

Original Article

Comparison of Sedimentation Rate Analysis of Lake Tondano using Empirical Methods and Direct Measurements

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Abstract - Sedimentation in the Lake Tondano watershed was assessed by comparing estimates from the Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), and Modified Universal Soil Loss Equation (MUSLE) with direct field observations from ten major inlet rivers. The analysis combined rainfall, soil, slope, and land-use data with laboratory measurements of sediment concentration. The calculated Erosivity (R) values were 1,703.14 MJ.cm/ha.jm/yr for USLE, 1,566.54 MJ.cm/ha.jm/yr for RUSLE, and 1,648.00 for MUSLE. The watershed had an average soil Erodibility (K) of 0.20, an LS factor of 0.496, a land-cover factor (C) of 0.241, and a conservation-practice factor (P) of 1. Using these parameters, the estimated annual sediment volumes were 46,081.70 m³/year with USLE, 73,588.18 m³/year with RUSLE, and 44,589.68 m³/year with MUSLE. Measurements from the inlet rivers showed sediment concentrations between 1.33 and 14.58 gr/m³, while peak discharge reached 662.31 m³/s. Among the three empirical approaches, the MUSLE estimate was closest to the direct measurements. Its closer agreement with the field data is consistent with the model's use of runoff-related variables, which are particularly relevant under the high-rainfall and strong-runoff conditions of the Lake Tondano watershed. These findings provide a basis for improving sediment-control and watershed-management efforts in Lake Tondano, where changes in land cover have contributed to increased erosion and sediment accumulation.

Keywords - Erosion, Sedimentation, Usle, Rusle, Musle, Lake Tondano.

1. Introduction

Land-use change constitutes a widespread environmental pressure because it alters ecosystem stability, hydrological behavior, and watershed morphology [1, 2]. When forest ecosystems are converted into farmland or residential areas, land cover decreases, resulting in less water infiltrating the soil and more water running off the surface. This causes the soil to erode more quickly and leads to more sediment entering waterways, especially in tropical regions with high rainfall [3, 4]. Research conducted in diverse tropical regions indicates that alterations in land use can elevate surface runoff by as much as 70% and sediment yield by up to 200% at the sub-watershed level [5], while also markedly enhancing sedimentation in lakes and reservoirs [6].

Lake Tondano, one of the largest natural lakes in North Sulawesi Province, plays a vital role in supplying raw water, irrigating agricultural land, supporting fisheries, and generating hydroelectric power. However, sedimentation within the lake threatens the sustainability of its utilization. Over the past 70 years, the lake's maximum depth has reportedly decreased from 36 m to 14 m [7]. Sediment influx

into the lake is influenced by the natural characteristics of the catchment area and surrounding land-use patterns. Forest clearing for agriculture or settlements can accelerate erosion, causing increased soil runoff into the lake [8, 9]. The conversion of natural vegetation cover into cultivated land or built-up areas strips the soil surface of some of its natural protection. Consequently, the soil becomes more susceptible to erosion, particularly on steep slopes during heavy rainfall [10, 11].

Research on erosion and sedimentation in the Lake Tondano catchment area generally employs empirical models. Hendratta et al. (2024) applied the Universal Soil Loss Equation (USLE) and the Sediment Delivery Ratio (SDR), finding that increased land-use change was associated with a rise in erosion of up to 61.56% [7]. Moningkey et al. (2021) also reported that the highest erosion rates occurred in the East Tondano Sub-watershed, particularly on sloping agricultural lands subject to high rainfall. While these studies provide information on the magnitude of potential erosion and sedimentation, the modeling results have not yet been directly compared with field measurements; thus, their alignment with actual conditions requires further evaluation.



Previous studies have focused predominantly on the USLE, whereas the application of RUSLE and MUSLE within the Lake Tondano catchment area remains limited. Each of the three models possesses distinct computational characteristics. RUSLE refines the determination of erosion factors to account for a wider range of slope and land-use conditions. MUSLE utilizes runoff volume and peak discharge to estimate sediment yield resulting from specific flow events [12, 13]. These differences provide a basis for comparing the outputs of all three models within the same study area.

