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Estimation of useful life of the Logung Reservoir using universal soil loss equation

Fahima Ulumia[1], Slamet Suprayogi[2*], Margaretha Widyastuti[2]

[1] Master Program in Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia
[2] Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta, Indonesia
* Corresponding author's e-mail: ssuprayogi@ugm.ac.id

ABSTRACT

Sedimentation significantly influences the operational lifespan and effectiveness of reservoirs, particularly in terms of their ability to supply irrigation and manage water resources. The Logung Reservoir in Central Java, Indonesia, experiences continual sediment deposition driven by erosion within its catchment area. This study estimates the reservoir's remaining useful life by combining erosion-based sediment yield modeling with empirical bathymetric data. The potential sedimentation rate was calculated using the universal soil loss equation (USLE), modified by the sediment delivery ratio (SDR) and trap efficiency (TE), resulting in a projected annual sediment volume of 158,945.2 m^3. Conversely, actual sediment accumulation derived from dead storage volume changes over five years was significantly higher at 4,818,622.4 m^3 per year. This discrepancy suggests that erosion-based models may underestimate sediment input when conservation measures are not fully accounted for, whereas field measurements provide a more accurate reflection of sediment dynamics. Based on these findings, the estimated remaining useful life of the Logung Reservoir is between 15 years based on the actual sedimentation rate and 30.3 years based on the potential sedimentation rate. These results highlight the urgent need for improved catchment area management and sediment mitigation efforts to ensure the long-term functionality of the reservoir beyond its original design lifespan.

Keywords: USLE model, erosion potential, bathymetric survey, reservoir useful life.

INTRODUCTION

The primary challenge in water resource planning and management lies in determining the optimal reservoir operation policy. A critical issue arises from the inability of some reservoirs to effectively perform their intended functions due to sedimentation. The process by which reservoirs become filled with sediments transported from the upstream watershed is known as reservoir sedimentation (Endalew and Mulu, 2022). Sediment accumulation within reservoirs represents a severe consequence of soil erosion, which threatens the long-term sustainability of dam infrastructure. The progressive increase in sediment deposition leads to a continuous reduction in the reservoir's water storage capacity from the onset of its operation.

The high rate of sedimentation is a key driver behind the decline in reservoir capacity in Indonesia. Various interrelated ecological factors – including topography, soil characteristics, land cover, drainage networks, and rainfall – collectively influence watershed erosion and sediment transport, ultimately contributing to sediment deposition within reservoirs (Marhendi, 2014). Periodic assessments of reservoir storage capacity are essential to quantify sedimentation rates and identify specific zones of sediment deposition (Wulandari et al., 2015).

The Logung Watershed spans an area of 43.81 km², comprising several major and minor tributaries. The Logung Watershed is located on the southeastern slopes of Mount Muria, extending from north to south. At the downstream section of the Logung Watershed lies the Logung

Reservoir, which is connected to a network of technical irrigation infrastructure. The Logung Watershed can also be referred to as a Catchment Area, where rainfall serves as the primary water supply to the reservoir, functioning as its outlet. The Logung Dam's irrigation network supplies water to 2,821 hectares of rice fields, consisting of 1,036 hectares in the West Logung Irrigation Area and 1.785 hectares in the East Logung Irrigation Area (Hartono & Roemiyanto, 2020).

The Logung Reservoir is situated at the downstream part of the Logung Watershed, at the confluence of the Logung River and the Gajah River, located in Slasang Hamlet, Tanjungrejo Village, Jekulo Subdistrict, and Kandangmas Village, Dawe Subdistrict, Kudus Regency, Central Java. The primary function of the Logung Reservoir is to provide irrigation for agricultural land. Additionally, the reservoir supplies 0.2 cubic meters per second of raw water and reduces flood discharge by 105 cubic meters per second (Hartono and Roemiyanto, 2020). Most residents in Tanjungrejo and Kandangmas Villages work as farmers. Since the agricultural land relies heavily on rainfall, water scarcity remains a significant issue during the dry season. Therefore, efforts to increase agricultural production and provide clean water are essential. The construction of this multipurpose reservoir is expected to generate significant positive impacts on the local community. The water resources from the Logung and Gajah Rivers, which were previously underutilized, can now be managed in an integrated manner to maximize their potential – particularly for improving irrigation systems and fulfilling the demand for raw water and clean water supplies.

Previous research on sedimentation in the Logung Reservoir was conducted by (Nur et al., 2019), which estimated that the service life of the Logung Reservoir could last up to 43 years from the time it was first operational. However, further research is necessary to reassess the reservoir's service life since no updated bathymetric maps and reservoir volume data are currently available. This study aims to obtain accurate bathymetric and volume data reflecting the reservoir's existing conditions, as the previous research relied on secondary data concerning sediment transport in the river. Accordingly, this research aimed to assess the erosion potential and sedimentation conditions within the Logung Reservoir catchment area and estimate the remaining useful life of the Logung Reservoir. The findings are expected to provide a scientific basis for formulating reservoir operation policies and sustainable land management strategies, ensuring that the reservoir's functional lifespan meets or even exceeds its planned service life.

METHODOLOGY

Analysis of erosion potential in the Logung Reservoir catchment area using the universal soil loss equation (USLE) model. The USLE approach is compatible with GIS-based analysis for assessing soil erosion risk, with certain modifications in the calculation of specific factors (El Jazouli et al., 2017). The methodology for spatial analysis in this study employed ArcMap to process erosion data derived from the USLE. The calculated parameters of rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practice (P) factors were first organized into spatial data layers. Each factor was converted into a raster format with uniform spatial resolution to ensure compatibility during overlay operations. Using raster calculator tools, these layers were integrated to generate the spatial distribution of annual soil loss. Subsequently, the results were classified into erosion severity categories based on predetermined threshold values, enabling clear visualization and interpretation. The final outputs were represented in thematic maps, which serve as an essential tool for assessing erosion-prone areas. The USLE model formula can be expressed in Equation 1 (Wischmeier and Smith, 1978).

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

where: Ea – erosion potential (Mg. a^{-1}),
R – rainfall erosivity (MJ.mm.h^{-1}. ha^{-1}),
K – soil erodibility (Mg ha h MJ^{-1} mm^{-1}),
LS – slope length and steepness factors,
CP – vegetative cover or crop management with support practices like soil conservation.

Study area

The study area is in Tanjungrejo Village, Jekulo Subdistrict, and Kandangmas Village, Dawe Subdistrict, Kudus Regency, Central Java. The confluence of the Logung River and the Gajah River in Slasang Hamlet, Tanjungrejo Village, Jekulo Subdistrict, Kudus Regency serves as the primary inflow for the Logung Reservoir. The reservoir inundation area covers the region of Slasang Hamlet, Tanjungrejo Village, Jekulo Subdistrict, and Sintru Hamlet, Kandangmas Village, Dawe Subdistrict, all within the administrative boundaries of Kudus Regency, Central Java.

