

Estimation of Soil Erosion Rate and Land Conservation in the Upstream Area of Unda Watershed Using a Geospatial Information Approach

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ABSTRACT: This study aimed to analyze soil erosion rates, erosion hazard levels, and to identify appropriate land conservation measures in the upstream area of the Unda Watershed using a geospatial information approach. The study employed the Universal Soil Loss Equation (USLE) method integrated with Geographic Information Systems (GIS). The analysis was conducted by combining rainfall data, soil type, land use, slope gradient, and land management factors to estimate soil erosion and determine erosion hazard levels. The results showed that soil erosion rates in the upstream area of the Unda Watershed varied from low to very high categories. The highest erosion rate ranged from 483.36 to 11,499.13 tons ha⁻¹ year⁻¹, covering an area of 1,469.98 ha (14.28% of the watershed area), while the lowest erosion rate ranged from 0 to 14.27 tons ha⁻¹ year⁻¹, covering 4,222.66 ha (41.02% of the watershed area). Based on the erosion hazard level (EHL) classification, different land conservation measures were recommended. Areas with Very Slight EHL require maintenance of land conditions through litter return, crop rotation, and simple ground cover. Slight EHL areas are recommended to apply contour planting, mulching, and cover crops. Moderate EHL areas require simple terracing, strip cropping, and a combination of vegetative and mechanical conservation techniques. Severe EHL areas should implement intensive terracing, reforestation with terrace-strengthening vegetation, and drainage channels. Meanwhile, Very Severe EHL areas require total land rehabilitation, permanent revegetation, and designation as protected areas. The integration of the USLE model and GIS proved effective in identifying spatial patterns of erosion risk and providing appropriate land conservation recommendations. Therefore, this approach can be used as a valuable tool for sustainable watershed management and soil conservation planning in the upstream area of the Unda Watershed.

KEYWORDS: Soil Erosion, Land Conservation, Upstream Unda Watershed, Geospatial Information, USLE.

INTRODUCTION

Soil erosion is one of the major causes of land degradation that threatens agricultural sustainability and environmental quality. The loss of topsoil rich in nutrients and organic matter reduces soil fertility, decreases water-holding capacity, increases surface runoff, and accelerates land degradation processes (Rendana et al., 2023). As a consequence, agricultural productivity declines due to nutrient depletion, reduced effective rooting depth, loss of organic matter, and increased dependence on external inputs such as fertilizers and irrigation. Studies have shown that land productivity decreases significantly in areas experiencing severe erosion if conservation measures are not implemented (Bhandari et al., 2021). Therefore, erosion prediction is essential for identifying vulnerable areas and developing effective land conservation strategies to support sustainable land management.

The Universal Soil Loss Equation (USLE) is one of the most widely used methods for estimating soil loss caused by water erosion. The model incorporates rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover and management (C), and conservation practice (P) factors. The method is widely applied because the required data, including rainfall, soil characteristics, topography, land use, and conservation practices, are relatively accessible and suitable for watershed-scale studies where spatial variability strongly influences erosion processes.

Watersheds are commonly used as study units because they function as integrated ecological and hydrological systems. Erosion occurring in upstream areas can significantly affect downstream regions through sedimentation, declining water quality, reduced reservoir capacity, and increased flood risk. The upstream area of the Unda Watershed was selected as the study area due to its steep slopes, high rainfall intensity, intensive agricultural land use, and its strategic role as one of the major water

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sources in eastern Bali. These conditions increase the susceptibility of the area to soil erosion and emphasize the importance of implementing appropriate land conservation measures.

Geospatial technologies, including Geographic Information Systems (GIS) and remote sensing, enable efficient spatial analysis of erosion factors and facilitate the mapping of erosion-prone areas. Several studies have successfully applied the USLE model in watershed management. Sumarniasih (2023) reported erosion rates ranging from 0.99 to 472.19 ton ha⁻¹ year⁻¹ in the Telagawaja Sub-watershed and recommended conservation measures such as mulching and terracing. Lesmana et al. (2024) found an average erosion rate of 22.78 ton ha⁻¹ year⁻¹ in the Winongo Watershed and identified an increase in areas with severe erosion hazards. Similarly, Aisy (2023) observed a decline in erosion rates in the Keduang Sub-watershed between 2016 and 2021, while Atmojo (2024) reported that land-use changes significantly contributed to high erosion levels in Panggang District, Gunungkidul.

Despite the growing number of erosion studies in Indonesia, information regarding soil erosion and land conservation in the upstream area of the Unda Watershed remains limited. Therefore, this study was conducted to estimate soil erosion rates, analyze erosion hazard levels, and formulate appropriate land conservation recommendations in the upstream area of the Unda Watershed using a geospatial information approach integrated with the USLE model.

RESEARCH METHOD

Research Design

This study employed the Universal Soil Loss Equation (USLE) integrated with Geographic Information Systems (GIS) to estimate soil erosion rates, determine erosion hazard levels, and formulate land conservation recommendations in the upstream area of the Unda Watershed. The USLE model was used to calculate annual soil loss based on rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover-management factor (C), and conservation practice factor (P). GIS techniques were applied to process, analyze, and visualize spatial data related to erosion and conservation planning.

Research Location and Time

The study was conducted in the upstream area of the Unda Watershed, Bali, Indonesia. Data processing and spatial analysis were carried out at Udayana University, Denpasar. The research commenced in August 2025 and included data collection, geospatial processing, erosion estimation, erosion hazard classification, and preparation of land conservation recommendations.

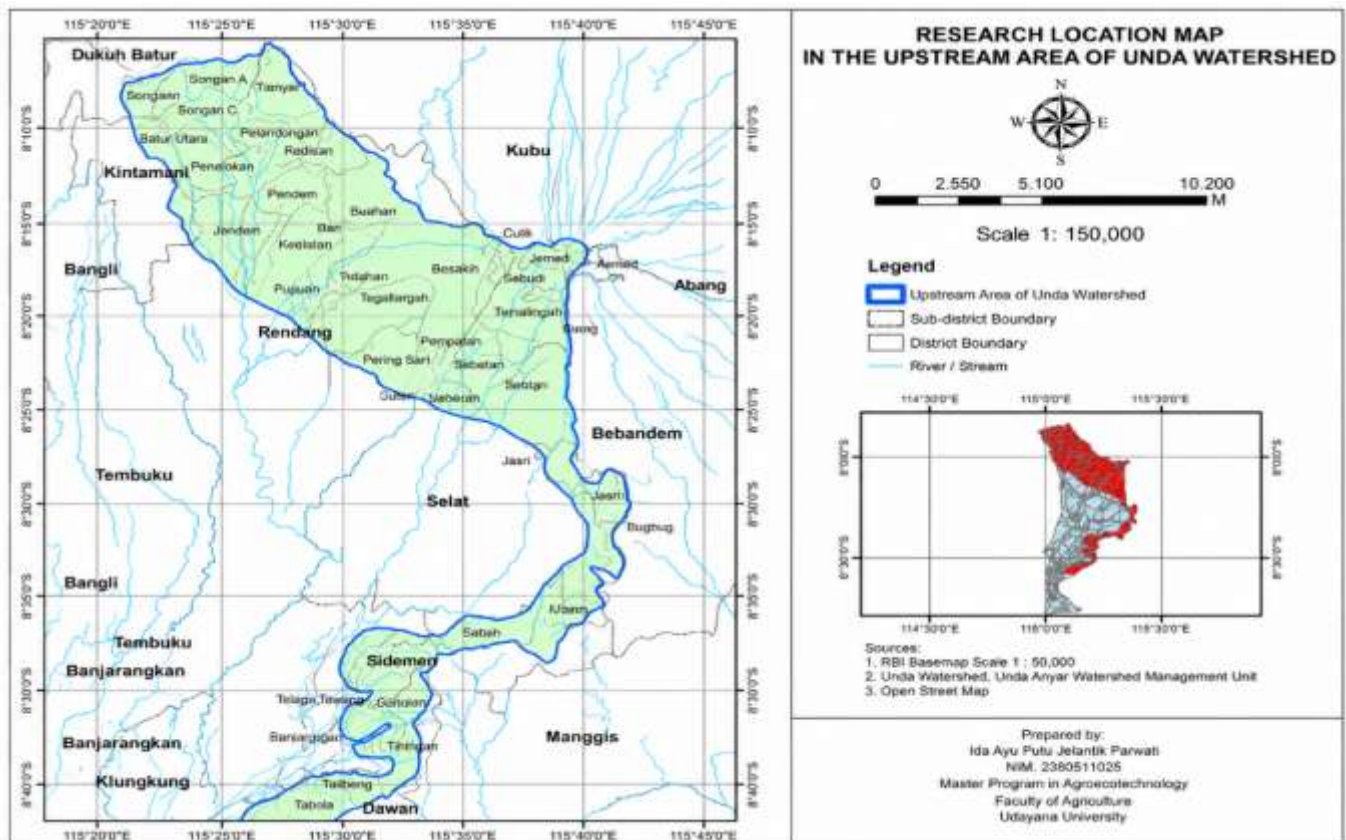


Figure 1. Research Location Map

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Tools and Materials

The tools used in this study included an Acer Aspire 5 laptop with 8 GB RAM, ArcMap 10.8 software, Microsoft Office applications, and stationery. The research materials consisted of rainfall data, soil type maps, Digital Elevation Model (DEM) data, land use maps, land cover maps, and other supporting spatial and non-spatial datasets obtained from relevant institutions.

Research Implementation

The research was conducted through the following stages:

1. Preparation Stage

A literature review was conducted on soil erosion, land conservation, watershed management, Geographic Information Systems (GIS), and the Universal Soil Loss Equation (USLE). Secondary data including rainfall records, soil maps, land use maps, DEM data, and administrative maps were collected from relevant agencies.

2. Data Collection

Secondary data were obtained from the Meteorological, Climatological and Geophysical Agency (BMKG), Geospatial Information Agency (BIG), Unda Anyar Watershed Management Agency, Forestry Service, local government institutions, satellite imagery sources, and other related agencies.