In tropical regions, high-intensity rainfall can rapidly increase runoff and sediment transport. This presents a limitation for USLE and RUSLE, as both models are designed to estimate long-term average soil loss. Consequently, their calculated results may not accurately reflect the volume of sediment transported during a specific rainfall event. The use of empirical models should be complemented by field measurements to allow for an assessment of the results against the actual conditions of the catchment area under study.

This study aims to compare estimates derived from USLE, RUSLE, and MUSLE with direct measurements taken from rivers flowing into Lake Tondano. This comparison is conducted to identify which model yields results that most closely align with field data. MUSLE is a focus of this evaluation because it incorporates runoff volume and peak discharge as input parameters. The study hypothesizes that MUSLE estimates align more closely with field observations than those of USLE and RUSLE.

All three models were applied using the same watershed parameters, adjusted to meet the specific input requirements of each model. The calculated results were then compared against sediment data from ten major rivers flowing into Lake Tondano. This evaluation aims to provide a basis for selecting a sediment estimation approach suited to the study area's conditions and to support sedimentation control planning and watershed conservation efforts, thereby ensuring the sustainability of Lake Tondano's functions.

2. Materials and Methods

2.1. Research Location

The Tondano Lake Catchment Area, Minahasa Regency, North Sulawesi Province, Indonesia, with coordinates 1.22691°N 124.8955°E, was the site of this research. It is about 18,662 hectares in size and has a wide range of terrain, from flat to steep. Lake Tondano gets water from ten big rivers that flow into it: Salu Koya, Toubek, Tolour Oki, Touliang Oki, Panasen, Onipus, Mawalelong, Tougela, Tonsaru, and Saluwangko. Because the watershed has a lot of different types of land use and soil conditions, it is very likely to erode and collect sediment. This watershed has a tropical climate with high annual rainfall, making it highly susceptible to erosion and sediment transport.

2.2. Research Data

This study combines two types of data: primary and secondary. Primary data was obtained by collecting river water samples from throughout the estuary to determine the amount of suspended sediment present. The samples were taken to a laboratory to obtain an accurate estimate of the sediment content. Secondary data was obtained from several relevant institutions.

The rainfall data used in this study consist of daily records over a 16-year period (e.g., 2008–2024) obtained from the Sulawesi 1 River Basin Office. Watershed land-cover characteristics were represented using the latest available 2023 map. Topographic information was derived separately from a 30-m-resolution Digital Elevation Model (DEM) accessed through the Tanah Air Indonesia portal.

River discharge data were collected from a single station, namely the Taler–Papakelan River, and were used for hydrological analysis and model calibration.

Primary data were obtained through field sampling conducted on ten major tributaries. Water samples were collected using the grab sampling method during peak flow conditions and analyzed in the laboratory to determine suspended sediment concentrations.

2.3. USLE Method

USLE provides an empirical framework for quantifying soil loss caused by water-driven erosion and has been applied extensively to agricultural landscapes. USLE was developed based on an analysis of data from thousands of experimental plots in the United States.

Today, this method has become the standard for soil conservation management worldwide [14]. USLE framework estimates the long-term mean quantity of soil removed annually from a unit land area, as expressed in Equation 1:

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

Where:

- A: average annual soil loss,
- R: rainfall erosivity factor,
- K: soil erodibility factor,
- L: slope length factor,
- S: slope steepness factor,
- C: land cover and management factor,
- P: conservation support practices factor

USLE is very simple and easy to use, but it does not go into much detail about things like ditch erosion, landslides, or seasonal changes. This model was changed to RUSLE to make it more accurate, account for more factors, and work in different types of land and weather [15].

