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Sedimentation Analysis Based on Land Use Change on Service Life Estimation in the Gerokgak Reservoir Buleleng Regency

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ABSTRACT

A common problem faced by most reservoirs during their operational period is sedimentation. Sedimentation problems occur due to high levels of land erosion which is influenced by land use in the reservoir catchment area. Based on this, the aim of this research is to determine changes in land use in the reservoir catchment area, the amount of erosion and sedimentation caused by land use and the influence of erosion on the estimated service life of the reservoir. The research location is in the water catchment area of the Gerokgak Reservoir, Buleleng Regency, Bali Province. The data needed in this research includes land use maps and topography of the reservoir catchment area, planning data for the Gerokgak Dam and soil types. The methods used in this research are the Universal Soil Loss Equation (USLE) method to predict the amount of land erosion and the Sediment Delivery Ratio to determine the percentage of sediment entering the reservoir as well as the dead storage comparison method with the amount of sediment to determine the estimated service life of the reservoir. Based on the land use map, the land use condition of the Gerokgak Reservoir water catchment area in 2023 is 95.5% forest and 4.5% rice fields. The average rate of land erosion from 2018 to 2023 is 27.427 tons/ha/year with potential sedimentation of 9,698.563 tons/year. Based on the amount of sediment, it can be analyzed that the service life of the Gerokgak Reservoir is around 5.279 years.

Keywords: erosion; sedimentation; method; USLE, reservoir service life.

INTRODUCTION

Buleleng Regency has several reservoirs, one of which is the Gerokgak Reservoir. The primary function of the Gerokgak Reservoir is to provide irrigation, aiming to serve 737 hectares of agricultural land in the Gerokgak District (Sistem Informasi Bendungan dan Waduk, 2023). To support its function as an irrigation water provider, the Bali Penida River Basin Center, as the managing authority, conducted a sedimentation study in 2018 for maintenance purposes. This study indicated that the Gerokgak Reservoir retained only 205,053 m³ of dead storage capacity from its original design capacity of 360,000 m³, reflecting a 43.04% reduction in dead storage over the past 13 years [1]. According to the reservoir storage curve, an increase in sediment accumulation within the reservoir will continue to reduce its capacity. The declining reservoir capacity will directly affect its service life.

To date, the Bali Penida River Basin Center has not updated the erosion estimates affecting sediment inflow to the Gerokgak Reservoir. An updated erosion analysis is necessary due to annual land use changes. The land use in the Gerokgak Reservoir's 18-hectare watershed, predominantly forest, has begun shifting towards agricultural land. These land use changes significantly impact erosion and sedimentation estimates [2]. Sediment estimation is a crucial initial step for making informed decisions in reservoir maintenance planning. Proper reservoir maintenance is essential for the reservoir's success in achieving its service goals, particularly in terms of extending its service life.

Based on these considerations, this study focuses on analyzing land erosion within the Gerokgak Reservoir's watershed, which can then be used to estimate sedimentation impacting the dead storage capacity of the Gerokgak Reservoir. The results of this analysis are expected to serve as an approach for decision-making in the maintenance planning of the Gerokgak Reservoir.

RESEARCH METHODS
Materials

The materials required for this research included equipment and data sources fundamental to the sedimentation and erosion analysis of the Gerokgak Dam. Data concerning dam specifications, land use, rainfall, and sedimentation were obtained from the Watershed and Dam Office of Bali-Penida and Esri Sentinel-2 satellite imagery [3]. Key software and instruments used in this study included ArcGIS 10.8 for mapping and modeling land use and GPS for location tracking. Field measurements utilized moisture and pH meters, a thermometer, and digital scales to accurately measure waste and sediment levels. A visual representation of the research process is shown in Figure 1, illustrating the systematic steps for analyzing sedimentation and erosion impacts on the dam's operations.

