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RESEARCH ARTICLE

A CONSERVATION MODEL TO REDUCE EROSION AND SEDIMENT RATE BASE ON GPM SATELLITE RAINFALL IN A RESERVOIR CATCHMENT AREA

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ABSTRACT

The phenomenon of erosion in river basins that have water infrastructure is a major problem in river basin management. Global climate change and high levels of change in watershed utilization that exceed their carrying capacity accelerate erosion and increase sedimentation. Modeling the effectiveness of bench terrace conservation by combining real-time rainfall data from satellites with erosion analysis using the MUSLE (Modified Universal Soil Loss Equation) method is expected to yield an appropriate model to reduce erosion rates. This research is novelty in developing an integrated land conservation model utilizing Global Precipitation Measurement (GPM) satellite rainfall data as the primary source of hydrological input for reservoir catchments. Unlike other studies, which generally rely on spatially limited station-based rainfall data, this study integrates GPM-based MUSLE results with a bench terrace conservation scenario to evaluate the effectiveness of conservation measures under spatially and temporally variable rainfall conditions. The results of the analysis show that the erosion rate reached 403.930 tons/year in a catchment area of 3325 hectares, indicating a fairly high level of erosion. The application of the open bench terrace conservation method can reduce erosion by 4.02% of the total area of the watershed, with the mechanism of reducing surface flow velocity, increasing infiltration capacity, and retaining soil particles. Modeling conservation practices using the terrace bench method can control erosion and is a crucial step in sustainable watershed management. Therefore, integrating erosion modeling and soil conservation practices is necessary to maintain environmental stability and extend the lifespan of water resource infrastructure within the watershed.

KEYWORDS

Erosion, Sedimentation, Conservation, Bench Terrace, Satellite, Infrastructure

1. INTRODUCTION

The existence of a dam in an area serves a very important function by providing water for multiple sectors and controlling flooding. The sustainability of dam function is greatly influenced by various factors, including climate change, erosion, sedimentation, and changes in land use by humans. Reservoir catchment areas play an important role in maintaining the sustainability of water resources, such as in flood control, clean water sources, water for irrigation, and other sector needs. In recent developments, the problem of river basin degradation has occurred very massively due to human activities in the form of land use for seasonal agriculture, as well as due to human activities (Bahadur, 2009; Kaiser et al., 2018).

Especially in tropical areas, river basins face problems in the form of very severe erosion caused by high rainfall intensity and changes in land use (Samir et al., 2026). Furthermore, damage to land, soil, and water resources can also be caused by land use for monoculture plantations, overexploitation, land reclamation, and forest conversion (Xiao-Jin Jiang et al., 2023; Tilman et al., 2017). Likewise, there are massive changes in the use or modification of river flows by humans for a wide range of interests (Haddeland et al., 2014). Economic factors are one of the causes of substantial changes in watershed hydrological processes and water resource conservation (Zhang et al., 2020).

The phenomenon of global climate change with its various impacts, particularly in water resource management, increases the understanding that water conservation is very important for the security of regional and global water ecosystems (Brauman et al., 2007; Pettinotti et al., 2018). Climate change also plays a major role in the damage to river basins, namely in the form of high rainfall intensity, which has an impact on high levels of land erosion (Paolo et al., 2025). Erosion material will be transported into the river and flow into the reservoir, causing the reservoir bed to become shallower. One of the major problems facing

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reservoir construction is the high sediment load entering the reservoir. Analysis of erosion and sedimentation rates in catchment areas is very important and crucial to accurately determine the sediment entering the reservoir (Abdelhak et al., 2025). Rainfall has an influence on changes in weather, climate, hydrology, and ecological systems in river basins (Dore, 2005; Oki and Kanae, 2006).

Rainfall and land use are the main factors that influence the erosion process through the mechanism of rain kinetic energy and increased surface runoff (Qin Zhang et al., 2023). Thus, accurate, real-time, and continuous rainfall information is needed in erosion analysis and conservation modeling of reservoir catchment areas. The development of remote sensing technology provides crucial solutions, particularly in the provision of rainfall data (Zhen-Gao et al., 2020).

