

Integrated assessment of land-use change, erosion, and reservoir sedimentation in a tropical volcanic watershed: Implications for sustainable watershed management in Indonesia

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ABSTRACT

Reservoir sedimentation is a major challenge affecting the long-term sustainability of water resources infrastructure in tropical watersheds. In the Upper Brantas River Basin, Indonesia, rapid land-use change and intensive agricultural activities have accelerated soil erosion and sediment delivery into the Sengguruh and Sutami reservoirs, significantly reducing their storage capacity and operational performance. This study aimed to evaluate the spatial distribution of erosion hazards, quantify sedimentation rates, and assess the effectiveness of soil and water conservation strategies in reducing sediment inflow into both reservoirs. An integrated approach combining the Universal Soil Loss Equation (USLE), Sediment Delivery Ratio (SDR), and Normalized Difference Vegetation Index (NDVI) analyses was applied using geospatial datasets, hydrological observations, sediment sampling, and land-use data for 2017 and 2023. The results indicate that annual erosion in 2023 reached 26.9 million tons/year in the Sengguruh watershed and 7.5 million tons/year in the Sutami watershed, with corresponding sediment delivery ratios of 8.34% and 9.30%, respectively. Land-use conversion from agricultural areas to built-up land substantially increased erosion susceptibility, particularly in steep upstream regions. Spatial analysis further revealed that moderate-to-very-high erosion hazard classes covered more than 62% of the watershed area. Reforestation and gully-plug interventions showed measurable, although limited, reductions in erosion and sedimentation rates, decreasing sediment delivery by up to 0.83%. The findings demonstrate that long-term sediment control in tropical volcanic watersheds requires integrated watershed management combining ecological restoration, structural conservation measures, and community-based land management. This study provides an important scientific basis for sustainable reservoir sediment management in rapidly developing tropical river basins.

1. Introduction

Reservoir sedimentation is one of the most critical challenges affecting the sustainability of water resources infrastructure worldwide, particularly in tropical developing regions where rapid land-use change and high rainfall intensity accelerate soil erosion processes. Sediment generated from upstream catchments is transported through river systems and deposited within reservoirs, gradually reducing storage capacity, hydropower efficiency, flood control performance, irrigation reliability, and water supply security [1, 2]. In many tropical watersheds, excessive sedimentation has become a major environmental and economic concern because it shortens reservoir service life and increases maintenance and operational

costs.

Sediment dynamics in river basins involve interconnected geomorphological processes including soil detachment, sediment transport, and deposition within downstream water bodies [3–5]. The magnitude of sediment delivery is strongly influenced by rainfall erosivity, topography, soil characteristics, vegetation cover, and human-induced land-use changes. Reservoirs located downstream of rapidly urbanizing and intensively cultivated watersheds are particularly vulnerable to accelerated sediment accumulation due to increased surface runoff and reduced soil protection. Furthermore, volcanic tropical regions commonly exhibit steep slopes and highly erodible soils, which amplify sediment transport during extreme rainfall events [6, 7].

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The Brantas River Basin in East Java Province, Indonesia, represents one of the most important and complex tropical watersheds in Southeast Asia. Covering approximately 11,832 km², the basin supports more than 22 million people and plays a strategic role in regional economic development, irrigation, hydropower generation, industrial activities, and domestic water supply [8–10]. The watershed is characterized by highly variable topography, intensive agricultural utilization, rapid urban expansion, and the presence of several active volcanoes that contribute large quantities of erodible volcanic material. These conditions make the Brantas Basin highly susceptible to erosion and sediment-related problems.

Among the reservoirs within the Brantas River system, Sengguruh and Sutami reservoirs are particularly important because they function as major hydropower and water regulation infrastructures in the upstream basin. However, both reservoirs have experienced severe sedimentation problems since their operation began. Sutami Reservoir has undergone substantial storage loss due to long-term sediment deposition, while Sengguruh Reservoir, which was originally constructed as a sediment trap to protect Sutami Reservoir, has also experienced accelerated sediment accumulation. The reduction in reservoir storage capacity has negatively affected hydropower production, dry-season water allocation, and flood mitigation capability during the rainy season [3, 11].

Previous studies on sedimentation in tropical watersheds have mainly focused on erosion estimation or sediment transport analysis separately, while limited studies have integrated land-use dynamics, vegetation conditions, erosion hazard assessment, and sediment delivery processes within a comprehensive watershed management framework [12, 13]. In addition, the effectiveness of soil and water conservation measures in reducing sediment delivery to reservoirs in tropical volcanic environments remains insufficiently quantified. Therefore, a spatially integrated assessment is needed to better understand the relationship between land-use change, erosion hazard, vegetation dynamics, and reservoir sedimentation in the Upper Brantas watershed [6, 14, 15].

