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ESTIMATION OF TOTAL EROSION IN THE BATANG GADIS WATERSHED, NORTH SUMATERA USING MODIFIED UNIVERSAL SOIL LOSS EQUATION METHOD (MUSLE)

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ABSTRACT

Watershed degradation due to soil erosion is a significant problem affecting soil fertility, water quality, and ecosystem sustainability. In the Batang Gadis watershed, concerns about increasing erosion per rainfall emphasize the need for effective soil and water conservation strategies. This study analyzes sedimentation rates and assess watershed stability to support conservation planning. The MUSLE was applied to estimate erosion per rainfall event. The watershed boundary was delineated using DEM data and satellite imagery. Sedimentation rates were evaluated based on factors including soil erodibility, runoff, slope length and steepness, land use, and conservation practices. GIS tools were used to generate thematic maps and spatially analyze these parameters. The results showed total erosion in the Batang Gadis watershed reaches 1,416,262,595 tons/year, with the Batang Salai sub-watershed contributing the most (1,021,173,987 tons/year), and Batang Angkola the least (2,179,742 tons/year). Despite this, most areas are classified under very light erosion, indicating overall watershed stability.

A. INTRODUCTION

One natural phenomenon that has a significant impact on the condition of watersheds is erosion. Erosion is a process in which soil particles or parts of soil move from one location to another carried by water or wind (Ilham, 2023). The soil particles that undergo this movement will collect in another place and are known as sediments or deposits, while the process of movement is called sedimentation. In the tropics, the main cause of erosion is generally rainfall (Arini, 2019).

The occurrence of erosion is closely related to land use and soil conservation efforts in an area, including in the upper watershed. To prevent erosion, communities often improve land use patterns and implement soil and water conservation practices (Nugraha, 2023). Erosion can be caused by two main factors: natural factors and human activities (Fang, 2021). Natural erosion occurs due to the process of soil

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formation and natural soil removal that maintains soil balance, generally still providing adequate media for plant growth. Meanwhile, erosion due to human activities is usually caused by the stripping of topsoil through agricultural practices that ignore soil conservation principles or through development activities, such as road construction in steep areas (Sari, 2024).

In general, erosion types can be further categorized based on their driving forces, namely overland flow and direct runoff (accumulated water runoff). For erosion caused by direct runoff, such as gully erosion and channel erosion, the main driving force is concentrated, high-volume runoff flowing down steep slopes. This condition makes the soil more vulnerable to erosion. To estimate soil loss caused by such erosion, the MUSLE (Modified Universal Soil Loss Equation) model can be used as a reference (Benavidez, 2018). This model considers various factors such as rainfall intensity, soil characteristics, slope, and land use to provide a more accurate prediction of erosion and sedimentation rates.

Several previous studies have demonstrated the application and reliability of MUSLE in various watershed conditions. Santoso et al. (2014) compared the estimation of erosion rates using MUSLE and RUSLE in the Progo watershed, revealing differences in results and highlighting the importance of selecting methods that match land characteristics. Research in the Babon watershed applied the MUSLE model along with peak discharge analysis for sedimentation prediction, affirming the robustness of MUSLE across diverse watershed conditions. Studies in the Batang Gadis watershed emphasize the role of physical characteristics and natural factors, such as land conversion and slopes greater than 40%, which greatly influence erosion and sedimentation potential. Erosion analysis in the Batang Gadis watershed using MUSLE underlines the importance of predicting erosion hazards to inform land conservation planning.

Additionally, research in the upper Duri Canal applied the MUSLE approach to estimate soil erosion, demonstrating its applicability across various watershed types. A study in the Bale sub-watershed used MUSLE to predict erosion magnitude in areas with steep topography and land use changes. Other studies have shown that integrating MUSLE with GIS can significantly improve the accuracy of erosion and sedimentation estimates in large and complex watersheds. The study conducted in the Beringin watershed, Semarang City, utilized GIS and MUSLE to map erosion hazard threats based on land use and conservation practices.

