Estimation of Soil Erosion Hazard in The Simpo Subwatershed, Indonesia

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Abstract. River siltation caused by sedimentation in the downstream area of Simpo River, Juli Sub-district, Bireuen Regency, is suspected to occur due to increased land erosion. The siltation leads to a decrease in river capacity and triggers overflow (flooding) during the rainy season. This affects residential areas, plantations, and tourist areas around the river. This research aims to estimate the rate of land erosion and map the Erosion Hazard Level (EHL) occurring in the Simpo Subwatershed. The estimation is carried out with the Universal Soil Loss Equation (USLE) method based on the Geographic Information System (GIS). The data used includes 10 years of monthly rainfall data, soil type maps, Digital Elevation Model (DEM) data, and land cover maps. Based on the calculation results, the rate of land erosion is found to be 52592.9 tons/ha/year. Furthermore, the erosion hazard in the Simpo Subwatershed ranges from low to high levels. The EHL in the subwatershed is dominated by the High-Moderate category, reaching 38.1%. Most of the areas affected by this erosion category are spatially located in the upstream area with moderately steep slopes (15–25%), primarily consisting of plantation areas. This indicates that soil conservation measures need to be adopted in the region.

1 Introduction

The rapidly increasing demand for food due to rapid population growth is one of the major global challenges today. This increased demand is accompanied by the conversion of forest land into agricultural and plantation land and illegal logging, which is a fundamental factor contributing to soil erosion if not properly managed. Erosion is the process of degradation and transportation of soil particles by geomorphic forces such as water and wind [1]. Although soil erosion is a natural geomorphic process, its rate can be accelerated by human activities on the land, such as land conversion, improper cultivation, and deforestation [2]–[5]. Additionally, climate change, which leads to changes in rainfall intensity and patterns, also contributes to erosion potential [6]–[8]. In the Simpo Subwatershed, land use for plantations (especially oil palm plantations) without proper conservation techniques can damage soil structure and increase vulnerability to land erosion. This is because the infiltration rate of oil palm plantation soils is relatively slow due to the high clay content and poor porosity [9]. Similarly, uncontrolled forest encroachment in the upstream area of the Simpo Sub-watershed in Bener Meriah Regency ([10], [11]) also contributes to increased

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https://doi.org/10.1051/e3sconf/202447601046

land erosion in that sub-watershed. This soil erosion contributes to sedimentation in the Simpo Subwatershed River, leading to siltation. The impact of this siltation reduces the river's capacity and causes river overflow (floods) during the rainy season [4]. These floods affect residential areas, plantations, and tourist areas located around the river. Furthermore, sedimentation in the river, urban drainage, and water structures can also result in high maintenance costs and reduce the resilience of these structures to floods [12]. Additionally, land erosion can decrease soil production and hydrological functions (environmental degradation) [13]–[15]. Therefore, soil erosion estimation is necessary to mitigate and reduce its impact in the Simpo Subwatershed. Field measurements are considered the most reliable method for estimating soil loss in some sub-watershed areas [13]. However, this method can be time-consuming and costly when applied at a regional scale [16]. Furthermore, the allocation of soil and water conservation requires mapping and prioritizing areas according to their vulnerability to erosion [17]. Spatial distribution modeling of potential soil erosion can be done using the Universal Soil Loss Equation (USLE) Model based on Geographic Information System (GIS) [18]–[22]. USLE factors are calculated using spatial data, and GIS techniques provide useful tools for mapping them [8], [23]. The combination of these results in an annual average soil loss and a map of the level of erosion risk (TBE) throughout the sub-watershed. This study can provide information for decision-making in the implementation of soil and water conservation methods. It can also raise awareness of soil and water conservation among the local communities in the study area [23]–[25].

