

Erosion and Sedimentation Rate Analysis to Determine the Useful Life of Meninting Dam

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Abstract: Meninting Dam, constructed in 2019 in West Lombok Regency, is a newly built reservoir that is vulnerable to sedimentation caused by land erosion in its upstream catchment area. This study aims to estimate the erosion rate, sedimentation rate, and predicted service life of the Meninting Dam as a basis for early sediment management planning. Erosion was calculated using the Modified Universal Soil Loss Equation (MUSLE), while sedimentation was estimated using the Sediment Delivery Ratio (SDR) based on the Boyce (1975) method, integrated with spatial analysis using QGIS. The results show that the erosion rate in the Meninting Dam catchment area reaches 884,467.83 tons/year, producing a sedimentation rate of 40,526.39 m³/year and an estimated dam service life of approximately 45 years. These findings indicate that erosion-induced sedimentation poses a significant long-term risk to the storage capacity of the Meninting Dam and highlight the importance of early erosion control and sediment management strategies for newly constructed reservoirs.

Keywords: Meninting Dam; Erosion; MUSLE method; Sedimentation

Introduction

Water is a vital natural resource found both above and below the Earth's surface and plays a crucial role in sustaining life (Soetoto, 2013). To maintain the balance between water availability and increasing demand, the development of water infrastructure such as dams is essential for water storage, regulation, and distribution (McCuen, 2003).

One of the dams currently under development is the Meninting Dam, located between Bukit Tinggi Village, Gunung Sari District, and Dasan Geria Village, Lingsar District, West Lombok Regency, West Nusa Tenggara Province. The dam is designed to support irrigation, water supply, flood control, and regional water resource management. However, sedimentation remains a major challenge for reservoir sustainability and directly affects the effective storage capacity and service life of the dam (NT-1, 2014).

Sedimentation in reservoirs is strongly influenced by soil erosion processes occurring in upstream catchment areas (Singgih et al., 2021). Several previous studies have applied the Modified Universal Soil Loss Equation (MUSLE) combined with Geographic Information System (GIS) techniques to estimate erosion and sedimentation in reservoir catchments (Kusuma, 2015). The integration of MUSLE and GIS has been widely recognized as an effective approach for spatially identifying erosion-prone areas and estimating sediment yield in watersheds (Sosrodarsono, S Takeda, 2003). These studies demonstrate that land-use change and hydrological characteristics significantly contribute to increased sediment delivery into reservoirs (Suripin, 2004).

Despite the extensive application of MUSLE and GIS in sedimentation studies, research focusing on newly constructed dams with limited observational sediment data remains limited (Chow et al., 1988). In addition, many previous studies rely on general assumptions without validating erosion and

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sedimentation estimates against comparable reservoir data (Fikri, 2023).

Therefore, this study aims to analyze erosion and sedimentation rates in the Meninting Dam catchment area using the MUSLE method integrated with GIS analysis (Adriansyah, 2023). The novelty of this research lies in the application of recent spatial and hydrological data to a newly constructed dam, combined with the use of the Sediment Delivery Ratio (SDR) approach to predict the service life of the Meninting Dam in the absence of bathymetric sedimentation data. This study provides an early quantitative assessment that can support sediment management planning and sustainable reservoir operation.

Methods

Research Location

The location of this research was conducted in the Meninting River Basin (DAS Meninting) area, which contains the Catchment Area (DTA) of the Meninting Dam. The Meninting Dam is located in Bukit Tinggi Village, Gunung Sari District, and Dasan Geria Village, Lingsar District, West Lombok Regency, West Nusa Tenggara Province. Research design and method should be clearly defined.



Figure 1. Research Area (Technical Specifications Report of the Meninting Dam, 2023)

Data Collection

The data used in this research include: Rainfall data in the Meninting Dam DTA from 1994 to 2023, Soil type map of the Meninting Dam DTA, Land-use map of the Meninting Dam DTA, Topographic map, Dead storage volume data for the Meninting Dam, and Annual inflow data for the Meninting Dam.

Analytical Model

1. *Thiessen Polygon Method*

The Thiessen Polygon method is a geostatistical technique used to measure and model the spatial distribution of rainfall in a region (Triadmojo, 2015). Ningsih (2012) said this method is adopted to calculate the areal average rainfall within the Meninting Dam

Catchment Area. Rainfall data is collected from multiple stations (Hardiyatmo, 2012).

