Evaluation of the Sediment Management Plan in a Forested Steep Catchment Reservoir

Ida Bagus Gede Indrayana[1*], Kurniawan Putra Santoso[2], Fransisca Natania Karina Rediasti[3]
Department of Civil Engineering, Udayana University, Badung, Indonesia[1]
Gadjah Mada University, Sleman, Indonesia[2]
Serayu Opak River Basin Office, Sleman, Indonesia[3]
[*]E-mail address: bb.indrayana@unud.ac.id

ABSTRACT

Gerokgak Reservoir in northern Bali plays a key role in supporting irrigation for Subak Gede Gerokgak. However, considering the forested steep catchment of Gerokgak Reservoir, ongoing sedimentation threatens its storage capacity and long-term performance. This study evaluates the sediment management plan by River Basin Organization (Balai Wilayah Sungai (BWS)), focusing on the effectiveness of the current dredging schedule and storage allocation. Using the Universal Soil Loss Equation (USLE) with land use, topographic, and rainfall data, the annual sediment yield was estimated at 29,277.85 m³, with a Sediment Delivery Ratio of 18.6 percent. Comparison with historical data showed only a 3 percent margin of error. Without additional dredging, dead storage is projected to be filled within 8 years, far before the 20-year target in the current plan. To meet that target, 0.59 million m³ of storage is needed, requiring 0.299 million m³ of extra dredging. These findings underscore the need to integrate sediment yield analysis into planning for more adaptive and effective reservoir management.

Keywords: Dredging, erodibility, sediment yield, soil erosivity, soil loss, Universal Soil Loss Equation

1. INTRODUCTION

Gerokgak Dam in Buleleng Regency is a single-purpose dam that supplies irrigation water to Subak Gede Gerokgak, serving 374 ha of crop area [1]. Optimal operation and maintenance are essential for sustaining a dam's functionality, but many reservoirs fall short of their purpose due to sedimentation from upstream erosion, which severely impacts the reservoirs' performances. [2]. Effective sedimentation management is crucial to preserving reservoir's capacity, as sediment buildup can reduce its storage, threaten irrigation supply, and raises flood risk. Addressing sedimentation is essential to ensure the reservoir continues to function properly. [3].

Gerokgak Dam reduces peak flood discharge by 25–28% 100 to 1000 return years period, but this drops to 16.53% and 12.00% during extreme events like PMF, indicating reduced effectiveness. Sediment yields have so far reduced the reservoir's dead storage, with notable fluctuations observed between 1999 and 2018, as shown in Table 1. From 1990 to 2012, the dead storage decreased due to accumulating sediment, but between 2012 and 2018, it increased following operation and maintenance efforts by the River Basin Organization (Balai Wilayah Sungai Bali-Penida (BWS BP).

Table 1. Gerokgak Reservoir Storage Comparison Between 1999, 2012, and 2018

Years	Dead Storage (million m^3)	Flood Storage (million m^3)
1999	0.540	2.99
2012	0.155	2.68
2018	0.241	2.82

Reservoir sedimentation can be managed through two main approaches: interventions within the catchment area and actions within the reservoir itself [4]. Dredging is the main reservoir maintenance method in Bali and is usually scheduled every 20 years. However, without early estimation of sediment inflow, such efforts can be ineffective. This study aims to estimate sediment yield in the Gerokgak catchment, evaluate its impact on reservoir capacity, and support appropriate sediment management. The Universal Soil Loss Equation (USLE) is used for its simplicity, low data demands, and suitability for tropical, data-limited regions. [5].

2. THEORY AND METHODS

2.1 Study Area

Gerokgak Dam is located in the northern part of Bali Island, to be precise in Gerokgak Village, Buleleng Regency [1]. According to the BWS-BP, the dam's catchment covers an area of 19.51 km^2. The Gerokgak Dam catchment features varied topography, volcanic geology, and mostly natural land cover, all influencing its hydrology and sediment flow. With 2.8 million m^3 of storage and steep slopes in some parts of its catchment area, managing runoff and sediment is crucial to maintaining reservoir function. For some details, Table 2 shows Gerokgak Dam catchment area's characteristics.