Global precipitation measurement (GPM) is a rainfall data provider with relatively high temporal and spatial resolution and can be used in areas where the availability of observational rainfall data is limited at relatively fine resolution (Yiding-Wang et al., 2026; Derin et al., 2023). The combination of satellite rainfall data and the application of watershed conservation models is a strategic approach to reducing erosion and sedimentation rates for reservoir maintenance. Watershed conservation models can be used to simulate the effects of various efforts or actions to reduce erosion rates.

Various conservation techniques can be applied, such as land cover vegetation, terracing, agroforestry, and technical conservation practices (Alebachew et al., 2025). By integrating GPM satellite rainfall data into conservation modeling, erosion and sedimentation analysis can be conducted more comprehensively and spatially, thus providing recommendations for planning more effective conservation actions.

2. Material And Methods

2.1 Research Location

The research location is the Meninting Dam River catchment area. The Meninting Dam is a water resource infrastructure whose construction is scheduled for completion in 2025. In an effort to maintain the dam's sustainable function, it is crucial to establish appropriate conservation measures. This is because almost 60% of the reservoir's catchment area is used as productive land for seasonal crops. The Meninting Watershed has an area of 114.92 km2 with a main river length of 40.83 km. Geographically, the Meninting Watershed is located at coordinates 116°06'42'' East Longitude and 8°32'57'' South Latitude, which includes the Meninting Dam Catchment Area.

2.2 DATA

This research requires several data points, including:

- Rainfall data for the Meninting Watershed at the Gunungsari rainfall station for 30 years, from 1994 to 2024.
- GPM satellite rainfall data.
- Digital Elevation Model (DEM) map.
- Soil type map of the Meninting Watershed.
- Land use map of the Meninting Watershed.

2.3 ANALYSIS STEPS

2.3.1 Preparation

- Preparation and download of GPM satellite rainfall data
- Automatic rainfall data collection at several Gunungsari rainfall stations with a data span of 30 years.
- Identification of watershed conditions
- Identification of land use

2.3.2 Satellite Rainfall Data Validation

The validation process for GPM satellite rainfall data and surface rainfall data. To validate the GPM rainfall data and surface rainfall data, statistical analysis was performed by calculating the correlation value (r) and RMSE (Root Mean Square Error).

Correlation (R), mean square error (RMSE), and Nash-Sutcliffe efficiency (NSE)

Correlation analysis is a statistical method commonly used to determine the strength of the relationship between two variables. The correlation coefficient formula is as follows (Berbosa et al., 2019):

$$r = \frac{n\sum_{i=1}^{n} X_i Y_i - (\sum_{i=1}^{n} X_i)(\sum_{i=1}^{n} Y_i)}{\sqrt{\left[n\sum_{i=1}^{n} X_i^2 - (\sum_{i=1}^{n} X_i)^2\right]\left[n\sum_{i=1}^{n} Y_i^2 - (\sum_{i=1}^{n} Y_i)^2\right]}} \quad (1)$$

where: Xi is observation data (rain gauge data), Yi is estimated data

(estimated satellite data), and n is the number of data.

The root mean squared error of prediction (RMSE), which is the root of the averaged squared difference between the observed value y and the estimated value yr

$$RMSE = \sqrt{\frac{\sum_i^n (y_i - y_r)^2}{N}} \quad (2)$$

N denotes the number of data samples; y and yr represent observed data and simulated data, respectively.

Nash–Sutcliffe Efficiency (NSE) is a statistical indicator utilized to assess the forecasting capability of models by comparing the values that are observed with those that are simulated (McCuen et al., 2006). The magnitude of the NSE value is shown as in equation 3 (Nash et al., 1970)

$$NSE = 1 - \frac{\sum (y_{obs(t)} - y_{sim(t)})^2}{\sum (y_{obs(t)} - y_{obs})^2} \quad (3)$$

where yob(t) is observed rainfall at time t, and ysim(t) is simulated rainfall at time t, and yobs is the average observed rainfall.

2.3.3 Erosion Rate Estimates

The estimated erosion rate is an estimate of the level of soil erosion that may occur in an area over a certain period of time, influenced by various factors, such as climate conditions, soil characteristics, topography, and human activities. In estimating the erosion rate based on the factors that influence it, the MUSLE (Modified Universal Soil Loss Equation) method can be used.