Building upon these previous findings, this study aims to obtain information on the physical characteristics of the Batang Gadis watershed by analyzing sediment accumulation and erosion rates in Mandailing Natal Regency (Madina), North Sumatra Province. A detailed understanding of the watershed's physical condition, especially related to soil erosion and sediment transport, is expected to support the development of regional planning strategies that are better aligned with the watershed's characteristics. Prioritizing conservation efforts based on erosion vulnerability can help minimize the risk of natural disasters such as landslides, flash floods, and other geological hazards.

B. METHODS

The research location is Batang Gadis watershed which is located at North Sumatra Province that flows from Mandailing Natal district, Padang Sidempuan City, and Padang Sidempuan Regency. Geographically, the Batang Gadis watershed is located at a 99°54’49” – 9°50’08” E dan 0°32’17” – 1°11’26” N. The total area of the watershed studied is 4.872,989 km^2.

Figure 1. Batang Gadis Sub-Watershed Map

(Source: Processed by the author, 2025)

The data used in the erosion study are several variables that are adjusted to the method used, namely:

1. Watershed Boundary Data
2. Rainfall Data
3. DEM Data
4. Landsat 8 OLI image
5. Landuse Data
6. Soil Type Data

Rainfall data is part of hydrometeorology that plays an important role in various purposes such as analyzing rainfall characteristics, flooding, climate, and water resource management planning (Kurniawan, *et al*., 2017). Good data quality is important in hydrological and meteorological analysis (Burhanuddin, *et al*., 2015 in Yogafanny & Legono, 2022). However, daily data in an area is often incomplete, resulting in decreased accuracy of analysis and ineffective water resources planning (Bagiawan, *et al*., 2011 in Yogafanny & Legono, 2022). Therefore, the best method is needed to estimate the missing data, but a method that is suitable in one place is not necessarily suitable in another place due to seasonal and topographical differences (Kashani & Dinpashoh, 2012).

One method that is often used is Inverse Square Distance, because this method considers the distance between stations as a control (Prawaka, *et al*., 2016). The rainfall data used was obtained from three nearby stations, namely FL Tobing Tapanuli Tengah BMKG Station, Aek Godang Padang Lawas Utara Meteorological Station, and Padang Panjang BMKG Station. Daily rainfall data from the three stations are incomplete, many data are empty or unmeasured data (8888), so the data need to be estimated using the Inverse Square Distance method with the formula:

$$P_X = \frac{\frac{P_1}{{L_1}^2} + \frac{P_2}{{L_2}^2} + \frac{P_3}{{L_3}^2} + \cdots + \frac{P_n}{{L_n}^2}}{\frac{1}{{L_1}^2} + \frac{1}{{L_2}^2} + \frac{1}{{L_3}^2} + \cdots + \frac{1}{{L_n}^2}}$$

Description:

Px : rainfall predicted at station X

Pn : rainfall at Station X (mm)

Ln : distance from station X to surrounding stations (km)

Calculation of total erosion using the MUSLE (Modified Universal Soil Loss Equation) method. The MUSLE method is a derivative of the USLE method that has been developed earlier. The MUSLE method is used to predict total sediment in a sub-watershed.

MUSLE formula:

$$SY = Rm \times K \times LS \times CP$$

Description:

SY : total sediment (tons/year)

Rm : surface runoff

K : soil erodibility factor

LS : slope length and slope factor

CP : land use and conservation factor

Surface runoff is the amount of water that flows over the ground (Arsyad, 2010). The water flows from a high place to a low place. Surface runoff calculations use the rational method with data from rainfall data and DEM data. Rainfall data is used to obtain rainfall intensity data, total runoff volume, and time of concentration. DEM data is used to obtain data on watershed area, main river length, height difference, and watershed area.

Rm formula:

$$Rm = 11{,}8(QpVp)^{0{,}56}$$

Description:

Rm : surface runoff / run off

Qp : peak flow (m3/dt)

Vp : total run off volume (m3)

Peak flow (Qp) is the water discharge that flows in a watershed. Peak flow calculation is done by estimating with rainfall data. This calculation uses rainfall data in the form of rainfall intensity during the time of concentration. This calculation also considers the area of the watershed and the Runoff Coefficient which is based on the surface relief of a watershed area.