Table 2. Characteristic of Gerokgak Dam catchment area

Parameter	Description
Area	19.51 km^2
Elevation	+131 meters (36 meters above riverbed)
Reservoir's Storage Capacity	2.8 million m^3
Reservoir's Inundation Area	32.47 hectares
Dominant Slope Class	Class I (0–8%) – Flat to Gentle
Overall Slope Class	Class III (18%) – Steep
Land Cover	88.08% forest, 9.35% shrubland
Geology	Volcanic rocks: breccia, lava, tuff
Coastal Geology	Alluvial deposits along northern coastline
Soil Type	Dominantly Regosol
Soil Texture	Mostly medium texture

2.1 Sediment Yield

Soil loss (A) is the amount of sediment transported from a catchment into a reservoir, usually measured in volume or mass per unit area over time. This sediment causes sedimentation and siltation, reducing reservoir capacity [6]. It is a key factor in reservoir sedimentation, leading to reduced storage, degraded water quality, and impaired functions like water supply, flood control, and hydropower generation.

Sediment entering a reservoir comes from upstream erosion, but only part of it, called sediment yield, reaches the reservoir. Sediment yield is largely determined by climate and catchment characteristics, which form the basis of most empirical models. [7]. Changes in these factors can cause significant variability in sediment yield and reservoir sedimentation rates [8]. Land use change and crop rotation are major contributors to future erosion risk. Additionally, recent reviews emphasize that converting natural vegetation to agricultural land, along with intensified soil management practices, is closely associated with increased soil erosion rates [9]–[11]. To account for data availability, this study estimated soil loss using the Universal Soil Loss Equation (USLE), as shown in Equation 1. The data used for this estimation are detailed in Table 3 [5].

$$A = R \times K \times L \times S \times C \times P \qquad (1)$$

Table 3. Components for USLE method

Components	Data Input
Rainfall erosivity (R)	Rainfall from (2000-2021)
Soil erodibility (K)	Land type map (2018)
Crop management and conservation (CP)	Land use map (2018)
Slope length and steepness (LS)	Slope map (2018)

The rainfall erosivity factor (R) measures the intensity and erosive power of rainfall, mainly driven by raindrop size and distribution, which determine its kinetic energy. Since detailed rainfall intensity data are often unavailable, many countries use alternative methods based on monthly rainfall records to estimate R [5], [12].

In this research, rainfall erosivity are calculated using Bols formula (Eq. 2) and (Eq.3) using data such as; monthly precipitation (P_m), number of precipitation days ($Days_m$), and maximum daily precipitation for every month ($Max\ P_m$) to determine monthly rainfall erosivity (R_m).

$$R_m = 6.119 \times {P_m}^{1.21} \times {Days_m}^{0.47} \times {Max\ P_m}^{0.53} \qquad (2)$$

$$R = \sum_{m=1}^{12} R_m \qquad (3)$$

The soil erodibility factor (*K*) measures the soil's susceptibility to being detached and transported by rainfall and surface runoff. It is determined by key soil properties, including texture, profile structure, permeability, and organic matter content, all of which influence how resistant the soil is to erosion [5], [13]. To determine *K*, a commonly used method involves calculating it with the help of a nomogram. However, some studies have instead relied on erodibility classifications, such as those presented in Table 4, to assign *K* values [5], [12], [14], [15].

Table 4. Soil type and erodibility value (*K*)

Soil Type	K Value
Yellow-Red Latosol	0.560
Grumusol	0.200
Alluvial	0.470
Regosol	0.400
Yellow Podzolic	0.107
Yellow-Red Podzolic (Tropudults)	0.320
Latosol (Epiaquic Tropodult)	0.310
Rensing and Litosol Complex	0.220

Slope length and steepness factor (*LS*) determined using Eq.4 and a nomogram by Ministry of Forestry (Kementrian Kehutanan Republik Indonesia) [16] based on the topography map of Gerokgak Dam's Catchment Area.

$$L = \sqrt{\frac{L_0}{22}}, S = \left(\frac{S}{9}\right)^{1.41} \qquad (3)$$

The classification for slope use in the USLE analysis as shown in Table 5, for incorporating the acquired slope data [17] [18]. Based on this classification, the slope data in Table 2 were then estimated proportionally.

Table 5. Slope Classification

Class	Slope Range (%)	Description
I	0 – 8%	Flat – Gentle
II	>8 – 15%	Moderately Steep
III	>15 – 25%	Steep
IV	>25 – 40%	Very Steep
V	>40%	Extremely Steep

The Crop Management Factor (*C*) is the ratio of soil loss from land with specific vegetation and management to that from bare soil, which indicates how well vegetation protects against erosion. The *C* value can range from 0.001 (forested land) to 1.0 (bare land), with lower value indicating better protection. Per Indonesian regulations (P.32/MENHUT-II/2009 and P.61/MENHUT-II/2014), *C* values vary by crop type and farming system. The Conservation Practice Factor (*P*) reflects conservation methods used per land unit. The combined *CP* values are shown in Table 6 [5], [17], [19].