2.4. RUSLE Method

The Revised Universal Soil Loss Equation (RUSLE) builds upon the original USLE framework to estimate long-term water-induced soil loss under a broader range of climatic, topographic, and land-management conditions. Its compatibility with Geographic Information Systems (GIS) and remotely sensed data enables spatial evaluation of erosion susceptibility across a watershed [16]. In RUSLE, soil loss (A) is obtained from the combined effects of the model factors presented in Equation 2:

$$A = R \times K \times L \times S \times C \times P \quad (2)$$

Where:

- A: average annual soil loss,
- R: rainfall erosivity factor,
- K: soil erodibility factor,
- L: slope length factor,
- S: slope steepness factor,
- C: land cover and management factor,
- P: conservation support practices factor

The method for calculating the R factor is based on the formula discovered by Ram et al. 2004, as reported by Imawan et al. 2024, which can be seen in Equation 3.

$$R = 81.5 + 0.38 P \quad (3)$$

Where P is the annual rainfall for regions where annual rainfall ranges from 340 to 3500 mm.

Both the USLE and RUSLE methods use the same basic equation structure to calculate erosion rates, but they differ in terms of the accuracy of their components and parameters. USLE is a classic empirical model developed in 1965 and based on long-term observations of agricultural land in North America. The USLE framework provides the basis for erosion estimation, although its performance may be limited in regions where climatic conditions and land use vary substantially, including tropical environments [17, 18]. RUSLE was developed to improve the representation of spatial and temporal variations in the erosion factors used by USLE. One of the principal differences between the two approaches lies in the treatment of rainfall erosivity (R). In the USLE application used in this study, the R factor is estimated from annual precipitation, while RUSLE represents rainfall erosivity using storm-energy characteristics together with the maximum 30-minute rainfall intensity (EI30). [19, 20].

Erosion parameters were determined by integrating data from various sources tailored to the conditions of the Lake Tondano watershed. Annual rainfall data were used to calculate the erosivity factor (R) using the Bols (1978) method. The erodibility factor (K) was determined based on soil characteristics and values available in the literature.

Meanwhile, the slope Length and Steepness Factor (LS) were calculated from Digital Elevation Model (DEM) data processed using ArcMap. Information on land cover and conservation practices in the study area served as the basis for establishing the C and P factors.

2.5. MUSLE Method

The Modified Universal Soil Loss Equation (MUSLE) was developed from the USLE by shifting the basis of calculation from long-term average erosion to an estimate of sediment yield for individual runoff events. To support this event-based estimation, MUSLE incorporates a runoff factor, which is intended to improve the accuracy of erosion prediction [21]. The formula for calculating using the MUSLE method can be seen in Equation 4.

$$A = 11.8(Q \times qp)^{0.56} \times K \times LS \times C \times P \quad (4)$$

Where:

- A: erosion rate (tons/ha/year)
- Q: event runoff volume
- qp: event peak runoff rate
- K: soil erodibility factor
- LS: combined slope-length and steepness factor
- C: land-cover and management factor
- P: support-practice factor

Unlike USLE-based formulations that rely on rainfall erosivity, MUSLE represents storm forcing through runoff volume and peak discharge. This allows the model to predict sediment yield, channel erosion, gully erosion, floodplain scouring, and deposition, which USLE and RUSLE cannot proceed. MUSLE calculates sediment yield directly, without needing a sediment delivery ratio, which is different from USLE/RUSLE. MUSLE is better than USLE/RUSLE because it can predict the amount of sediment that will come from one storm [22, 23]. Runoff volume (Q) and peak discharge (qp) were analyzed using hydrological modeling with HEC-HMS based on rainfall-runoff simulations. The model was calibrated using available discharge data to improve accuracy.

2.6. K Factor (Soil Erodibility)

Previous studies indicate that variations in soil erodibility (K) are closely associated with soil-textural characteristics and the amount of organic matter present. Higher K values are generally associated with soils dominated by sand and silt, where clay and organic-matter fractions are comparatively limited. Clay and organic matter strengthen soil aggregates, thereby lowering the K value. Conversely, high proportions of sand and silt make the soil more susceptible to disintegration and being washed away by rainwater. [24]. Soil aggregates are less stable when there is not enough organic matter in the soil. This makes the surface of the soil more likely to break up when it rains heavily, which is common in wet tropical climates [25]. Figure 1 shows the soil type map for the Tondano watershed.