The MUSLE method is a modification of the USLE (Universal Soil Loss Equation), in which the rainfall erosivity factor (E) is replaced by the flow or surface runoff factor (R). The MUSLE method considers both erosion processes and sediment movement in the watershed based on a single rainfall event, with the following equation used (Simon and Senturk, 1992)

E = R x K x LS x C x P (4)

Where: E is the amount of eroded soil (tons/ha/year), R is surface flow/runoff, K is the soil erodibility factor, LS is the land length and slope factor, and C is the flow coefficient.

2.3.4 Runoff (R)

Surface flow (runoff) is the process of moving rainwater that is not absorbed by the soil and flows over the earth's surface toward water bodies such as rivers, lakes, or the sea.

Runoff can occur due to high rainfall intensity, low soil infiltration capacity, or the presence of impermeable surfaces such as roads and buildings. Factors influencing runoff include land slope, soil type, vegetation cover, and land use. The runoff factor can be calculated using the following equation:

$R = a \times (Vq \times Qp)^b$ (5)

Where: R = surface runoff (m^3/s), Vq is surface flow volume (m^3), Q_p is peak discharge (m^3/s), a is 11.8 (constant), b = 0.56 (constant)

2.3.5 Flow Volume (Vq)

According to Chow et al. (1988), flow volume (vq) is the total amount of water flowing through a river or channel cross-section over a specific time period. This volume is influenced by rainfall intensity, catchment area, and land characteristics, such as infiltration rate and surface type. It can be calculated using the following equation:

Vq = CHmax x C x A (6)

Where: Vq is surface flow volume (m^3), Chmax is the maximum rainfall (m), A is the drainage area (m^2), and C is the flow coefficient

2.3.6 Conservation Model

The analysis of land conservation guidelines was conducted using ArcGIS software using the MUSLE method. At this stage, the P factor values, as shown in Table 1, were adjusted to reflect the type of conservation action planned. The land conservation guidelines analyzed in this study were the bench terrace method.

Table 1: P Factor Values For Various Specific Soil Conservation Measures (Asdak, 2010)

Special soil conservation techniques	P value
Without erosion control measures	1.000
Bench terrace:	
• Good construction	0.040
• Fair construction	0.150
• Poor construction	0.350
• Traditional terrace	0.400
Plant strips:	
• Bahia grass	0.400
• Crotalaria	0.640
• Contoured	0.200
Land management and planting according to contour lines:	
• Slope 0 – 8%	0.500
• Slope 8 – 20%	0.750
• Slope >20%	0.900

3. Results

3.1 Correlation Coefficient, RMSE, and NSE

Based on the equation 1,2, and 3, the relationship between GPM satellite rainfall data and rainfall data measured by the Gunungsari rainfall station shows a correlation coefficient (R) value of 0.5849, root mean square error (RMSE) of 36.222, and Nash-Sutcliffe Efficiency (NSE) of 0.421. A correlation value of 0.594 indicates a moderate and positive correlation between the two datasets. This indicates that the rainfall variation pattern captured by the GPM satellite rainfall data matches the field measurements from the Gunungsari rainfall station (Figure 1).

The RMSE value of 36.222 indicates the magnitude of the average error between the satellite rainfall estimates and field measurement data. This value indicates that there is still a difference between the satellite data and the measurement data, which is likely influenced by factors such as the satellite's wider spatial resolution compared to field measurement data, topographic conditions, and local rainfall variability. Meanwhile, the Nash-Sutcliffe Efficiency (NSE) value of 0.421 indicates that the satellite rainfall data's performance in representing observational data is in the sufficient category.

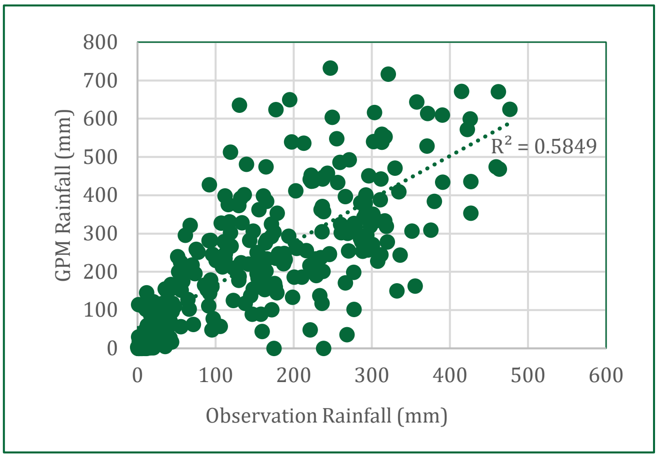

Figure 1: Correlation of Rainfall Observation Gunungsari Stations with GPM Rainfall