2. *Erosion Modeling using Modified Universal Soil Loss Equation (MUSLE)*

Erosion is closely linked to hydrological processes, either directly or indirectly (Asdak, 2010). In this study, the magnitude of the erosion rate is estimated using the Modified Universal Soil Loss Equation (MUSLE) (Arsyad, 2010). MUSLE is a key modification of the Universal Soil Loss Equation (USLE), where the rainfall erosivity factor (EI) is replaced by the surface run-off factor (R) to provide better results for sediment yield from run-off events (Palupi et al., 2023).

The MUSLE formula is expressed as:

$$E = R \times K \times LS \times CP \tag{1}$$

where:

- E = Total eroded soil (ton/ha/year)
- R = Surface flow / Runoff factor (m³/hour)
- K = Soil erodibility factor
- LS = Slope length and steepness factor
- C = Crop management factor
- P = Conservation practice factor

3. *Sedimentation Analysis*

Sedimentation is the process where eroded material transported by water or wind is deposited, in this case, into the reservoir (Rivardi, 2012). The amount of sediment that actually reaches the reservoir is calculated using the Sediment Delivery Ratio (SDR), which relates the total amount of eroded soil from the catchment area to the actual sediment yield in the dam (Suripin, 2004). The sedimentation yield (Y) is calculated as follows (Indiarto, 2015) :

$$Y = E \times SDR \tag{2}$$

where:

- Y = Sediment yield / Sedimentation (ton/year)
- E = Erosion (ton/year)
- SDR = Sediment Delivery Ratio

The sedimentation value (Y) in tons/year is subsequently converted to m³/year using the specific weight of the sediment.

4. *Dam Useful Life Prediction*

The useful life of a dam (T) is defined as the service period until the dam's dead storage volume is completely filled with sediment. This analysis is crucial for dam management and maintenance planning (Qohar, 2002). The useful life is determined by the ratio of the remaining dead storage volume to the effective

annual sediment volume. The equation used for prediction is (Kironoto et al., 2003):

$$T = V / (Y \times Te) \tag{3}$$

Where:

T = Dam useful life (year)

V = Remaining dead storage volume (m³)

Y = Sedimentation (m³/year)

Te = Trap Efficiency

Trap Efficiency (Te) represents the percentage of incoming sediment that is actually retained by the reservoir (Wamidzil, 2022). It is estimated using the relationship between the reservoir's capacity and the annual inflow, often determined using empirical curves such as the Brune (1953) curve (Annas, 2021).

5. QGIS

QGIS (Quantum GIS) is an open-source Geographic Information System (GIS) software utilized in this research to process and analyze spatial data (Sihaloho et al., 2020). QGIS was specifically used to integrate and calculate the spatial factors within the MUSLE equation, including the LS factor derived from the topographic

map and the K, C, and P factors derived from the soil type and land-use maps (Windusari, 2023).

Research Stages

1. Calculation of the areal average rainfall for the Meninting River Basin using the Thiessen Polygon method.
2. Calculation of the surface run-off factor (R) value for the Meninting River Basin.
3. Calculation of the soil erodibility factor (K) value for the Meninting Dam Catchment Area (DTA).
4. Calculation of the slope length and steepness factor (LS) value for the Meninting Dam Catchment Area (DTA).
5. Calculation of the crop management factor (C) and the support practice factor (P) values for the Meninting Dam DTA.
6. Calculation of the sedimentation rate due to land erosion using the Modified Universal Soil Loss Equation (MUSLE) formula.
7. Calculation of the reservoir useful life based on the sedimentation rate, utilizing the trap efficiency (Te) value with the Brune 1953 graph.

