

Analysis of Erosion and Sedimentation Rates of Pengga Dam Using MUSLE Method

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DOI: [10.22178/pos.104-21](https://doi.org/10.22178/pos.104-21)

LCC Subject Category: T1-995

Received 15.04.2024

Accepted 28.05.2024

Published online 31.05.2024

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Abstract. Pengga Dam is a water resource in the Pelambik Village area, Southwest Praya, Central Lombok, West Nusa Tenggara. This dam experienced sedimentation problems caused by land erosion, threatening its helpful life. Preventing the decline in the useful life of the dam can be done by predicting the amount of erosion that occurs in the dam's catchment area. The erosion rate can be estimated and analyzed using the Modified Soil Loss Equation (MUSLE) method using ArcGIS 10.8 software. The MUSLE method consists of several factors that influence its analysis; there are surface runoff factor (R), soil erodibility factor (K), length and slope factor (LS), land use factor (C), and erosion control-practice factor which are analyzed into a layout based on the catchment area of Pengga Dam. Using the erosion value, the sedimentation of Pengga Dam is calculated based on the Sediment Delivery Ratio (SDR) using the Boyce (1975) method and the Menhut (2005) method. The results of data analysis show that the erosion rate in the Pengga Dam Catchment Area (CA) is 38456.98 tons/year with an eroded catchment area of 19537.56 ha. Based on the Brune and Churchill graphs, the trap efficiency value of Pengga Dam is 96%. Therefore, the sedimentation of Pengga Dam is 1583.936 m³/year using the Boyce method and 2093.06 m³/year using the Menhut method. From the results of this erosion and sedimentation analysis, it is hoped that erosion at Pengga Dam can be predicted and controlled in the future so that it does not have a harmful impact.

Keywords: Erosion; Sedimentation; MUSLE Method; SDR; Pengga Dam.

INTRODUCTION

Water is one of the essential needs for living things, but water availability is often insufficient for the various needs of humans, animals, and plants [1]. The primary function of water requires a good and optimal water utilization system; one of the realizations is a dam. Pengga Dam is a dam in Pelambik Village, Southwest Praya, Central Lombok, West Nusa Tenggara. According to data from BWS Nusa Tenggara 1, as the authorities responsible for hydraulic structures, Pengga Dam is a multi-functional dam that is used for irrigation of 3585 ha, raw water for residents around the reservoir, micro hydro power plant with an installed power of 400 KVA, flood control, means of raising fish and tourism respectively.

Pengga Dam does not escape the sedimentation problem caused by land erosion. The causes of erosion and sedimentation are influenced by various factors, including rain characteristics, slope, land use, soil absorption ability, and surface water runoff [2]. Sedimentation at the dam's base will decrease the dead capacity, reducing the useful life of the Pengga Dam. Sedimentation can come from land use changes in the Pengga Dam catchment area, namely the Dodokan watershed. Land use in the Dodokan watershed from 2011 to 2014 experienced significant changes where forest land decreased by 14.59%, plantations increased by 9.19%, shrubs decreased by 11%, and land for settlements increased by 0.28% [3]. These land use changes cause the rainwater catchment area to decrease so that the rainwater

runoff that must be discharged back into the river becomes larger.

There are several methods to estimate erosion rates, including the Universal Soil Loss Equation (USLE), Modified Soil Loss Equation (MUSLE), and Revised Universal Soil Loss Equation (RUSLE). MUSLE is a development of USLE in which surface runoff (R) replaces rainfall erosivity (EI) [4, 5, 6, 7]. Incorporating the runoff factor as a standalone element in erosion, the MUSLE model can enhance the precision of soil erosion predictions compared to the USLE and RUSLE models. Likewise, the RUSLE method also modifies USLE, where there are developments in the rain erosivity model [8, 9, 10]. Essentially, the choice of methods for modelling soil erosion depends on the data needed and what data is accessible (including both its quality and quantity), as well as the constraints of a given model (such as its underlying assumptions and principles) and how well it performs under certain conditions [11]. The advantages of this method are easy to administer, is widely used worldwide, describes critical processes in hydrology, and can measure the amount of sediment produced. Soil carried away by erosion will only sometimes end up as sediment in the river, which can be predicted by the sediment delivery ratio (SDR) method. There are many SDR methods, but in this study, two methods were used to compare the final results: the Boyce and Menhut methods.