3.2 GPM Rainfall Intensity

Rainfall intensity is an important parameter in runoff modeling. Using the Mononobe equation, the maximum rainfall intensity occurred in the first hour at 61.11 mm/hour, while in the 24th hour, the intensity decreased to around 24 mm/hour (Figure 2).

High rainfall intensity in the initial phase has the potential to produce large surface runoff because the soil's infiltration capacity is limited in a short time.

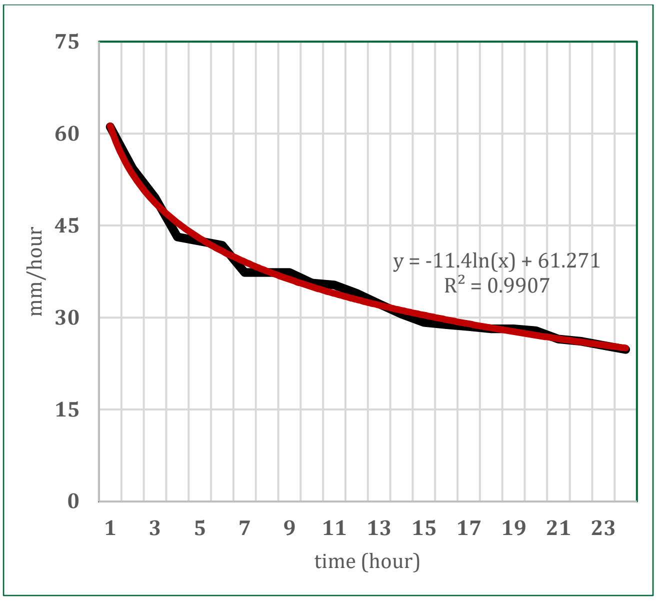

Figure 2: Average Rainfall Intensity GPM For 24 Hours

3.3 Surface Runoff (R)

Figure 3 shows surface runoff in the Meninting River watershed during the 1994-2024 period, which showed significant variation.

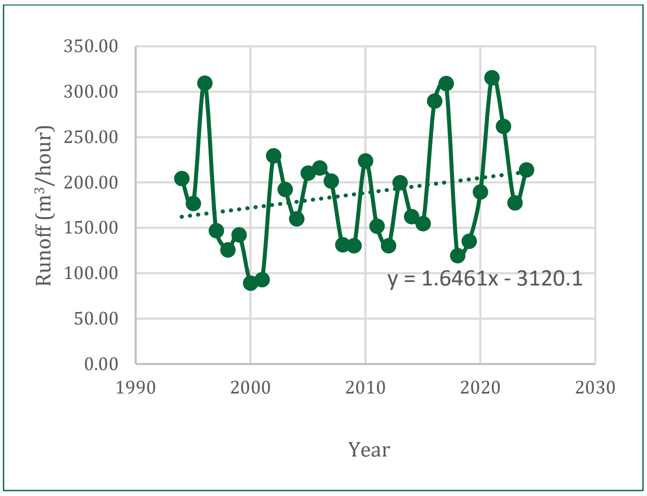

Figure 3: Surface Runoff That Occurred in The Meninting River Watershed During the Period 1994-2024

3.4 Soil Erodibility (K)

The soil erodibility in the Meninting Watershed is dominated by brown soils, which exhibit moderate to high susceptibility to erosion. An erodibility factor (K) of 0.323 indicates that the soil is highly dispersible and transported by surface runoff, especially during heavy rainfall. Brown soils generally have a well-developed structure and are susceptible to particle release if land cover is inadequate.