Result and Discussion

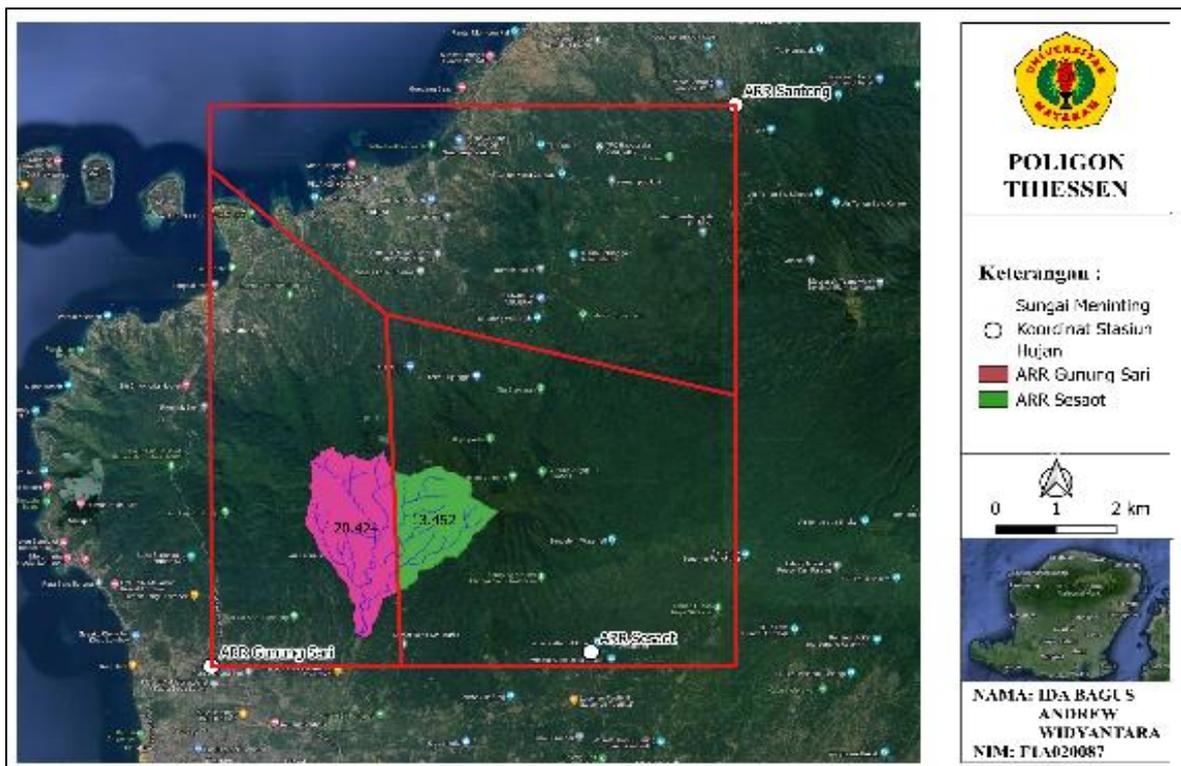


Figure 2. Results of the Thiessen Polygon Analysis

Figure 2 displays the application of the Thiessen Polygon method to the study area, showing the

boundaries of influence for the Gunung Sari and Sesaot rain gauge stations within the Meninting River Basin.

The distinct colored areas correspond to the respective stations used to calculate the areal average rainfall. The area of influence for each station, derived from Figure 2, is detailed in Table 1.

Table 1. Area of Influence for Each Rain Gauge Station

Rain Gauge Station	Area	
	Ha	Km ²
Gunung Sari	2042.4	20.42
Sesaot	1345.2	13.45
Total	3387.6	33.88

Table 1 presents the area of influence for the Gunung Sari and Sesaot rain gauge stations, indicating that the Gunung Sari station influences an area of 2,042.4 Ha (20.42 km²), and the Sesaot station influences an area of 1,345.2 Ha (13.45 km²), totaling 3,387.6 Ha (33.88 km²) for the DTA. Based on the areal influence, the maximum annual average rainfall for the period 1994 to 2023 was analyzed (Table 2).

Table 2. Maximum Average Annual Rainfall

Year	Max Average Rainfall (mm)	Year	Max Average Rainfall (mm)
1994	53.84	2009	144.97
1995	49.39	2010	115.45
1996	115.95	2011	53.41
1997	55.97	2012	57.73
1998	49.44	2013	71.23
1999	43.60	2014	80.90
2000	37.12	2015	61.97
2001	30.96	2016	86.05
2002	93.01	2017	101.23
2003	52.91	2018	88.54
2004	81.97	2019	67.21
2005	115.32	2020	130.65
2006	73.43	2021	122.34
2007	64.24	2022	94.45
2008	58.42	2023	77.32

Table 2 lists the maximum average annual rainfall values recorded from 1994 to 2023, which serve as foundational data for subsequent runoff and erosion calculations. Frequency analysis using the Log Pearson Type III distribution was used to determine the design rainfall for various return periods. The interpolated K values for this distribution are provided in Table 3.