Predicting the magnitude of erosion and sedimentation values of the Pengga Dam is expected to be used as a reference for managing and planning future activities because Pengga Dam is a significant source of water for the Central Lombok region, which has now begun to become a prime tourism area, and the Mandalika Special Economic Zone, which is starting to become a national and international concern.

METHODS

The study is located in the Pengga Dam catchment area in the Dodokan watershed, with a catchment area of 19537.56 ha based on analysis using ArcGIS 10.8. Pengga Dam is located downstream of Batujai Dam, making these two cascade dams. Therefore, estimating the amount of sediment escapes from Batujai Dam is also necessary.

The method used to predict the value of erosion and sedimentation is the MUSLE method [12, 13]. This method combines surface runoff value, soil

type, slope length, land use, and land management. MUSLE method has included erosion and sedimentation values in the watershed for an individual rainfall event.

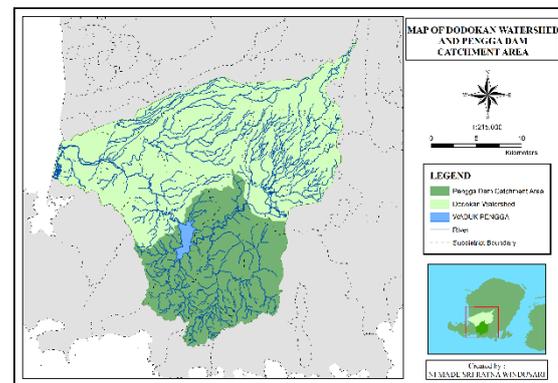


Figure 1 - Catchment area map of Pengga Dam and Dodokan watershed

It can be determined using the following formula (1):

$$E = R \times K \times LS \times CP \quad (1)$$

where E is the amount of land erosion (tons/ha/yr), R is surface runoff (m^2/h), K is the soil erodibility factor, LS is the length and slope factor, C is the land use factor, and P is the erosion control-practice factor [14].

Surface runoff, or direct runoff, consistently travels across the ground surface before and after reaching a channel [15]. The runoff factor in the MUSLE signifies both the energy employed in transporting and dislodging sediment, making it the most reliable indicator for estimating sediment yield during specific storm occurrences [11]. The K factor is determined by assessing the soil's ability to withstand the erosive forces of rainfall and runoff energy. Determining the K factor for soil erodibility depends on various soil properties, including the distribution of particle sizes, the amount of organic matter, the structure of the soil, and its permeability [16]. Steep and unstable slope factors (LS) make the soil saturated with groundwater, so the soil will quickly fall and erode [17]. The land cover layer (C) plays a crucial role in stabilizing the top layer of soil, thereby mitigating soil degradation. Areas with limited vegetation typically exhibit higher C values, indicating a greater vulnerability to soil ero-

sion due to the absence of a mature vegetation layer [18]. Land utilization and management (P) significantly influence the intensity and occurrence frequency of both overland flow and soil loss [19, 20].

The first step in this research is to calculate the average rainfall of the Dodokan watershed area using the Thiessen Polygon method [21]. The surface runoff value can be calculated using the following equation (2):

$$R = a \times (Vq \times Qp)^b \tag{2}$$

where *R* is surface runoff (m²/h), *Vq* is surface runoff volume (m³), *Qp* is peak discharge (m³/s), *a* is 11.8 (constant), and *b* is 0.56 (continuous) [22].