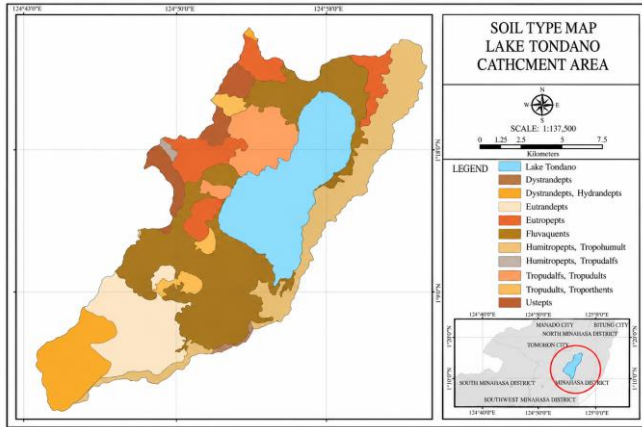


Fig. 1 Soil type map of the lake Tondano catchment area

2.7. LS Factor (Slope Length Gradient)

The influence of topography on erosion in the Lake Tondano catchment area is accounted for using the LS factor, which combines slope length and steepness. The calculated LS value is 0.496. The study area is characterized predominantly by gentle to moderate slopes; however, certain sub-watersheds feature steep slopes that serve as sediment sources. On these slopes, increased surface runoff velocity can accelerate the transport of eroded soil.

The LS calculation in this study utilizes Digital Elevation Model (DEM) data. Processing this data yields spatial slope characteristics that help identify erosion-prone areas, particularly upstream zones and steep slopes connected to drainage paths leading to Lake Tondano. The slope distribution map used for the LS calculation is presented in Figure 2.

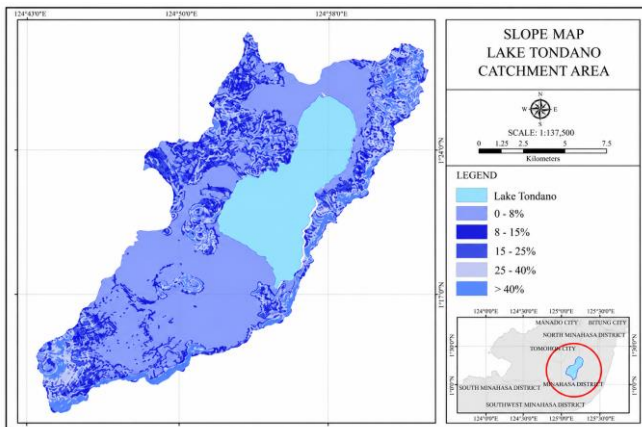


Fig. 2 Slope map lake of Tondano cathement area

2.8. Factor C (Cover and Land Management)

The influence of land cover on erosion within the Lake Tondano watershed is represented by the C factor, which was calculated as 0.241. This value reflects the mixture of land-cover types across the watershed, including agricultural areas, settlements, and natural vegetation. Agricultural land under

continuous cultivation generally contributes higher C values because the soil can remain exposed after harvest and become more vulnerable to erosion. By contrast, forested and densely vegetated areas tend to have lower C values, as canopy and ground cover reduce the direct impact of rainfall and support greater infiltration. The C value obtained for Lake Tondano is consistent with the substantial presence of agricultural land where vegetation cover is not always sufficient to protect the soil surface. In this context, land-cover conditions contribute to soil loss, particularly in areas used for dryland farming. The spatial distribution of land cover used in the analysis is presented in Figure 3.