3. Geospatial Data Processing

Spatial data processing was performed using ArcGIS 10.8 through several stages:

- Watershed delineation using topographic and RBI maps.
- Preparation of thematic maps including rainfall, soil type, slope, and land use maps.
- Overlay analysis to generate land units as the basis for erosion assessment.

4. Erosion Analysis Using the USLE Method

Soil erosion was estimated using the USLE equation:

$$A = R \times K \times LS \times C \times P$$

where A is annual soil loss ($\text{ton ha}^{-1} \text{ year}^{-1}$), R is rainfall erosivity, K is soil erodibility, LS is slope length and steepness, C is cover-management factor, and P is conservation practice factor.

The factors analyzed included:

- Rainfall erosivity factor (R)
- Soil erodibility factor (K)
- Slope length and steepness factor (LS)
- Cover-management factor (C)
- Conservation practice factor (P)

5. Soil Erosion Estimation

The values of R, K, LS, C, and P were integrated using raster calculations in GIS to generate spatial erosion maps and estimate annual soil loss throughout the study area.

6. Erosion Hazard Classification

The estimated erosion rates were classified into five erosion hazard levels:

Erosion Hazard Level	Soil Loss ($\text{ton ha}^{-1} \text{ year}^{-1}$)
Very Slight	< 15
Slight	15–60
Moderate	60–180
Severe	180–480
Very Severe	> 480

The results were presented as Erosion Hazard Level (EHL) maps.

7. Land Conservation Recommendation

Land conservation measures were formulated based on erosion hazard levels, slope conditions, land capability, and existing land use. The recommended conservation practices included:

- Vegetative conservation: reforestation, agroforestry, cover crops, strip cropping, and contour planting.
- Mechanical conservation: bench terraces, ridge terraces, drainage channels, check dams, and sediment control structures.

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8. Result Presentation

The outputs of this study included maps of rainfall erosivity, soil erodibility, slope factors, land cover factors, erosion rates, erosion hazard levels, and land conservation recommendations for the upstream area of the Unda Watershed.

Observation Variables

The variables observed in this study included:

1. Rainfall erosivity factor (R)
2. Soil erodibility factor (K)
3. Slope length and steepness factor (LS)
4. Cover-management factor (C)
5. Conservation practice factor (P)
6. Soil erosion rate ($\text{ton ha}^{-1} \text{ year}^{-1}$)
7. Erosion hazard level (EHL)
8. Land conservation recommendations.

Data Analysis

Data analysis was conducted using the USLE model and GIS-based spatial analysis. The values of R, K, LS, C, and P were calculated and integrated to estimate annual soil loss. The resulting erosion rates were classified into erosion hazard levels and subsequently used as the basis for developing land conservation recommendations. The outputs were presented in the form of thematic maps and descriptive analyses to support sustainable land management in the upstream area of the Unda Watershed.

RESULTS

General Description of the Study Area

The study was conducted in the upstream area of the Unda Watershed, which is located in Karangasem Regency and partly within Bangli Regency and Klungkung Regency, Bali Province, Indonesia. The total area of the upstream Unda Watershed is 10,293.26 ha, covering eight sub-districts: Kintamani, Bebandem, Kubu, Rendang, Manggis, Selat, Sidemen, and Dawan. This area was selected because it has steep topography, high rainfall distribution, and rapid land-use changes, making it highly susceptible to soil erosion.

The upstream area of the Unda Watershed has a tropical climate characterized by two seasons, namely the rainy season and the dry season. The dominant soil types are reddish-brown latosol, lithosol, gray regosol, and humic regosol. Existing land uses include settlements, paddy fields, shrublands, primary dryland forest, secondary dryland forest, mixed dryland agriculture, dryland agriculture, and open land. The coverage and total area of the upstream Unda Watershed are presented in Table 1.

Table 1. Coverage and Total Area of the Upstream Unda Watershed

No.	Watershed Zone	Village	Sub-district	Regency	Province	Area (Ha)
1	Upstream	Trunyan	Kintamani	Bangli	Bali	0.01
2	Upstream	Suter	Kintamani	Bangli	Bali	263.73
3	Upstream	Abangsongan	Kintamani	Bangli	Bali	859.39
4	Upstream	Sibetan	Bebandem	Karangasem	Bali	18.64
5	Upstream	Jungutan	Bebandem	Karangasem	Bali	286.35
6	Upstream	Buana Giri	Bebandem	Karangasem	Bali	15.20
7	Upstream	Dukuh	Kubu	Karangasem	Bali	10.12
8	Upstream	Ban	Kubu	Karangasem	Bali	19.68
9	Upstream	Gegelang	Manggis	Karangasem	Bali	106.30
10	Upstream	Besakih	Rendang	Karangasem	Bali	2,054.06
11	Upstream	Pempatan	Rendang	Karangasem	Bali	3,091.27
12	Upstream	Duda Timur	Selat	Karangasem	Bali	324.12
13	Upstream	Duda	Selat	Karangasem	Bali	196.59
14	Upstream	Duda Utara	Selat	Karangasem	Bali	212.25
15	Upstream	Amerta Bhuana	Selat	Karangasem	Bali	37.57
16	Upstream	Sebudi	Selat	Karangasem	Bali	1,585.54
17	Upstream	Lakasari	Sidemen	Karangasem	Bali	135.04
18	Upstream	Talibeng	Sidemen	Karangasem	Bali	259.42
19	Upstream	Tri Eka Buana	Sidemen	Karangasem	Bali	249.42

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20	Upstream	Telaga Tawang	Sidemen	Karangasem	Bali	126.96
21	Upstream	Sidemen	Sidemen	Karangasem	Bali	286.75
22	Upstream	Sinduwati	Sidemen	Karangasem	Bali	154.82
23	Upstream	Besan	Dawan	Klungkung	Bali	0.02
Total						10,293.26

Source: Data Analysis

Rainfall Erosivity (R Factor)

Rainfall erosivity (R) is the ability or erosive power of rainfall to cause soil erosion. Erosivity indicates the amount of rainfall energy available to detach and transport soil particles from one location to another. It was calculated using the Bols method (Wischmeier & Smith, 1978).

Factors affecting rainfall erosivity include rainfall intensity, rainfall amount, raindrop size, and rainfall duration. The rainfall erosivity factor (R) was derived from average monthly rainfall data, average monthly rainy days, and maximum daily rainfall within a given month. These data were obtained from the Meteorological, Climatological, and Geophysical Agency (BMKG) from four rainfall observation stations covering a twenty-year period from 2002 to 2021.

The rainfall data were collected from the Pempatan Rainfall Station (Agricultural Extension Center of Rendang Sub-district), Duda Rainfall Station (Agricultural Extension Center of Selat Sub-district), Dawan Rainfall Station (Agricultural Extension Center of Dawan Sub-district), and Ulakan Rainfall Station (Agricultural Service Unit of Manggis Sub-district). Spatial analysis was performed using GIS to generate the rainfall erosivity (R) map. Based on the analysis, the highest R-factor value was 2,298 ton/ha/cm, while the lowest was 1,422 ton/ha/cm (Figure 2).

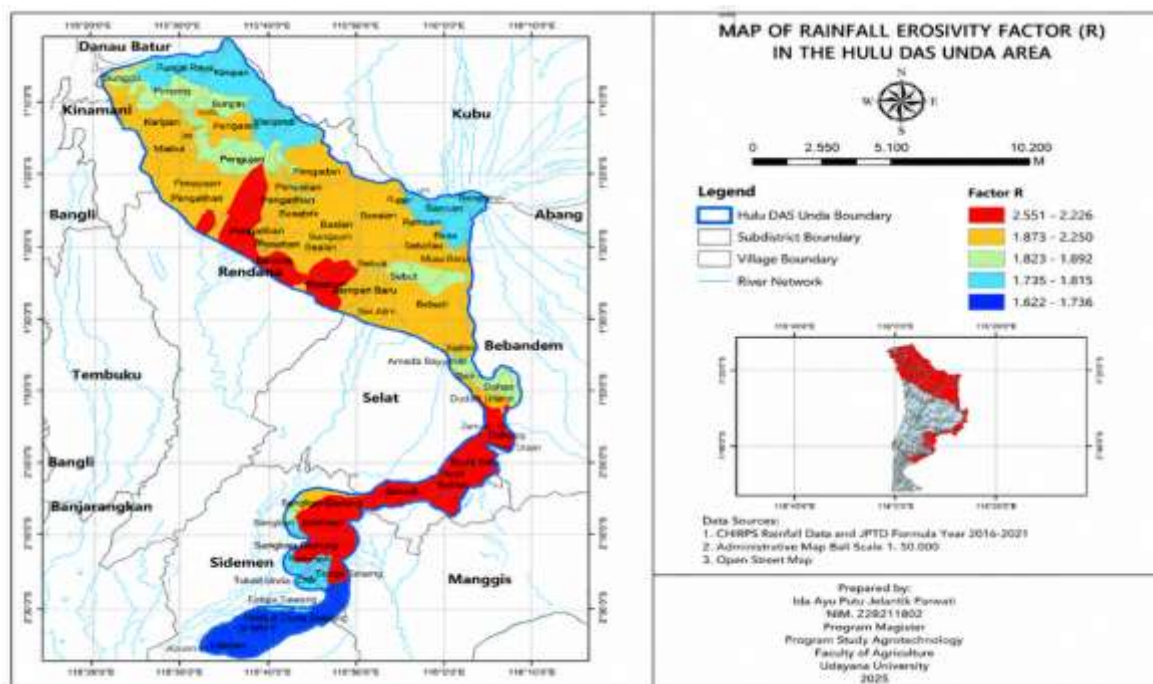


Figure 2. Rainfall Erosivity Factor (R) Map of the Upstream Unda Watershed

The area distribution and percentage of R values associated with each rainfall station in the upstream Unda Watershed are presented in Table 2.