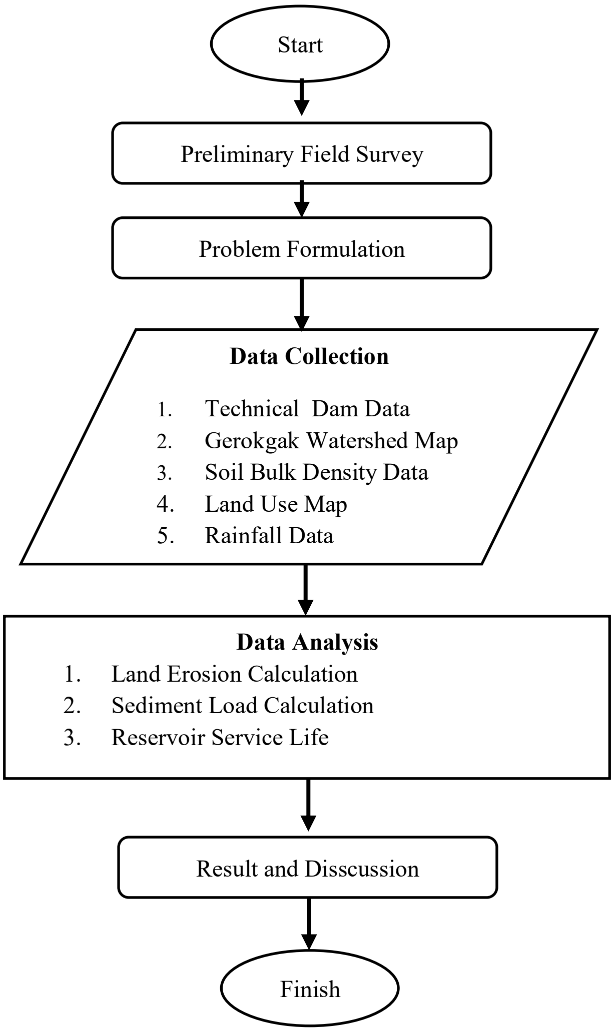

Figure 1. Flow chart

Methods

The research was conducted in Gerokgak, Buleleng, Bali, between October and November 2020**.** The study began with a preliminary survey to observe sedimentation patterns at the Gerokgak Dam and its watershed [5]-[7]. Following this initial survey, data collection included both primary and secondary data sources. Satellite land-use maps were obtained to identify environmental changes over time, and technical dam specifications were reviewed to assess its design and operational

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capabilities [8]. Soil texture and density data were collected from the surrounding dam areas to evaluate potential sediment loads entering the reservoir.

Table 1. Data types and sources

No.	Data Type	Data Source
1	Rainfall Data from Gerokgak Station	Bali-Penida River Basin Center
2	Technical Data of Gerokgak Dam	Bali-Penida River Basin Center
3	Soil Bulk Density Data around Gerokgak Reservoir Area	Bali-Penida River Basin Center
4	Gerokgak Reservoir Storage Data	PT. Multimera Harapan
5	Land Use Map	Esri Sentinel-2 Landcover

Data processing involved various analytical models. The Universal Soil Loss Equation (USLE) was employed to calculate erosion rates, with adjustments made for factors such as rainfall intensity, soil properties, and slope characteristics [9]. The Sediment Delivery Ratio (SDR**)** model provided an estimate of the sediment load directed into the dam (Kementerian Pekerjaan Umum dan Perumahan Rakyat. Lastly, the AHP model structured the decision-making process by ranking sediment control strategies based on cost-effectiveness, feasibility, and their impact on the dam's service lifespan [12].

Data Analysis

Data analysis was conducted descriptively, focusing on assessing changes in erosion rates, sediment volumes, and the projected operational lifespan of the Gerokgak Dam. Daily measurements of moisture content, pH, and temperature were collected to monitor environmental conditions affecting sedimentation [1]. Sediment volume and density were recorded at the start and end of the study to assess current sediment loads and estimate the dam's functional lifespan. The results were then compared with Indonesian standards for sedimentation and dam longevity, which provided a basis for evaluating the dam's ability to meet its intended service goals and informed recommendations for improved sediment management and lifespan extension [10].