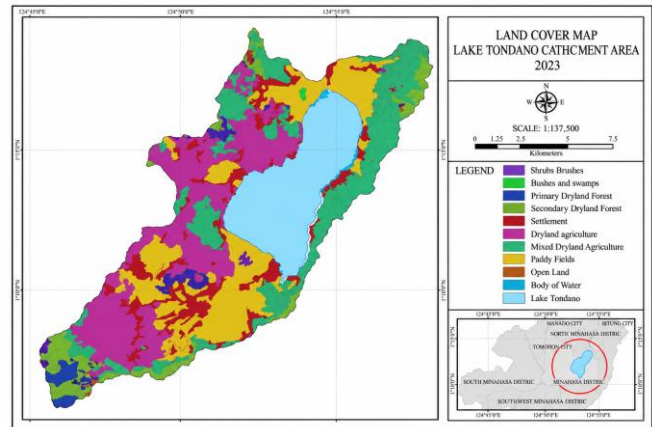


Fig. 3 Land cover in the lake Tondano catchment area

2.9. Factor P (Conservation Measures)

Erosion in the Tondano watershed is represented by the P-factor. This study employs a value of $P = 1$, meaning no erosion reduction resulting from conservation measures is factored into the model. This value reflects the assumption that the implementation of conservation practices in the upstream areas remains limited or has not yet yielded a measurable impact on reducing erosion.

In traditional agricultural areas, such limitations may include the lack of widespread adoption of terracing, row cropping, contour farming, and minimum tillage. Without adequate control, runoff flows more easily down slopes, carrying soil material with it. The potential for erosion increases significantly when steep slopes are subjected to high-intensity rainfall. Therefore, setting $P = 1$ is a modeling assumption and does not imply that conservation measures are entirely absent across the Tondano watershed.

2.10. Sedimentation Estimation using Sediment Delivery Ratio (SDR)

The Sediment Delivery Ratio (SDR) is a way to estimate how fast sediment will settle in watersheds and drainage basins. Watersheds that have sediment deposits at the ends of rivers or lakes. Conceptually, SDR expresses the proportion of gross soil erosion that reaches the watershed outlet or another designated receiving point. The factors that affect SDR are

mostly the same as those that cause erosion [26]. In general, the ratio is less than one because of deposition on the ground and in the flow system [27]. In some cases, it can be more than one because estimates of surface erosion do not always take into account channel erosion and/or sediment resuspension in the flow system. SDR estimation commonly considers the catchment area together with watershed characteristics such as soil properties, land-cover conditions, and terrain configuration. As the size of the watershed and the drainage system grow, the SDR will clearly get closer to one. A graph that shows the relationship between area and SDR value is often used to figure out how big the SDR value is in terms of estimating erosion or sediment yield [28].

2.11. Field Sediment Measurement

Model validation was performed by measuring sediment directly in the field. Measurements were taken by collecting water samples from ten major sediment-laden river mouths and testing them in the laboratory to determine actual sediment concentrations. The actual sediment levels were determined by summing the sediment concentrations and peak discharges of each river. These levels were then used to compare the results of the USLE, RUSLE, and MUSLE calculations. Samples were collected from ten locations. Sampling was conducted during periods of high-water flow to detect peaks in sediment transport. Water samples were collected in clean containers and transported to the laboratory for analysis. Suspended Sediment Concentration (SSC) was determined using the standard gravimetric method by filtering and drying the samples.

2.12. Data Analysis and Model Evaluation

Field measurement results serve as a reference for comparing sedimentation estimates derived from the USLE, RUSLE, and MUSLE models. Discrepancies between estimated and observed values are quantified in terms of absolute differences and percentage errors. The model yielding the lowest error is considered to align most closely with actual field conditions. This comparison enables a

quantitative evaluation of the three models' reliability within tropical watersheds.

3. Results and Discussion

3.1. Changes in Land Surface Cover within the Tondano Lake Drainage Basin

The study area comprises ten land cover types, including primary and secondary dryland forests, shrublands, scrub and swamp areas, settlements, dryland agriculture, mixed dryland agriculture, paddy fields, open land, and water bodies. Mapping conducted in 2023 was used to determine the distribution and extent of each land cover type within the Lake Tondano catchment area. Land use for agricultural activities is evidenced by the presence of paddy fields as well as dryland and mixed dryland agriculture. The area and proportion of each category serving as the basis for analysis are presented in Table 1.

