Jurnal Lahan Suboptimal : Journal of Suboptimal Lands
ISSN: 2252-6188 (Print), ISSN: 2302-3015 (Online, www.jlsuboptimal.unsri.ac.id)
Vol. 14, No.1: 51–61 April 2024
DOI: 10.36706/JLSO.14.1.2025.731

Conservation strategy based on soil erodibility with several land covers and slopes in the upstream of Air Bengkulu Watershed

Vinni Lovita[1*)], Bambang Sulistyo[2]
[1]Department of Soil Science, Faculty of Agriculture, Universitas Pembangunan Nasional "Veteran" Yogyakarta, Jl. Ringroad Utara No. 104, Daerah Istimewa Yogyakarta 55283, Indonesia
[2]Department of Soil Science, Faculty of Agriculture, University of Bengkulu, Jl. WR. Supratman, Bengkulu 38371, Indonesia
[*)]Email address: vinnilovita@upnyk.ac.id

(Received: 31 January 2025, Revision accepted: 17 March 2025)

Citation: Lovita, V., & Sulistyo, B. (2025). Conservation strategy based on soil erodibility with several land covers and slopes in the upstream of Air Bengkulu Watershed. *Jurnal Lahan Suboptimal : Journal of Suboptimal Lands. 14* (1): 51–61. https://doi.org/10.36706/JLSO.14.1.2025.731.

ABSTRACT

Global land cover changes driven by increasing demand for agricultural, residential, and industrial land have caused various environmental issues, including soil erosion. The study aimed to analyze soil erodibility values upstream of the Air Bengkulu watershed based on land cover and slope factors. The analysis was conducted using soil samples obtained through purposive sampling based on soil map units, topography, and land cover. Soil erodibility values were determined through laboratory analysis of organic matter, texture, structure, and soil permeability, followed by calculating erodibility. After obtaining the distribution of erodibility values, the next step involves identifying erodibility values based on slope and land cover to analyze the interaction between slope and land cover on erodibility values. Conservation recommendations are provided based on slope, land cover and consideration of community aspects to reduce erodibility values and minimize erosion risk. Results indicate that soil erodibility in the Air Bengkulu watershed ranges from *very low* to *very high*, with most areas classified as *low*. The findings suggest that soil erodibility values vary depending on land cover and slope. Higher erodibility values were observed in areas with minimal land cover, especially in mining and cultivated land with poor management practices. In contrast, dense vegetation such as forests and well-maintained plantations significantly reduced soil erodibility values. The interaction between slope and land cover plays a crucial role in determining soil susceptibility to erosion risk. Vegetative and mechanical conservation strategies are suggested to mitigate erosion risks, improve land productivity, and support ecosystem sustainability in the region.

Keywords: conservation strategy, erodibility, land cover, slope, watershed

INTRODUCTION

Global land cover change has become a critical concern in recent decades. Population growth and the increasing demand for agricultural, residential and industrial land have driven the conversion of natural landscapes, particularly forests, into non-forest areas. Global land conversion has risen significantly over the past two decades (2001-2020) (Li et al., 2021). These transformations have led to various environmental issues, such as soil erosion, sedimentation, flooding and water quality deterioration, especially in the river basins.

Soil erosion is a prevalent form of environmental degradation worldwide (Cen et al., 2024), resulting in the depletion of soil nutrients and reduced agricultural productivity (Li & Fang, 2016; Wang et al., 2024a). Erosion also contributes to river sedimentation (Zhang et al., 2024) and poses socio-economic and ecological risks to society. Significant global climate change in recent years, especially the heightened intensity of rainfall, has contributed to the annual increase in erosion rates. Erosion is driven by the complex of several factors, including erosivity, erodibility, topography and anthropogenic (land cover and land use) factors.

Soil erodibility indicates the soil's resistance to erosion. A lower erodibility value in an area corresponds to a higher risk of erosion. Soil erodibility is a function of soil texture, soil structure, organic matter, and permeability, which determine the soil's susceptibility to erosion. Land use patterns and land cover are the primary factors affecting soil erodibility values (Chen et al., 2023; Wang et al., 2019). Erodibility values vary based on soil formation processes and are closely related to soil characteristics and properties. Consequently, soil characteristics and their erodibility values continuously change in response to land formation processes and vegetation types (Wang et al., 2013; Wang et al., 2019).

Air Bengkulu watershed is one of the watersheds that has experienced significant land cover changes in recent years (Lovita et al., 2022; Supriyono et al., 2017; Tunas, 2005), impacting land use and hydrology. In the upstream, several forested areas have been converted into plantations, residential areas and mining sites. These land use changes have diminished the ecological function of forests, increased the annual risk of flood, erosion and sedimentation. It contributes significantly to land degradation and the deterioration of water quality.

This study will provide an overview of the effects of land cover and slope on soil erodibility in the upstream of Air Bengkulu watershed. By identifying soil erodibility values and the factors influencing them across various land cover types and slopes, this research seeks to provide essential insights for developing effective management strategies to mitigate erosion and flooding risks in the watershed. The objective of this research was to analyze soil erodibility values in the upstream of the Air Bengkulu watershed based on land cover and slope factors.