RESULT AND DISCUSSION

The results and discussion presented in this research explore the erosion and sedimentation rates in the Gerokgak Reservoir catchment area. This assessment is based on the methodologies outlined in the Universal Soil Loss Equation (USLE) approach, coupled with sediment delivery ratios and erosion indices specific to rainfall and soil erodibility. Utilizing a structured approach, this study ensures that each methodological phase aligns with the objectives of estimating sedimentation impacts on the reservoir's operational life. The findings below present both initial measurements and the outcomes of various analyses related to soil characteristics, rainfall erosivity indices, and their implications on soil conservation practices and reservoir maintenance planning.

The Rainfall Erosivity Index (EI30), calculated annually from 2018 to 2023, is shown in Table 2. The highest erosivity value was recorded in 2020, reaching 639.6 KJ/ha, which underscores the erosive power of rainfall and its role in accelerating soil erosion during periods of intense precipitation. Demonstrated the utility of EI30 as a quantitative measure for rainfall-induced erosion potential, and the high values observed in 2020 align with this understanding. The elevated EI30 values highlight the importance of implementing seasonal erosion control practices, particularly in high-rainfall months, to mitigate soil displacement and sediment buildup in the reservoir.

Table 2. Rainfall erosivity index (EI30)

Rainfall Erosivity Index (EI30)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2018	160.2	87.4	107.8	48.4	0.0	0.0	4.3	0.0	0.0	0.0	22.9	0.0	431.0
2019	93.4	208.0	70.8	67.6	0.0	0.0	0.0	0.0	0.0	0.0	17.2	0.0	457.0
2020	37.9	247.3	232.1	68.4	0.0	0.0	7.7	0.0	0.0	0.0	46.3	0.0	639.6

Rainfall Erosivity Index (EI30)													
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
2021	160.7	165.3	131.0	10.6	0.0	0.0	0.0	0.0	0.0	0.0	100.5	0.0	568.1
2022	245.4	53.2	137.0	41.3	0.0	0.0	2.7	0.0	0.0	0.0	10.6	0.0	490.2
2023	109.9	182.9	37.3	19.2	0.0	0.0	10.2	0.0	0.0	0.0	4.5	0.0	364.2

Based on the Soil Type Map published by the Regional Development Planning Agency of Bali Province, as shown in Figure 1, the soil types in the Gerokgak Reservoir Catchment Area (RCA) consist of Brown Latosol and Lithosol. The Soil Erodibility Index (K), calculated for the Gerokgak catchment area, reflects the soil's susceptibility to erosion under natural conditions [13], [14]. According to soil classification data, the dominant soil types Brown Latosol and Lithosol show moderate erodibility values ($K = 0.02$). This aligns with the findings of Wischmeier and Smith [15], who noted that the K value is essential in estimating erosion potential, especially on sloped land. This K value indicates a moderate erosion risk, particularly in areas with limited vegetation cover and steeper slopes [16].

Additionally, the slope length (L) and slope steepness (S) indices are determined using height differences across eight slopes representing each slope condition on the Gerokgak Dam Catchment Area topographic map, as shown in Figure 3.