Table 6. Crop management factor for various types of land use

Type of land use	CP value
Shrubs/meadows	0.300
Open land	1.000
Dryland agiculture	0.500
Secondary dryland forest	0.030
Residential area	0.500
Mixed dryland agriculture	0.013

Soil loss from the catchment area that is transported as sediment to the reservoir does not retain the same initial mass. The ratio between the amount of sediment deposited in the reservoir and the total sediment produced in the catchment area is called the Sediment Delivery Ratio (SDR). The SDR can also be defined as the ratio of sediment yield at the catchment outlet to the total erosion occurring within the catchment area [20]. Based on that, the SDR can be interpolated from the relationship between catchment area and SDR in Table 7 [5], [15].

Table 7. Typical Sediment Delivery Ratios (SDR) for some catchment areas

Catchment area (ha)	SDR (%)
10	53
50	39
100	35
500	27
1000	24
5000	15

3. RESULTS AND DISCUSSION

3.1 Soil Loss

The results show clear seasonal variation as shown in Figure 1, with high erosion risk in January, February, March, and December. The fluctuation is in similar pattern with the Subak Gede planting schedule, which started in December for paddy-paddy-maize [1], indicating a high erosion risk during early planting stages.

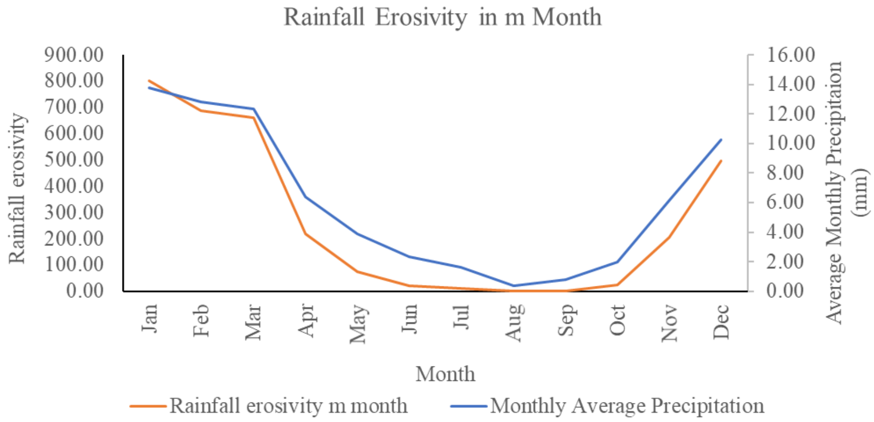

Figure 1. Rainfall erosivity within the Gerokgak Dam's catchment area

According to Table 4, the *K* value for the Gerokgak Dam catchment area with regosol soil is 0.4, while the *CP* value is calculated as shown in Table 8.

Table 8. Crop management and conservation (*CP*) factor

Land Use	Area (Ha)	CP Value	Percentage
Shrubs/Meadows	182.39	0.300	0.09
Secondary Dryland Forest	1718.68	0.030	0.88
Mixed Dryland Agriculture	12.67	0.013	0.01
Dryland Agriculture	37.57	0.500	0.02

As stated in Table 2, Gerokgak Dam catchment area are mostly forest with small *CP* that reduces soil erosion. However, despite covering a much smaller area, shrubs and dryland agriculture have significantly higher *CP* values compared to dryland forest, which can substantially contribute to increased soil erosion. Based on the map, the overall slope steepness is ≤18%, resulting in *LS* of `5.67. From the acquired rainfall erosivity (R_m), soil erodibilty (*K*), crop management and conservation (*CP*), and slope length and steepness (*LS*), the monthly soil loss are shown in Table 9.

Table 9. Calculation of the soil loss within the Gerokgak Dam's catchment area

Month	R_m	K	LS	CP	Soil Loss (A) (ton/ha/year)
Jan	802.8	0.4	5.7	0.030	54.58
Feb	687.5	0.4	5.7	0.030	46.74
Mar	660.8	0.4	5.7	0.030	44.93
Apr	219.7	0.4	5.7	0.030	14.93
May	75.6	0.4	5.7	0.030	5.14
Jun	20.3	0.4	5.7	0.030	1.38
Jul	10.2	0.4	5.7	0.030	0.69
Aug	1.3	0.4	5.7	0.030	0.09
Sep	2.1	0.4	5.7	0.030	0.15
Oct	24.9	0.4	5.7	0.030	1.69
Nov	204.0	0.4	5.7	0.030	13.87
Dec	495.0	0.4	5.7	0.030	33.66

The values of *K, LS,* and *CP* were constant to accommodate the approach to analyzing soil loss by its monthly variation. So, it was given that the major indicator for soil loss between each month is the rainfall erosivity, considering subak activity also highly depends on rainfall period. However, since only two subak groups (*tempekan*) are located upstream of the Gerokgak Dam [1], the crop management factor (*CP*) remains low at 0.03.