Qp formula:

$$Qp = 0{,}278\ C.I.A$$

Description:

C : Runoff Coefficient

I : Rain Intensity

A : Watershed Area

Table 1. Run Off Coefficient

State of the region	Run Off Coefficient
Hilly and steep	0,75 – 0,90
Mountainous river	0,75 – 0,85
Tertiary mountains	0,70 – 0,80
Rice field flow time	0,70 – 0,80
River with land and forest	0,50 – 0,75
River plains	0,45 – 0,75
Subgrade that is drained	0,45 – 0,60

(Source: Sosrodarsono, 1998)

Rainfall intensity during the time of concentration. This value is obtained by rainfall from water flowing from the peak to the outlet of a watershed. This calculation requires Tc data from the watershed that will be measured. In addition to Tc, this intensity calculation also calculates daily rainfall.

Intensity formula:

$$I = \frac{R}{25} \times \left(\frac{24}{Tc}\right)^{\frac{2}{3}}$$

Description:

I : rainfall intensity (mm/hour)

R : daily rainfall (mm)

Tc : time of concetration (hour)

Time of concentration (Tc) is the time required for water to flow from the highest point to the lowest point, namely the outlet of the watershed. Tc calculation is done by the method developed by Kirpich by taking into account the length of the main river with a height difference between the highest and lowest point of a watershed.

Tc formula:

$$Tc = \frac{(0{,}869 \times L^3)^{0{,}385}}{H}$$

Description:

Tc : time of concertation (hour)

L : length of the main river (km)

H : height difference between the highest point and the lowest point in the Subwatershed (m)

The total volume of run off is the amount of water that flows in the stream. The calculation of the total volume is to calculate the rainfall in one year, the area of the watershed, and the value of the land use and conservation factor.

Vp formula:

$$Vp = D \times A \times CP$$

Description:

Vp : total run off volume (m)

D : rainfall in one year (mm/year)

A : watershed area (km)

CP : land use and conversion factor value

Table 2. Erodibility Coefficient

Soil Type	K Factor
Podsolik	0,167
Grumusol dan Andosol	0,20
Latosol	0,31
Reddish yellow Latosol and Latosol	0,36
Regosol	0,40
Reddish brown Latosol and Latosol	0,43
Mediterranean and latosol complex	0,46
Aluvial	0,47
Reddish yellow latosol	0,56

(Source: Asdak, 2014)

Soil erodibility is the strength of soil to resist erosion. Erodibility is determined by topography, slope, amount of human disturbance, physical properties of soil and its management (Arsyad, 2012). Soil data is obtained from data reduction using DEM data assisted by data from Soilgrid. DEM data is used to obtain data in the form of relief, landforms, and water flow. While Worldsoil data is soil data, but the type does not match the coefficient to be used. The two data were combined to obtain data in accordance with the soil erodibility coefficient published by the Office of Land Rehabilitation and Soil Conservation, Ministry of Forestry.

Table 3. Length and Slope Coefficient

Slope class	Slope inclination	LS
I	0-8 %	0,4
II	8-15 %	1,4
III	15-25 %	3,1
IV	25-40 %	6,8
V	>40 %	9,5

(Source: Kironoto and Yulistianto, 2000)

Slope length and slope factors were obtained from DEM data extraction. DEM data was extracted to obtain slope classes. The slope class is based on the percentage of slope relative to a flat plane. The slope is measured because it determines the location of erosion and the area of deposition. The slope class is divided into 5 classes with corresponding slopes as shown in the following tab.

Table 4. Coefficient of Landuse and Conservation Factors

Land Use	CP Factor
Building	0
Water	0
Settlements	0
Swamp	0
Forest	0,03
Irrigated Rice Paddy	0,05
Rainfed Rice Field	0,05
Grass	0,07
Garden	0,2
Shrub	0,3
Moor	0,75

(Source: Indonesia Forestry Department, 1986)

Land use and land conservation factors are strongly influenced by the presence of vegetation or buildings. Land use factors will greatly affect erosion because land use becomes a soil protector against erosion. Land conservation also affects the amount of erosion because with appropriate conservation the water that flows is not on the entire surface which can minimize erosion that occurs in a watershed. Land use and conservation data were obtained from KLHK data and Landsat 8 OLI imagery. Both data were extracted to obtain land use data.