This study aims to (1) quantify erosion and sedimentation rates in the Sengguruh and Sutami reservoir watersheds using the Universal Soil Loss Equation (USLE) approach, (2) evaluate spatial patterns of erosion hazard levels and vegetation conditions through Geographic Information System (GIS) and Normalized Difference Vegetation Index (NDVI) analyses, and (3) assess the potential effectiveness of soil and water conservation strategies, including reforestation and gully-plug development, in reducing sediment delivery to the reservoirs. The findings of this study are expected to provide scientific insights and practical recommendations for sustainable watershed and reservoir sediment management in tropical river basins experiencing rapid environmental change.

2. Materials and Methods

2.1. Study area

The study was conducted in the Sengguruh and Sutami reservoir watersheds located in the Upper Brantas River Basin, East Java Province, Indonesia (Fig. 1). The study area covers approximately 2,008 km² and is characterized by mountainous topography, volcanic landforms, high annual rainfall, and intensive agricultural activities. The watershed plays an important role in supporting hydropower generation, irrigation systems, flood control, and domestic water supply in East Java Province [4, 16].

Sutami Reservoir, also known as Karangates Reservoir, is located in Sumberpucung District, Malang Regency, approximately 35 km southwest of Malang City. The reservoir was constructed on the Brantas River between 1962 and 1973 and has been operating primarily for hydropower generation and water resources regulation. Initially, the reservoir had a total storage capacity of 343 million m³ and an effective storage capacity of 253 million m³. However, long-term sediment deposition has substantially reduced its storage volume. Based on reservoir surveys conducted in 2016, the total storage capacity decreased to approximately 187.24 million m³, while the effective storage capacity declined to 161.09 million m³ [17, 18].

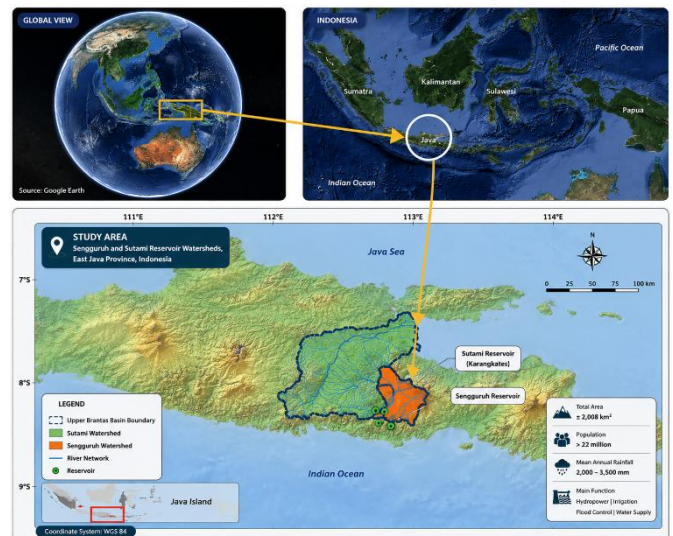


Fig. 1. Location of the Sengguruh and Sutami reservoir watersheds within the Upper Brantas River Basin, East Java Province, Indonesia.

To reduce sediment inflow into Sutami Reservoir, Sengguruh Dam was constructed upstream and began operation in 1989. Sengguruh Reservoir functions primarily as a sediment trapping reservoir and hydropower facility with an installed capacity of 2×14.5 MW. Although Sengguruh Reservoir has successfully reduced sediment delivery to Sutami Reservoir, it has experienced rapid sediment accumulation due to its role as the primary sediment trap within the Upper Brantas watershed system. Consequently, both reservoirs currently face significant sediment management challenges that threaten their long-term operational sustainability [3, 6, 16].

The watershed area is dominated by mixed land uses consisting of forests, agricultural land, plantations, rice fields, settlements, and shrubland. Rapid urban development and land-use conversion have altered hydrological responses and erosion characteristics in recent decades, increasing sediment transport into the reservoir system [19–21].

2.2. Data collection

Several spatial, hydrological, and environmental datasets were used in this study to evaluate erosion, sediment delivery, and reservoir sedimentation dynamics. The spatial datasets included:

- Digital Elevation Model Nasional (DEMNAS) with a spatial resolution of 8×8 m;
- Land-use and land-cover maps for 2017 and 2023;
- Rupa Bumi Indonesia (RBI) topographic maps at a scale of 1:25,000 obtained from the Geospatial Information Agency (BIG);
- Soil type and soil solum depth maps obtained from the Brantas Sampean Watershed Management Agency (BPDAS Brantas Sampean).

For the hydrological datasets included:

- Daily and monthly rainfall records;
- River discharge data;
- Suspended sediment concentration measurements;
- Reservoir sediment sampling data obtained from Perum Jasa Tirta I (PJT I).

Satellite imagery data were additionally used for NDVI analysis to evaluate vegetation density and spatial vegetation conditions across the watershed. Fig. 2 presents the detailed spatial distribution of the Sengguruh and Sutami reservoir watersheds, including reservoir locations, river networks, and watershed boundaries used in this study.