The Logung Watershed features three dominant geological formations: the leucite mineral formation, the volcanic formation, and the alluvial plain formation. The upstream section originates from Mount Muria, characterized by steep elevation and slopes exceeding 40%. In the middle catchment area, on the eastern side, lies Mount Patiayam, which belongs to the paleo-volcanic formation – an older formation than Mount Muria (Mulyaningsih, 2008). The Logung sub-watershed is situated within a tropical climate zone with seasonal rainfall distribution and localized rainfall variability influenced by the presence of Mount Muria. The annual rainfall ranges between 1.500 mm and 3.000 mm.

According to the 2023 data from the Main River Basin Agency of Pemali Juana, the Logung Reservoir has a total storage capacity of 20,150,000 m³ and an inundation area of 1.23 km² or approximately 122.89 hectares. The reservoir's maximum flood water elevation is at ±93.3 m. The Logung Dam is classified as a random earth-fill dam with a vertical core, with a dam height of approximately 55.2 meters from the foundation excavation base. The reservoir's effective storage capacity and dead storage capacity are 13,720,000 m³ and 6,430,000 m³, respectively. The construction of the Logung Reservoir was designed primarily for flood control and water utilization for both irrigation and non-irrigation demands. A map showing the Logung Reservoir catchment area is presented in Figure 1.

Data and sources

The data sources for this study were obtained from both primary and secondary data. Primary data were collected through direct field measurements and laboratory analysis, whereas secondary data were acquired from various relevant institutions. The data used in this study are presented in Table 1.

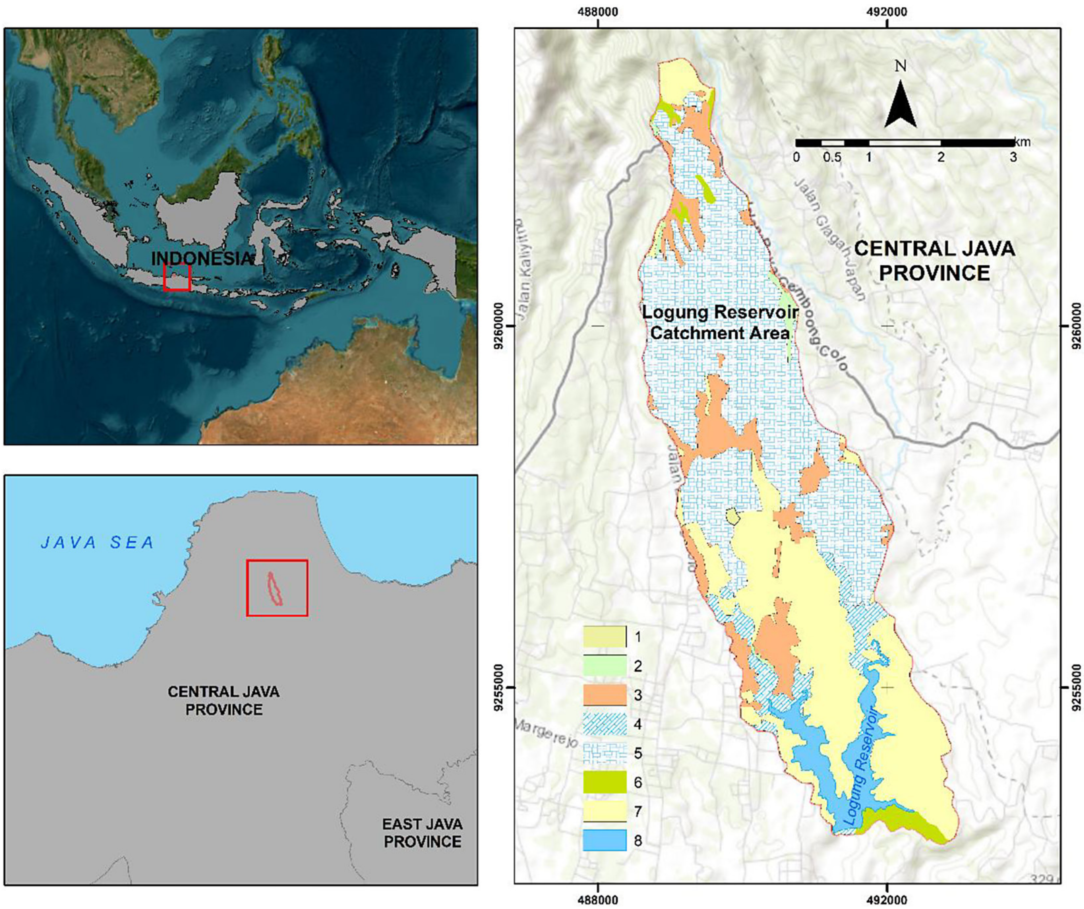

Figure 1. Study area

Table 1. Data and data sources

No	Data	Data source
1	Rainfall data at Rahtawu, Gembong, and Tanjungrejo (2014–2023)	Water Resources Management Center for Pemali Juana
2	Soil texture data at Logung Reservoir catchment area	Field survey and laboratory-tested
3	Depth of reservoir (2024)	Field survey
4	Digital elevation model	Indonesia Geospatial Information Agency
5	Land use data	Indonesia Geospatial Information Agency

Rainfall erosivity (R) factor

The R factor measures the impact of rainfall on erosion in MJ mm ha^{-1} h^{-1} year^{-1} and is designed to represent the input driving sheet and rill erosion processes through climatic factors (Carollo et al., 2018). It is generally determined as a function of rainfall volume, intensity, and duration. Therefore, its calculation requires detailed data on rainfall quantity and intensity. Rainfall data were obtained from the Rahtawu Rainfall Station, Tanjung Rejo Rainfall Station, and Gembong Reservoir Rainfall Station for the period of 2014–2023. These data were processed into regional rainfall values to represent the spatial distribution of rainfall in the Logung Reservoir catchment area by applying GIS analysis using ArcGIS software. The R factor was calculated using the Bols equation (1978), as shown in Equation 2.

$$R = 6.119(Hb)^{1.21} \times (HH)^{-0.47} \times (maxHb)^{0.53} \quad (2)$$

where: R – monthly rainfall erosivity (Mg/ha/month), Hb – average monthly rainfall (cm), HH – number of rainy days in the corresponding month, $maxHb$ – maximum daily rainfall in the corresponding month (cm).

Soil erodibility (K) factor

The soil erodibility factor represents the soil's susceptibility to erosion and runoff rates. The value of the K factor is determined by soil properties such as texture, structure, permeability, and organic matter content. The soil erodibility value can be calculated based on the function of soil structure, permeability, organic C content percentage, and soil particle size fraction percentage using equations 3&4 (Wischmeier dan Smith, 1978).

$$K = \frac{[2.723\, M^{1.14}.10^{-4}.(12-a)] + [3.25\,(b-2)] + [2.5(c-3)]}{100} \quad (3)$$

and

$$M = (\textit{percentage of very fine sand and silt}) \times (100\% - \textit{percentage of clay}) \quad (4)$$

where: K – soil erodibility (Mg ha h MJ^{-1} mm^{-1}), M – particles percentage, a – organic matter content (%C × 1.724), b – soil structure class, c – soil permeability class

Slope length (LS) and steepness factor

The LS factor reflects the topographic effect on erosion, which is proportional to the length and steepness of the slope. The calculation and generation of the LS factor layer were performed using ArcGIS software based on DEMNAS data. The slope class, which serves as the basis for LS factor analysis, is referenced in Table 2.