C. RESULT AND DISCUSSION

C.1. RESULT

The Batang Gadis watershed has an area of 4.835,29 km2 with an accumulation of streams entering through the river. The Batang Gadis watershed consists of 5 sub-watersheds namely Sirkosik Sub-watershed, Batang Gadis Lower Sub-watershed, Batang Salai Sub-watershed, Batang Angkola Sub-watershed, Batang Gadis Upper Sub-watershed. These sub-watersheds are based on the boundaries defined by the Forestry Department of the Ministry of Environment and Forestry.

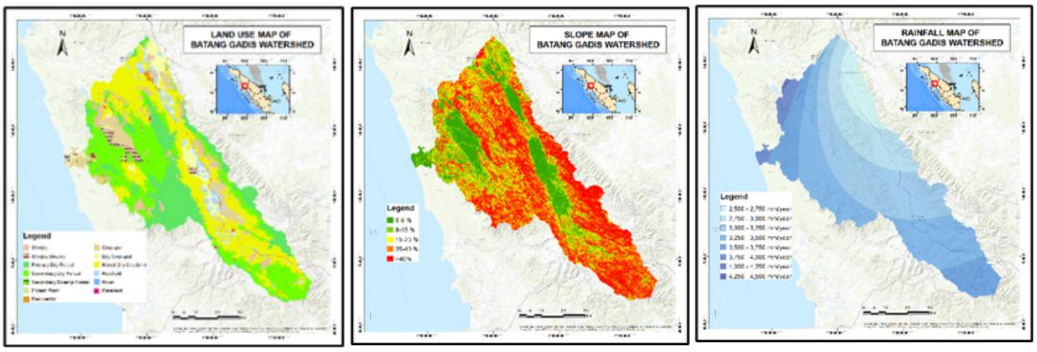

Figure 2. Variable map to determine the amount of erosion of Batang Gadis Watershed

(Source: Processed by the author, 2025)

The results of the total erosion estimation of the five sub-watersheds of Batang Gadis are presented in the form of tables 6 and figure 3 of total erosion estimation. There are 3 maps of the calculation results of parameters that affect the total erosion in each sub-watershed Batang Gadis. These parameters are surface runoff (Rm), soil erodibiliats (K), length and slope (LS), and land use or conservation (CP).

The calculation of surface runoff aims to determine the amount of energy used in sediment transport. Surface runoff is influenced by the peak flow rate (Qp) and total runoff volume (Vp). Peak flow (Qp) is determined by the level of rain intensity and the area of the sub-watershed. The results of the surface runoff calculation resulted in a value of 2.617,246 m3/s in the Sirkosik Subwatershed, 2.961,780 m3/s in the Batang Gadis Lower Subwatershed, 1.652,441 m^3/s in the Batang Salai Subwatershed, 2.044,238 m3/s in the Batang Angkola Subwatershed, 4.590,507 m^3/s in the Batang Gadis Upper Subwatershed.

Soil erodibility (K) is determined based on the type of soil that dominates in the area of each Batang Gadis Subwatershed. Each soil type has a different soil erodibility value, giving the soil erodibility value based on the classification compiled by Asdak (2014). The Batang Gadis Subwatershed area mostly has a soil type of alluvial soil with a soil erodibility value of 0,47 for the entire Batang Gadis Subwatershed area.

The length and slope of the slope (LS) were obtained using data from the slope data processing which shows the level of slope based on the percentage of slope. The length and slope values are based on the classification prepared by Kironoto and Yulistiyanto (2000). Slopes with steep slopes will have a higher erosion rate so that the value of the length and slope of the slope will be higher. The Batang Gadis watershed area has a different classification of slope classes, Batang Angkola sub-watershed has a slope value classified in class I with a value of 0,3, Batang Gadis Lower and Batang Salai sub-watershed has a slope classified in class II with a value of 1,4, and Sirkosik and Batang Gadis Upper sub-watershed has a slope classified in class III with a value of 3,1.