Table 2. Area Distribution and Percentage of Rainfall Stations in the Upstream Unda Watershed

No.	Rainfall Station	Area (Ha)	Percentage (%)	R Value
1	Kusamba Rainfall Station (AEC Dawan Sub-district)	0.02	0.00	1,538
2	Ulakan Rainfall Station (AEC Manggis Sub-district)	106.29	1.03	1,804
3	Duda Rainfall Station (AEC Selat Sub-district)	2,355.79	22.89	2,024.54
4	Pempatan Rainfall Station (AEC Rendang Sub-district)	5,144.94	49.99	1,890.62
5	Others	2,685.53	26.09	1,822.38
Total		10,292.38	100	

Source: Data Analysis

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Soil Erodibility (K Factor)

The soil erodibility values obtained in this study were presented based on the modified soil classification system of 1978/1982 (PPT) and soil erodibility values calculated using the corresponding equation. Three soil types were identified in the upstream Unda Watershed, namely latosol, regosol, and lithosol. The corresponding K values were 0.43, 0.20–0.40, and 0.29–0.304, respectively. The spatial distribution of these values is presented in Figure 3.

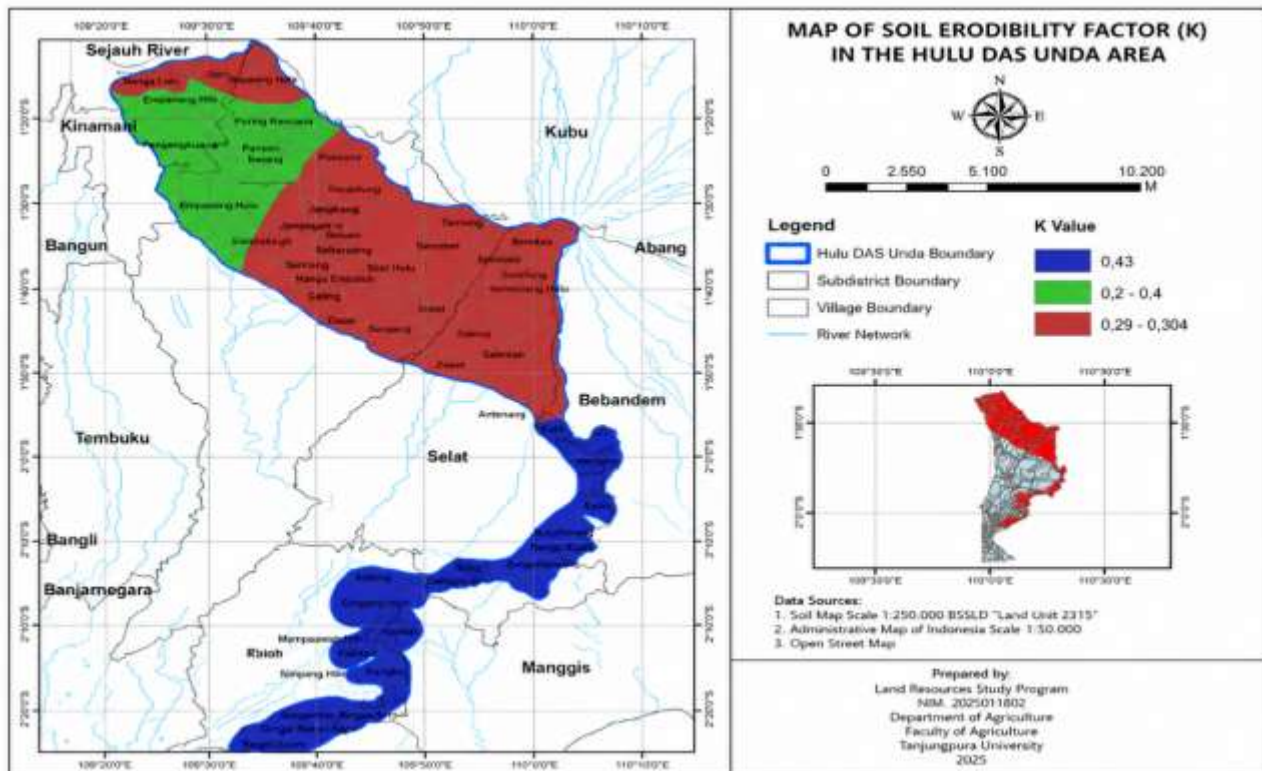


Figure 3. Soil Erodibility Factor (K) Map of the Upstream Unda Watershed

The area coverage and percentage of soil types in the upstream Unda Watershed are presented in Table 3.

Table 3. Area Coverage and Percentage of Soil Types in the Upstream Unda Watershed

No.	Soil Type	Area (Ha)	Percentage (%)	K Value
1	Reddish Latosol and Lithosol	2,054.10	19.96	0.43
2	Humic Regosol	2,281.16	22.16	0.20–0.40
3	Gray Regosol	5,957.12	57.88	0.29–0.304
Total		10,292.38	100.00	

Source: Data Analysis

Slope Length and Slope Steepness (LS Factor)

Topographic factors that strongly influence soil erosion are slope length and slope steepness. Based on the slope class assessment index, LS values were determined for each land unit and presented spatially in Figure 4.

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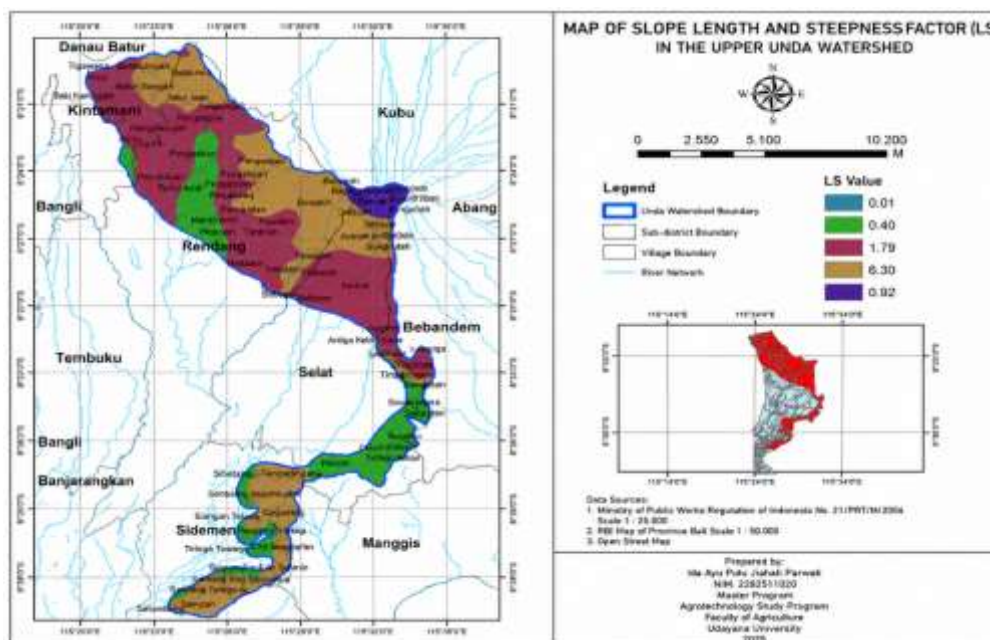


Figure 4. Slope Length and Slope Steepness Factor (LS) Map of the Upstream Unda Watershed

The LS factor (Slope Length and Steepness Factor) in the USLE model describes the influence of slope length (L) and slope steepness (S) on soil erosion. The longer and steeper a slope is, the greater the surface runoff velocity, thereby increasing the capacity of water to detach and transport soil particles.

Slope conditions in the upstream Unda Watershed vary from flat to very steep. The slope length and steepness indices (LS), area coverage, and percentages are presented in Table 4.

Table 4. Slope Class Assessment Index

Slope Class (%)	Description	LS Value
I (0–8%)	Flat	0.01
II (8–15%)	Gentle	0.40
III (15–25%)	Moderately Steep	1.79
IV (25–40%)	Steep	6.30
V (>40%)	Very Steep	9.20

Source: Data Analysis

Land Cover Vegetation and Land Management (CP Factor)

The C factor is the ratio between the average soil loss from land planted with specific crops and management practices and the average soil loss from bare land under the same soil, slope, and rainfall conditions. The C factor values for various land-use types are presented in Table 5.

Table 5. C Factor Values for Various Land Use Types

No.	Land Use Type	C Value
1	Bare land / land without vegetation	1.0
2	Paddy field	0.01
3	Dryland farming	0.70
4	Soybean	0.399
5	Peanut	0.20
6	Mixed garden	
	High density	0.10
	Medium density	0.20
	Low density	0.50
7	Shifting cultivation	0.40

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8	Natural forest	
	Abundant litter	0.001
	Limited litter	0.005
9	Production forest	
	Clear-cutting	0.50
	Selective logging	0.20
10	Shrubland	0.30
11	Dense Imperata grassland	0.001

Source: Arsyad (2012)

The P factor, or conservation practice factor, is closely related to the C factor. Currently, conservation measures in agricultural areas are still limited. Excessive land cultivation practices and the expansion of settlements in the upstream Unda Watershed have contributed to the decline of conservation efforts. Therefore, the P values for specific soil conservation practices adopted from Arsyad (2012) are presented in Table 6.

Table 6. P Values for Specific Conservation Practices

No.	Specific Soil Conservation Practice	P Value
1	Bench terrace	
	Good construction	0.04
	Moderate construction	0.15
	Poor construction	0.35
	Traditional terrace	0.40
2	Bahia grass strip cropping	0.40
3	Tillage and planting along contour lines	
	Slope 0–8%	0.50
	Slope 9–20%	0.75
	Slope >20%	0.90
4	Without conservation practices	1.00

Source: Arsyad (2012)

The CP factor (Cover and Conservation Practice Factor) is a combination of the C factor (Cover Management Factor) and the P factor (Support Practice Factor) in the USLE model. It represents the influence of land cover vegetation and conservation practices on reducing soil erosion. In this study, the CP factor was derived from land cover maps obtained from the Ministry of Environment and Forestry (KLHK) and RBI maps. Based on the land management and conservation practice assessment index, CP values for each land unit were determined and presented spatially in Figure 5. The area coverage and percentage of land use in the upstream Unda Watershed are shown in Table 5.