Table 3. K Values for Each Return Period

Cv	Year (T)	K	K	K
0.067	2	0.04	0.054	0.06
0.090	5	0.83	0.823	0.82
0.1	50	1.607	1.629	1.639
	100	2.470	2.526	2.55

Table 3 shows the K values, a statistical coefficient used in the Log Pearson Type III distribution,

corresponding to return periods (T) of 2, 5, 50, and 100 years. The resulting design rainfall (XT) for the calculated return periods are summarized in Table 4.

Table 4. Design Rainfall Values

Return Period (Years)	Log X	K	Sd(log)	Log XT	XT
2	1.86	0.054	0.168	1.87	73.89
5	1.86	0.823	0.168	2.00	99.40
50	1.86	1.63	0.168	2.13	135.66
100	1.86	2.53	0.168	2.28	191.71

Table 4 presents the final design rainfall values for the respective return periods, with the 50-year return period design rainfall being 135.66 mm.

Erosion Rate Calculation (MUSLE Method)

1. *Runoff Factor (R)*

The calculation of the runoff factor (R) requires determining the time of concentration (Tc), rainfall intensity (I), and runoff volume (Vq). Using the main river length of 10.08 km, the Tc was calculated to be 1.058 hours. The rainfall intensity (I) was then computed using the design rainfall, resulting in an I value of 45.2863 mm/hour

Table 5. Runoff Coefficient (C) Values

Land Cover	C Value	Area (ha)
Primary Dry Land Forest	0.11	1,795.58
Secondary Dry Land Forest	0.03	1,340.89
Settlement	0.6	3.30
Mixed Dry Land Agriculture	0.1	236.20
Paddy Field	0.15	7.20
Total		3,383.17
Average C	0.20	

The average runoff coefficient (C) was derived from the land cover classification using QGIS. Table 5 lists the land cover types, their corresponding C values, and the area they cover in the DTA, resulting in an average C value of 0.20. Using the average C value, the rainfall intensity, and the DTA area of 33.8317 km², the peak discharge (Qp) was determined to be 84.33 m³/hour. Following this, the annual runoff volume (Vq) was calculated for each year, resulting in a volume of 360,625.14 m³ for 1994. The complete Vq values for the study period (1994 to 2023) are presented in Table 6.

Finally, the runoff factor (R) was calculated using the runoff volume (Vq) and peak discharge (Qp). For the year 1994, the R factor was calculated to be 182,975.90 m³/hour. The complete R factor values for the study period are shown in Table 7, with an average R value of 220,812.07 m³/hour used for the total erosion calculation.

Table 6. Runoff Volume (Vq) Values

Year	Vq Value (m ³)	Year	Vq Value (m ³)
1994	360.625,141	2009	971.127,767
1995	330.852,692	2010	773.379,417
1996	776.701,704	2011	357.783,602
1997	374.917,787	2012	386.709,641
1998	331.170,422	2013	477.145,097
1999	292.069,418	2014	541.934,090
2000	248.655,919	2015	415.127,880
2001	207.362,600	2016	576.398,698
2002	623.065,670	2017	678.106,344
2003	354.452,772	2018	593.133,287
2004	549.096,904	2019	450.218,932
2005	772.498,599	2020	875.175,098
2006	491.867,236	2021	819.489,471
2007	430.315,581	2022	632.719,547
2008	391.356,714	2023	517.936,549

Table 7. Runoff Factor (R) Values

Year	R Value (m ³ /hour)	Year	Nilai R (m ³ /hour)
1994	182.975,90	2009	318.652,48
1995	174.356,42	2010	280.506,15
1996	281.180,31	2011	182.167,11
1997	187.002,20	2012	190.273,42
1998	174.450,17	2013	214.035,98
1999	162.597,83	2014	229.854,26
2000	148.585,99	2015	197.981,40
2001	134.218,25	2016	237.929,01
2002	248.531,52	2017	260.596,93
2003	181.215,45	2018	241.773,01
2004	231.550,63	2019	207.185,73
2005	280.327,20	2020	300.618,50
2006	217.709,48	2021	289.752,25
2007	202.005,54	2022	250.680,66
2008	191.550,50	2023	224.097,70
	Rerata R		220.812,07