Land use and conversion (CP) were analyzed using visual interpretation of land use data. Different land use or land use will have different levels of erosion influence. Land use and land conversion were classified based on guidelines developed by the Forestry Department (1986). The land use of the Batang Sirkosik, Angkola, and Batang Gadis Hulu sub-watersheds is dominated by forest land use with a value of 0,03, the land use of the Batang Gadis Hilir sub-watershed is dominated by garden land use with a value of 0,2, and the land use of the Batang Gadis Salai sub-watershed is dominated by land use in the form of dry cropland with a value of 0,75.

Estimated total erosion is calculated using the calculation of the amount of sediment (SY) to determine the total sediment accumulated each year for 10 years. The calculation of the amount of sediment (SY) is carried out in each Batang Gadis Sub-watershed using the MUSLE (Modified Soil Loss Equation) approach method based on 4 factors that have been mentioned by obtaining predictive values through spatial analysis. The more the use of forming factors, the watershed modeling will be closer to the actual conditions. Geospatial modeling forms information into certain classes that will facilitate the data analysis process.

The final result is an estimate of total erosion expressed by the value of SY (Sediment Yield), which is a value that indicates the amount of eroded mass accumulated per year. The summation of the factors that form SY is done directly with the assumption that all factors directly affect the soil particles that are eroded. Based on the SY equation, the Batang Gadis watershed has an estimated total erosion of 1.329.354,84 tons/year. Batang Gadis watershed is dominated by alluvium soil type. The length and slope factor (LS) value in this watershed averages 9,3 with the dominance of forest land use in the Sirkosik, Batang Angkola, and Batang Gadis Hulu sub-watersheds, gardens in the Batang Gadis Hilir sub-watershed, and moorland in the Batang Salai sub-watershed. The total area in each sub-watershed may not represent the total amount of erosion according to its size. It can also be influenced by other factors, such as erodibility, length and slope factors, and land use and conservation factors. The results of the SY calculation in each Batang Gadis Subwatershed are presented in the following table.

Table 5. Calculation of total annual erosion with MUSLE of Batang Gadis watershed

Sub DAS	Rm	K	LS	CP	SY (ton/year)	Wide (km^2)
Sirkosik	562315.6	0.47	3.1	0.03	24578.81	837.008
Batang Gadis Hilir	1778788.9	0.47	1.4	0.2	234088.61	894.057
Batang Salai	2069248.2	0.47	1.4	0.75	1021173.99	543.318
Batang Angkola	515305.5	0.47	0.3	0.03	2179.74	1023.72
Batang Gadis Hulu	1082902.8	0.47	3,1	0.03	47333.68	1574.89
Total					1329354,846	4872,993

(Source: Processed by the author, 2025)

Based on table 5 there are 5 sub-watersheds of Batang Gadis with their respective total amount of erosion. The total erosion in the Batang Gadis watershed is 1.329.354,86 tons/year. The sub-watershed with the highest total estimated erosion is the Batang Salai sub-watershed with a total estimated erosion of 1.021.173,99 tons/year. Meanwhile, the sub-watershed with the smallest total erosion estimate is the Batang Angkola Sub-watershed with a total erosion estimate of 2.179,74 tons/year. From the calculation of the total estimated erosion, the determination of erosion rate can be done. The determination of the erosion rate can be calculated through the division between the total estimated erosion of each sub-watershed with the area of each sub-watershed. Classification of erosion rates can be seen in table 6 and figure 5.