3.2 Sediment Yield

The annual soil loss for Gerokgak Dam catchment area is 217.84 ton/ha/year. Based on Sediment Delivery Ratio (SDR) obtained from interpolation (18.6%), the sediment yield (S_y) from the Gerokgak Dam's catchment area is shown in the Table 10.

Table 10. Recapitulation of sediment yield (S_y) analysis

Area (ha)	Soil loss (ton/ha/year)	SDR (%)	Bulk density (ton/m^3)	Sediment yield, S_y (m^3/year)
1,951	217.84	18.6	2.7	29,277.85

The Sediment Delivery Ratio (SDR) indicates that only 18.6% of the total soil loss reaches the reservoir, while the remainder is deposited along the riverbed and within the catchment area. This ratio reflects the watershed’s natural capacity to intercept sediment. The calculated sediment yield (S_y) serves as a basis for anticipating future sedimentation in the reservoir. To validate the analysis result, comparison between the observed and analyzed changes in dead storage can be seen in Table 11.

Table 11. Observed and Analyzed Changes in the Gerokgak Reservoir's Dead Storage from 1999 to 2012

Observed dead storage (million m^3)		S_y (million m3/year)	Time period (year)	S_y (million m3)	Analyzed Dead storage (million m^3)	
1999	2012				1999	2012
0.540	0.155	0.029	13	0.380	0.540	0.159

There is a 0.004 million m³ difference in 2012 dead storage between the existing data and the results of the sediment yield analysis. With a margin of error around ±3%, the sediment yield can be considered reliable for predicting future conditions. Based on 2018 post-dredging data, which restored dead storage to 0.241 million m³, sediment yield analysis projects it will be filled again within 8 years. This is significantly shorter than the planned 20-year dredging interval stated in the O&M plan.

To meet the 20-year target, the reservoir must provide 0.59 million m³ of available storage to accommodate 20 years total of sediment yield. However, this volume exceeds the original design dead storage capacity of 0.54 million m³, making the most effective option to restore the capacity to its initial design. To achieve this, an additional 0.299 million m³ of dredging is required in accordance with the O&M plan, which could potentially extend the reservoir's service life from 8 to 18 years. Based on the sediment yield (S_y) analysis, dredging should be scheduled approximately every 18 years within the intended 20-year window. In the future, this interval may shorten or lengthen depending on the changes in rainfall patterns and land use over the next 20 years.

4. CONCLUSIONS

To achieve the 20-year service life target, at least 0.59 million m³ of available capacity is needed, which exceeds the dam's original dead storage design. As a result, the dredging target is set at 0.54 million m³ which is its initial dead storage capacity design, requiring an additional 0.299 million m³ of dredging. This would extend the reservoir's service life to approximately 18 years, with dredging recommended as part of the operation and maintenance (O&M) cycle every 18 years at most. These results emphasize the need for adaptive sediment management. Relying solely on fixed schedules is inadequate; effective management must consider actual sediment inflow, accumulation rates, and upstream land conditions. For Gerokgak Dam, regular sediment yield monitoring and timely, responsive dredging are essential for long-term operational sustainability.

.

5. ACKNOWLEDGEMENTS

The author extends sincere gratitude to the Gerokgak Dam Operator for providing technical data and valuable insights into the dam's operational conditions. Special thanks are also given to the Subak Gede Gerokgak farming community for their cooperation and for sharing field-level information on agricultural practices and seasonal patterns. Appreciation is further expressed to the consultant team involved in the reservoir's planning and monitoring, whose input and technical guidance were instrumental to the completion of this study.

REFERENCES

[1] I. B. G. Indrayana, F. Nurrochmad, and E. P. A. Pratiwi, "Analysis of factors affecting the intake gate operations of Gerokgak Reservoir for command areas of Subak Gede," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1311, no. 1, 2024, doi: 10.1088/1755-1315/1311/1/012043.

[2] I. Rahmandhani, "Analisa Rezim Sedimentasi Waduk Studi Kasus: Waduk Kefungombo dan Wasuk Sermo," *Media Komun. Tek. Sipil*, vol. 27, no. 1, pp. 80–87, 2021.