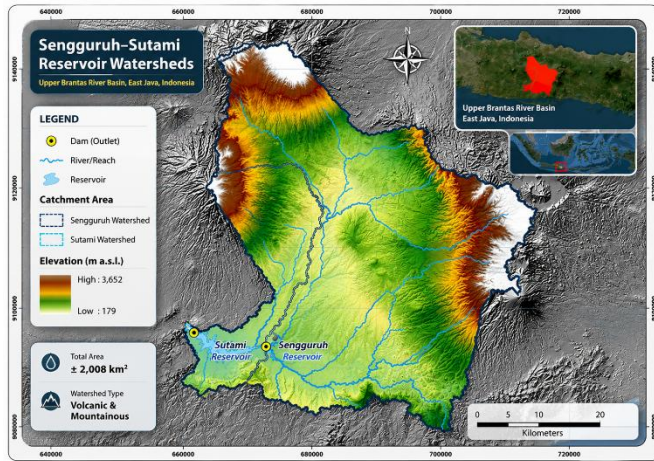


Fig. 2. Topographic and hydrological characteristics of the Sengguruh and Sutami reservoir watersheds in the Upper Brantas River Basin, East Java, Indonesia.

2.3. Research framework

This study employed an integrated geospatial and hydrological assessment framework to analyze watershed erosion and reservoir sedimentation processes. The research workflow consisted of the following stages:

- Watershed delineation and catchment modeling using DEM data;
- Rainfall erosivity (R-factor) calculation;
- Spatial analysis of land use, soil type, slope, and soil depth;
- Estimation of erosion rates using the Universal Soil Loss Equation (USLE);
- Sediment delivery and sedimentation analysis;
- Classification of erosion hazard levels;
- Vegetation assessment using Normalized Difference Vegetation Index (NDVI);
- Evaluation of soil and water conservation strategies for erosion and sediment reduction.

All spatial analyses were conducted using Geographic Information System (GIS)-based techniques to generate spatially distributed erosion and sedimentation assessments [3, 6, 16].

2.4. Erosion estimation using the USLE model

Soil erosion rates within the study area were estimated using the Universal Soil Loss Equation (USLE) developed by [7]. The USLE model is widely applied for predicting long-term average annual soil erosion caused by sheet and rill erosion under different land-use and management conditions [6, 14, 15]. The USLE equation is expressed as equation 1 :

$$A = R \times K \times LS \times C \times P \quad \dots (1)$$

where: A = estimated annual soil loss (tons ha⁻¹ year⁻¹); R = rainfall

erosivity factor; K = soil erodibility factor; LS = slope length and slope steepness factor; C = cover-management factor; P = conservation practice factor.

Each USLE parameter was generated spatially using GIS analysis and thematic datasets. Rainfall erosivity factor (R) represents the potential ability of rainfall to cause soil erosion. The erosivity factor was calculated using the empirical equation 2 developed by [2] for tropical regions in Java and Madura Islands [19–21].

$$EI_{30} = 6.119 \times (P_b)^{1.21} \times (N)^{-0.47} \times (P_{max})^{0.53} \quad \dots (2)$$

where: EI_{30} = monthly rainfall erosion index; P_b = monthly rainfall (cm); N = number of rainy days per month; P_{max} = maximum daily rainfall within the month (cm). Annual rainfall erosivity values were obtained by summing monthly erosivity indices.

The soil erodibility factor (K) describes the susceptibility of soil particles to detachment and transport by rainfall and surface runoff. The K -factor was determined based on soil texture, organic matter content, soil structure, permeability, and soil depth characteristics obtained from soil maps and previous watershed studies.

The LS -factor (LS) represents the combined effect of slope length and slope steepness on erosion processes. Steeper and longer slopes generally increase runoff velocity and erosive power, thereby increasing soil loss potential. The LS -factor was derived from DEM data using GIS-based terrain analysis.

The cover-management factor (C) reflects the effect of vegetation cover and land management practices on soil erosion rates. C -factor values were assigned based on land-use and land-cover classifications, where forested areas generally exhibited lower C values compared to agricultural or built-up land.

The conservation practice factor (P) represents the effectiveness of soil conservation measures in reducing erosion. The P -factor values were assigned according to land management practices, slope conditions, and conservation interventions present within the watershed.

Erosion hazard levels were classified based on the estimated annual soil loss and soil solum depth. The erosion hazard categories were grouped into five classes: very light, light, moderate, heavy, and very heavy erosion hazard levels. Spatial distribution maps of erosion hazard classes were generated using GIS analysis.

For the sediment transport entering the reservoirs was evaluated using suspended sediment concentration measurements and river discharge observations. Suspended sediment transport was estimated using the sediment rating curve relationship (equation 3).

$$Q_s = aQ_w^b \quad \dots (3)$$

where: Q_s = sediment discharge (kg s⁻¹); Q_w = water discharge (m³ s⁻¹); a and b = empirical constants derived from field observations. Daily sediment transport was estimated using equation 4.

$$Q_s = 86.4 \times C \times Q_w \quad (4)$$

where: C = suspended sediment concentration (mg L⁻¹); Q_w = water discharge (m³ s⁻¹). Annual sediment inflow into the reservoirs was estimated by integrating daily sediment transport values over one hydrological year. The Sediment delivery ratio (SDR) was used to estimate the proportion of eroded soil that reaches the reservoir system. SDR values were determined based on watershed area using the empirical relationship proposed by [6]. Higher SDR values indicate more efficient sediment transport from upstream erosion sources to downstream reservoirs.