Crop management-soil conservation (CP) factor

The CP factor consists of the crop management factor and the soil conservation factor. Both factors significantly influence the rate of surface erosion. The crop management factor represents the combined effect of vegetation, litter, soil surface conditions, and land management on the amount of soil lost due to erosion processes (Assaoui et al., 2023). Consequently, the value of the crop management factor (C) is not constant throughout the year. The soil conservation factor reflects the ratio of soil loss under specific support practices to

Table 2. LS Classification (Sutapa, 2010)

Slope (%)	LS value	Classification
0–8	0.4	I
8–15	1.4	II
15–25	3.1	III
25–40	6.8	IV
>40	9.5	V

the loss that would occur under the natural slope characteristics. Improved tillage practices, soil-based crop rotation, and field fertility maintenance significantly contribute to erosion control.

Sediment delivery ratio (SDR) and sedimentation rate

The sediment delivery ratio (SDR) represents the ratio between the amount of sediment transported by river flow or deposited in a reservoir and the amount of soil eroded within a river basin or reservoir catchment area. SDR value approaching one indicates that all eroded soil is transported into the river or reservoir. This condition is more likely to occur in small watersheds with steep slopes, high drainage density, and fine-grained sediment, or in general, in areas where sediment deposition is not hindered (Kaffas et al., 2021). Conversely, as the size of a watershed increases, the SDR value tends to decrease. The equation for calculating the SDR value is expressed in Equation 5.

$$SDR = \frac{Y}{E} \quad (5)$$

where: *SDR* – ratio of sediment yield to total erosion (%), *Y* – sediment yield (Mg/year), *E* – erosion potential (Mg/year).

The SDR value and sediment yield are then used to calculate the reservoir sedimentation rate using Equation 6.

$$Reservoir\ Sedimentation\ Rate = \frac{SY}{\rho} \quad (6)$$

where: *Reservoir sedimentation rate* – (m³/year), *SY* – sediment yield (Mg/year), ρ – sediment bulk density (Mg/m³).

Useful life determination

The 2024 bathymetric survey results were used to determine the volume of the Logung Reservoir. The results were visualized as a contour map based on predefined contour intervals. The reservoir volume was calculated using the Frustum formula as shown in Equation 7.

$$V = \frac{1}{3} \times H \times (A_n + A_{(n+1)} + \sqrt{A_n + A_{(n+1)}}) \quad (7)$$

where: *V* – reservoir volume (m³), *H* – contour interval (m), *A* – surface area between two contour lines (m²).

The reservoir's service life is estimated to decrease compared to the originally projected lifespan at the time of construction. This reduction is attributed to sediment deposition at the reservoir bed. The remaining service life of the reservoir can be predicted using Equation 8.

$$Tw = \frac{Dead\ storage\ capacity\ (m^3)}{Reservoir\ sedimentation\ rate\ (m^3/year)} \quad (8)$$

where: *Tw* – Estimated time required for sediment to fill the dead storage capacity (years).

RESULTS AND DISCUSSION

Erosion potential

The calculation of erosion potential in the Logung Reservoir catchment area was conducted using the USLE model, which involves six factors combined to estimate the potential and spatial distribution of erosion on a monthly and annual basis. The analysis and evaluation of the key USLE model factors play a crucial role in the erosion process, serving to quantify and develop spatial distribution maps of erosion potential within the Logung Reservoir catchment area. The spatial analysis of rainfall erosivity factors was conducted based on data from three representative rainfall stations, namely Rahtawu Station, Gembong Reservoir Station, and Tanjungrejo Station, using a temporal analysis from 2015 to 2024 based on monthly recorded data. Several parameters were used in calculating rainfall erosivity values, including the total monthly rainfall (cm), the number of rainy days in the corresponding month, and the maximum 24-hour rainfall within the same month (cm). The rainfall erosivity factor at each station was calculated based on the average monthly rainfall erosivity over the period of 2015–2024.

The results of the rainfall erosivity calculations at each rainfall station are Rahtawu Station 3,548.37, Gembong Reservoir Station 2,795.33, and Tanjungrejo Station 2,463.63, all in units of MJ mm ha^{-1} h^{-1} year^{-1}. The calculation of rainfall erosivity in the Logung Reservoir catchment area was carried out using the concept of areal rainfall through a weighting approach. The Thiessen Polygon method was used to determine the annual rainfall distribution, allowing the influence area of each rainfall station to be identified. Based on the areal rainfall analysis presented in Table 3, the rainfall erosivity value in the Logung Reservoir catchment area was found to be 2,743.52 MJ mm ha^{-1} h^{-1} year^{-1}. Rainfall erosivity values may vary from month to month. Higher erosivity tends to occur during the months of January–February and November–December. The distribution of rainfall erosivity factor shown in Figure 3a.

The soil erodibility factor represents the susceptibility of soil to erosion and surface runoff. In general, the K value can be optimally applied at a 1:50,000 scale based on a soil type map. However, due to the unavailability of a detailed soil map in the study area, the K factor was derived from the geomorphological landform map of the Logung Reservoir catchment area at a 1:50,000 scale (Figure 2), soil analysis, and literature data. The physical data for estimating soil erodibility were obtained from collected soil samples covering the study area. These samples were analyzed to determine soil texture (sand, silt, and clay content), permeability, structure, and organic matter (Table 4). The distribution of the soil erodibility factor (K) in the Logung Reservoir catchment area ranges from 0.085 to 0.111 (Figure 3b). Higher K values were observed in the upper watershed, where the land is open and barren, as well as in the lower area, characterized by agricultural land without forest cover (Jiang et al., 2020). As such, soils in these areas are highly vulnerable to erosion (Lin et al., 2019).

The next factor is slope steepness, with the calculation results presented in Table 5. The results indicate that most of the land exhibits high LS (topographic factor) values. The distribution of LS values in the Logung Reservoir catchment area, as shown in Figure 3c, demonstrates the dominance of slope gradients greater than 40%. This reflects the hilly terrain and steep slopes characteristic of the Logung catchment area, which consequently possesses a high potential for soil erosion. The findings suggest that the slopes are very steep, and the slope lengths are relatively short. This combination leads to intense surface runoff, significantly increasing the severity of soil erosion (Pham et al., 2018).

Land use in the Logung Reservoir catchment area is predominantly comprised of rice fields, including both rain-fed and irrigated paddy fields. Meanwhile, the area surrounding the Logung Reservoir is primarily occupied by dryland agriculture (mixed gardens/fields). Each land use type responds differently to rainfall events, particularly in terms of resistance to soil erosion. The watershed area was classified into six types of land use through manual interpretation of Google Earth imagery supported by extensive field surveys. A land cover factor was assigned to each land use type, as presented in Table 6. Based on the land use classification, paddy fields were identified as the dominant land use type (52.2%) within the Logung Reservoir catchment area, followed by dryland farming (32.4%). According to the assigned crop cover factor values, a C-factor map was subsequently generated for the final overlay analysis.