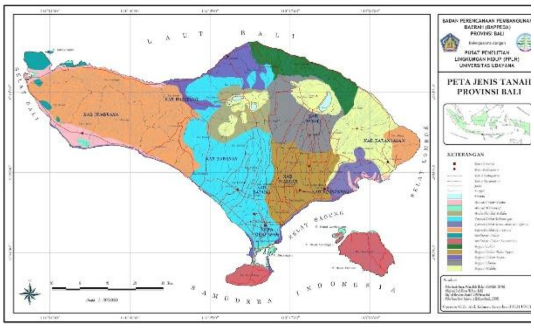

Figure 2. Soil type map of Bali province

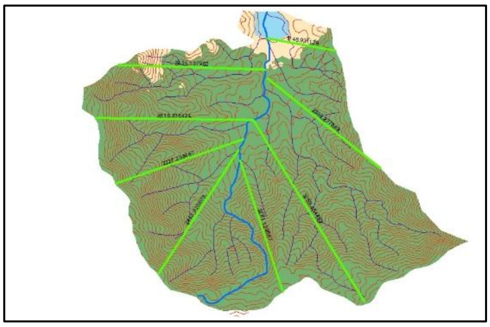

Figure 3. LS in the Gerokgak RCA

Slope Length and Steepness (LS) factors across the Gerokgak catchment area contribute significantly to erosion, as shown in Table 4. Longer and steeper slopes yield higher LS values, which, amplify the susceptibility of soil to erosion under rainfall conditions. The high LS factors in this catchment area suggest that soil conservation practices are necessary to reduce the sediment load transported to the reservoir, particularly in regions with steep slopes.

Table 3. Slope Length and Steepness Factors (LS)

No.	**Elevation**		**Delta H**	**Length (L)**	**Slope (%)**	**L Factor**	**S Factor**	**LS**
	Start	**End**		**(m)**				
1	1023.653	201.409	822.244	3759.454	21.871	13.072	3.316	43.347
2	875.000	201.571	673.429	2610.816	25.794	10.894	4.143	45.133
3	1028.179	248.154	780.025	2443.321	31.925	10.539	5.525	58.227
4	724.500	153.681	570.819	2435.138	23.441	10.521	3.641	38.308
5	628.207	173.095	455.112	2388.278	19.056	10.419	2.753	28.685
6	900.410	264.000	636.410	2281.130	27.899	10.183	4.606	46.901
7	877.840	225.761	652.078	2227.238	29.277	10.062	4.916	49.461
8	243.000	122.000	121.000	1148.931	10.532	7.227	1.264	9.135

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Average LS	**39.900**

The management of vegetation in the Gerokgak Reservoir Catchment Area (RCA) is determined based on land use maps from the Environmental Systems Research Institute [3], covering the period from 2018 to 2023. These maps provide data on land use types and the area covered by each type annually. A summary of land cover, along with area measurements and the land management factor (C), is presented in Table 4. During this period, changes in vegetation cover were observed, with portions of forest area being converted to rice fields and other agricultural activities, resulting in an increased C value. This rise in the C value indicates reduced protection against soil erosion, view that vegetation, especially forests, plays a critical role in erosion control by maintaining soil stability more effectively than open agricultural land. Meanwhile, the land management factor for the Gerokgak Reservoir Catchment Area is 1.00, as no land conservation efforts have yet been implemented in this region [17].

Table 4. Crop Management Index (C) for Gerokgak Dam Catchment Area

Year	Vegetation Cover	C	Area (km^2)	C x Area (km^2)	C
2018	Natural Forest (Low Litter)	0.05	17.830	0.891	
	Rice Field	0.561	1.142	0.641	0.081
			18.972	1.532	
2019	Natural Forest (Low Litter)	0.05	17.893	0.895	
	Rice Field	0.561	1.079	0.606	0.079
			18.972	1.500	
2020	Natural Forest (Low Litter)	0.05	18.574	0.929	
	Rice Field	0.561	0.398	0.223	0.061
			18.972	1.152	
2021	Natural Forest (Low Litter)	0.05	18.560	0.928	
	Rice Field	0.561	0.409	0.229	0.061
	Buildings	1	0.003	0.003	
			18.972	1.161	
2022	Natural Forest (Low Litter)	0.05	18.505	0.925	
	Rice Field	0.561	0.467	0.262	0.063
			18.972	1.187	
2023	Natural Forest (Low Litter)	0.05	17.669	0.883	
	Rice Field	0.561	1.303	0.731	0.085
			18.972	1.615	

Using the equation from the Universal Soil Loss Equation (USLE) method, the estimated erosion occurring in the Gerokgak Dam Catchment Area is presented in Table 5.