2.5. Normalized difference vegetation index (NDVI) analysis.

Vegetation conditions within the watershed were evaluated using the Normalized Difference Vegetation Index (NDVI), which

was derived from satellite imagery. NDVI analysis was used to assess vegetation density, identify degraded land areas, and evaluate spatial vegetation dynamics associated with erosion susceptibility. The NDVI equation is expressed as equation 5.

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (5)$$

where: *NIR* = near-infrared reflectance; *Red* = red-band reflectance.

Higher NDVI values indicate denser and healthier vegetation cover, while lower values indicate sparse vegetation or degraded land conditions.

To evaluate the potential reduction in erosion and sedimentation, conservation scenarios involving reforestation and gully-plug construction were simulated. Reforestation planning considered land-use suitability, rainfall conditions, slope characteristics, and socio-economic benefits for local communities. In addition, gully plugs were planned in critical erosion zones to reduce runoff velocity, trap sediment, and stabilize small drainage channels. The effectiveness of conservation interventions was assessed by comparing erosion hazard levels and estimated sediment delivery before and after conservation implementation scenarios.

3. Results and discussion

3.1. Land-use change dynamics

Land-use and land-cover changes between 2017 and 2023 indicate substantial landscape transformation within the Sengguruh and Sutami reservoir watersheds. The dominant changes were associated with the expansion of built-up areas and plantations, accompanied by a reduction in rice fields and shrubland areas (Table 1 and Fig 3). Built-up areas increased from 478.66 km² (23.83%) in 2017 to 557.50 km² (27.76%) in 2023, reflecting rapid urbanization and infrastructure development within the Upper Brantas Basin. Meanwhile, plantation areas increased from 94.13 km² to 150.00 km², while rice-field areas decreased from 649.75 km² to 527.50 km².

The increase in built-up areas has important hydrological implications because impervious surfaces reduce infiltration capacity and increase surface runoff generation. Increased runoff contributes to higher flow velocity and sediment transport during

rainfall events, particularly in steep volcanic terrain. Similar findings have been reported in tropical watersheds where urban expansion significantly increases erosion susceptibility and sediment yield due to land surface disturbance and vegetation removal.

In contrast, forest areas slightly increased from 718.15 km² to 732.80 km² between 2017 and 2023. This increase may partially contribute to the reduction of erosion rates in some upstream areas because forest vegetation improves soil stability, reduces raindrop impact, and enhances infiltration processes. Nevertheless, the positive impact of increased forest cover appears insufficient to fully offset the effects of expanding built-up land and intensive agricultural activities [14, 22, 23].

Table 1

Land-use and land-cover changes in the Sengguruh and Sutami reservoir watersheds between 2017 and 2023

No	Landuse/ Landcover	2017		2023	
		Area (Km ²)	Percentages (%)	Area (Km ²)	Percentages (%)
1	Water	15.54	0.77	15.36	0.76
2	Forest	718.15	35.75	732.80	36.48
3	Bare Land	0.34	0.02	0.33	0.02
4	Built-up Areas	478.66	23.83	557.50	27.76
5	Plantation	94.13	4.69	150.00	7.47
6	Rice-field	649.75	32.35	527.50	26.26
7	Shrubs/Bushes	52.02	2.59	25.09	1.25
Total		2,008.58	100.00	2,008.58	100.00

3.2. Erosion and sedimentation assessment

The spatial analysis results indicate that erosion rates within the Sengguruh and Sutami watersheds remain very high. In 2023, estimated annual erosion in the Sengguruh watershed reached approximately 26.9 million tons year⁻¹, while the Sutami watershed produced approximately 7.5 million tons year⁻¹. Sediment delivery ratio (SDR) values were estimated at 8.34% and 9.30% for Sengguruh and Sutami watersheds, respectively. The estimated sediment delivery resulted in annual sedimentation potentials of approximately 1.246 million m³ year⁻¹ for Sengguruh Reservoir and 387 thousand m³ year⁻¹ for Sutami Reservoir. Although the sedimentation rate in Sengguruh Reservoir slightly decreased compared to 2017, sediment accumulation remains critically high and continues to threaten reservoir sustainability.