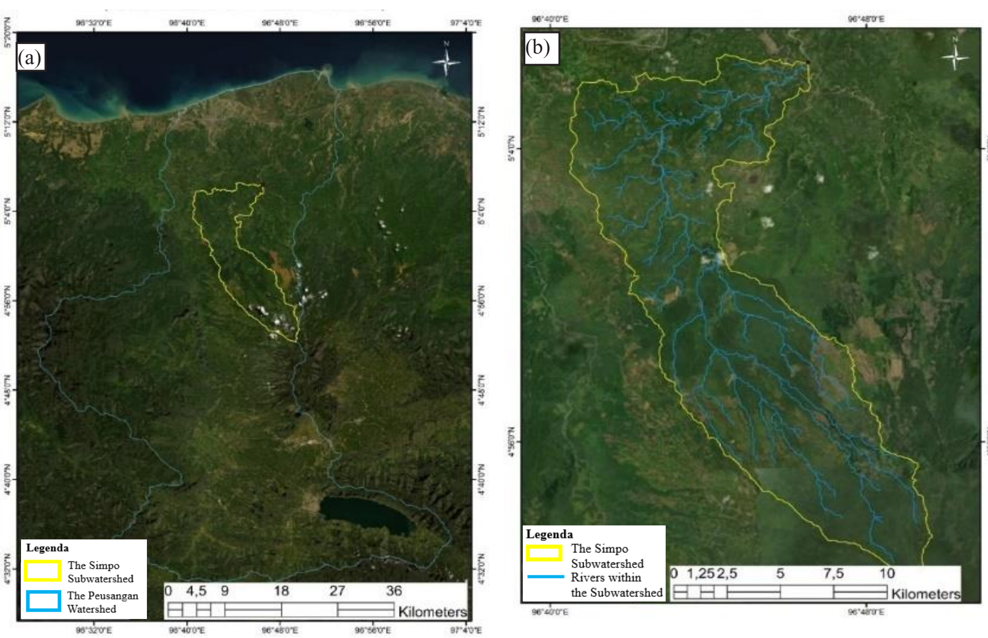

Fig. 1. Map of the Simpo Subwatershed (Figure b) in the Peusangan Watershed (Figure a) (the map derived from DEM SRTM data of Aceh Province with 30 m resolution) [26]

2 Methodology

Erosion estimation was conducted in the Simpo Subwatershed, which covers an area of 179.08 km^2. The Simpo Sub-watershed is one of the sub-watersheds within the Peusangan Watershed, as indicated in Figure 1. Administratively, this subwatershed spans three regencies, namely Bireuen Regency (Juli District, South Peusangan, and Siblah Krueng Peusangan), Bener Meriah Regency (Pinto Rime Gayo District), and a small portion of North Aceh Regency (Sawang District).

2.1 Data Collection

The data used (Table 1) are secondary data obtained from official agencies. These data are required as input for the analysis process using Geographic Information System (GIS) techniques.

Table 1. Required data and its usage

No	Data Type	Data Source	Data Usage
1	Monthly rainfall for 10 years (2009–2018) at each nearest station	Aceh Province Irrigation Service	Calculate the rainfall erosivity value (R) of the subwatershed
2	Soil Type Map	Regional Development Planning Agency (BAPPEDA) of Banda Aceh City	Determine the soil erodibility value (K) of the subwatershed
3	Digital Elevation Model (DEM) Data	DEMNAS	Analyze and determine the slope length (LS) values of the subwatershed
4	Land Cover Map for the Year 2020	Ministry of Environment and Forestry (KLHK)	Determine the crop management and soil conservation practice (CP) values

2.2 Data Analysis

The estimation of erosion is carried out using the USLE formula [27], with the equation as follows:

$$A = R \; x \; K \; x \; L \; x \; S \; x \; C \; x \; P \qquad (1)$$

Explanation:
A = amount of lost soil (Ton/ha/year);
R = annual average rainfall erosivity factor (mj.cm/ha/hour/year);
K = soil erodibility factor (Ton.ha.hour/ha/mj.cm);
L = slope length factor;
S = slope steepness factor;
C = crop management factor;
P = soil conservation factor.