3.5 Land Cover

The land cover factor value in the Meninting Watershed shows the important role of vegetation in controlling the rate of erosion. The primary dryland area is 1792.74 hectares with a C value of 0.02, which reflects the excellent condition of vegetation cover, so that it is able to provide optimal protection to the land surface from the kinetic energy of rain and surface flow. The secondary forest area is 1337.99 hectares with a slightly higher C value, 0.03, which indicates that although the vegetation is still quite good, the level of protection is slightly lower compared to the primary forest. The rest is mixed primary forest with a C value of 0.1, which indicates a lower level of protection (Figure 4).

3.6 Erosion Rate Using the MUSLE Methods

Table 2 shows the erosion hazard level was then classified into five classes: Class I (<15 tons/hectares/year) categorized as very light; Class II (15–60 tons/hectares/year) categorized as light; Class III (60–180 tons/hectares/year) categorized as moderate; Class IV (180–480 tons/hectares/year) categorized as severe; and Class V (>480 tons/hectares/year) categorized as very severe, each with varying extents.

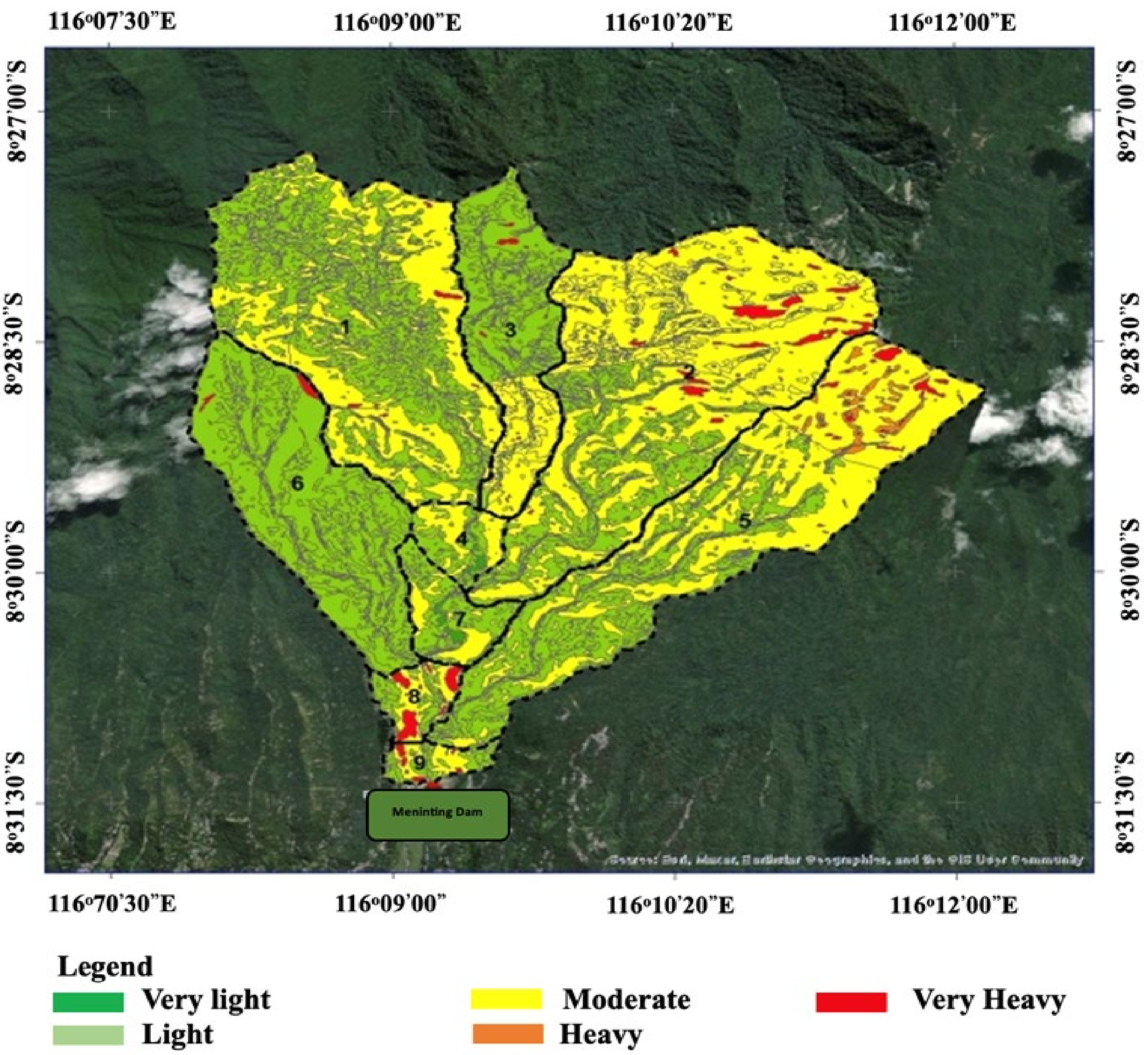

Figure 4: Map of the Erosion Hazard Level in the Menintting Dam Catchment Area.

Table 2: Recapitulation of Erosion Rate and Erosion Danger Level in the Menintting Dam Catchment Area

Class	Erosion rate Ton/hectares/year	Area		Erosion Danger Level
		hectares	%	
I	< 15	9.94	0.30	Very light
II	15 – 60	1788.43	53.78	Light
III	60 – 180	1435.48	43.16	Moderate
IV	180 – 480	29.06	0.87	severe
V	> 480	62.71	1.89	Very severe

3.7 Bench Terrace Method Conservation