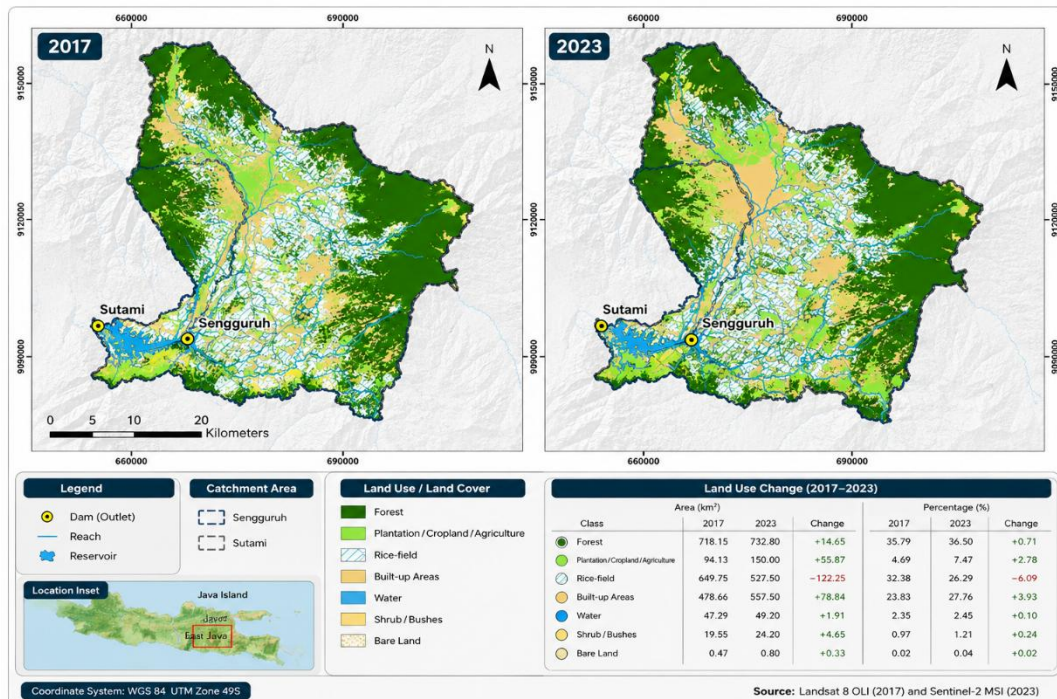


Fig. 3. Spatial distribution of land-use and land-cover changes in the Sengguruh and Sutami reservoir watersheds between 2017 and 2023.

The relatively high sediment production within the watershed is strongly associated with steep slopes, highly weathered volcanic soils, intense tropical rainfall, and land-use conversion. Spatial analysis showed that erosion hotspots were primarily concentrated in upstream mountainous areas characterized by steep topography and limited vegetation protection. These findings are consistent with previous studies showing that tropical volcanic watersheds are highly susceptible to accelerated erosion due to unstable soil structure and high rainfall erosivity.

Interestingly, sedimentation in Sutami Reservoir increased from approximately 365 thousand m³ year⁻¹ in 2017 to 387 thousand m³ year⁻¹ in 2023 despite a slight increase in forest cover. This indicates that localized land degradation, urban expansion, and hydrological connectivity may play more important roles than total forest area alone. The increase in built-up areas likely enhanced runoff efficiency and sediment transport connectivity from upstream erosion sources to downstream reservoirs.

The continued sediment accumulation in both reservoirs demonstrates that current watershed management efforts remain insufficient to significantly reduce sediment delivery. Long-term sediment management strategies therefore require integrated interventions combining ecological restoration, engineering-based conservation measures, and sustainable land-use planning

3.3. Erosion hazard levels

The erosion hazard assessment classified the watershed into five erosion hazard categories: very light, light, moderate, heavy, and very heavy erosion hazard levels (Fig. 4 and Table 2). In 2023, moderate erosion hazard dominated the watershed area, covering approximately 40.12% of the total catchment area, followed by light erosion hazard at 31.66%. Areas categorized as heavy and very heavy erosion hazard accounted for approximately 22.69% of the watershed area, indicating the presence of extensive critically degraded land requiring immediate conservation intervention. These high-risk areas were generally associated with steep slopes,

sparse vegetation cover, agricultural cultivation on hillslopes, and exposed soil surfaces.

Compared to 2017, the moderate and heavy erosion hazard classes increased slightly in 2023, while the very light and light erosion hazard categories decreased. This trend suggests that land-use intensification and urban development have gradually increased watershed vulnerability to soil erosion processes. The spatial distribution of erosion hazard levels further highlights the importance of topography and vegetation conditions in controlling erosion susceptibility. Areas with dense forest cover generally exhibited lower erosion hazard classes, whereas cultivated and sparsely vegetated areas showed substantially higher erosion potential. These findings emphasize the critical role of vegetation cover in maintaining watershed stability in tropical mountainous environments.