Table 1. Distribution of land-cover classes in 2023

Land-Cover Category	Area in 2023	%
	ha	
Primary Forest on Dry Land	249.442	1.34%
Secondary Forest on Dry Land	1210.477	6.49%
Shrubland	434.961	2.33%
Residential Areas	2003.378	10.73%
Unvegetated Land	59.421	0.32%
Water Bodies	120.605	0.65%
Dryland Cropland	5889.953	31.56%
Mixed Dryland Cropland	4196.872	22.49%
Rice Fields	4471.427	23.96%
Shrub and Swamp Areas	25.619	0.14%

3.2. USLE Rainfall Erosivity

In the USLE calculation, annual rainfall data from the study site are used to determine the erosivity factor via the Bols (1978) equation. This factor represents the capacity of rainfall to detach soil particles, a capacity that increases with rising rainfall energy. The steps for calculating the erosivity value are summarized in Table 2.

Table 2. Rainfall data and erosivity estimates for 2023

Year	Month	Rainfall	Rainy Days	Max. Rainfall	Rm	R
		[cm]		[cm]		
2023	Jan	12,0608	12	3,74	58,38	1.703,14
	Feb	15,9645	14	7,69	124,24	
	Mar	31,7048	20	9,65	202,83	
	Apr	37,8501	12	11,87	385,50	
	May	40,7487	16	9,88	347,35	
	Jun	25,8184	13	10,63	243,29	
	Jul	12,7466	9	6,68	77,89	
	Aug	5,01566	3	2,00	22,73	
	Sep	9,27492	6	3,11	47,27	
	Oct	7,44442	7	3,06	33,20	
	Nov	15,0895	14	5,56	93,32	
	Dec	12,4941	13	8,72	67,15	

The erosivity estimates at the study site reflect the impact of high-intensity rainfall characteristic of wet tropical regions. The greater the rainfall energy, the more easily soil particles are detached from the surface; these materials can then be transported by runoff to lower sections of the slope.

3.3. Rain Erosivity *RUSLE*

Rainfall erosivity in the *RUSLE* method is calculated using the Lenvain equation (Equation 3), with annual rainfall as the input. Data from 2023 yielded an *R*-value of 1,566.54 MJ·cm/ha·h/yr, slightly lower than the *USLE* calculation result. This discrepancy is attributed to the specific response of each formulation to rainfall characteristics. In this study, this response is considered a potential advantage of *RUSLE* in accounting for varying rainfall conditions.

3.4. Rain Erosivity *MUSLE*

Peak discharge estimation was conducted by delineating catchment boundaries and performing hydrological assessments of the main rivers flowing into Lake Tondano. The delineation results were used to calculate the drainage area for each river. An analysis of ten years of rainfall data was then used to derive the Time of Concentration (*T_c*) value, which was input into *HEC-HMS* to estimate the peak discharge for a 100-year return period (*qp*). Subsequent *MUSLE* calculations utilized this *qp* value, a catchment area of 18,662 hectares, and the rainfall volume derived by multiplying rainfall depth by the area. These calculations yielded a value of 1,648.00, designated as the erosivity factor (*R*). By incorporating runoff volume and peak discharge components, *MUSLE* is able to characterize high-flow responses.

3.5. Soil Erodibility

Soil classification using the *USDA* (1975) and Soil Survey Staff (1999 and 2003) soil classification systems is a

grouping of soil types based on soil type groups. This soil classification is based on the relationship between parent material properties, geographical relationships, and distribution within a map unit according to a specific pattern.

The determination of the soil erodibility factor (*K*) was based on soil type data from *BPDASHL* Tondano. Each soil type was assigned a *K*-value by referencing various sources. These values were then weighted according to the areal proportion of each soil type to derive a value representative of the watershed. Calculation results indicate that *K*-values in the Lake Tondano watershed range from 0.16 to 0.28, with a weighted average of 0.20.

3.6. Slope Gradient Factor

The *LS* value for the Lake Tondano catchment area was determined by weighting slope gradient conditions based on the area each represents. The analysis yielded an *LS* value of 0.496. Slopes exceeding 40% indicate the presence of steep terrain, a factor that must be considered in erosion analysis; under such conditions, surface runoff flows more rapidly, thereby increasing the potential for soil erosion. The distribution and proportions of the *LS* classes used in the calculation are presented in Figure 2.