2. Soil Erodibility Factor (K)

Table 8. K Values for Meninting Dam Catchment Area

Elevasi (mdpl)	Soil Type	Area (ha)	K Value
126 - 403	Brown Mediteranean	639.9	0.323
403 - 589	Complex Mediteranean and Reddish Brown Mediteranean	1010	0.323
589 - 770	Complex Mediteranean and Reddish Brown Mediteranean	947.2	0.323
770 - 1006	Complex Mediteranean and Reddish Brown Mediteranean	551.1	0.323
1006 - 1415	Complex Mediteranean and Reddish Brown Mediteranean	229.6	0.323

The soil erodibility factor (K) was determined based on the soil map. Given that the entire DTA is dominated by brown mediteranean and complex mediteranean and reddish brown mediteranean soil types, a constant average K value of 0.323 was applied across all elevations, as detailed in Table 8, which confirms the uniformity of the K factor across the DTA's elevation ranges.

3. Slope Length and Steepness Factor (LS)

Table 9. LS Values for Meninting Dam Catchment Area

Elevation	Slope Gradient	Area (ha)	LS V
126 - 403	0 - 8 %	18.513	0.4
	8 - 15 %	46.648	1.4
	15 - 25 %	100.566	3.1
	25 - 40 %	226.67	6.8
	> 40 %	251.785	9.5
403 - 589	0 - 8 %	12.236	0.4
	8 - 15 %	38.659	1.4
	15 - 25 %	117.213	3.1
	25 - 40 %	295.994	6.8
	> 40 %	545.849	9.5
589 - 770	0 - 8 %	5.67	0.4
	8 - 15 %	17.098	1.4
	15 - 25 %	64.356	3.1
	25 - 40 %	235.099	6.8
	> 40 %	625.267	9.5
770 - 1006	0 - 8 %	1.653	0.4
	8 - 15 %	5.417	1.4
	15 - 25 %	18.387	3.1
	25 - 40 %	71.262	6.8
	> 40 %	454.45	9.5
1006 - 1415	0 - 8 %	0.365	0.4
	8 - 15 %	1.13	1.4
	15 - 25 %	3.999	3.1
	25 - 40 %	15.632	6.8
	> 40 %	208.498	9.5

The LS factor was calculated based on elevation and slope class, derived from the topographic map using QGIS. Table 9 presents the LS factor values, which vary significantly based on the combination of elevation range and slope gradient, ranging from a low of 0.4 for gentle slopes (0-8%) to a high of 9.5 for slopes greater than 40%.

4. Crop Management (C) and Conservation Practice (P) Factors

The C factor was assigned based on land cover type and elevation. Table 10 lists the C factor values for different land cover types across the elevation zones, with low values for forest areas (0.03 to 0.11) and a high value for settlement areas (0.6). The P factor (Conservation Practice) was assumed to be uniform across the land use areas.

Table 10: C Values for Meninting Dam Catchment Area

Elevation (mdpl)	Land Type	Area (ha)	C
126 - 403	Primary Dry Land Forest	29.701	0.11
	Secondary Dry Land Forest	368.06	0.03
403 - 589	Settlement	3.221	0.6
	Mixed Dry Land Agriculture	235.766	0.1
	Paddy Field	7.199	0.15
589 - 770	Primary Dry Land Forest	402.306	0.11
	Secondary Dry Land Forest	607.276	0.03
	Mixed Dry Land Agriculture	0.085	0.1
770 - 1006	Primary Dry Land Forest	600.498	0.11
	Secondary Dry Land Forest	346.692	0.03
1006 - 1415	Primary Dry Land Forest	532.592	0.11
	Secondary Dry Land Forest	18.468	0.03
1006 - 1415	Primary Dry Land Forest	229.587	0.11
	Secondary Dry Land Forest		