The land management and conservation factors are represented by the CP index, which is the result of a combination between crop cultivation

Table 3. Rainfall erosivity in the Logung Reservoir catchment area based on rainfall weighting

Rain station	Rainfall erosivity (R)	Area (A) (km^2)	R x A
Rahtawu	3,548.367	2.94	10,441.67
Waduk Gembong	2,795.331	8.03	22,432.86
Tanjungrejo	2,463.628	9.95	24,506.99
Total		20.92	57,381.53
Rainfall erosivity (R)			2,743.52

Table 4. Soil erodibility (K) in the Logung Reservoir catchment area

Landform	Texture (%)			M	a	b	c	K
	Sand	Silt	Clay					
Lower volcanic slope	9	56	35	56.162	3.584	3	6	0.110
Volcanic footslope	14	63	24	62.784	1.197	3	6	0.111
Volcanic footplain	9	41	51	40.516	1.332	3	6	0.109
Anticlinal hills	30	59	11	59.179	1.868	3	5	0.085

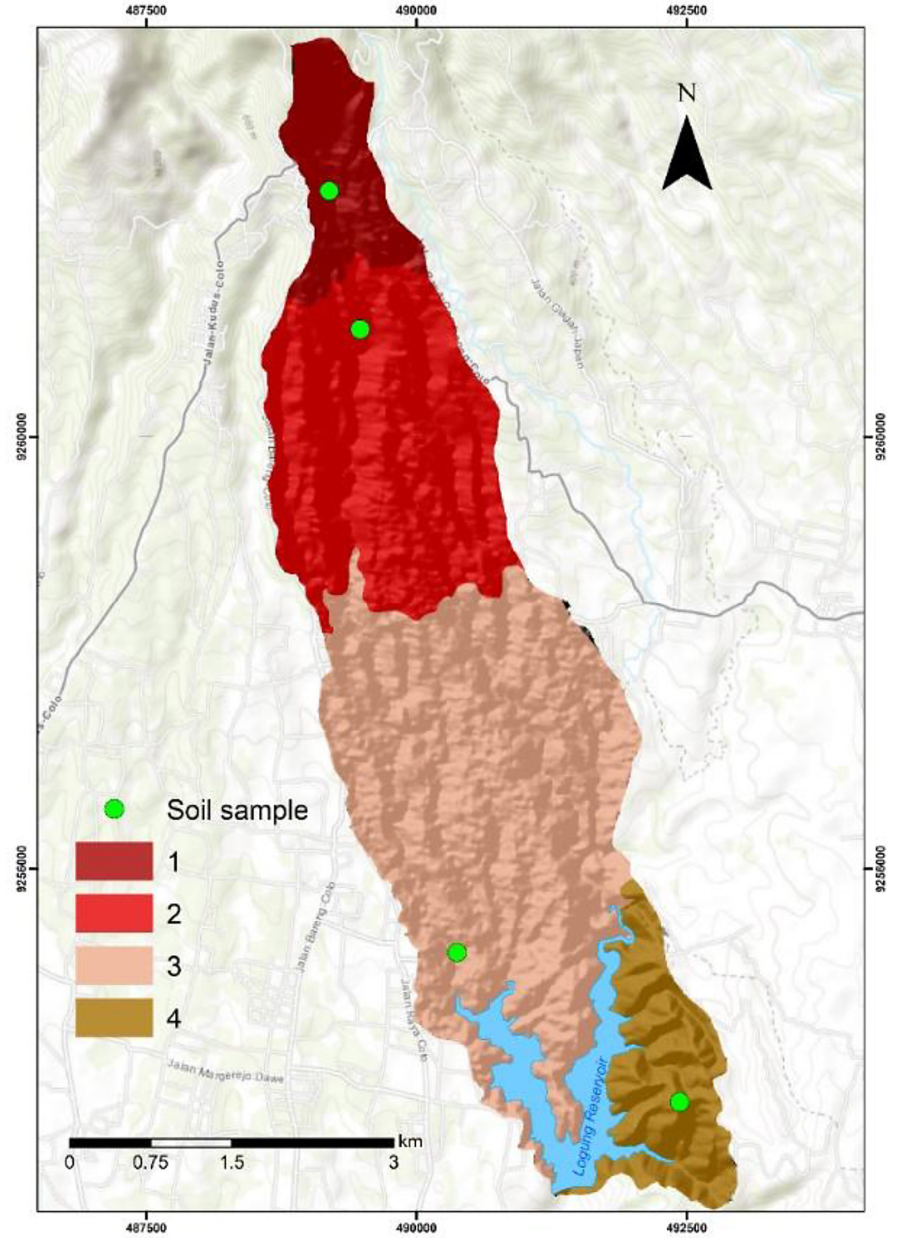

Figure 2. Landform map and soil sampling points in the Logung Reservoir catchment area, Landforms: 1 – lower volcanic slope, 2 – volcanic footslope, 3 – volcanic footplain, 4 – anticlinal hills

practices and soil conservation measures. The lower the CP index value, the lower the potential for erosion, indicating more effective land management and conservation efforts (Alves et al., 2022). Figure 3d presents the spatial distribution of CP values in the Logung Reservoir catchment area. The CP value for water bodies (reservoirs and rivers) is set to zero (0), based on the assumption that no erosion occurs in these areas.

The results of the study show that CP values in the study area range from 0.004 to 1. The lowest CP value, 0.004, is associated with rain-fed paddy fields. These areas are concentrated in the northern part of the reservoir and the central region of the catchment. Meanwhile, the highest CP value is 1, which corresponds to residential areas. This value indicates that settlements have the highest erosion potential compared to other land use types. The distribution of CP values equal to 1 is generally found in the northern part of the Logung Reservoir, both in the upstream and central parts of the catchment and is also related to the presence of dryland farming areas.

The erosion potential in the Logung Reservoir catchment area was calculated using the USLE, based on the overlay analysis of rainfall erosivity,

Table 5. LS classification in the Logung Reservoir catchment area

Slope (%)	Slope Classification	Length and steepness (LS)	Area (ha)	Percentage (%)
0.3–8	I	0.4	10.57	0.51
8–15	II	1.4	26.53	1.27
15–25	III	3.1	72.16	3.45
25–40	IV	6.8	237.32	11.35
>40	V	9.5	1744.24	83.42

Table 6. CP in the Logung Reservoir catchment area

Land use	C	Conservation management	P	CP	Area (ha)	Percentage (%)
Waterbody	-	-	-	-	115.33	5.5
Mixed cropping area	0.1	Without conservation	1	0.1	20.16	1
Settlement	1	Without conservation	1	1	241.79	11.6
Paddy field	0.01	Traditional terraces	0.4	0.004	931.83	44.6
		Conservation with terraces	1	0.01	99.02	4.7
Dryland farming	0.7	Planting along contour lines (slope 9–20%)	0.75	0.525	525.07	25.1
		Planting along contour lines (slope > 20%)	0.9	0.63	114.09	5.5
Shrubland	0.3	Without conservation	1	0.3	40.51	1.9
Grassland	0.3	Without conservation	1	0.3	3.11	0.1
Total					2090.92	100

soil erodibility, slope length and steepness, as well as land management and conservation factors. The total estimated erosion potential in the Logung Reservoir catchment area is 1,554,978.02 Mg per year. Table 7 presents the classification of erosion vulnerability levels and the percentage of each class within the catchment. The dominant erosion vulnerability class is categorized as very low (< 15 Mg/ha/year), covering 50.59% of the total catchment area. Meanwhile, the very high erosion class also shows a considerable proportion, accounting for 41.97%.