Table 2

Erosion hazard level of sengguruh and sutami reservoir watersheds

No	Erosion Hazard Level	2017		2023	
		Area (Km ²)	Percentages (%)	Area (Km ²)	Percentages (%)
1	<15 tons/ha/year (very light)	124.78	6.21	111.08	5.53
2	15 - 60 tons/ha/year (light)	664.27	33.07	635.90	31.66
3	60 - 180 tons/ha/year (moderate)	754.00	37.54	805.82	40.12
4	180 - 480 tons/ha/year (heavy)	300.61	14.97	312.80	15.57
5	>480 tons/ha/year (very heavy)	164.91	8.21	142.98	7.12
Total		2,008.58	100.00	2,008.58	100.00

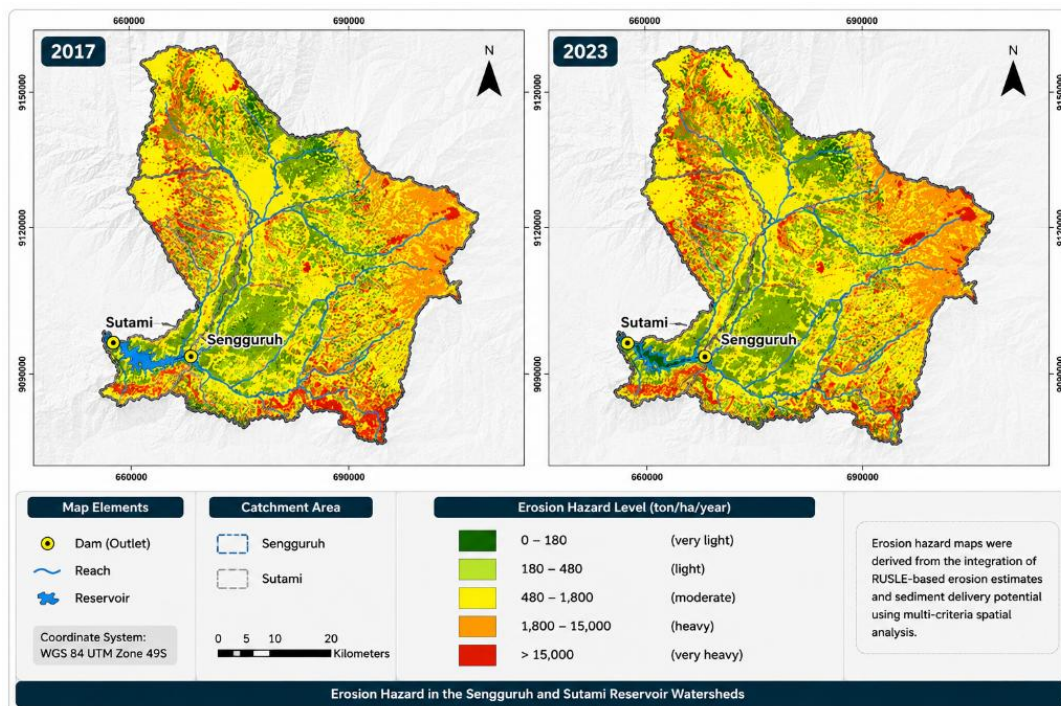


Fig. 4. Spatial distribution and temporal changes of erosion hazard levels in the Sengguruh and Sutami reservoir watersheds between 2017 and 2023.

3.4. Vegetation dynamics based on NDVI analysis

The NDVI analysis provided important information regarding vegetation density and spatial vegetation conditions within the study area (Fig. 5). Areas with high NDVI values were mainly distributed in forested upstream regions and mountainous terrain, indicating dense and healthy vegetation cover. In contrast, low

NDVI values were observed in urban areas, agricultural land, and degraded hillslopes characterized by limited vegetation protection. The NDVI spatial pattern showed strong correspondence with erosion hazard distribution. Areas with low vegetation density generally coincided with moderate-to-very-high erosion hazard classes, confirming the important role of vegetation in reducing rainfall impact and improving soil stability.

Vegetation degradation in several sub-watersheds may be associated with agricultural expansion, settlement development, and land clearing activities. Reduced vegetation cover increases surface runoff and soil detachment, thereby enhancing sediment transport toward downstream reservoirs. The NDVI analysis also demonstrates the usefulness of remote sensing techniques for identifying critical land areas requiring priority conservation treatment. Integrating NDVI analysis with erosion modelling provides an effective approach for spatial watershed management and environmental monitoring in tropical regions.

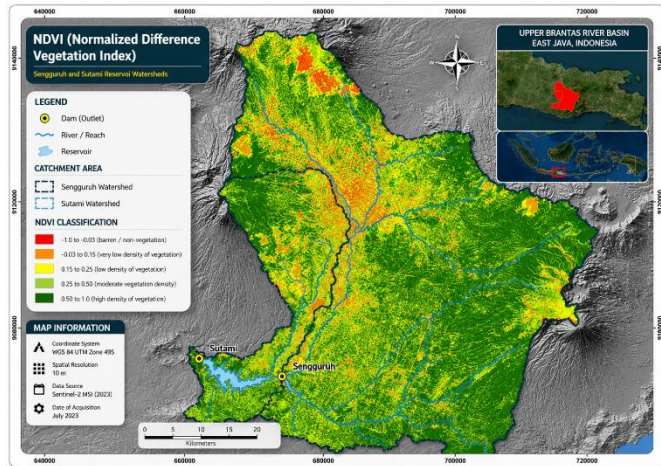


Fig. 5. Spatial distribution of NDVI values in the Sengguruh and Sutami reservoir watersheds.