5. Total Erosion Calculate

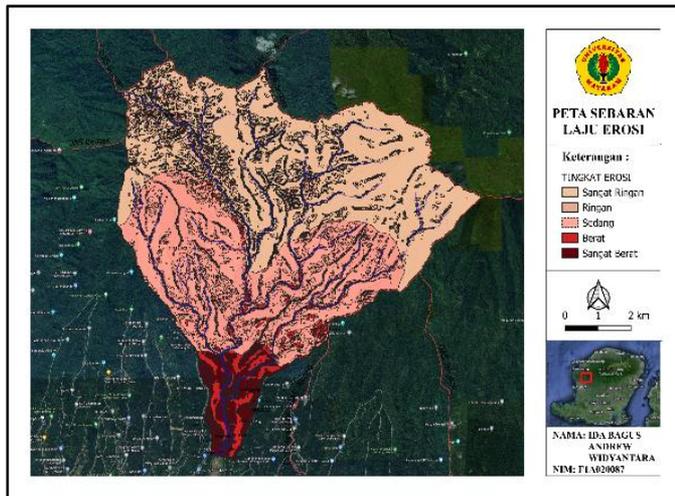


Figure 3: Erosion Rate Analysis Map of the Meninting Dam Catchment Area

The total erosion for the DTA was calculated by multiplying the respective factors ($E = R \times K \times LS \times C \times P$) for each segment. The spatial distribution of the calculated erosion rates, categorized by severity, is mapped in Figure 3, which illustrates the distribution, showing that the most severe erosion levels (heavy and very heavy) are concentrated in the lower elevation areas closer to the dam.

Table 11. Land Erosion Values for Meninting Dam DTA

Elevation	Erosion (ton/ha/year)	Erosion (ton/year)
126 - 403	676.7759	441,556.35
403 - 589	369.9383	373,514.88
589 - 770	64.7932	61,337.18
770 - 1006	12.3238	6,775.62
1006 - 1415	5.6053	1,283.80
Total	1,129.44	884,467.83

The total calculated land erosion values for the Meninting Dam catchment area are summarized in Table 11. Table 11 shows the erosion rate in ton/ha/year for each elevation band and the corresponding total erosion in ton/year. The cumulative total erosion rate for the entire Meninting Dam catchment area is determined to be 884,467.83 tons/year.

6. Sediment Delivery Ratio (SDR) and Sedimentation Rate

The Sediment Delivery Ratio (SDR) was calculated using the Boyce (1975) method based on the Catchment Area (A). With a DTA area of 33.87 km², the SDR formula ($SDR = 0.421 \times A^{-0.3}$) resulted in an SDR value of 0.143. The Sedimentation Rate (Y) was then calculated by multiplying the total erosion value (E) by the SDR. After converting the value in ton/year to volume (m³/year) using the specific weight of the sediment, the predicted sedimentation rate is 40,526.39 m³/year.

7. Dam Useful Life Prediction

The Trap Efficiency (Te) was determined using the Brune (1953) curve, which relates the dam's capacity-inflow ratio (C/I) to its sediment retention efficiency. With an Annual Inflow (I) of 40,050,720 m³/year and a Capacity (C) of 9,910,000 m³, the C/I ratio was calculated as 0.247.

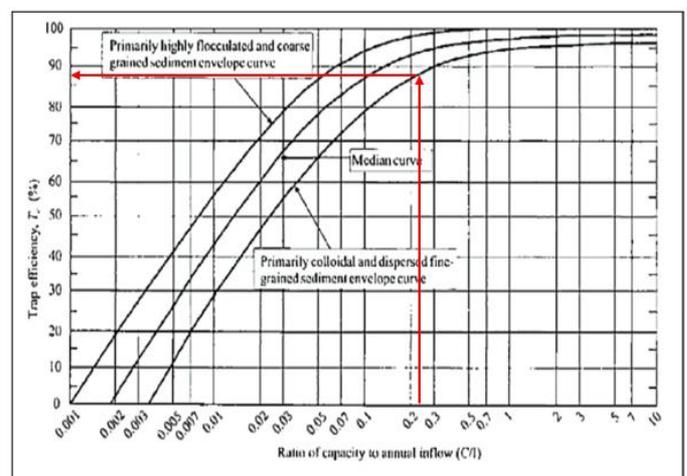


Figure 4. Trap Efficiency Value of Meninting Dam

Figure 4 plots the C/I ratio (0.247) against the Brune (1953) curve. Based on this plot, the Trap Efficiency (Te) for Meninting Dam is determined to be 88% (0.88).