Table 5. Calculation of Predicted Erosion Values Using the USLE Method

Year	R	K	LS	C	P	A (tons/ha/yr)
2018	431.035	0.02	39.900	0.081	1	27.779
2019	457.025	0.02	39.900	0.079	1	28.838
2020	639.624	0.02	39.900	0.061	1	30.995
2021	568.116	0.02	39.900	0.061	1	27.739
2022	490.187	0.02	39.900	0.063	1	24.480
2023	364.155	0.02	39.900	0.085	1	24.731
Average						**27.427**

Generally, not all eroded soil is transported into water bodies or to other areas, as some sediment is deposited on the soil surface. Sediment Delivery Ratio (SDR) is the ratio between the amount of erosion in the catchment area and the amount of sediment transported to the water body. In this study, the SDR value was calculated using the equation from the Directorate General of Water

Resources, resulting in an SDR value of 0.186 for the Gerokgak Reservoir catchment area, as shown in Table 6. A higher SDR value indicates that most of the eroded soil reaches the reservoir, directly impacting sediment load and reducing the reservoir's storage capacity. Emphasized the importance of SDR in evaluating sediment yield, which is closely related to the effectiveness of erosion control in the catchment area. After calculating the SDR value for the Gerokgak Reservoir Catchment Area, the sedimentation rate, which represents the amount of erosion entering the water body, can be calculated as shown in Table 6

Table 6. Sediment Rate of Gerokgak Reservoir Catchment Area (RCA)

Year	A		SDR	Sediment Rate
	tons/ha/yr	tons/km^2/yr		tons/yr
2018	27.779	2,777.940	0.186	9,823.09
2019	28.838	2,883.821	0.186	10,197.50
2020	30.995	3,099.508	0.186	10,960.19
2021	27.739	2,773.936	0.186	9,808.93
2022	24.480	2,448.008	0.186	8,656.42
2023	24.731	2,473.129	0.186	8,745.247

The amount of sediment used in the calculation is an estimate of the erosion occurring in the Gerokgak Dam Catchment Area (RCA), where this land erosion amount represents the sediment carried by river flow into the reservoir's dead storage, subsequently affecting the reservoir's service life per year. Other factors that affect the service life of a reservoir besides land erosion are the water catchment area and the specific gravity of the soil. The catchment area of the Gerokgak reservoir is 18,972 km^2 and the soil density is 2.662 tons/m^3

Table 7. Reservoir Service Life of Gerokgak Reservoir Catchment Area (RCA)

Year	Dead Storage Volume	Erosion	Sediment Load		Reservoir Service Life
	m^3	*tons/km^2/yr*	*tons/yr*	*m^3/yr*	*year*
2018	205,053.390	27.779	9,823.090	26,147.428	7.842
2019	191,684.165	28.838	10,197.498	27,144.039	6.591
2020	177,805.370	30.995	10,960.192	29,174.204	5.202
2021	162,888.549	27.739	9,808.935	26,109.749	4.695
2022	149,538.589	24.480	8,656.417	23,041.940	4.187
2023	137,757.205	24.731	8,745.247	23,278.390	3.155
Reservoir Service Life Average					**5.279**

The calculation results for the Gerokgak Reservoir's service life are shown in Table 7, with an estimated average service life of around 5.279 years due to accelerated sediment accumulation. Emphasizes the importance of sediment management in reservoir maintenance, as uncontrolled sedimentation can significantly reduce the reservoir's service life [16], [19].

CONCLUSION

The results of erosion and sedimentation analysis in the Gerokgak Reservoir Catchment Area (RCA) reveal that the erosion rate in the area ranges from 24,480 to 30,995 tons/ha/year, with an average of 27,427 tons/ha/year. The sedimentation rate resulting from this erosion reaches between 8,656.42 and 10,960.19 tons/year, with an average sedimentation rate of 9,698.563 tons/year. Considering the sedimentation rate and the dead storage capacity of the reservoir, it is projected that the average service life of the Gerokgak Reservoir is approximately 5.279 years. These findings underscore the importance of implementing effective sediment management strategies to maintain the reservoir's storage capacity and extend its service life, ensuring that the reservoir can sustainably support the region's needs in the long term.

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