Based on the above erosion estimation equation, the following is a description of each factor determining the magnitude of erosion:

2.2.1 Rainfall Erosivity Factor (R)

According to Arsyad (2010) [1], the value of R represents the erosive power of rainfall at a location or the annual rainfall erosivity. The calculation of the rainfall erosivity factor has been presented by Lenvain (1975) with the following equation:

$$R = 2.21 \times P^{1.36} \quad (2)$$

Explanation:
R = rainfall erosivity index (unit/month);
P = monthly average rainfall (cm).

2.2.2 Soil Erodibility Factor (K)

Arsyad (2010) [1] explains that soil erodibility (K) indicates the soil's susceptibility to erosion, which means how easily soil can erode. Soil erodibility is influenced by soil characteristics such as soil texture, soil aggregate stability, infiltration capacity, and soil organic and chemical content [28]. The values of K for various soil types have been determined by El-Swaify and Dangler (1976) in [29].

2.2.3 Slope Length and Steepness Factor (LS)

The values of the slope length factor (L) and slope steepness factor (S) are integrated into the LS factor, which is the result of multiplying the slope length factor (L) by the slope steepness factor (S). Sutapa (2010) [30] provides LS values based on slope steepness categories (%), indicating that the steeper the slope of a watershed, the larger the LS factor, reaching a value of 9.5. This is because slope steepness can influence surface runoff speed, which is one of the triggers for erosion.

2.2.4 Crop Management and Soil Conservation Practice Factor (CP)

The land cover and management factor (C) represents the overall influence of vegetation, surface residue, soil surface conditions, and land management on the amount of soil lost (erosion). The value of P is determined based on a table of soil conservation indices. Under conditions where erosion control efforts are absent, P is assigned a value of 1, and less than 1 for land use with mechanical handling [31]. The parameter CP can also be established separately for C and P or as a single value for both parameters (CP). CP values based on land cover types have been presented by the Ministry of Forestry Regulation (2014) in [32] and by the River Basin Management Agency (BPDAS) in Krueng Aceh [33].

The final step is soil erosion estimation by calculating A (Equation 1) or the maximum amount of lost soil in tons/ha/year in each land unit, and then classifying erosion according to the predetermined criteria in Table 2 as follows.

Table 2. Erosion Hazard Levels Based on Erosion Rate [1]

Class	Erosion Rate (tons/ha/year)	Erosion Hazard Level
I	< 15	Very Low
II	15 - 60	Low
III	60 - 180	Moderate
IV	180 - 480	High
V	> 480	Very High

3 Result and Discussion

3.1 Rainfall Erosivity Factor

The rainfall measuring stations around the Simpo Sub-watershed are Balai Pelatihan Pertanian (BPP) Peudada, Balai Pelatihan Pertanian (BPP) Alur Gading, and Klimatologi Malikussaleh. The average monthly rainfall in the sub-watershed must first be calculated using the Thiessen method to determine the influence area of each station on the sub-watershed. The calculation results show that BPP Peudada and BPP Alur Gading stations have influences on the rainfall distribution in the sub-watershed of 23.9% and 76.1%, respectively. Meanwhile, the Klimatologi Malikussaleh station does not influence the sub-watershed, as shown in Figure 2.

The values of monthly rainfall erosivity factors are calculated using the average monthly rainfall values according to Equation 2. Table 3 shows that the highest rainfall erosivity occurs in November, while the lowest erosivity is recorded in July. Subsequently, the annual rainfall erosivity, which is the total erosivity of rainfall for each month, is determined as the R factor to obtain the soil erosion rate value.

Fig. 2. Influence of Each Station on the Simpo Subwatershed (Thiessen Method)

Table 3. Rainfall Erosivity Value (R) in the Simpo Subwatershed

Month	Monthly Average P for Each Station			Average P Thiessen (mm)	Rainfall Erosivity. (R)
	BPP Alur Gading	BPP Peudada	Klim. Malikussaleh		
January	310.0	249.9	127.1	295.6	221.1
February	194.7	118.1	58.7	176.4	109.5
March	247.7	178.0	91.8	231.0	158.1
April	310.0	112.5	76.2	262.8	188.4
May	225.4	160.4	118.1	209.9	138.7
June	88.0	132.5	99.1	98.6	49.7
July	77.9	109.3	81.7	85.4	40.9
August	159.0	146.9	130.9	156.1	92.8
September	222.4	196.1	86.5	216.1	144.4