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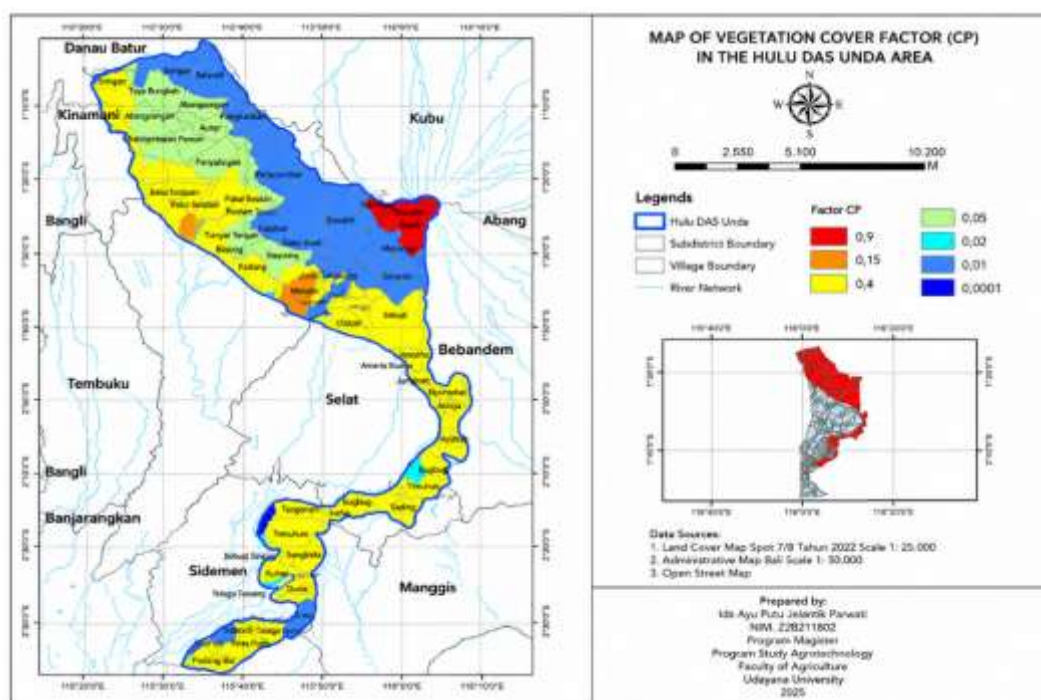


Figure 5. Land Cover and Land Use Factor (CP) Map of the Upstream Unda Watershed

Table 7. Area Coverage and Percentage of Land Use in the Upstream Unda Watershed

No.	Land Use Type	Area (Ha)	Percentage (%)
1	Primary Dryland Forest	2,581.12	25.08
2	Secondary Dryland Forest	1,853.36	18.01
3	Settlement	114.22	1.11
4	Dryland Agriculture	314.33	3.05
5	Mixed Dryland Agriculture	4,462.74	43.36
6	Paddy Field	85.27	0.83
7	Shrubland	520.05	5.05
8	Open Land	361.28	3.51

Source: Data Analysis

DISCUSSION

Analysis of USLE Factors and Erosion Rate

The research results indicate that the erosion rate in the Upper Unda Watershed area is strongly influenced by a combination of topographic factors, rainfall, soil type, and land use. The spatial variation of the USLE factors (R, K, LS, C, and P) illustrates that no single factor stands alone; rather, it is the interaction among these factors that determines the level of vulnerability of an area to erosion. The analysis of the Universal Soil Loss Equation (USLE) factors in the study of erosion rates in the upstream area of the Unda Watershed aims to identify the contribution of each biophysical and land-management factor to the magnitude of soil loss. The USLE model used in this study is an empirical approach that integrates five main factors, namely rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and soil conservation practices (P). The combination of these five factors provides a spatial depiction of the level of erosion vulnerability occurring in the study area.

A. Rainfall Erosivity Factor (R)

The rainfall erosivity factor (R) is one of the main components in the soil erosion process, particularly within the Universal Soil Loss Equation (USLE). This factor reflects the ability of rainfall to cause erosion, primarily through the kinetic energy of raindrops and the intensity of rainfall. The R factor is a measure that describes the destructive power of rainfall on the soil. The higher the R value, the greater the potential for erosion to occur. R is influenced by rainfall intensity (mm/hour), rainfall duration, rainfall frequency, and the kinetic energy of raindrops. The higher the rainfall intensity within a short period, the greater the R value. The impacts that occur when the R value is high include an increasing risk of topsoil loss, declining soil fertility or land

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degradation, accelerated river sedimentation, and an increased potential for flooding and landslides. An example is a tropical region such as Bali, which has high rainfall with high intensity over short periods, causing many open lands to become highly susceptible to erosion. According to research by Andriyani, I. et al. (2023) on the Analysis of the Rainfall Erosion Factor (R) in Erosion Yield Predictions Using the USLE and RUSLE Models; A Case Study in the Mayang Watershed, Jember Regency, Indonesia, it is stated that the rainfall erosivity factor has a significant influence on erosion yield predictions.

Rainfall erosivity is the ability of rainfall to cause soil erosion, which is determined by the kinetic energy of raindrops, rainfall intensity (mm/hour), and the duration and frequency of rainfall. Scientifically, erosivity is expressed as the R factor in the USLE (Universal Soil Loss Equation) method. High rainfall energy will increase the destructive power on the soil and surface runoff.

The upstream area of the Unda Watershed, located in the Karangasem-Bangli region on the slopes of Mount Agung, has climatic and topographic characteristics that greatly influence the high level of rainfall erosivity. Climatologically, this region has an annual rainfall ranging from approximately 1,500 to 2,500 mm per year, with a tropical rainfall pattern dominated by heavy-intensity rainfall events of relatively short duration. This condition causes the kinetic energy of rainfall falling onto the ground surface to become quite large within a short period, thereby increasing the potential for soil particle detachment and surface runoff.

Various studies show that rainfall intensity has a very strong correlation with the magnitude of runoff and erosivity values; in fact, several rainfall simulation studies have reported very high coefficients of determination ($R^2 \approx 0.98$), confirming that the variability of rainfall intensity is a dominant factor in the erosion process.

Based on research approaches in Bali and other regions of Indonesia with comparable biophysical characteristics, the rainfall erosivity factor (R) value in the upstream area of the Unda Watershed is estimated to range from 1,000 to 2,000 MJ·mm/ha/hour/year. This value indicates that the level of rainfall erosivity in this region falls into the medium-to-high category. This category shows that rainfall in the upstream area of the Unda Watershed has a fairly significant destructive power on the ground surface, particularly on lands that do not have adequate vegetation cover. This high rainfall energy plays a role in accelerating splash erosion and increasing the volume of surface runoff that carries soil material down the slope.

The steep topographic conditions in the Mount Agung slope area further reinforce the impact of this rainfall erosivity. Steep slopes cause rainwater to turn into surface runoff more quickly rather than infiltrating into the soil, so that the contact time between water and the ground surface becomes shorter but with greater flow energy. The combination of high rainfall, heavy short-duration rainfall intensity, and steep slope conditions makes the upstream area of the Unda Watershed highly susceptible to erosion, particularly during the rainy season when soil saturation increases significantly.

It can thus be concluded that climatic factors, particularly rainfall and rainfall intensity, together with the topographic conditions of the upstream area of the Unda Watershed, are the main controlling factors behind the high rainfall erosivity (R) value. This condition has important implications for the need for land-management strategies based on soil and water conservation, especially in areas with open land cover that have the highest level of erosion vulnerability.

The factors controlling the high erosivity in the upstream area of the Unda Watershed cannot be separated from several main controlling factors that interact with one another, particularly related to rainfall characteristics, topographic conditions, and the seasonal distribution pattern of rainfall.. The controlling factors of high erosivity are as follows:

- a. The first factor is tropical rainfall with high kinetic energy. Rainfall in this region is generally dominated by large raindrops with high intensity, producing substantial impact energy when striking the ground surface. This condition triggers splash erosion, the initial process of soil particle detachment caused by the direct impact of raindrops. In the long term, this high rainfall energy becomes one of the main determinants of the increase in the rainfall erosivity (R) value, which directly contributes to the magnitude of the erosion rate in the study area.
- b. The second factor is the topographic condition dominated by steep slopes in the upstream area of the Unda Watershed. This mountainous characteristic causes rainwater to undergo little infiltration but instead rapidly turns into surface runoff. The high flow velocity on steep slopes increases the sediment-carrying capacity, thereby enhancing the water's ability to erode and transport soil material from the upper part to the lower part of the watershed. This condition makes topography a major reinforcing factor in the erosion process, particularly through the increase in the slope length and steepness component (the LS factor) in the USLE model.
- c. The third factor is the seasonal distribution of rainfall. In this region, peak erosivity generally occurs during the rainy season, particularly between November and March. During this period, high rainfall intensity often coincides with soil conditions that are already saturated with water, causing infiltration capacity to decrease significantly. The combination of high rainfall intensity and soil saturation causes a drastic increase in surface runoff, which ultimately produces

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maximum erosion. This seasonal condition shows that the temporal variability of rainfall also plays an important role in determining the dynamics of the erosion rate in the upstream area of the Unda Watershed.

Overall, these three controlling factors show that the high erosivity in the upstream area of the Unda Watershed is the result of the interaction between tropical rainfall energy, steep topographic conditions, and an intensive seasonal rainfall pattern. The combination of these three factors reinforces the erosion process, so an adaptive land-management approach based on the biophysical characteristics of the region is needed to sustainably reduce the impact of soil degradation.

