope length causes an increase in soil erosion due to the progressive accumulation of rain droplets in the downslope direction, on the other hand, an increase of slope steepness refers to an increase of velocity.

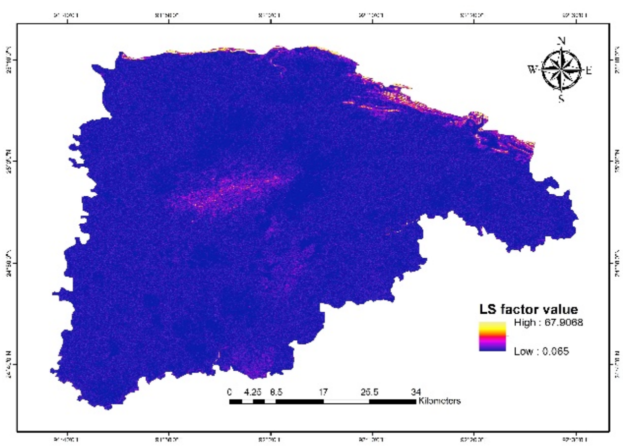

Figure 5 Spatial patterns of slope length and steepness in Sylhet District

3.4 Support Practice Factor (P)

The support practice factor (P) is the proportion of natural soil depletion to ploughing loss in an undulating landscape. P values were determined in this analysis using the slope value of DEM maps. The soil support practice factor fluctuates from 0.55 to 1 (Figure 6). The maximum P-value is found in the hilly areas bordering the north, indicating that there is very little protection against soil erosion in that region. A slope of 0.8 refers to a region with a mild slope. P values ranging from 0.55 to 0.6 suggest a low-sloped zone that does not demand extra support. A large portion of the study area comprises a low P-value. It is clear from previous studies that zones with moderate to high P values are seemed to be more erodible.

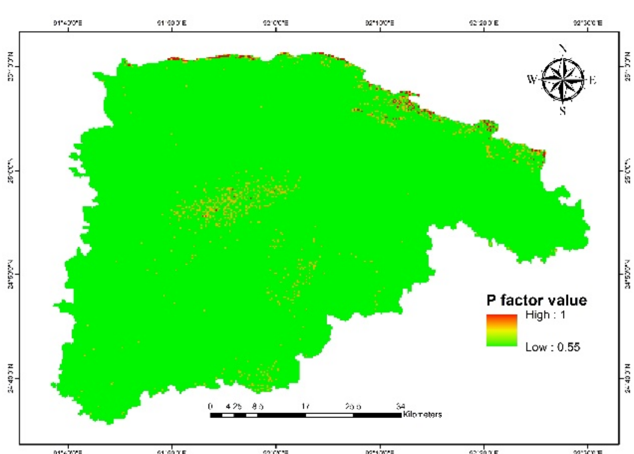

Figure 6 Spatial patterns of conservation practice factor (P factor) in Sylhet District

3.5 Cover Management Factor (C)

For the creation of a Cover management factor (C) map, NDVI values were calculated from radiometrically corrected images. It refers to integrated effects of vegetation cover, cropping pattern and management practices on soil erosion (Wischmeier and Smith, 1978). Land use with a high value of the C factor leads considerably to soil erosion. Agricultural land tends to fix the soil to a degree by agriculture, but it also increases degradation by disrupting the soil texture and organic matter (Meghraoui et al., 2017). The crop management factor (C) for the sample area (Figure 7) ranges from -0.08 to 0.51, based on the satellite image. The average C factor value is 0.299.

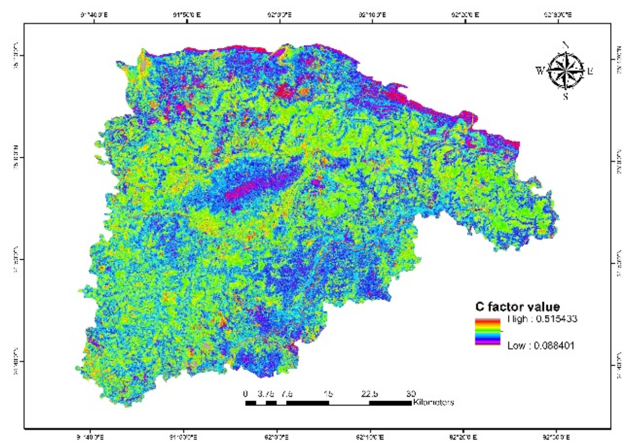

Figure 7 Spatial patterns of cover management factor (C) in Sylhet District

3.6 Potential Erosion Map

The soil erosion map (Figure 8) was determined by reviewing all the RUSLE parameters in ArcGIS which depicts the distribution pattern of erosion risk as a result of various natural causes. The projected values of the depletion of soil differ from 0 to 799.67 t/ha/year with a modal value of 7.32 t/ha/year. Owing to better understanding, the potential erosion map was categorized as low, moderate, average, high, very high, and critic soil erosion area using RUSLE value (Bou-Imajjane and Belfoul, 2020).