Month	Monthly Average P for Each Station			Average P Thiessen (mm)	Rainfall Erosivity. (R)
	BPP Alur Gading	BPP Peudada	Klim. Malikussaleh		
October	270.1	154.7	139.5	242.5	168.9
November	409.1	280.5	231.1	378.4	309.3
December	338.2	325.3	252.2	335.1	262.2
Total					**1883.9**

3.2 Soil Erodibility Factor

The soil type map in Figure 3 indicates that the soil in the Simpo Subwatershed is divided into three types: andisol, inceptisol, and ultisol. Andisol soil is the dominant soil type in the sub-watershed, covering approximately 47.214% of the area and being mainly distributed in the upstream areas of the sub-watershed. Andisol soil contains high organic matter content and low bulk density, resulting in high porosity and water retention capacity [34]. Therefore, the soil erodibility value for this type of soil is the lowest compared to other soil types.

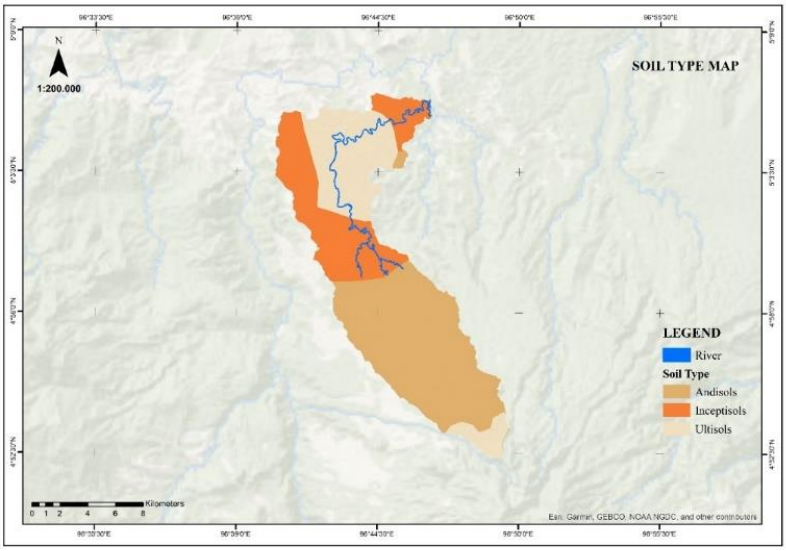

Fig. 3. Map of Soil Type Distributions in the Simpo Subwatershed

Table 4. K Factor Values and Distribution of Each Soil Type in the Simpo Subwatershed

Soil Type	Area Size (km^2)	Catchment Area (km^2)	Percentage LA/LD (%)	Soil K Value
Andisols	84.551	179.080	47.214	0.07
Inceptisols	49.053		27.391	0.23
Ultisols	45.476		25.394	0.16

Meanwhile, the inceptisols found in the central and downstream areas of the sub-watershed are young soils still in the developmental stage [35]. Due to their high clay content, these soils have the lowest permeability and infiltration rates compared to the other two soil types. Consequently, these soils are susceptible to surface runoff (high erodibility) [36]. The percentage of area and erodibility values (K) for each soil type are presented in Table 4. The distribution map for each soil type is shown in Figure 3.

3.3 Slope Factor

Subwatershed Simpo features diverse topography. The slope classification and LS factor values for this subwatershed can be found in Table 5. Slopes within the sub-watershed are predominantly in the range of 15–25%, covering 27.460% of the sub-watershed area. These moderately steep slopes are distributed from the upstream to the downstream of the sub-watershed, as shown on the map in Figure 4. Additionally, steeper slopes (>40%) are also present in the sub-watershed, accounting for 9.290% of the watershed area.