[3] P. Utomo, "Mrica Reservoir Sedimentation: Current Situation and Future Necessary Management," *J. Civ. Eng. Forum*, vol. 3, no. 2, p. 365, 2017, doi: 10.22146/jcef.26640.

[4] F. Mardwiono, L. Sedyowati, and G. Wibisono, "Integrated Sediment Management as a Sustainable Effort of Reservoir Function: A Case Study on the Sengguruh and Sutami Reservoirs," *Int. J. Innov. Sci. Res. Technol.*, vol. 7, no. 2, pp. 492–501, 2022, [Online]. Available: www.ijisrt.com492.

[5] A. Azmeri, N. Nurbaiti, N. Mawaddah, H. Yunita, F. Z. Jemi, and D. Sundary, "Surface erosion hazard and sediment yield for Keuliling Reservoir in Indonesia," *J. Water L. Dev.*,

vol. 52, pp. 108–118, 2022, doi: 10.24425/jwld.2022.140380.
[6] W. H. Tatipata, I. Soekarno, A. Sabar, and L. S. Dan, “Analysis of settle sediment volumes after t-year reservoirs in operation (Case study: Cirata Reservoir),” *J. Civ. Eng. Theor. Appl. J. Civ. Eng.*, vol. 22, no. 3, pp. 235–242, 2015.
[7] C. T. Yang, A. Molinas, and B. Wu, “Sediment transport in the Yellow River,” *J. Hydraul. Eng.*, vol. 122, no. 5, pp. 237–244, 1996.
[8] A. R. Bachiller, J. L. G. Rodríguez, J. C. R. Sánchez, and D. L. Gómez, “Specific sediment yield model for reservoirs with medium-sized basins in Spain: An empirical and statistical approach,” *Sci. Total Environ.*, vol. 681, pp. 82–101, 2019, doi: https://doi.org/10.1016/j.scitotenv.2019.05.029.
[9] P. Panagos *et al.*, “Projections of soil loss by water erosion in Europe by 2050,” *Environ. Sci. Policy*, vol. 124, no. May, pp. 380–392, 2021, doi: 10.1016/j.envsci.2021.07.012.
[10] T. Vanwalleghem *et al.*, “Impact of historical land use and soil management change on soil erosion and agricultural sustainability during the Anthropocene,” *Anthropocene*, vol. 17, pp. 13–29, 2017, doi: https://doi.org/10.1016/j.ancene.2017.01.002.
[11] J.-B. Paroissien *et al.*, “A method for modeling the effects of climate and land use changes on erosion and sustainability of soil in a Mediterranean watershed (Languedoc, France),” *J. Environ. Manage.*, vol. 150, pp. 57–68, 2015, doi: https://doi.org/10.1016/j.jenvman.2014.10.034.
[12] C. Asdak, S. Supian, and Subiyanto, “Watershed management strategies for flood mitigation: A case study of Jakarta’s flooding,” *Weather Clim. Extrem.*, vol. 21, no. September 2017, pp. 117–122, 2018, doi: 10.1016/j.wace.2018.08.002.
[13] N. Hoyos, “Spatial modeling of soil erosion potential in a tropical watershed of the Colombian Andes,” *CATENA*, vol. 63, no. 1, pp. 85–108, 2005, doi: https://doi.org/10.1016/j.catena.2005.05.012.
[14] B. A. Kironoto, *Sedimen Transpor*. Yogyakarta: Civil Engineering Program, Gadjah Mada Press, 2003.
[15] S. Arsyad, *Conservation of Land and Water*, 2nd ed. Bogor: IPB Press, 2012.
[16] Kementerian Kehutanan Republik Indonesia, *Peraturan Menteri Kehutanan Nomor P.32/Menhut-II/2009*, vol. 2008. 2009, pp. 1–23.
[17] C. Asdak, *Hydrology and Watershed Management*. Yogyakarta: UGM Press, 1995.
[18] Kementerian Pertanian Republik Indonesia, *KRITERIA DAN TATA CARA PENETAPAN HUTAN LINDUNG*. Indonesia, 1980.
[19] Kementerian Kehutanan Republik Indonesia, *Peraturan Menteri Kehutanan Nomor P.61/Menhut-II/2014*, vol. No. 43, no. 879. 2014, pp. 2004–2006.
[20] S. Dutta, “Soil erosion, sediment yield and sedimentation of reservoir: a review,” *Model. Earth Syst. Environ.*, vol. 2, no. 3, pp. 1–18, 2016, doi: 10.1007/s40808-016-0182-y.