Figure 5 shows that the results of the analysis show that the application of the bench terrace land conservation method causes changes in the distribution of erosion hazard class. In erosion hazard class I (<15 tons/hectare/year), the area increased from 9.95 hectares (0.30%) to 39.62 hectares (1.19%), indicating a shift in some areas towards lower erosion hazard classes. In erosion hazard class II (15–60 tons/hectare/year), the area increased slightly from 1788 hectares (53.78%) to 1.805 hectares (54.29%).

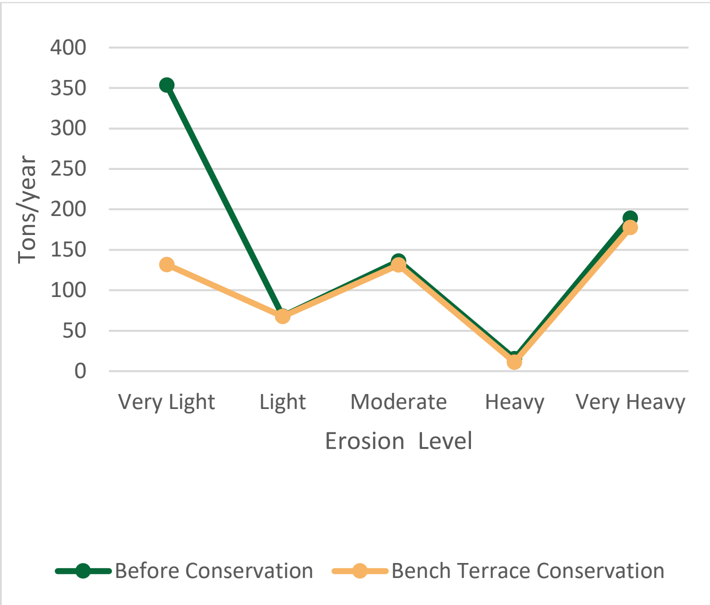

Figure 5: Comparison of Sediment Volume Before Conservation and After Conservation.

4. Conclusion

Based on the analysis and discussion, the following conclusions can be drawn:

- Analysis using the Modified Universal Soil Loss Equation (MUSLE) shows that the watershed erosion rate is 403.930 tons/year, with an eroded area of 3325 hectares. This indicates a moderate level of erosion vulnerability and the potential to accelerate land degradation and sedimentation downstream.
- The application of the bench terrace conservation method can reduce the eroded land area by 4.02%. This indicates that the bench terrace conservation technique is effective in reducing surface runoff, increasing infiltration, and retaining soil particles from transport.
- The erosion prediction approach using the MUSLE method and the application of bench terrace conservation can be an appropriate strategy in watershed management to suppress erosion, maintain land productivity, and extend the lifetime of water resource infrastructure.
- The research can be used as an initial identification tool for establishing conservation priority areas and understanding watershed responses to rainfall variability, rather than as a basis for precise technical calculations. Therefore, further research development requires improved field-based calibration, integration of multiple conservation scenarios, and the use of more detailed process-based models to improve the accuracy of erosion and sedimentation.

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