Table 5. LS Factor Values and Distribution of Each Slope Category in the Simpo Subwatershed

Slope Gradient (%)	Area Size (km^2)	Catchment Area (km^2)	Percentage LA/LD (%)	LS
0 – 8	29.003		16.196	0.4
8 – 15	45.777		25.562	1.4
15 – 25	49.175	179.08	27.460	3.1
25 – 40	38.489		21.493	6.8
> 40	16.636		9.290	9.5

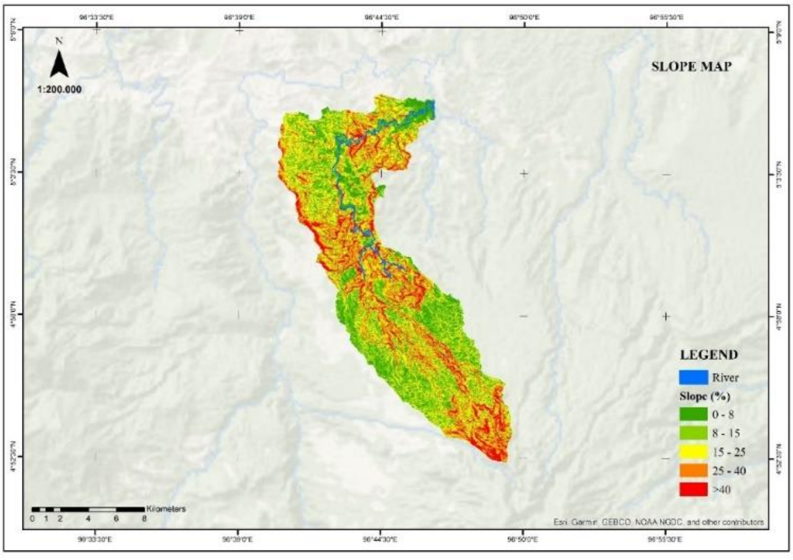

Fig. 4. Slope Gradient Map of the Simpo Subwatershed

3.4 Land Use Factor

The majority of the Simpo Subwatershed is covered by plantations, accounting for 78.136% of the area and extending from upstream to downstream (Table 6 and Figure 5). Other types of land cover found include shrublands, mixed dryland agriculture with shrubs, and settlements. Meanwhile, the percentage of secondary dryland forest cover in the sub-watershed is very small, less than 5%. The table also indicates that the denser the vegetation cover on the land, the smaller the CP value. This is because dense canopy cover in land use is more effective in preventing the impact of raindrops, which can cause splash erosion [37].

Table 6. CP Factor Values and Distribution of Each Land Cover in the Simpo Subwatershed

Land Cover 2020	Area Size (km^2)	Catchment Area (km^2)	Percentage LA/LD (%)	CP
Water Body	0.083		0.046	0
Secondary Dryland Forest	8.697		4.856	0.1
Plantation	139.926		78.136	0.5
Settlement	2.212	179.08	1.235	0.95
Mixed Dryland Agriculture with Shrubs	5.871		3.278	0.013
Shrubs	19.804		11.059	0.3
Undeveloped/Open Land	2.488		1.389	1