Figure 4 displays the graphical determination of the Trap Efficiency value for Meninting Dam using the calculated ratio of capacity to annual inflow. The Dam Useful Life (T) is calculated using the equation: $T = V/(Y \times Te)$, where the dead storage volume (V) is 1,590,000 m³. Based on the sedimentation rate and trap efficiency, the useful life of the Meninting Dam is projected to be approximately 45 years.

Table 12. Comparison of Analysis Results with Consultant Calculations

	Current Analysis Result	Planning Consultant Result
Sedimentation Rate (m ³)	40,526.39	34,278.55
Useful Life (Year)	45	50

The results of this study indicate that the sedimentation rate estimated for the Meninting Dam is higher than that reported in the initial calculation conducted by the planning consultant. The sedimentation rate obtained from the present analysis reaches 40,526.39 m³/year, resulting in a predicted useful life of approximately 45 years, whereas the planning consultant estimated a lower sedimentation rate of 34,278.55 m³/year and a longer service life of 50 years.

The higher sedimentation rate obtained in this study can be attributed to the use of updated spatial, hydrological, and land-use data, which better represent current watershed conditions. Several previous studies have shown that changes in land use and increased runoff significantly affect erosion rates and sediment yield in dam catchment areas. Studies employing the MUSLE method integrated with GIS have consistently reported that erosion estimates increase when recent land-cover data and higher-resolution rainfall inputs are used, particularly in rapidly developing watersheds.

Furthermore, the application of the Sediment Delivery Ratio (SDR) using the Boyce (1975) approach tends to produce relatively higher sediment delivery values for medium-sized watersheds compared to other empirical SDR formulations. Similar findings were reported in previous sedimentation studies, where the Boyce method demonstrated sensitivity to watershed area and slope characteristics, resulting in higher sedimentation estimates when compared with conventional planning assumptions.

The discrepancy between the present results and the planning consultant's estimates is also consistent with findings from earlier research, which indicate that sedimentation rates derived during the planning stage are often underestimated due to limited field data and simplified assumptions. As reported by several researchers, post-construction or updated analyses

frequently reveal shorter reservoir service lives when more detailed erosion and sediment delivery modeling is applied.

From a management perspective, the shorter predicted service life obtained in this study emphasizes the importance of early sediment control and watershed conservation measures in the upstream catchment of the Meninting Dam. The results support the argument that erosion control strategies and land management interventions should be integrated into reservoir operation planning to ensure long-term sustainability.

Overall, the comparison with the planning consultant's estimates and previous studies confirms that the methodology applied in this research provides a more conservative and realistic assessment of sedimentation risk in the Meninting Dam, particularly under current land-use and hydrological conditions.

Conclusion

The analysis conducted on the Meninting Dam Catchment Area (DTA) using the Modified Universal Soil Loss Equation (MUSLE) revealed a significant erosion rate of 884.467,83 tons/year across the Catchment area 3.387,60 ha. This erosion directly impacts the reservoir's capacity through sedimentation. By applying the Boyce (1975) method, the Sediment Delivery Ratio (SDR) was calculated at 0,143, resulting in a predicted sedimentation rate of 40.526,39 m³ /year. Based on these calculations, the useful life of the Meninting Dam is projected to be approximately 45 years. This finding underscores the critical need for immediate and continuous efforts in land conservation to mitigate soil erosion and safeguard the dam's intended service period

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Author Contributions

The First Author, I.B.A.W, was responsible for the core work, contributing to the study's designing, execution, and writing of the manuscript. The Second Author, I.W.Y, contributed to validating the instruments used in the research and supported the technical execution of the study. The Third Author, Y.S, provided guidance (supervision) and reviewed the entire writing process until the article was completed. All authors have read and approved the final manuscript for publication.

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Conflicts of Interest

The authors confirm that the research presented was conducted in the absence of any commercial or financial relationships that could lead to a potential conflict of interest.

The integrity and outcomes of this publication are solely based on scientific merit.

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