If the risk of erosion is less than 5 t/ha/yr, it is considered to belong to the low soil erosion zone. About 1755 sq. km of land belongs to this region, which is about 54.1 percent of the total land of Sylhet. The second group is called the moderate soil erosion zone, which ranges from 5 t/ha/year to 25 t/ha/year. This zone comprises about 43.61 percent of the total land of Sylhet. The third group is called the average erosion zone, which contains the erosion level from 25 t/ha/year to 50 t/ha/year. This region contains approximately 63 sq. km of land, with about 1.83 percent of Sylhet's total land area. Having potential erosion between 50 and 200 t/ha/year is assumed as the high and very high erosion zone. Only 0.45% land of Sylhet district is covered by these two groups. When soil erosion exceeds 200 t/ha/year, then is called the critic erosion zone. It counts about 0.06 percent of the total territory. The overall surface area (%) affected by soil erosion is shown in Figure 9 in the range low to critic.

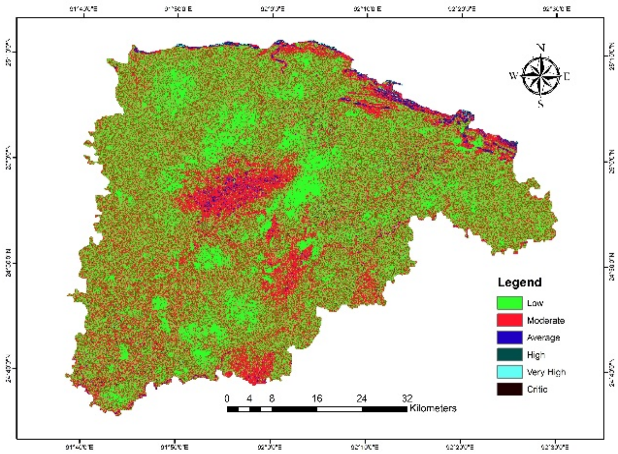

Figure 8 Spatial patterns of potential erosion risk map in Sylhet District

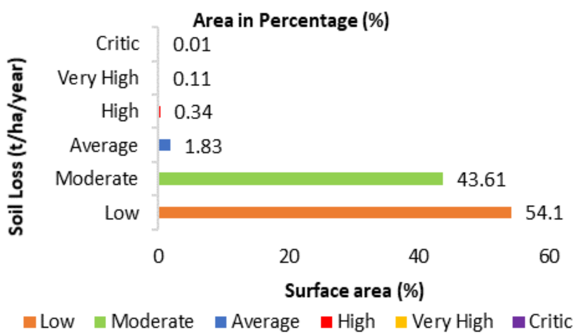

Figure 9 Estimated surface area (%) considering soil loss intensity at Sylhet District

4.0 CONCLUSIONS

In this study, quantitative analysis of soil erosion at Sylhet District has been performed using the RUSLE approach which provides soil erosion with limited information. Although this approach does not integrate soil organic matter, permeability, soil structure, soil particle size, it is simple to predict soil erosion pattern. Moreover, modeling is complex and difficult to validate. In the empirical model, all of these factor maps were formed with the ArcGIS, and this approach identifies areas at risk from a soil erosion point of view where soil conservation management actions are needed. The following output from different maps are identified:

a. The lowest and highest values of annual rainfall erodibility had been estimated at 1120.55 MJ mm/ha.h.year and 1488.55 MJ mm/ha.h.year, respectively. The mean annual rainfall erodibility has been found 1435.76 MJ mm/ha.h.year.
b. The soil erodibility factor values range between 0.0147127 to 0.048874 t h/ MJ mm. The mean annual soil erodibility factor value has been found at 0.03352 t h/ MJ mm.
c. The LS factor values range from 0 to 67.91. The mean LS value is 0.95.
d. The annual soil loss that has been found in this research ranges between 0 to 799.67 t/ha/year.

Though annual soil loss (799.67 t/ha/year) is very high, but this critic loss comprises a few areas of the Sylhet District. Only 0.06% of the total area is under this critic loss. The maximum area is under low soil erosion about 5 t/ha/year which includes around 54.1% areas of the total areas.

The moderate soil erosion ranges between 5 to 25 t/ha/year, including 43.1% of the Sylhet District. The severity assessment of soil erosion GIS-based RUSLE equation is unable to picture out the distribution of massive rainfall events. In this study, the C factor is determined based on NDVI, so it provides a better qualitative analysis. Approximation of the P factor based on empirical equation will provide a more accurate estimation. A comprehensive study based on regression analysis based on the highest correlation coefficients of most significant factors will estimate soil erosion more accurately.

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