The high level of rainfall erosivity in the upstream area of the Unda Watershed has various important implications for the environmental conditions and the sustainability of the watershed's overall hydrological function. The large rainfall energy, particularly that occurring at high intensity over short durations, causes an increase in the occurrence of sheet erosion and rill erosion on lands with moderate to steep slopes. This process gradually erodes the topsoil layer, which is the most fertile part of the soil and plays a vital role in supporting agricultural productivity. The long-term loss of topsoil not only reduces soil fertility but also diminishes the soil's ability to absorb and store water.

In addition to its direct impact on soil quality in the upstream region, the high erosion rate also contributes to increased sedimentation in the Unda River. Soil material carried by surface runoff enters the river network and is deposited along the river channel as well as in the downstream part of the watershed. This sediment accumulation can reduce the river's storage capacity, disrupt the smooth flow of water, and increase the risk of flooding, particularly in downstream areas such as Klungkung Regency. Thus, the impact of rainfall erosivity is not only local to the upstream region but also has broad hydrological consequences that are integrated into the watershed system as a whole.

Overall, the analysis results show that the upstream area of the Unda Watershed has a rainfall erosivity level that falls into the medium-to-high category, influenced by the characteristics of a wet tropical climate with high rainfall intensity, large annual rainfall, and predominantly steep mountainous topographic conditions. These conditions make this region highly susceptible to soil erosion, especially in areas with suboptimal land cover and minimal implementation of conservation measures. The impact of high erosivity not only affects the loss of the topsoil layer in the upstream region but also contributes to increased sedimentation in the Unda River and the potential for hydrological disturbances in downstream areas. Therefore, these findings underscore the importance of implementing soil and water conservation strategies based on biophysical conditions and spatial approaches in order to reduce the erosion rate and maintain the sustainability of the watershed's ecological functions as a whole. Thus, the results of this study can serve as a scientific basis for planning more effective, focused, and sustainable land management in the upstream area of the Unda Watershed.

B. Soil Erodibility Factor (K)

The soil erodibility factor (K) is an index that indicates the degree of soil susceptibility to erosion, namely the ability of the soil to undergo particle detachment and transport by rainfall and surface runoff. The K factor reflects the intrinsic properties of the soil, so that under the same rainfall conditions, soil with a high K value will experience greater erosion. The K value is determined by the physical and chemical properties of the soil. The physical factors of the soil include soil texture, soil structure, permeability, and infiltration, while the chemical property is the soil's organic matter content. Soil texture consists of sand, silt, and clay, where sand has a low K value, silt has a high K value, and clay has a relatively stable K value if its aggregation is good. Soil structure is divided into two types: granular (crumb) structure, which tends to be resistant to erosion, and dense or massive structure, which tends to be easily eroded. Soil permeability and infiltration are also divided into two conditions: if infiltration is high and runoff is low, erosion will be low, whereas if infiltration is low and runoff is high, erosion will be high. As for organic matter, a high content can strengthen aggregates, causing the K value to become low, while a low content increases susceptibility to erosion itself. Thus, if the K value is high, the soil will easily break apart and be carried away, resulting in high erosion, whereas at a low K value, the soil is more stable and erosion tends to be low.

Based on the research of Wischmeier & Smith (1978), the K value generally ranges from 0.02 to 0.64, with values below 0.10 classified as low soil erodibility (K), values of 0.10-0.30 classified as moderate soil erodibility (K), and values above 0.30 classified as high erodibility (K). The K factor plays a very important role in controlling soil vulnerability to erosion, can determine the amount of soil particles released, and has a direct effect on the magnitude of erosion, even under the same rainfall conditions. In tropical regions, under conditions of high rainfall (high R) combined with high soil K, the risk of erosion is very large. This condition is prone to occur on open land, with low organic matter content, and on steep slopes without conservation measures. As an example, the research of Lengkon, M.A. et al. (2015) on the Soil Erodibility of Manado-Tomohon shows K values ranging from 0.37-0.43, which fall into the high erodibility category. This indicates that the soil in that location is vulnerable to erosion, particularly under conditions of steep slopes and high rainfall.

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The Regosol soils commonly found in the upstream area of the Unda Watershed are closely related to the soil erodibility factor (K) in the USLE model, because their physical and chemical characteristics strongly determine the level of soil vulnerability to erosion. As young soils belonging to the Entisol order, Regosols have not yet developed mature horizons, stable soil structure, or high organic matter content. This condition causes the bonding strength between soil particles to be weak, so that the soil is easily detached and carried away by surface runoff during high-intensity rainfall. The relatively coarse texture and the dominance of sandy material or young volcanic material also give this soil high permeability, but at the same time increase the potential for erosion because water flows more easily over the surface and carries soil particles with it.

In the context of the erodibility factor (K), these properties of Regosol soils indicate a relatively high K value, which means that the level of soil susceptibility to erosion is also high. This is further reinforced by the low organic matter content, which functions as a binder for soil aggregates, so that the soil structure becomes less stable and easily breaks apart due to the impact energy of raindrops. In the upstream area of the Unda Watershed, which has high rainfall and hilly to steep topography, the presence of Regosol soils further increases the risk of erosion, particularly on open lands or agricultural lands without adequate conservation measures.

It can thus be concluded that the presence of Regosol soils in the upstream area of the Unda Watershed contributes significantly to the high value of the soil erodibility factor (K), which ultimately increases the potential erosion rate in the region. This condition underscores the importance of implementing soil conservation techniques such as increasing organic matter content, providing vegetation cover, and applying contour-based land management to reduce the level of erosion vulnerability and maintain the sustainability of the agroecosystem function in the upstream area of the Unda Watershed.

Soil erodibility is the level of soil susceptibility to the erosion process, namely how easily soil particles are detached and transported by the impact energy of rainfall and surface runoff. Within the USLE concept, erodibility is expressed as the K factor, which is influenced by soil texture, soil structure, organic matter content, and soil permeability. In general, the K value ranges from 0-0.5, where a higher value indicates a greater vulnerability of the soil to erosion.

In the upstream area of the Unda Watershed, the soil characteristics are dominated by volcanic Regosol soils originating from material from Mount Agung. This soil generally has a coarse to sandy clay texture, a soil structure that is still weak due to immature soil development, and a tendency to easily detach when exposed to high-intensity rainfall. This condition causes the Regosol soils in the region to be classified as highly vulnerable to erosion, as also reported in various academic studies,

In addition, the level of erodibility in the upstream area of the Unda Watershed is also exacerbated by the low organic matter content of the soil. A decrease in organic carbon (C-organic) causes weak bonding between soil particles, making the soil more easily dispersed and carried away by water flow. The less stable soil structure and suboptimal porosity also reduce infiltration capacity, so that more rainwater becomes surface runoff rather than infiltrating into the soil. This condition directly increases the potential for erosion.

Overall, although the exact value of the K factor in the upstream area of the Unda Watershed varies, the characteristics of young volcanic soils indicate an erodibility range of moderate to high ($\pm 0.20-0.40$). This condition is further increased by topographic factors in the form of steep slopes and less conservative land use, such as the clearing of agricultural land and Class C mining activities. The impact is seen in increased surface erosion, the loss of nutrient-rich topsoil layers, sedimentation in the Unda River, and a sustained decline in land productivity.

Overall, soil erodibility in the upstream area of the Unda Watershed can be categorized as being at a moderate-to-high level. This condition is primarily influenced by the dominance of volcanic Regosol soils, which are easily eroded, have low organic matter content, and have a soil structure that is still weak and unstable. The combination of these characteristics makes the soil highly susceptible to particle detachment and transport processes caused by rainfall. Based on the soil characteristics, the K factor value is estimated to range from 0.20-0.40, indicating a fairly high level of erosion vulnerability. Therefore, this region is highly susceptible to erosion events, particularly in areas with open slopes that are not equipped with adequate soil and water conservation measures.

C. Slope Length and Steepness Factor (LS)

The LS factor (Slope Length and Steepness Factor) is a component in the Universal Soil Loss Equation (USLE) that indicates the influence of slope length (L) and slope steepness (S) on the magnitude of soil erosion. The LS factor represents the influence of topography on the erosion process. The larger the LS value, the greater the potential for soil loss. Slope length is the distance from the point where surface runoff begins to the point where the flow becomes concentrated. The longer the slope, the greater the accumulation of runoff, and as the volume of water increases, the carrying capacity for soil particles also increases. The erosion rate increases as the slope length increases.

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Slope steepness indicates the degree of inclination of the ground surface. The steeper the slope, the higher the flow velocity, and as the kinetic energy of the flow increases, the erosive power becomes greater. Steep slopes accelerate the detachment and transport of soil. The LS factor affects erosion through runoff accumulation: the longer the slope, the greater the volume of water; flow acceleration occurs; the steeper the slope, the faster the flow; and as the sediment-carrying capacity increases, more soil particles are carried away.

An example of a case study in Indonesia is the Serayu Watershed (Central Java), where research results show that slopes with a gradient of less than 15% have high LS values, and agricultural land without conservation measures experiences severe erosion, while the application of terracing is able to reduce the LS value and lessen erosion. Another example is the Upper Citarum Watershed (West Java), where research results show that hilly areas have high LS values; the combination of long, steep slopes and high rainfall causes very severe erosion, and open land worsens the erosion conditions. From these conditions, it is known that LS is directly proportional to the erosion rate, slope steepness has a greater (exponential) influence than slope length, and LS becomes a dominant factor in hilly and mountainous areas. Without proper management, regions with high LS values are highly susceptible to land degradation.

In soil erosion studies, slope length (L) and slope steepness (S) are the two main components combined into the LS (slope length and steepness) factor in the USLE method, which strongly determines the magnitude of erosion potential. Slope length is the distance from the point where surface runoff begins to the point where the water enters a drainage channel or undergoes deposition, while slope steepness describes the degree or percentage of the ground surface's inclination. The longer and steeper a slope is, the higher the surface flow velocity becomes, the greater the sediment transport energy, and ultimately the higher the erosion potential.