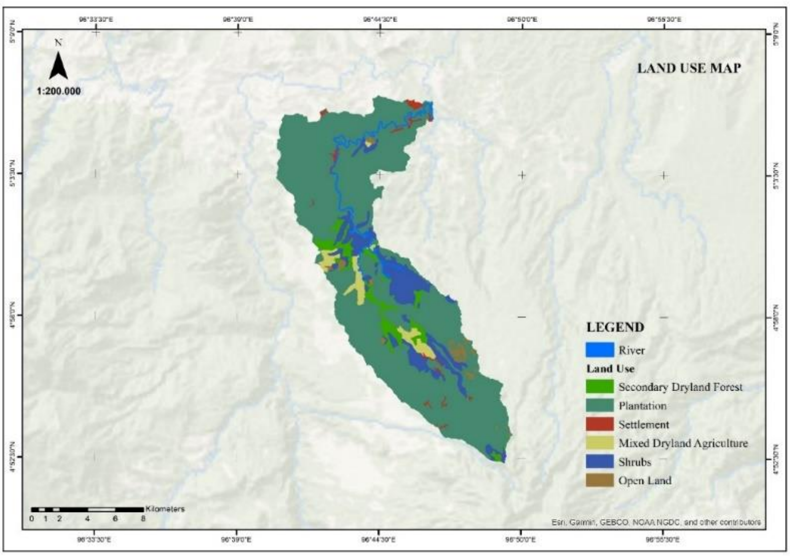

Fig. 5. Land Cover Map of the Simpo Subwatershed

3.5 Soil Erosion Estimation

Once the erosion determinants factors are available as mentioned earlier, the rate of soil erosion (A) can be calculated. In the Simpo sub-watershed, the total rate of soil erosion obtained is 52,592.9 tons/ha/year. Based on the obtained rate of soil erosion, a mapping of erosion hazard levels is conducted for the entire sub-watershed. From the depiction presented in Figure 6 and Table 7, it can be identified that the erosion hazard in Sub-watershed Simpo ranges from very light to very severe. The dominant hazard level in the sub-watershed is severe erosion with a percentage of 38.1%, which is distributed from upstream to downstream. The sub-watershed also indicates severe and moderate erosion hazards at 24.6% and 23.5%, respectively. The erosion hazard in these three categories is mostly indicated on land with moderately steep slopes (15–25%) and is managed as plantations. Oil palm plantations established on sloping terrain need to adopt appropriate soil and water conservation techniques to reduce potential erosion [38]. One of these techniques involves vegetative methods such as planting legume cover crops (LCC). This conservation technique can suppress weed growth, protect the soil from splash erosion caused by rainfall, and reduce runoff, which increases soil erosion rates [39]–[41]. Additionally, mulching and constructing terraces in plantations can also help mitigate sedimentation caused by erosion in plantation areas [42].

Table 7. Percentage of Erosion Hazard Levels in the Simpo Subwatershed

Class	Erosion Hazard Levels	Percentage (%)
I	Very Low	2.0
II	Low	11.8
III	Moderate	23.5
IV	High	38.1
V	Very High	24.6
Total		**100.0**

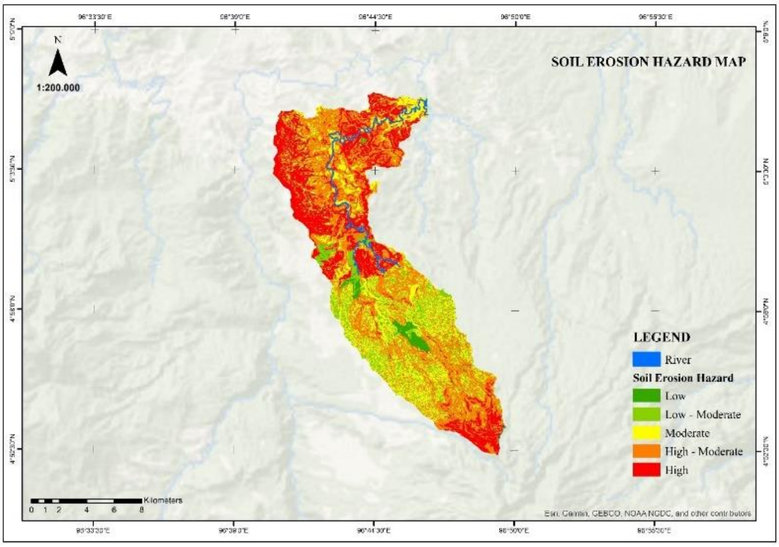

Fig. 6. Map of Erosion Hazard Levels in the Simpo Subwatershed

4 Conclusion

The use of a GIS-based USLE model successfully estimated soil loss and delineated areas affected by erosion in the Simpo Subwatershed. The calculation using this combination resulted in a total soil erosion rate of 52592.9 tons/ha/year. The research findings indicate that 38.1% of the sub-basin area experiences severe erosion, 24.6% very severe erosion, 23.5% moderate erosion, and 13.8% light to very light erosion. High vulnerability to erosion hazards mostly occurs in sloped plantation areas (15%–25%). Therefore, appropriate soil and water conservation techniques are needed to mitigate and minimize the risk of soil erosion. This study can serve as an initial step in contributing to sub-basin management.

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