The temporal variation of erosion potential in the Logung Reservoir catchment area exhibits a seasonal trend that closely follows the pattern of monthly rainfall erosivity, with a strong interrelationship between the two variables. Monthly fluctuations in rainfall erosivity directly reflect the variation in erosion potential. The higher the rainfall erosivity in each month, the greater the rate of erosion that may occur during that period (Pham et al., 2018). Generally, erosion potential increases significantly during the rainy season and decreases during the dry season. This is evident from the data showing the highest monthly erosion occurring in January at 158.16 Mg/ha/month, while the lowest is recorded in August at 6.64 Mg/ha/month. Overall, the total annual erosion potential in the Logung Reservoir catchment area is 746.84 Mg/ha/year. The formulation of monthly erosion potential is highly dependent on rainfall, as this parameter serves as the primary controlling factor influencing the magnitude of erosion.

The spatial distribution of erosion potential in the Logung Reservoir catchment area is illustrated in Figure 4. Areas classified as having very severe erosion rates are predominantly located in the downstream part of the catchment, surrounding the Logung Reservoir on its northern and eastern sides. This high erosion potential is closely related to land use dominated by dryland farming or mixed-crop fields situated on steep slopes, which significantly increases susceptibility to erosion. In contrast, the central region of the catchment is characterized by very low erosion rates, primarily consisting of rainfed rice fields with gentler slopes and more stable land cover.

Logung reservoir's morphometry

Bathymetric data of Logung Reservoir in 2024 were obtained through the processing of direct field depth survey measurements. The

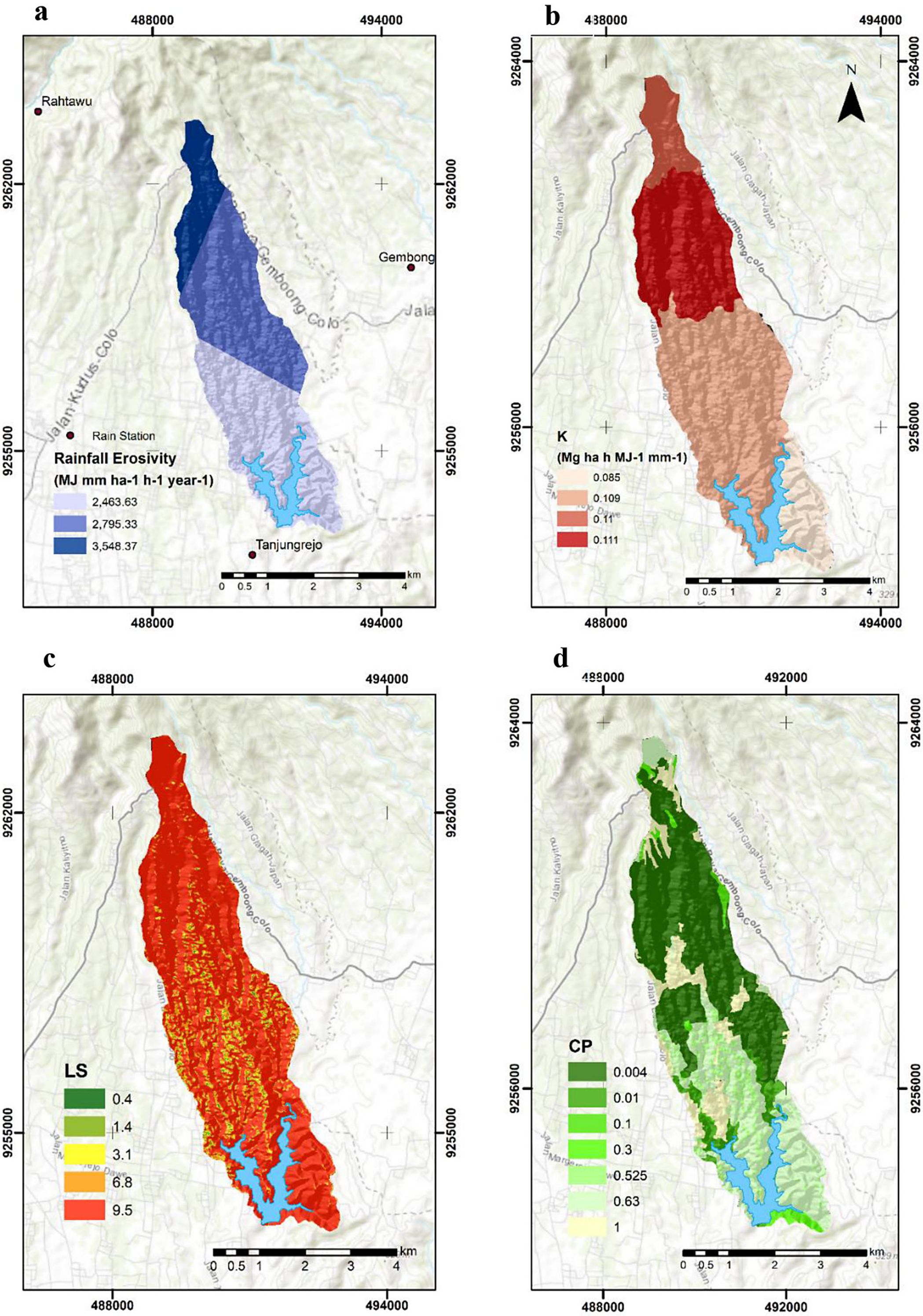

Figure 3. Parameters used in estimating erosion potential with the USLE model, a. rainfall erosivity (R) factor, b. soil erodibility (K) factor, c. slope steepness (LS) factor, d. land management and conservation (CP) factor

depth survey of Logung Reservoir was conducted on October 14, 2024, starting at approximately 09:00 WIB and concluding at 13:00 WIB. The set of instruments used in this survey included an echosounder as the depth monitoring and recording device, a transducer for transmitting sound waves to the reservoir bed, a geodetic GPS for recording coordinate points via satellite, and a battery as the power source for the echosounder. Depth measurements were carried out by navigating across the Logung Reservoir using a motorized boat operated by