3.5. Soil and water conservation strategies

3.5.1. Reforestation planning

Reforestation and agroforestry were identified as key strategies for reducing erosion and sediment delivery within the watershed. Conservation planning considered rainfall characteristics, slope conditions, land-use suitability, and socio-economic benefits for local communities. Forest restoration was prioritized in areas with moderate-to-very-high erosion hazard levels. Recommended species included both ecological and economically valuable plants such as pine, sengon (*Falcataria moluccana*), clove, eucalyptus, avocado, durian, mangosteen, and jackfruit. Integrating conservation with community-based agroforestry systems is particularly important in tropical developing regions because local economic incentives strongly influence the long-term sustainability of conservation programs.

The implementation of agroforestry systems may significantly improve vegetation cover while simultaneously increasing community income through agricultural and plantation products. Similar approaches have been widely recognized as effective strategies for balancing ecological restoration and socio-economic development in tropical watersheds [24].

3.5.2. Gully plug development

In addition to vegetation-based conservation, engineering measures in the form of gully plugs were proposed to reduce runoff velocity and trap sediment within critical erosion channels. A total of 20 gully-plug locations were proposed within the Sengguruh watershed and 10 locations within the Sutami watershed (Fig. 6). Gully plugs function by stabilizing drainage channels, reducing channel incision, and promoting local sediment deposition before sediment reaches the main river system. These structures are particularly effective in steep mountainous areas where concentrated surface runoff accelerates channel erosion. However, the effectiveness of gully-plug structures depends on appropriate site selection, maintenance, and integration with upstream vegetation restoration. Structural conservation alone is generally

insufficient to substantially reduce sediment yield without broader landscape-scale ecological rehabilitation [20, 21, 25].

3.6. Effectiveness of conservation scenarios

The simulated conservation scenarios showed relatively limited reductions in erosion hazard and sediment delivery after reforestation and gully-plug implementation (Fig. 7 and Table 3). Reforestation covering approximately 17.11 km² combined with 30 gully-plug structures reduced sedimentation rates by approximately 0.5% in the Sengguruh watershed and 0.83% in the Sutami watershed.



Fig. 6. Spatial distribution of proposed soil and water conservation interventions in the Sengguruh and Sutami reservoir watersheds.

Although the reduction appears relatively small, the results indicate that conservation measures can gradually improve watershed conditions when implemented continuously and consistently over long periods. The modest reduction is likely related to the extensive scale of watershed degradation and the limited spatial extent of conservation interventions compared to the total watershed area. The findings further suggest that effective sediment management in large tropical watersheds requires integrated long-term strategies rather than isolated short-term interventions. Large-scale reforestation, sustainable land-use regulation, erosion control infrastructure, and community participation are essential components for reducing sediment delivery into reservoirs [16, 26, 27].

Community involvement represents one of the most critical factors determining conservation success. In many upstream watershed areas, local communities depend heavily on agriculture and land resources for their livelihoods. Therefore, conservation programs must incorporate economic incentives and participatory approaches to ensure sustainable implementation [28, 29].

Table 3

Erosion hazard level of sengguruh and sutami reservoir watersheds after reforestation

No	Erosion Hazard Level	2023		Reforestation	
		Area (Km ²)	Percentages (%)	Area (Km ²)	Percentages (%)
1	<15 tons/ha/year (very light)	111.08	5.53	113.92	5.67
2	15 - 60 tons/ha/year (light)	635.90	31.66	637.58	31.74
3	60 - 180 tons/ha/year (moderate)	805.82	40.12	803.54	40.01
4	180 - 480 tons/ha/year (heavy)	312.80	15.57	312.63	15.56
5	>480 tons/ha/year (very heavy)	142.98	7.12	140.91	7.02
Total		2,008.58	100.00	2,008.58	100.00