3.7. Crop Management and Soil Conservation Factors

The *C* and *P* factors in the *USLE* method are used to assess the impact of land management and conservation practices on estimated soil loss. Both values are determined based on land cover conditions at the study site.

Specifically for the *P* factor, calculations assume the absence of erosion-reducing conservation measures in the study area. Details regarding the *C* and *P* values are presented in Table 3 below.

Table 3. Land-Cover contributions to the catchment *C* factor

No.	Land-Cover Category	Area (ha)	Area Share	C	C × Area
1	Primary Forest on Dry Land	249.44171	1%	0.001	0.25
2	Secondary Forest on Dry Land	1,210.47650	6%	0.005	6.05
3	Shrubland	434.96073	2%	0.30	130.49
4	Residential Areas	2,003.37761	11%	1.00	2,003.38
5	Unvegetated Land	59.42052	0.3%	1.00	59.42
6	Water Bodies	120.60	0.6%	0.01	1.21
7	Shrub and Swamp Areas	25.61861	0%	0.04	0.96
8	Dryland Cropland	5,889.95260	32%	0.19	1,119.09
9	Mixed Dryland Cropland	4,196.87207	22%	0.28	1,175.12
10	Rice Fields	4,471.42687	24%	0.01	44.71
Overall Total		18,662.15	100%		4,495.97
Weighted C				0.241	

3.8. Sediment Yield and Volume Estimates

The Sediment Delivery Ratio (SDR) represents the ratio between the amount of sediment reaching the outlet point and the total material eroded within the catchment area. This ratio allows for an indirect estimate of the sediment supply to rivers or lakes. Its value depends on the location of sediment sources, transport path length, material characteristics, flow connectivity, and the physical conditions of the terrain traversed.

The SDR value is typically less than 1 because a portion of the eroded material is retained and deposited on the land surface or along drainage channels before reaching the catchment outlet. In some cases, however, SDR may exceed 1 when estimates of surface erosion do not fully account for channel erosion and/or sediment redeposition within the drainage system. Empirical SDR estimation considers drainage area together with catchment characteristics such as soil properties, land cover, and terrain. Under the area-based relationship applied in this analysis, SDR tends to approach 1 for a medium-sized river basin and decreases as the basin area and drainage system become larger. The SDR value used for estimating erosion or sediment yield is commonly obtained from the relationship between watershed area and SDR. Based on this approach, the amount of sediment estimated for 2023 was calculated as follows.

$$\text{USLE: } 1,069,473.294 \times 0.11 = 118,834.3904 \text{ tons/year} = 46,081.70 \text{ m}^3/\text{year}$$

$$\text{RUSLE: } 109,303.1319 \times 0.11 = 192,433,082.69 \text{ tons/year} = 73,588.18 \text{ m}^3/\text{year}$$

$$\text{MUSLE: } 118,834.3904 \times 0.11 = 116,602,026.18 \text{ tons/year} = 44,589.68 \text{ m}^3/\text{year}$$

3.9. Sedimentation Analysis with Direct Measurement

The previous analysis provided the peak discharge estimate for the Salu Koya River, which has a watershed area of 8.10 km². Peak discharge values for the other major inlet rivers were then estimated by comparing their respective watershed areas, with the results summarized in Table 4.

From the results of sediment flow sampling and after analysis at the Soil Mechanics Laboratory, the Sediment Concentration (gr/m³) of each inlet river is as follows.