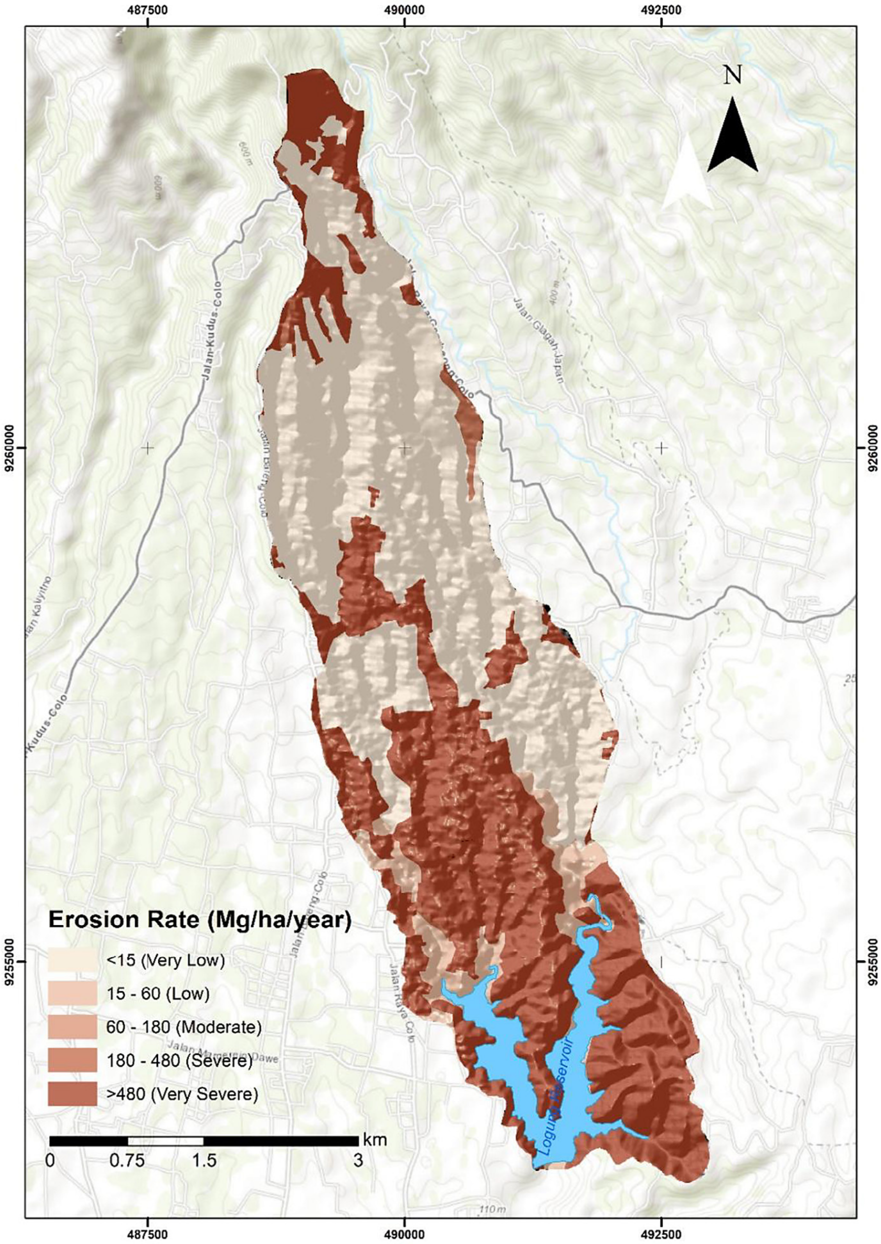

Figure 4. Erosion rate distribution in the Logung Reservoir catchment area using the USLE model

Table 7. Distribution of erosion susceptibility in the Logung Reservoir catchment area

Susceptibility level	Erosion rate (Mg/ha/year)	Area (ha)	Percentage (%)
Very low	<15	1057.72	50.59
Low	15–60	96.06	4.59
Moderate	60–180	3.69	0.18
Severe	180–480	55.87	2.67
Very severe	>480	877.59	41.97
Total		2090.92	100

residents, following predetermined sounding transects. The boat's trajectory was guided by previously designed sounding tracks using the Avenza map application.

The recorded depth data points from Logung Reservoir are shown in Figure 5. comprising a total of 640 points. Each point contains information on both coordinates and depth. The recorded depths ranged from a minimum of 0.3 meters to a maximum of 30.5 meters. The transformation of these depth points into elevation data forms the basis for estimating the volume or storage capacity of Logung Reservoir. These points were then interpolated into a raster format to generate the reservoir's contour.

Interpolation was performed using ArcMap software with the geostatistical analyst tool. The selection of the most suitable interpolation method was based on the RMSE value. RMSE represents the average magnitude of prediction error between the model and actual data. A lower RMSE value indicates a better model performance in accurately predicting the true values. Validation of the interpolation results was conducted using depth points obtained from the echo-sounding survey. The total population used consisted of 640 points. A validation sample comprising 20% of the population, or 128 points was selected using purposive random sampling. Figure 6. illustrates the depth points used for both interpolation and validation. The validation test was carried out using simple linear regression analysis specifically, by calculating the coefficient of determination (R^2) to assess the relationship between the predicted and actual depth values.