The calculation of the K factor value in the Pengga Dam catchment was based on a table of soil erodibility values in Table 1 [23]. The value of the LS factor is determined through a table of slope percentage levels in Table 2 [24]. L and S variables can be combined because erosion will increase with the land surface's slope and the hill's length. The C and P factors are based on values in the land use in Table 3 and Table 4, respectively [25, 26].

Table 1 – K-factor values of some soils in Indonesia [23]

Soil Types	K-Values
Gray Regosol & Lithosol Complexes	0.172
Brown Mediterranean & Lithosol Complex	0.273
Gray Brown Regosol & Lithosol Complex	0.172
Brown Mediterranean	0.323
Brown Mediterranean Complex Gray Grumusol Brown Regosol & Lithosol	0.188
Brown Regosol & Litosol Complex	0.302
Brown Mediterranean & Reddish Brown Mediterranean Complex	0.323

Table 2 - Assessment of slope class and LS-factor [24]

Slope Classes	Slope	LS-Values
I	0–8	0.4
II	8–15	1.4
III	15–25	3.10
IV	25–40	6.80
V	>40	9.5

Table 3 - Runoff coefficient value based on land use [25]

Types of Land Use	C-Values
Secondary Dryland Forest	0.03
Scrub	0.07

Primary Forest	0.02
Industrial Plantation Forest	0.05
Secondary Swamp Forest	0.15
Plantation	0.4
Dry Land Agriculture	0.1
Dryland Agriculture Mixed with Shrubs	0.1
Settlement	0.6
Rice Field	0.15
Pond	0.05
Open Land	0.2
Waters	0.05

Table 4 – P-factor values for various special soil conservation measures [26]

Specialized Soil Conservation Techniques	P-Values
No erosion control measures	1.000
Bench terrace :	
-Good construction	0.040
-Medium construction	0.150
-Bad construction	0.350
-Traditional terrace	0.400
Strip crops :	
-Bahlia grass	0.400
-Clotararia	0.640
-With contour	0.200
Soil management and planting according to contour lines :	
-Slope 0 – 8%	0.500
-Slope 8 – 20%	0.750
-Slope >20%	0.900

The ratio of the amount of sediment to the land erosion that occurs can be calculated using the Sediment Delivery Ratio (SDR) method [27, 28, 29]. The SDR value can be analyzed with the Boyce and Menhut methods [28, 30, 31, 32]. Sediment originating from Batujai Dam, located upstream of Pengga Dam, can be estimated from the difference in the storage volume of Batujai Dam in 1982 and 2018.

RESULTS AND DISCUSSION

The Thiessen Polygon method determines the area of rainfall station influence with a polygon that divides the watershed into several regions [33]. Thiessen Polygon analysis of the Dodokan watershed can be seen in Figure 2 using four rainfall stations. The location of each rainfall station is Mangkung Station 134.53 km², Serumbung Station 83.18 km², Kabul Station 202.95 km², and Pengadang Station 158.26 km².

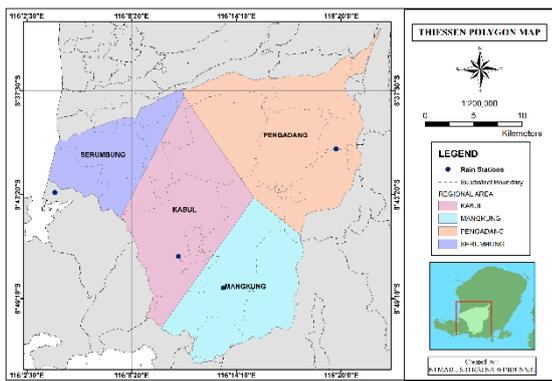


Figure 2 - Thiessen polygon results

From the area based on the Thiessen Polygon, the maximum average rainfall each year can be analyzed by multiplying the rainfall station area by the maximum daily rainfall each year, as in Table 5.