Topographically, the upstream area of the Unda Watershed, located in the slope area of Mount Agung and the mountains of East Bali, has slope characteristics dominated by steep to very steep classes. Based on the slope-gradient classification, this region largely falls within the range of >25% to over 40%, with a small portion in gentle to moderately steep conditions. This condition indicates that the upstream area of the Unda Watershed is generally dominated by rugged topography. In addition, the slope lengths in this mountainous region are relatively large, ranging from 50 to 200 meters or more, depending on the morphological form and land use, thereby allowing for the accumulation of surface runoff along the slope.

Based on the approach to determining LS factor values, areas with a slope of 15-35% have an LS value of around 4.25, while at a slope of 35-50% it can reach 7.50, and at slopes above 50% it can increase to around 12.00. Thus, the upstream area of the Unda Watershed can be estimated to have a high LS value, ranging from 4 to 12, indicating a very high level of erosion vulnerability. This condition is further exacerbated by the combination of steep slopes and significant slope lengths, which causes an increase in the volume and energy of surface runoff, thereby enhancing the water's ability to erode and transport soil particles.

With these characteristics, the LS factor becomes one of the dominant factors causing erosion in the upstream area of the Unda Watershed. Steep slopes accelerate surface runoff, while long slopes increase the accumulation of flow and sediment. The combination of both, especially under open-land conditions, makes this region highly susceptible to severe erosion, landslides, and high sedimentation carried to downstream areas such as Klungkung. Therefore, it can be concluded that the topographic conditions in the upstream area of the Unda Watershed play a very significant role in increasing the potential for land degradation.

Overall, the slope length and steepness in the upstream area of the Unda Watershed show characteristics that are predominantly steep to very steep, with relatively long slope lengths and high LS values ($\pm 4-12$). This condition makes the region highly susceptible to erosion, particularly when combined with the high rainfall erosivity and the high soil erodibility in the area.

D. Land Cover Vegetation and Land Management Factor (CP)

The CP factor (Cover and Management Factor) in the USLE equation indicates the influence of land-cover vegetation (C) and land-management practices (P) on the level of erosion. The CP value ranges from 0 to 1. A value close to 0 indicates very low erosion (good protection), while a value close to 1 indicates high erosion (open/unmanaged land). The role of land-cover vegetation (C) in reducing erosion includes intercepting rainfall to reduce the impact energy of raindrops, covering the ground surface to prevent particle detachment, and plant roots that strengthen soil structure and increase infiltration to reduce runoff. The denser the vegetation, the smaller the C value. Meanwhile, in conservation practices, the P factor reflects management techniques to reduce erosion through terracing, contour planting, strip cropping, the use of mulch, and the application of agroforestry. These practices function to reduce flow velocity, effective slope length, and sediment-carrying capacity. Without vegetation, erosion will increase drastically.

An example of a case study in Indonesia is the Upper Citarum Watershed (West Java), where research results show that land without vegetation has a C value close to 1, erosion is very high on open land, and the application of cover vegetation reduces

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erosion by more than 50%. Another example is on maize farmland (Central Java), where research results show that land without mulch experiences high erosion, whereas on land with mulch and cover crops, erosion decreases significantly, with the C value decreasing from ≥ 0.5 to ≥ 0.1 . From these conditions, it can be seen that CP has an inverse relationship with erosion: the smaller the CP value, the smaller the erosion; vegetation is the most effective factor in suppressing erosion, and land management can reinforce the effect of vegetation. Soil without vegetation can experience erosion tens of times greater than soil covered by vegetation. There are two ways to control erosion through CP: vegetation and management. Vegetation involves cover crops, reforestation, and agroforestry, while management involves the application of terracing, contour planting, mulching, and crop rotation. The combination of both produces a very low CP value.

The land-cover vegetation and land-management factor (C and P) in the USLE method is an important component that strongly influences the magnitude of the erosion rate, because this factor represents the level of protection of the ground surface from the impact of rainfall and the effectiveness of the conservation measures applied. The C factor (cover management) indicates how much the ground surface is protected by vegetation, while the P factor (support practice) describes land-management measures such as terracing, contour planting, and other soil-conservation techniques. The better the vegetation cover and conservation practices applied, the smaller the CP value will be, so that the erosion rate can be suppressed.

In the upstream area of the Unda Watershed, land-cover conditions tend to be non-uniform, and several areas show a fairly high level of land openness. This is influenced by the presence of dryland farming activities, mixed gardens, and land clearing that is not always accompanied by optimal vegetation cover. In several locations, open land is also found as a result of Class C mining activities and land-use changes, which cause the ground surface to be directly exposed to the impact energy of rainfall. This condition significantly increases the value of the C factor, because the vegetation's protection of the soil is reduced.

The land-cover vegetation factor (C) in USLE acts as an important component that determines the level of protection of the ground surface against the impact energy of rainfall and the velocity of surface runoff. Land-cover vegetation functions to protect the soil from the direct impact of raindrops, reduce the rate of runoff, and increase infiltration and the soil's organic matter content. Scientifically, vegetation is the primary controller of erosion because it is able to dampen the kinetic energy of rainfall and improve soil structure and physical properties. However, in the upstream area of the Unda Watershed, the condition of land-cover vegetation is uneven and tends to decline in several locations due to land clearing for agriculture and Class C mining activities. This condition causes part of the land to become open and increases soil vulnerability to erosion, as also shown by the declining soil quality resulting from the high erosion rate and low organic matter content.

The types of vegetation recommended for conservation in this region include bamboo, coffee, cacao, coconut, as well as forestry plants such as pine and mahogany. Agroforestry systems, such as the combination of bamboo with coffee, cacao, or coconut, are considered effective in sustainably increasing land cover while reducing the erosion rate, as they are able to keep the ground surface protected throughout the year.

Meanwhile, the land-management factor (P) in the upstream area of the Unda Watershed shows that most of the land is still managed conventionally, with limited application of conservation techniques. Agricultural activities on steep-sloped land, as well as mining activities, cause an increase in open land and damage to soil structure, resulting in decreased infiltration and increased surface runoff. To reduce this impact, it is necessary to apply conservation techniques such as terracing to reduce slope length and steepness, agroforestry systems to maintain vegetation cover, and the use of ground-cover plants such as grasses and legumes that can maintain soil moisture and improve soil structure. In addition, organic fertilization is also recommended to increase the organic-carbon (C-organic) content and improve soil aggregation.

In general, the main problems in the upstream area of the Unda Watershed are the suboptimal vegetation cover, the presence of critical land due to erosion, land use that does not match land capability, and pressure from human activities such as intensive agriculture and Class C mining. If the condition of land-cover vegetation and land management is not improved, the impacts may include an increase in severe erosion (sheet, rill, and even gully erosion), a decline in soil fertility, sedimentation of the Unda River, and an increased risk of flooding in downstream areas such as Klungkung.

Erosion Rate in the Upper Watershed Area of DAS Unda

The analysis results of soil erosion rates in the upper watershed area of DAS Unda were obtained through the Universal Soil Loss Equation (USLE) model approach integrated with Geographic Information Systems (GIS). This model considers five main factors: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and conservation measures (P). The modeling results indicate that the erosion rate in the study area varies considerably, ranging from very low to very high categories. Areas with steep slopes and open land cover show the highest erosion rate values. This is caused by increased surface flow velocity, which amplifies the kinetic energy of rainwater in transporting soil particles. Conversely, areas with dense vegetation

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cover such as forest areas and agroforestry show relatively low erosion rates. Vegetation plays a role in reducing the direct impact of raindrops on the soil surface and increasing water infiltration, thereby reducing the potential for surface runoff.

Spatially, the mapping results indicate that zones with high erosion rates are concentrated in areas with a combination of steep slopes and intensive agricultural activities without adequate conservation measures. This condition indicates that the land use factor makes a significant contribution to the increase in erosion rates in the upper watershed area of DAS Unda. The distribution of erosion rates in the upper DAS Unda shows an uneven pattern. Areas with a combination of steep slopes, high rainfall, and intensive land use generally fall into the moderate to very high erosion rate categories. Meanwhile, areas with forest cover or permanent vegetation show relatively low to very low erosion rates. This pattern indicates a strong relationship between biophysical factors and anthropogenic activities on the magnitude of soil loss.

Furthermore, the results of this erosion rate estimation have important implications for the overall sustainability of the watershed function. Soil eroded from upstream areas will be carried by surface runoff to downstream areas, causing sedimentation in rivers, reservoirs, or irrigation channels. This sedimentation not only reduces the storage capacity of water bodies but also increases the risk of flooding during the rainy season. Thus, erosion in upstream areas cannot be viewed solely as a local phenomenon, but rather as part of an interconnected hydrological system.

From an agroecotechnology perspective, controlling erosion rates in the upper watershed area of DAS Unda is critically important for maintaining the balance of agricultural and environmental ecosystems. A geospatial information-based approach provides advantages in identifying conservation priority zones more precisely. Thus, land management interventions can be directed more effectively, for example through the application of vegetative conservation such as agroforestry, mechanical conservation such as terracing, or a combination of both according to the level of erosion vulnerability.

In addition, the results of the erosion rate analysis can also serve as a basis for formulating more sustainable watershed management policies. The spatial information generated from the USLE model can be used by policymakers to determine protected zones, limited cultivation zones, as well as rehabilitation zones. This approach is highly relevant in efforts to mitigate land degradation that is increasingly intensifying due to development pressures and changes in land use. Thus, it can be concluded that the soil erosion rate in the upper watershed area of DAS Unda is the result of complex interactions between climatic, soil, topographic, vegetation, and human activity factors. The Geospatial Information System-based approach provides the ability to analyze this phenomenon more comprehensively and spatially, thereby producing more accurate information to support sustainable soil and water conservation planning.