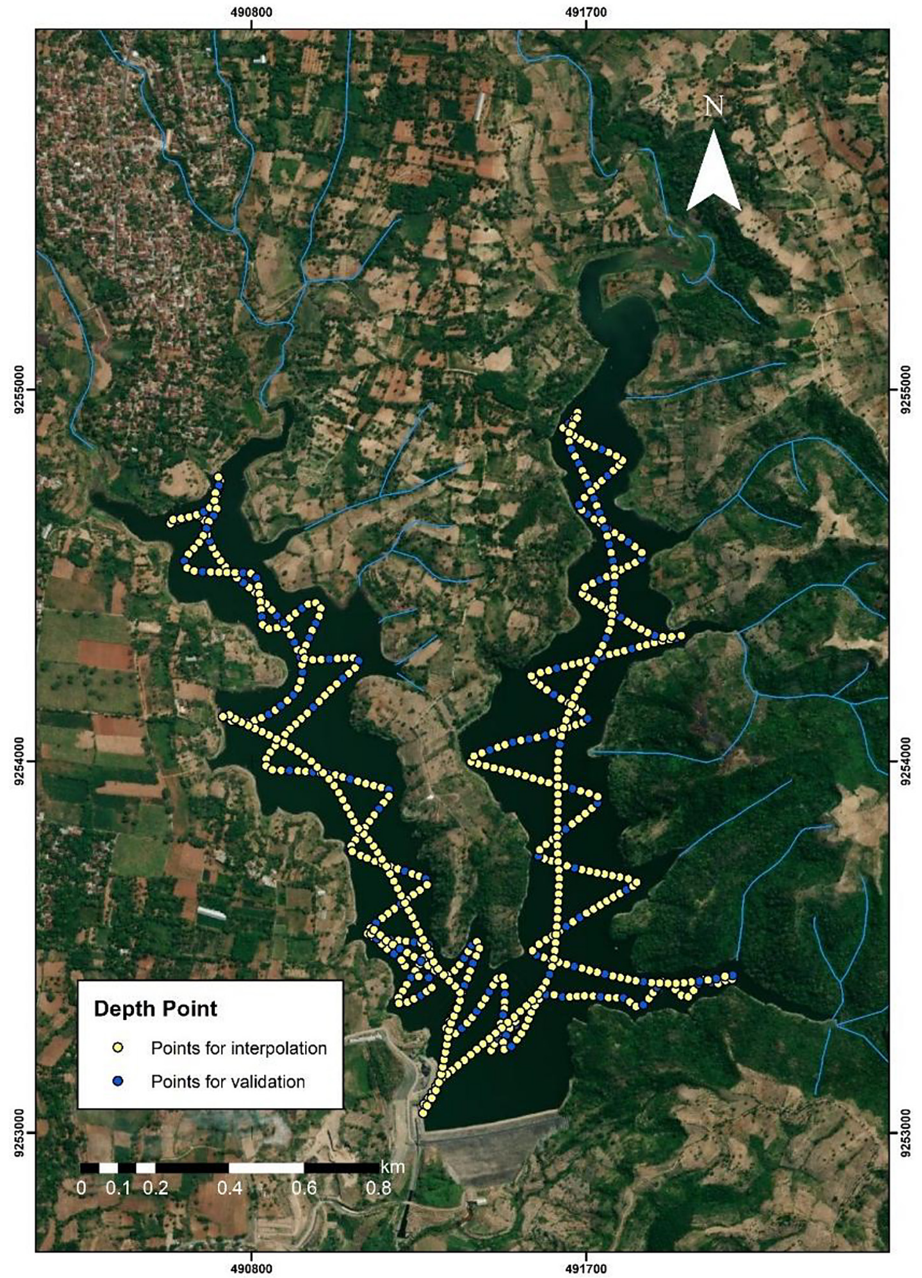

Figure 5. Echo-sounding measurement points to record the depth of the Logung Reservoir

Simple linear regression analysis of the observed and predicted data yielded an R^2 value of 0.9897, indicating a very strong correlation between the two datasets. A regression coefficient approaching 1 reflects excellent model performance. In addition to the regression test, validation was also conducted using the Nash-Sutcliffe efficiency (NSE) and mean absolute percentage error (MAPE). The NSE test produced a value of 0.9897, which falls within the very good classification. This suggests that the predictive data are acceptable and demonstrate strong performance. The MAPE test yielded a value of 6.34%, also classified as very good. Therefore, the interpolated data can be considered valid and capable of accurately representing the observed data, as evidenced by the consistently high performance across the R^2, NSE, and MAPE validation metrics.

Trap efficiency

Trap efficiency refers to the ratio of the mass of sediment captured by the trap to the total mass of material entering the reservoir system over a specific period. The trap efficiency percentage reflects the ability of the Logung Reservoir to

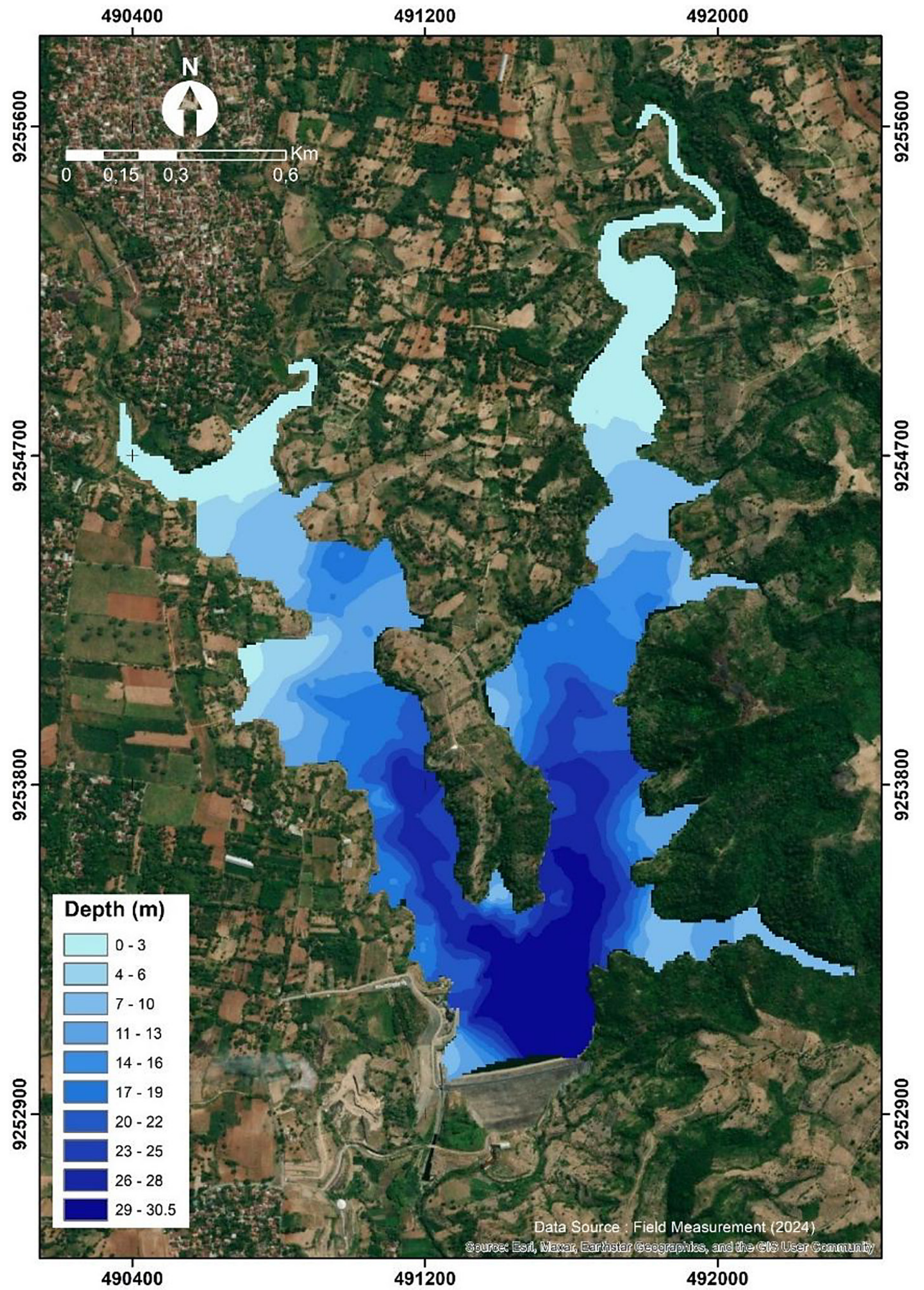

Figure 6. Bathymetric map of the Logung Reservoir interpolated using inverse distance weighting

capture incoming sediment. The TE value is determined based on the reservoir's capacity and the annual inflow discharge. The inflow discharge data used in this study are from 2019 to 2023, as presented in Table 8.

The annual inflow discharge of the Logung Reservoir during the 2019–2023 period was 22,396,801.97 m^3/year. Meanwhile, the reservoir capacity, based on the conducted echo-sounding survey, was 19,118,282.15 m^3. Based on the trap efficiency calculation using the modified Brune formula, a value of 96.17% was obtained, with a capacity-to-inflow ratio (CI) of approximately 0.854. This value indicates that 96.17% of the total sediment entering the Logung Reservoir is expected to settle within the reservoir. The remaining sediment is considered to have the potential to be transported out of the reservoir through the outlet channel or spillway (Budiman and Suprayogi, 2024). The TE value serves as a key parameter for estimating sedimentation rates (Cooper et al., 2018).