Table 5 - Maximum Average rainfall

Year	Max Average Rain (mm)	Year	Max Average Rain (mm)
1994	34.298	2008	33.913
1995	52.715	2009	111.308
1996	25.638	2010	33.547
1997	41.759	2011	51.562
1998	102.434	2012	48.149
1999	52.123	2013	79.358
2000	68.833	2014	45.331
2001	23.630	2015	44.261
2002	36.889	2016	62.380
2003	63.799	2017	96.622
2004	50.752	2018	60.967
2005	41.791	2019	17.242
2006	30.397	2020	31.817
2007	29.346		

According to the analysis of the maximum average rainfall in Table 5, the highest rainfall occurred in 2009. Based on the results of the maximum average rainfall, it is necessary to analyze the type of rain distribution on the data, where the kind of rain distribution will be used to calculate the design rainfall for each specific return period. There are several types of rain distribution [34, 35]; from the data in Table 5, it can be determined that the kind of distribution is Log-Normal [36]. The Log-Normal distribution was used to analyze the short-term rainfall estimates.

This helped determine rainfall's highest depth and intensity for different durations across all stations [37]. The result of the rainfall design using Log normal distribution is 97.455 mm.

To determine the value of R, it is necessary to determine the value of TC and rain intensity (I) by the Nakayasu method and the Mononobe equation first [28, 38]:

$$T_c = 0.21 L^{0.7} = 0.21 (9.92)^{0.7} = 1.047 \text{ hours}$$

$$R_{24} = 97.455 \text{ mm}$$

$$T_c = 1.047 \text{ hours}$$

$$I = \frac{97.455}{24} \times \left(\frac{24}{1.047} \right)^{\frac{2}{3}} = 32.775 \text{ mm/h}$$

The types of land used in the Pengga Dam catchment area include dryland forests, shrubs, settlements, grasslands, water bodies, dryland agriculture, mixed dryland agriculture, rice fields, and airports based on BWS Nusa Tenggara 1 data. The value of coefficient C was obtained through data processing with ArcGIS 10.8 software with the Catchment Area of Pengga Dam 19537.56 ha, and the values in Table 3 are 0.15. Then, the peak discharge (Qp) is calculated as follows:

$$Q_p = 0.278 \times 0.15 \times 32.775 \times 19537.56 = 264658.75 \text{ m}^3/\text{h}$$

Flow volume (Vq) can be calculated by multiplying the maximum rainfall value for each year in Table 1 with the coefficient C. Then the R-value can be analyzed with formula (2) as in Table 6 below.

Table 6 - Value of flow volume (Vq) and surface runoff (R)

Year	Vq (m ³)	R (m ² /h)	Year	Vq (m ³)	R (m ² /h)
1994	0.005	668.01	2008	0.0050	663.80
1995	0.007	849.80	2009	0.0165	1291.48
1996	0.003	567.56	2010	0.0050	659.77
1997	0.006	745.85	2011	0.0077	839.34
1998	0.015	1232.76	2012	0.0072	807.76
1999	0.008	844.44	2013	0.0118	1068.57
2000	0.010	986.73	2014	0.0067	780.93
2001	0.004	542.21	2015	0.0066	770.56
2002	0.006	695.82	2016	0.0093	933.81
2003	0.01	945.65	2017	0.0144	1193.09

Year	Vq (m ³)	R (m ² /h)	Year	Vq (m ³)	R (m ² /h)
2004	0.008	831.93	2018	0.0091	921.90
2005	0.006	746.17	2019	0.0026	454.48
2006	0.0045	624.33	2020	0.0047	640.51
2007	0.0044	612.16			

Soil erodibility factor (K) in Pengga Dam Catchment Area based on BWS Nusa Tenggara 1 consists of two types of soils: Mediterranean complex, grumusol, grey, regosol, brown and litosol with K coefficient of 0.188 and Complex of brown Mediterranean and reddish brown Mediterranean with K coefficient of 0.323. The LS factor was analyzed with topographic maps processed with ArcGis 10.8 and then divided into several slope categories in percent, each with its own LS coefficient value, as shown in Table 2. The average slope coefficient of the analyzed Pengga Dam catchment is 1.85. The calculation of the P factor was also analyzed using ArcGIS 10.8 based on the soil management and planting values according to the contour lines in Table 4. The data processing results indicate that the average P factor in the Pengga Dam catchment is 0.65.