Inlet:	
Tolour Oki	= 6.30
Onipus	= 1.89
Touliang Oki	= 2.26
Salu koya	= 5.25
Toubeke	= 9.03
Tougela	= 4.4
Tonsaru	= 1.33

Mawalelong	= 14.58
Panasen	= 8.77
Saluwangko	= 4.55

Table 4. Catchment areas and estimated peak discharges of lake Tondano inlet rivers

Inlet River	Basin Area	Q ₅	Q ₁₀	Q ₂₅	Q ₅₀	Q ₁₀₀
	Km ²	m ³ /sec	m ³ /sec	m ³ /sec	m ³ /sec	m ³ /sec
Tolour Oki	7.31	7.76	13.99	26.80	48.01	83.39
Touliang Oki	2.57	2.73	4.92	9.42	16.88	29.32
Salu Koya	8.10	8.60	15.50	29.70	53.20	92.40
Toubeke	17.49	18.57	33.47	64.13	114.87	199.52
Tougela	5.18	5.50	9.91	18.99	34.02	59.09
Tonsaru	2.82	2.99	5.40	10.34	18.52	32.17
Panasen	58.06	61.64	111.10	212.89	381.33	662.31
Onipus	1.7	1.80	3.25	6.23	11.17	19.39
Mawalelong	31.74	33.70	60.74	116.38	208.47	362.07
Saluwangko	37.76	40.09	72.26	138.45	248.00	430.74

The analysis used the 100-year peak discharge. The full catchment area was 18,662 ha, while the ten sampled inlets represented 17,273 ha.

3.10. Model Comparison and Validation

Comparison with the field measurements showed that MUSLE produced the sediment estimates closest to the observed values, while USLE and RUSLE showed larger deviations. Model performance was evaluated from the differences between predicted and measured sediment values, with MUSLE yielding the smallest error among the three approaches. The agreement between MUSLE estimates and field measurements is linked to the use of runoff volume and peak discharge as model inputs. These two variables help characterize sediment transport during high-intensity rainfall. In contrast, USLE and RUSLE rely more heavily on rainfall erosivity, meaning their calculated relationship to sediment transport processes during a rainfall event is more indirect.

4. Conclusion

The condition of the catchment area, particularly land cover and topography, plays a role in determining sedimentation in Lake Tondano. The conversion of vegetated land into agricultural and residential areas reduces surface protection, thereby increasing runoff and the detachment of soil particles. Furthermore, the high rainfall characteristic of wet tropical regions intensifies the erosive energy exerted on the soil surface. These processes drive the breakdown of soil aggregates and the transport of eroded material into the lake.

The analysis results show that the values of the main factors causing erosion include R = 1,703.14 MJ.cm/ha.jm/yr (USLE), K = 0.20, LS = 0.496, C = 0.241, and P = 1, which overall describe land conditions that are prone to erosion. Based on the calculations, the estimated annual sedimentation

volume was 46,081.70 m³/year using the USLE method, 73,588.18 m³/year using RUSLE, and 44,589.68 m³/year using MUSLE. These values were then compared with direct measurements in the field on 10 major rivers flowing into Lake Tondano, namely Tolour Oki, Touliang Oki, Salu Koya, Toubeke, Tougela, Tonsaru, Panasen, Onipus, Mawalelong, and Saluwangko.

Measurement results show variations in sediment concentration between rivers, with the highest value in the Mawalelong River at 14.58 gr/m³ and the lowest in the Tonsaru River at 1.33 gr/m³. The highest peak discharge (Qp) was recorded in the Panasen River at 662.31 m³/sec, while the lowest was in the Onipus River at 19.39 m³/sec. After comparing the results with the model calculations, it was found that the MUSLE method provided the results closest to the actual conditions in the field, because it directly calculated the peak discharge and runoff volume from extreme rainfall events.

Among the three empirical approaches evaluated, MUSLE showed the closest agreement with the field observations and was therefore considered the most appropriate for estimating sedimentation under the wet tropical conditions of Lake Tondano. The comparison with measured data also supports the use of empirical modeling

together with direct field observations when assessing sedimentation in the watershed.

The findings support the need for watershed-management measures in areas of the Lake Tondano catchment that are susceptible to erosion, especially where agriculture is practiced on steep slopes. Reducing exposed soil, improving slope protection, and maintaining vegetative cover through measures such as terracing and ground-cover establishment may help decrease sediment delivery to the lake. These efforts are relevant to maintaining Lake Tondano's roles in water supply, irrigation, fisheries, and hydropower generation.

Conflicts of Interest

"The authors declare that there is no conflict of interest regarding the publication of this paper."

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