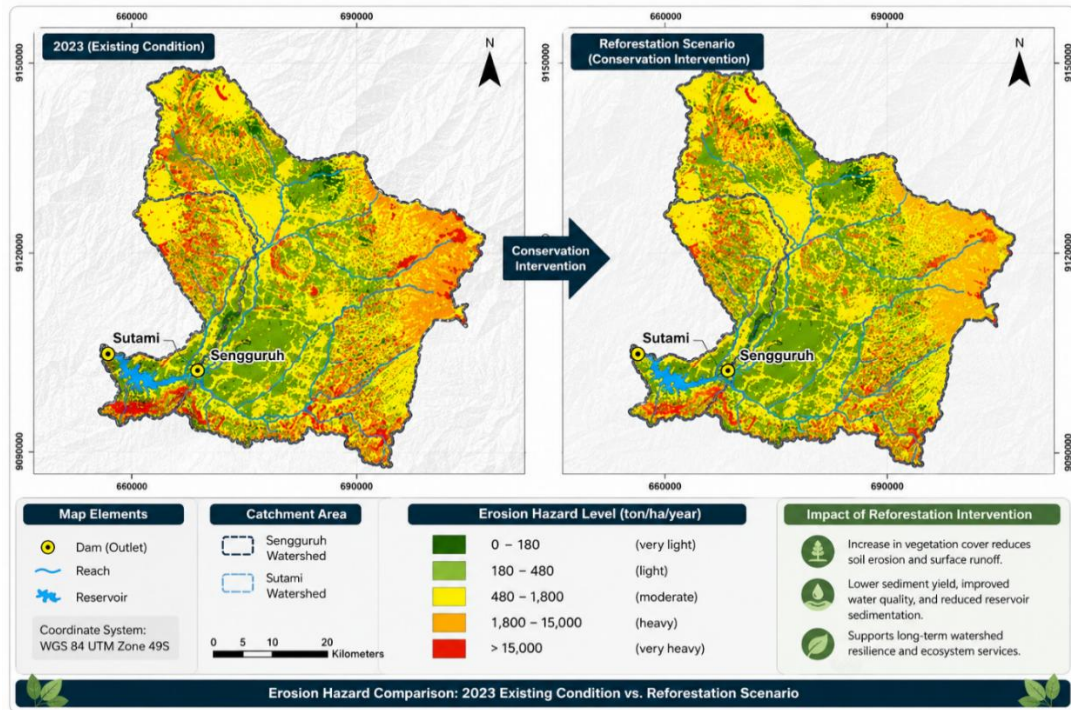


Fig. 7. Comparison of erosion hazard levels before and after reforestation interventions in the Sengguruh and Sutami reservoir watersheds.

Overall, the study demonstrates that combining spatial erosion assessment, vegetation monitoring, and conservation scenario analysis provides valuable scientific information for sustainable watershed management and reservoir sediment mitigation in tropical river basins.

For the future watershed management programs in the Upper Brantas Basin should prioritize large-scale reforestation and sustainable land-use management in areas classified as moderate-to-very-high erosion hazard zones. Continuous monitoring using remote sensing and GIS-based approaches is also recommended to evaluate long-term vegetation dynamics and watershed degradation processes.

Further studies are recommended to incorporate hydrological modelling, climate variability, and sediment transport simulation under future land-use and climate-change scenarios. In addition, more detailed field-based sediment measurements and uncertainty analysis are needed to improve the accuracy of erosion and sedimentation estimates.

Periodic reservoir sediment management, including dredging and sediment flushing operations, should also be considered to maintain reservoir storage capacity and operational sustainability. Finally, strengthening collaboration among government agencies, reservoir operators, researchers, and local communities is essential to ensure the successful implementation of integrated soil and water conservation strategies in the Upper Brantas River Basin.

4. Conclusion

This study demonstrated that the Sengguruh and Sutami reservoir watersheds in the Upper Brantas River Basin are highly vulnerable to soil erosion and reservoir sedimentation due to the combined influence of steep topography, high rainfall intensity, land-use change, and intensive human activities. Spatial analysis revealed that land-use conversion, particularly the expansion of built-up areas and agricultural activities, has increased watershed susceptibility to erosion and enhanced sediment delivery into both reservoirs.

The USLE-based assessment showed that annual erosion rates in 2023 reached approximately 26.9 million tons year⁻¹ in the Sengguruh watershed and 7.5 million tons year⁻¹ in the Sutami watershed. Corresponding sediment delivery ratios were estimated at 8.34% and 9.30%, respectively, resulting in substantial annual sedimentation potential within the reservoir

system. Moderate-to-very-high erosion hazard classes covered more than 62% of the total watershed area, indicating extensive land degradation and the urgent need for watershed rehabilitation measures.

NDVI analysis further confirmed that vegetation density strongly influences erosion susceptibility. Areas with low vegetation cover generally corresponded to high erosion hazard zones, emphasizing the importance of maintaining vegetation cover for watershed stability and sediment control in tropical mountainous environments.

The conservation scenario analysis indicated that reforestation and gully-plug interventions can contribute to reducing erosion and sedimentation rates, although the reduction achieved in this study remained relatively limited. Reforestation covering approximately 17.11 km² and the installation of 30 gully-plug structures reduced sedimentation rates by approximately 0.5% in the Sengguruh watershed and 0.83% in the Sutami watershed. These results suggest that small-scale conservation measures alone are insufficient to significantly reduce sediment delivery in large tropical watersheds.

Effective long-term sediment management therefore requires integrated watershed management strategies that combine large-scale ecological restoration, structural erosion control measures, sustainable land-use planning, and active community participation. Conservation programs should also incorporate socio-economic considerations to ensure sustainable implementation and improve local community livelihoods.

Overall, this study highlights the importance of integrating geospatial analysis, erosion modelling, vegetation assessment, and conservation scenario evaluation to support sustainable reservoir and watershed management in tropical river basins experiencing rapid environmental change.

CRedit authorship contribution statement

Ariet Setiawan: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.
Rr Diah Nugraheni Setyowati: Writing – review & editing, Investigation.
Glenaldo Achmad Zhafran Evito: Formal analysis, Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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