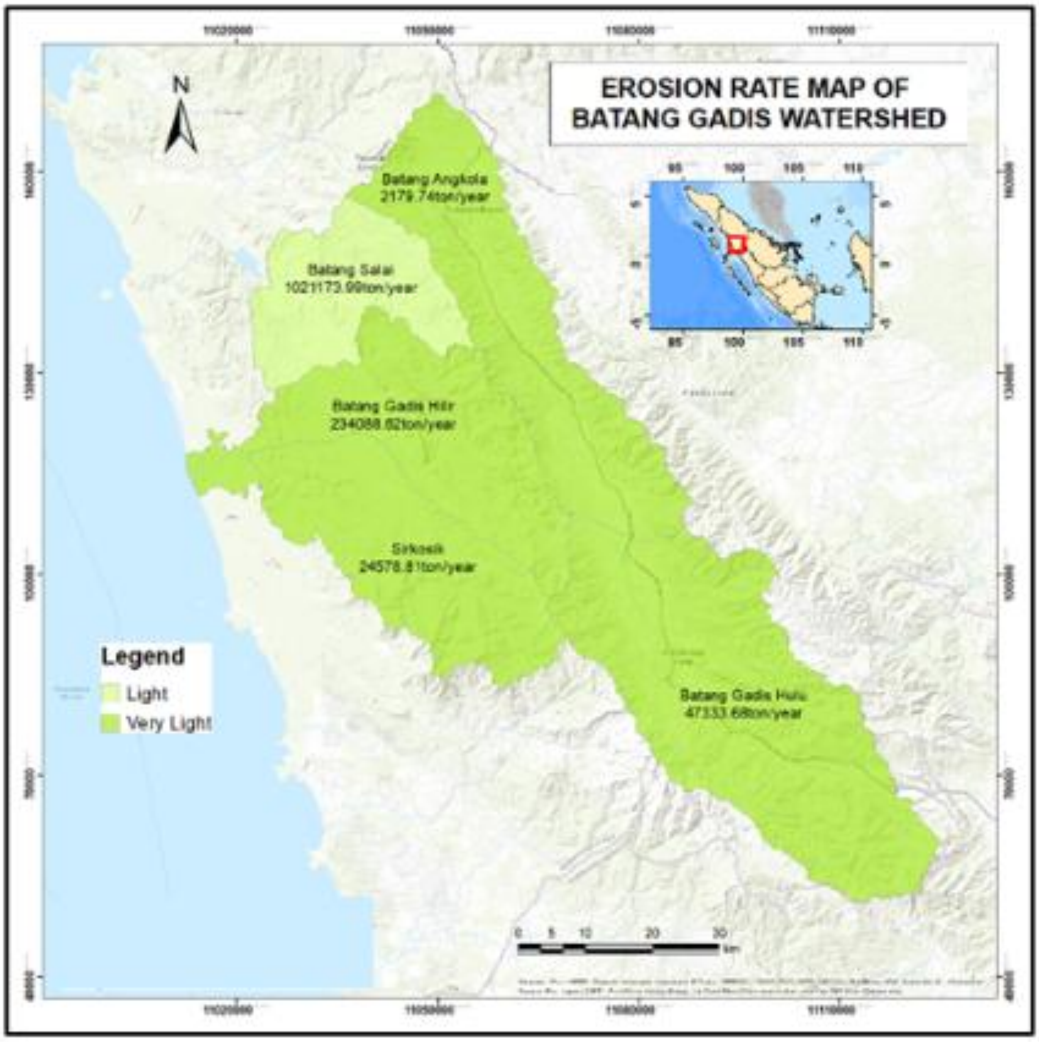

Figure 3. Erosion Rate Map of Batang Gadis Watershed

(Source: Processed by the author, 2025)

Table 6. Classification of Erossion Rate

No	Erosion Class	Erosion Value (ton/ha/year)
1.	Very light	<15
2.	Light	≥15 – 60
3.	Moderate	≥60 – 180
4.	Heavy	≥180 – 480
5.	Very heavy	>480

(Source: Ministry of Forestry, 2013)

Calculation of the total erosion of each Batang Gadis sub-watershed with its respective area resulted in two levels of erosion classes, namely light and very light. The light class is owned by the Batang Salai sub-watershed. Meanwhile, the other four sub-watersheds fall into the very light erosion level.

The Sikorsik, Batang Gadis Hilir, Batang Angkola, and Batang Gadis Hulu sub-watersheds have total erosion rates of 0,29; 2,62; 0,02; and 0,30, respectively. All these values have a value of <15 tons/ha/year so that the erosion rate is categorized into the very light class. The very light erosion rate in these four sub-watersheds is caused by the ratio between the total estimated erosion and the sub-watershed area which is very small because the sub-watershed area is quite large when compared to the Batang Salai Sub-watershed.