A. Erosion Hazard Level (TBE) of the Upper Watershed Area of DAS Unda

The analysis of erosion hazard level (TBE) was conducted based on the classification of the actual erosion rate generated from the USLE model. The TBE classification is divided into several categories: very low, low, moderate, high, and very high. The analysis results indicate that a portion of the upper watershed area of DAS Unda falls within the moderate to high TBE categories. Areas with high TBE are generally located on land with slopes exceeding 25% and have suboptimal land cover. This condition indicates that the soil in these areas is in a vulnerable state to further degradation if conservation efforts are not undertaken.

Meanwhile, areas with low TBE are generally found in areas with permanent vegetation and relatively flat topography. This indicates that the presence of vegetation plays an important role in significantly reducing the erosion hazard level. Overall, the spatial distribution of TBE in the study area shows a pattern consistent with the erosion rate, where the higher the erosion rate, the higher the erosion hazard level that occurs.

Based on the erosion calculation results (A) using the USLE equation from Smith & Wischmeier (1978), the erosion hazard level in the Upper Watershed Area of DAS Unda is divided into 5 categories: very light, light, moderate, heavy, and very heavy. The overlay results from the rainfall map, soil type, slope class, and land cover produced an TBE distribution map in the Upper Watershed Area of DAS Unda as shown in Figure 8.

Figure 8 shows that the upper watershed area of DAS Unda is largely classified under the Very Heavy Erosion Hazard Level (TBE). Data on land area in each erosion hazard level class are presented in the diagram in Figure 9 and Table 11.

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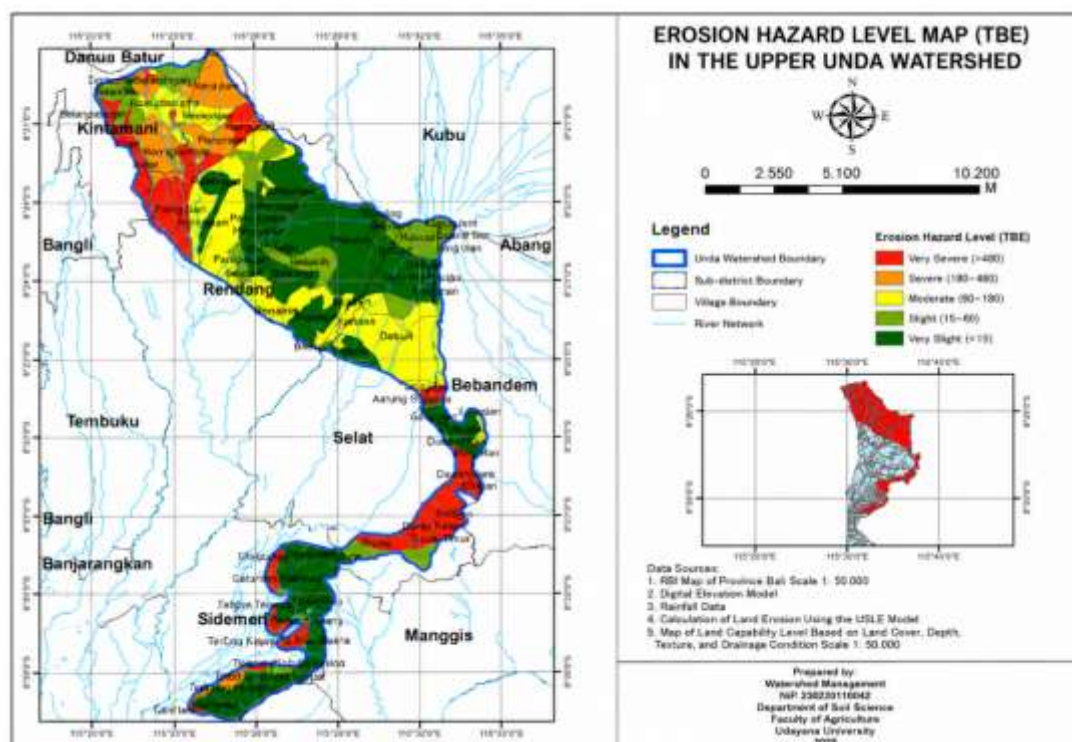


Figure 9. Erosion Hazard Level Map in the Upper Watershed Area of DAS Unda

Table 11. Erosion Hazard Level in the Upper Watershed Area of DAS Unda

Erosion Hazard Level (TBE)	Erosion Rate (ton/ha/yr)	Area (Ha)	Percentage (%)
Very Light (I)	<15	1,624.25	15.78
Light (II)	15 – 60	891.50	8.66
Moderate (III)	60 – 180	2,468.10	23.98
Heavy (IV)	180 – 480	1,226.86	11.92
Very Heavy (V)	>480	4,081.66	39.66
Total		10,292.38	100

Source: Data Analysis

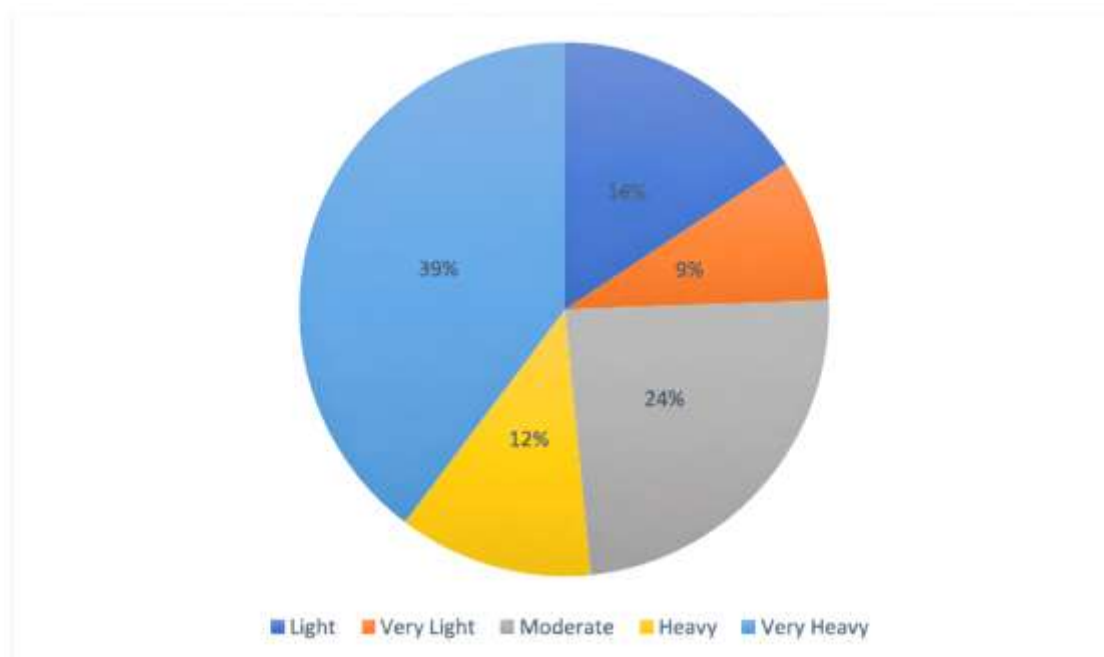


Figure 10. Percentage Diagram of Erosion Hazard Level Values in the Upper Watershed Area of DAS Unda

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The Erosion Hazard Level (TBE) in the upper watershed area (DAS) of Unda is an important indicator in assessing the level of land vulnerability to soil degradation processes caused by water erosion. TBE essentially describes the relationship between the magnitude of the actual erosion rate and the available soil solum depth, thus indicating how great the threat of land productivity loss would be if the erosion process continues without adequate control. In the context of the upper watershed area of DAS Unda, TBE analysis is highly relevant given the biophysical characteristics of the area dominated by undulating to steep slopes and relatively high rainfall intensity throughout the year.

The analysis results show that the erosion hazard level in the upper watershed area of DAS Unda varies from very low to very high categories, which are spatially distributed according to topographic conditions and land use. Areas with high slope gradients and open land cover tend to have higher erosion hazard levels compared to areas with dense vegetation or conservation-based land use systems. This indicates that slope gradient and land cover factors have a dominant influence in determining the level of erosion vulnerability in the area.

Spatially, areas with high to very high TBE are generally found in hilly zones with dryland agricultural activities that are not accompanied by adequate soil conservation measures. In these areas, rainwater surface runoff carries sufficient energy to transport soil particles, thereby accelerating the erosion of the topsoil layer. This condition is exacerbated by low water infiltration due to minimal vegetation cover, which causes an increase in the volume and velocity of surface runoff.

Conversely, areas with low TBE are generally located in areas with forest cover or permanent vegetation that remains relatively well preserved. Vegetation plays an important role in reducing the kinetic energy of raindrops before they reach the soil surface, increasing water infiltration, and strengthening soil structure through the root system. Thus, the presence of vegetation becomes the main protective factor in reducing the erosion hazard level in the upper watershed area of DAS Unda.

In addition to biophysical factors, human activities also make a significant contribution to the increase in TBE. Changes in land use from forest to intensive agricultural land or open land without proper conservation management result in a decrease in the soil's ability to resist erosion. Cultivation practices on steep slopes without terracing or other conservation techniques accelerate soil degradation and increase the level of land vulnerability to erosion.

Geographic Information System (GIS)-based analysis shows that the distribution of TBE in the upper watershed area of DAS Unda has a pattern strongly influenced by the combination of topographic factors, land use, and soil characteristics. This spatial approach enables the identification of critical zones that require priority conservation interventions. Thus, the TBE map not only functions as a scientific analytical tool, but also as a basis for sustainable land management planning.

Ecologically, the high erosion hazard level in the upper watershed area of DAS Unda has the potential to cause downstream impacts, such as increased river sedimentation, reduced water channel storage capacity, and increased risk of flooding. Therefore, controlling TBE in the upstream area is critically important in maintaining the overall balance of the DAS system. Thus, it can be concluded that the erosion hazard level in the upper watershed area of DAS Unda is strongly influenced by the interaction between natural factors and human activities, and demonstrates the urgency of implementing soil and water conservation strategies based on a spatial approach to support the sustainability of the agroecosystem in the area.