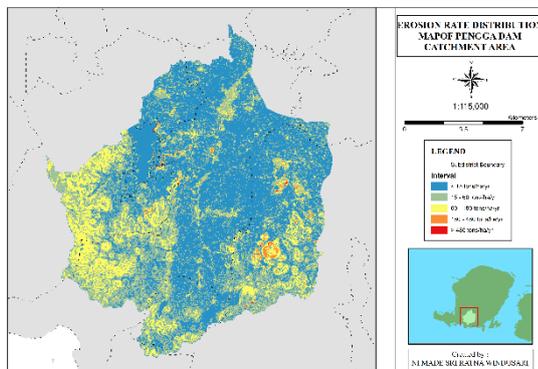


Figure 3 - Land erosion rate distribution of Pengga Dam Catchment Area

Using formula 1, it can be obtained that the total land erosion in the Pengga Dam Catchment Area is 38456.98 tons/year with an eroded area of 19537.56 ha, with the distribution of erosion values seen in Figure 3. Before calculating the sedimentation value, using Brune and Churchill graphs, it is necessary to know the amount of trap efficiency in a dam located upstream of Pengga Dam, namely Batujai Dam. The trap efficiency value of Batujai Dam is 90%, which means 10% of sediment will pass through Batujai Dam and enter the Pengga Dam Catchment Area. With

the sedimentation rate of Batujai Dam, estimated at 60611.11 m³/year, the amount of sediment that escapes from Batujai Dam is 6061.111 m³/year.

Therefore, the sedimentation value of Pengga Dam was analyzed based on the SDR Boyce and Menhut methods.

$$E = 38456.98 \text{ t/year} = 13580.95 \text{ m}^3/\text{year}$$

$$E_{\text{total}} = E_{\text{Pengga Dam}} + E_{\text{Batujai Dam}} = 13580.95 + 6061.11 = 19642.064 \text{ m}^3/\text{year}$$

Based on the SDR Boyce method,

$$E_{\text{boyce}} = E \times \text{SDR} = 19642.064 \times 0.084 = 1649.93 \text{ m}^3/\text{year}$$

Based on SDR Menhut method,

$$E_{\text{menhut}} = E \times \text{SDR} = 19642.064 \times 0.111 = 2180.27 \text{ m}^3/\text{year}$$

Using the same Brune and Churchill graphs, the trap efficiency value of Pengga Dam is 96%, which is used to calculate the sedimentation deposited in Pengga Reservoir.

Based on the SDR Boyce method,

$$Y = E_{\text{boyce}} \times Te = 1649.93 \times 96\% = 1583.936 \text{ m}^3/\text{year}$$

Based on SDR Menhut method,

$$Y = E_{\text{menhut}} \times Te = 2180.27 \times 96\% = 2093.06 \text{ m}^3/\text{year}$$

According to the analysis results, it can be estimated that the sedimentation of the Pengga Dam based on the Boyce method is 1583.936 m³/year, and with the Menhut method is 2093.06 m³/year.

CONCLUSIONS

The erosion rate of the Pengga Dam catchment was analyzed with the values of R, K, LS, and CP factors using ArcGIS 10.8 software, resulting in a land erosion rate of 38456.98 tons/year. The amount of erosion in the Pengga Dam catchment area is 1649.93 m³/year based on the Boyce method and 2180.27 m³/year based on the Menhut method.

Sedimentation deposited at Pengga Dam, with its trap efficiency value of 96% obtained from the Brune and Churchill graphs, shows that with the Boyce method, the sedimentation of Pengga Dam

is 1583.936 m³/year, while using the Menhut method, there are 2093.06 m³/year.

research, especially Balai Wilayah Sungai Nusa Tenggara 1.

Acknowledgements

The authors are very grateful to all parties who have helped collect the necessary data for this

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