Sedimentation rate

The sedimentation rate of the Logung Reservoir can be determined through the estimated erosion potential and the characteristics of the deposited sediment, particularly the sediment bulk density (Bekele and Gemi, 2021). Based on laboratory testing, the average bulk density of sediment in the Logung Reservoir is 2.12 Mg/m^3. The erosion potential in the Logung watershed is estimated at 1,554,978.02 Mg/year. The volume of eroded material entering the reservoir is calculated using the sediment delivery ratio (SDR). In reservoir service life calculations, SDR is used to estimate the annual volume of sediment that will accumulate in the reservoir (El Amarty et al., 2024). Once the total erosion from a catchment area is estimated (e.g., using the USLE method), the volume of sediment delivered and deposited in the reservoir is determined by multiplying the erosion amount by the SDR.

Based on the calculations, the SDR of the Logung Reservoir was determined to be 0.2167, indicating that 21.67% of the total erosion potential from the Logung Reservoir catchment area contributes to sediment entering the reservoir (Getachew and Woldemariam, 2024). Consequently, the estimated sedimentation rate accumulated in the reservoir is 337,430.23 Mg/year or 159,165.2 m^3/year. The amount of sediment deposited in the Logung Reservoir is adjusted based on the previously calculated trap efficiency (TE) value of 96.17%. Therefore, the actual deposited sediment is estimated to be 336,963.74 Mg/year or 158,945.16 m^3/year.

The actual sedimentation rate in the Logung Reservoir is calculated based on changes in the dead storage capacity over a defined period, specifically between 2019 and 2024. The dead storage capacity in 2019 was obtained from official reports by the Main River Basin Agency Pemali Juana, while the 2024 capacity was derived from field measurements. The difference between these two values is interpreted as the

Table 8. Monthly discharge of the Logung Reservoir

Months	Monthly discharge (million m^3/month)					
	2019	2020	2021	2022	2023	Averages
January	4.035	2.645	4.341	7.303	5.358	4.736
February	1.528	2.508	9.860	1.619	8.485	4.800
March	1.926	1.017	2.257	3.529	6.309	3.007
April	1.248	1.652	2.085	2.942	2.451	2.076
May	0.431	1.101	1.439	1.543	1.574	1.218
June	0.072	0.617	1.338	1.429	0.843	0.860
July	0.349	0.552	0.660	2.533	0.718	0.962
August	0.329	0.301	0.532	0.673	0.546	0.476
September	0.332	0.312	0.649	0.566	0.507	0.473
October	0.332	0.532	0.695	0.898	0.456	0.583
November	0.332	0.972	2.006	1.163	0.673	1.029
December	0.340	3.346	1.819	4.460	0.917	2.176
Annually discharge (million m^3/year)						22.397

accumulated sediment volume deposited over the five-year period. The annual actual sedimentation rate is then calculated by dividing the sediment volume by the duration of the period. Detailed calculations regarding the actual sedimentation rate in the Logung Reservoir shows that the dead storage of Logung Reservoir decreased from 6,430,000 m^3 in 2019 to 4,818,622.4 m^3 in 2024, indicating a storage loss of 1,611,377.6 m^3. This corresponds to an actual sedimentation rate of about 322,275.5 m^3 per year, reflecting a high level of sediment inflow that reduces reservoir capacity over time.

Useful life of the Logung Reservoir

Service life refers to the period during which sediment accumulation in a reservoir does not yet impact its planned primary functions (Garg and Jothiprakash, 2008). The service life of a reservoir is a crucial parameter in evaluating the sustainability of its functions in relation to its planning objectives. It is determined by the gradual accumulation of sediment that fills the reservoir storage, particularly the dead storage zone, which is designed to accommodate sediment deposits without affecting the effective storage capacity. In this context, the service life of the Logung Reservoir is estimated by comparing the dead storage volume with the annual sedimentation rate occurring in the reservoir's catchment area. The estimated service life of the Logung Reservoir indicates that with a dead storage volume of 4,818,622.4 m^3 and a sedimentation rate of 322,275.5 m^3 per year, the actual remaining useful life of the Logung Reservoir is estimated at only 15 years, while under potential conditions it could reach 30.3 years. This highlights that the reservoir's lifespan is significantly shortened by current sedimentation pressures, underscoring the urgency of sediment management efforts.

The service life of Logung Reservoir has been estimated using two approaches: potential sedimentation rate and comparison of dead storage capacity across two different time periods. Based on the potential sedimentation rate approach, the service life is estimated to end within 30.3 years from the baseline year of observation. Meanwhile, the approach based on changes in dead storage capacity over time yields a service life estimate of 15 years. This estimation assumes that all sediment transported by river flow is deposited entirely within the dead storage zone.

Logung Reservoir was originally designed with an effective service life of 43 years from the time of construction, meaning it is expected to operate optimally until the year 2062 (Nur et al., 2019). Based on a comparative analysis of dead storage volumes, it can be concluded that the reservoir cannot retain sufficient capacity to remain functional up to its planned service year. However, the service life estimation based on potential sedimentation has limitations, particularly in terms of assumptions regarding sediment deposition distribution. Sediment does not accumulate solely in the dead storage zone but is distributed more evenly across the entire reservoir bed. Therefore, the actual volume of sediment occupying the dead storage may be less than estimated, suggesting that the service life of Logung Reservoir may extend beyond the initially predicted 15 and 30 years. Consequently, calculations based on actual measurements and periodic surveys are essential to obtain a more representative and accurate service life estimate.

CONCLUSIONS

The monthly erosion rate in the Logung Reservoir catchment area is closely linked to the amount of rainfall received each month. Monthly temporal variations indicate that the highest and lowest monthly erosion rates in the Logung Reservoir catchment area occur in January and August, respectively. Spatial variations show that the dominance of very light erosion classes is observed in the central part of the catchment area, which is predominantly characterized by paddy fields with relatively gentle slopes. In contrast, areas classified as having very severe erosion rates are generally distributed in the downstream region of the Logung Reservoir catchment area, particularly surrounding the reservoir on the northern and eastern sides. The high concentration of erosion in these areas is closely correlated with the prevalence of land use in the form of dryland agriculture or mixed farming on steep slopes. Moreover, anthropogenic land disturbances and inadequate soil conservation measures contribute to an increased susceptibility to erosion processes.

The annual erosion rate, which has been calculated using the USLE model, has resulted in a shortened useful life of the Logung Reservoir due to significant sedimentation. Based on the potential sedimentation rate approach, the reservoir's service life is estimated to end within 30.3 years from the base year of observation. Meanwhile, an alternative approach that compares the change in dead storage capacity between two years yields a much shorter estimate of 15 years. This estimate assumes that all sediment transported by river flow is deposited in the dead storage zone of the reservoir. It is important to note that these erosion potential estimates may be prone to overestimation. This is because such estimates do not adequately account for existing conservation efforts, such as the construction of check dams. These sediment control structures play a crucial role in reducing the rate of erosion and mitigating sedimentation within the Logung Reservoir catchment area. The presence of such structures helps to lower erosion and sedimentation rates, thereby extending the useful life of the reservoir and supporting the sustainability of its functions for the surrounding community.

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