The Batang Salai sub-watershed has a total erosion of 1.021.173,987 tons/year with an area of 543,318 km2, so the erosion value is 18,80 tons/ha/year. This value is in the range of 15-60 tons/ha/year so it is categorized as a light class. The erosion rate in the Batang Salai sub-watershed is one level higher than the other four Batang Gadis sub-watersheds. This is strongly influenced by total erosion and the area of each sub-watershed.

The total erosion of the Batang Salai sub-watershed is the highest among the others, exceeding 1 million tons/year. Meanwhile, when compared to the area of the other sub-watersheds, Batang Salai has the smallest area. This results in the erosion rate in Batang Salai being the highest among the others. In addition, the magnitude of total erosion in Batang Salai is strongly influenced by the magnitude of one of the coefficients in the parameters used, namely the land use and conservation factor in Batang Salai, namely the dry cropland land use which has the highest CP factor value among other land use types, namely 0,75.

Dry cropland is one type of land use that is most prone to erosion. This is because it is a type of land use where the land is quite dry with short-lived crops. Dry cropland is a type of land use that is intensively managed every season. This causes the soil on the moor to be more easily exposed by rainwater energy so that erosion occurs (Muchlis et al., 2012).

This land use factor is the main factor that increases the total erosion estimate Batang Gadis Watershed, as tough the calculation of the highest total erosion estimate in the Batang Salai sub-watershed is strongly influenced by the land use factor. Factors such as surface runoff, slope, and soil erodibility must also be considered. This is because each region has its own characteristics that can affect the total erosion estimate.

C.1. DISCUSSION

The study aimed to estimate total erosion in the Batang Gadis watershed using the Modified Universal Soil Loss Equation (MUSLE) method, revealing a total erosion rate of 1,416,262,595 tons/year. This significant figure highlights the importance of monitoring sedimentation rates for effective soil and water conservation strategies in the region. The results indicate that the Batang Salai sub-watershed experiences the highest erosion at 1,021,173,987 tons/year, categorized as mild erosion, while the Batang Angkola sub-watershed shows a much lower erosion rate of 2,179,742 tons/year, classified as very mild.

The findings align with previous studies conducted in similar geographical contexts. For instance, research by Erwanto and Lestari (2020) in the Badeng watershed revealed varying erosion rates based on land use classifications, with total erosion reaching 13,037.07 tons/ha/year. This comparison underscores the variability of erosion rates influenced by land use and management practices. The use of Geographic Information System (GIS) tools in both studies facilitated detailed spatial analysis and thematic mapping, which are crucial for understanding the dynamics of erosion processes.

Moreover, the majority of areas within the Batang Gadis watershed fall into the very light erosion category, suggesting that the watershed remains in a stable condition. This finding is consistent with observations made by Antoko and Sukmana (2007), who noted that effective land management practices contribute to minimizing soil loss in similar watersheds. The data on hydrology and soil types further support this conclusion; for example, the presence of latosol and podsolik merah kuning soils can influence erodibility factors (K) used in MUSLE calculations.

It is essential to emphasize that ongoing monitoring and implementation of conservation practices are vital for maintaining soil health and preventing future degradation. As highlighted by U.S. Army Corps of Engineers (2025), understanding sediment transport dynamics is crucial for developing effective watershed management strategies. Future research should focus on long-term monitoring of erosion rates and the effectiveness of implemented conservation measures to ensure sustainable management of the Batang Gadis watershed.

D. CONCLUSION

The estimation of erosion rates using the MUSLE method shows that the Batang Gadis watershed experiences a total sediment yield of approximately 1.4 billion tons per year. The erosion is predominantly classified in the very light to light categories across most areas. Most sub-watersheds exhibit minimal soil loss, suggesting that the overall watershed condition remains relatively stable from an erosion perspective. Although some areas, such as the Batang Salai sub-watershed, experience higher erosion levels within the light category, the sediment yield is still within a manageable range. Meanwhile, sub-watersheds like Batang Angkola show very light erosion, reinforcing the conclusion that the watershed as a whole is in good condition and does not yet face a critical threat of land degradation due to erosion.

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