B. Appropriate Land Conservation Directives in the Upper Watershed Area of DAS Unda Using a Geospatial Information Approach

Land conservation directives in the upper watershed area of DAS Unda need to be formulated based on the complex biophysical conditions of the area, particularly encompassing the factors of slope gradient, soil type, land cover, and the level of erosion that occurs. By utilizing a geospatial information approach, such as Geographic Information Systems (GIS) and remote sensing, spatial analysis can be conducted more accurately to identify erosion-prone zones, land use distribution, and the level of vulnerability of each land unit. This approach enables the preparation of location-specific conservation directives rather than general ones, making them more effective in controlling land degradation.

Based on the results of spatial analysis of the biophysical characteristics of the upper watershed area of DAS Unda, this area is dominated by steep to very steep slopes with volcanic Regosol soil types that have moderate to high erodibility levels. This condition is reinforced by uneven vegetation cover and the presence of land use activities that pay insufficient attention to conservation aspects, such as sloped-land agriculture and quarrying activities (galian C). Under these conditions, the geospatial approach enables the delineation of conservation priority zones based on erosion vulnerability levels, namely very critical, critical, and somewhat critical zones, each requiring different handling strategies.

The recommended land conservation directives in this area encompass the application of vegetative, technical, and managerial conservation measures tailored to spatial conditions. In zones with very steep slopes, the main priority is reforestation and the development of agroforestry systems based on perennial crops such as bamboo, coffee, cocoa, and other forestry plants.

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In steep to moderately steep zones, soil conservation techniques such as terracing, contour planting, and the use of ground cover plants are recommended to reduce the rate of surface runoff. Meanwhile, in zones with lower vulnerability levels, sustainable land management can be carried out through a combination of conservation agriculture and improvement of soil organic matter.

The geospatial information approach also plays an important role in monitoring temporal changes in land use, so that the progression of land degradation and the effectiveness of conservation efforts already undertaken can be tracked. By integrating spatial data, such as Digital Elevation Models (DEM), satellite imagery, and soil data, conservation planning can be carried out more precisely and evidence-based.

Thus, geospatial information-based land conservation directives in the upper DAS Unda not only function as an analytical tool, but also as a basis for decision-making in sustainable watershed management. This approach is expected to suppress erosion rates, reduce sedimentation in downstream areas, and improve the overall ecological balance of DAS Unda.

Erosion control recommendations in the upper watershed area of DAS Unda need to focus on soil and water conservation efforts tailored to the topographic conditions dominated by steep to very steep slopes. One highly effective technique is the application of terracing, as it is capable of reducing slope length while simultaneously slowing the rate of surface runoff, thereby reducing the erosive energy of water on the soil. In addition, reforestation and the development of agroforestry systems are also critically important for sustainably increasing vegetation cover, maintaining soil structural stability, and increasing water infiltration. Planting ground cover crops (cover crops) such as grasses and legumes is also recommended to protect the soil surface from direct rainfall impact and reduce the risk of surface erosion. Furthermore, contour-following tillage needs to be applied to impede surface water flow and minimize soil loss, so that the overall erosion rate in the area can be reduced.

Conservation in the upper watershed area of DAS Unda is critically important given its biophysical conditions dominated by steep to very steep slopes, Regosol soil types that are vulnerable to erosion, and high land use pressure. Therefore, conservation directives are formulated with the primary objectives of suppressing erosion rates, improving soil quality, and maintaining hydrological balance of the watershed sustainably.

Vegetative conservation directives represent the primary step, beginning with forest rehabilitation and reforestation on steep slope areas to restore the ecological function of the land. These efforts serve to absorb the energy of rain impacts and increase soil infiltration capacity, thereby significantly reducing erosion potential. Research shows that watershed areas with high vegetation cover have erosion rates far lower than open land. In addition, the development of conservation plants such as bamboo, coffee (robusta), cocoa, coconut, and forestry plants such as mahogany, pine, and teak are highly recommended as they are suitable for the land conditions in DAS Unda.

Agroforestry combination systems such as bamboo with coffee, cocoa, or coconut have also been proven effective in increasing land cover while simultaneously reducing erosion rates. Planting ground cover plants such as legumes, grasses, and creeping plants also plays an important role in protecting the soil surface, reducing surface runoff, and increasing soil organic matter content.

On the aspect of mechanical conservation, terracing is the main technique that is highly effective in reducing slope length and gradient, thereby slowing surface runoff. In addition, the construction of ridges and drainage channels is needed to regulate water flow so that it does not become concentrated and trigger gully erosion. The construction of check dams or sediment control structures also constitutes an important component in retaining sediment material in the upstream portion, thereby reducing the impact of sedimentation in downstream areas.

From a land management perspective, adjustment of land use based on slope gradient level is required. Very steep slopes are directed as protected forest or conservation areas, moderate slopes can be used for agroforestry systems, while gentle slopes can be used for limited agriculture while still applying conservation principles. Agroforestry systems represent a sustainable solution as they are capable of maintaining land cover while simultaneously providing economic benefits for the community. In addition, organic fertilization is highly recommended to increase soil organic matter content and improve soil structure that has undergone degradation.

Control of human activities also constitutes an important part of the conservation strategy, particularly the restriction of quarrying activities (galian C) which have been proven to accelerate the destruction of soil structure and increase erosion rates. In addition, control of land use conversion from forest areas to open land needs to be carried out to maintain the stability of the watershed ecosystem.

Overall, conservation in DAS Unda must be carried out in an integrated manner from upstream to downstream. The upstream area focuses on soil and vegetation conservation, the middle area on land and water management, while the downstream area focuses on flood and sedimentation control. With this integrated conservation approach, the ecological and

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hydrological functions of DAS Unda can be sustainably maintained. Below are several types of plants and their land conservation functions in the upper watershed area of DAS Unda.

Table 12. Types of Plants and Their Land Conservation Functions in the Upper Watershed Area of DAS Unda

No	Plant Type	Vegetation Type	Conservation Function
1	Bamboo	Perennial vegetation	Binds soil with strong fibrous roots, prevents landslides, reduces bank erosion
2	Coffee (Robusta)	Agroforestry	Covers soil surface, increases infiltration, provides economic value
3	Cocoa	Agroforestry	Protects soil from direct rainfall, increases organic matter
4	Coconut	Perennial crop	Reduces surface runoff velocity, soil stabilization
5	Mahogany	Forestry crop	Strong roots, improves soil structure, long-term conservation
6	Pine	Forestry crop	Prevents erosion, increases litter layer, maintains soil moisture
7	Teak	Forestry crop	Stabilizes soil and improves long-term land quality
8	Vetiver Grass	Ground cover plant	Reduces runoff, retains sediment, highly effective on slope contours
9	Legumes (Arachis, Centrosema)	Cover crop	Adds soil nitrogen, increases organic matter
10	Creeping plants (Mucuna, etc.)	Cover crop	Rapidly covers soil, prevents splash erosion

Source: Data Analysis

Land conservation directives in the upper watershed area of DAS Unda are formulated based on biophysical approach and erosion hazard level (TBE), which shows that the higher the TBE level of an area, the more stringent the conservation efforts that must be applied. In general, conservation directives in the upper DAS Unda encompass three main approaches, namely vegetative, mechanical, and land management. On the vegetative aspect, efforts undertaken include reforestation, development of conservation plants, agroforestry systems, and the use of ground cover plants to increase land cover and reduce rain impact energy. On the mechanical aspect, conservation is carried out through the application of terracing, construction of drainage channels, and sediment control structures to reduce surface runoff velocity and retain erosion material. Meanwhile, from the management aspect, adjustment of land use according to land capability is required, along with control of quarrying activities (galian C) and land use conversion so as not to exacerbate environmental degradation.

Based on the Erosion Hazard Level (TBE) classification, conservation directives are tailored to the level of vulnerability. For verylight TBE, conservation can be carried out through ordinary farming, crop rotation, and simple land cover. For light TBE, techniques such as contour planting, mulching, and ground cover crops (cover crops) are applied. For moderate TBE, a combination of vegetative and mechanical methods is needed, such as simple terracing and strip cropping. For heavy TBE, conservation is carried out more intensively through terracing, reforestation, and construction of water disposal channels.

Whereas for very heavy TBE, land is not recommended for intensive agricultural activities and must be directed toward total rehabilitation, permanent greening, and designation as a protected area.

With the application of appropriate conservation strategies based on the erosion hazard level — whether through vegetative, mechanical, or land management approaches — the erosion rate in the upper DAS Unda can be significantly suppressed. Furthermore, the ecological function of the watershed as a balanced hydrological system can be restored and sustainably maintained.

CONCLUSION

GIS-based analysis showed that the highest erosion rate in the Upper Unda Watershed ranged from **483.36–11,499.13 ton ha⁻¹ year⁻¹**, covering **1,469.98 ha (14.28%)**, while the lowest erosion rate ranged from **0–14.27 ton ha⁻¹ year⁻¹**, covering **4,222.66 ha (41.02%)** of the study area.

The Erosion Hazard Level (EHL) in the Upper Unda Watershed varied from **Very Slight to Very Severe**, with respective areas of **4,081.66 ha (39.66%)**, **1,226.86 ha (11.92%)**, **2,468.10 ha (23.98%)**, **891.50 ha (8.66%)**, and **1,624.25 ha (15.78%)**.

Land conservation recommendations were developed according to erosion hazard levels to ensure effective and sustainable management. Recommended measures include conventional farming and crop rotation for very slight erosion areas; contour planting, mulching, and cover crops for slight erosion; terracing and integrated vegetative–mechanical conservation for

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moderate erosion; intensive terracing and reforestation for severe erosion; and permanent rehabilitation and protected area designation for very severe erosion zones.

ADVICE

Integrated watershed management should be strengthened through improved planning and enhanced human resource capacity to reduce erosion and environmental degradation. Conservation efforts should prioritize protecting upstream areas from land-use conversion, implementing conservation practices on open and post-mining land, and promoting collaboration among government agencies, environmental organizations, and local communities.

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