MATERIALS AND METHODS

Study Area

This study was conducted in the upstream of Air Bengkulu Watershed (Figure 1), which was divided into two sub-watersheds: the Susup sub-watershed and the Rindu Hati sub-watershed. Geographically, the study area was located between 3°45'36.95"–3°44'36.92" South Latitude and 102°30'11.52"–102°32'18.22" East Longitude. Administratively, it was located in Central Bengkulu Regency, Bengkulu Province. The research area covers 29,097 hectares and has an average annual rainfall of 3,500-4,500 mm, which falls into the *very high* category. Based on the Soil and Land Map Unit Book sheet 0912, the study area was predominantly covered by Inceptisols, accounting for 28,986 hectares, and Ultisols covering 110.03 hectares.

The upstream of Air Bengkulu watershed was geographically characterized by a relatively flat to hilly topography, as detailed in Figure 2. There were 13 types of land use, namely forest, rubber, mixed garden, young palm oil, old palm oil, coffee, coffee and shrubs mixed, cultivated land, bare land, settlement, ricefield, shrub, and mining. The distribution of land use in the upstream of Air Bengkulu watershed could be seen in Figure 3.

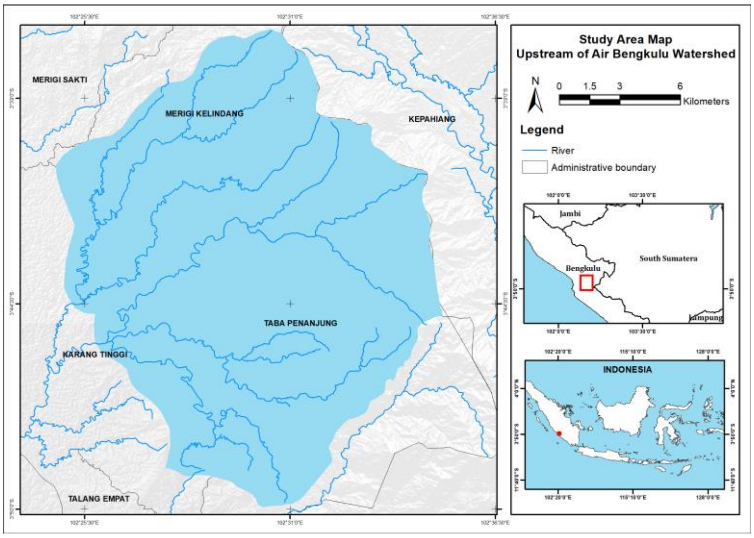

Figure 1. Map of study area

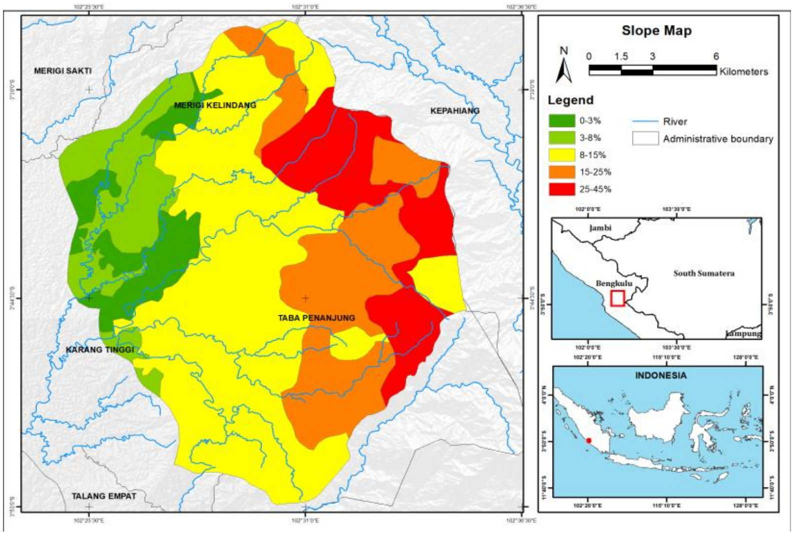

Figure 2. Map of slope in the Upstream of Air Bengkulu Watershed

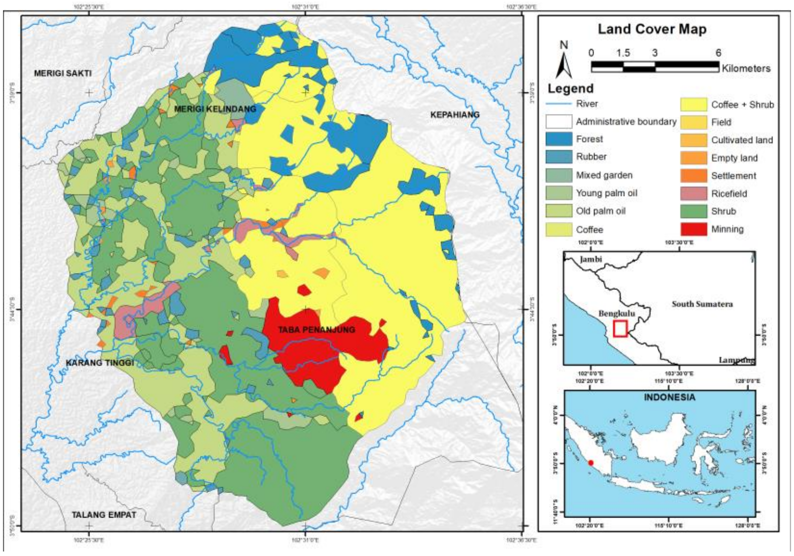

Figure 3. Map of land cover

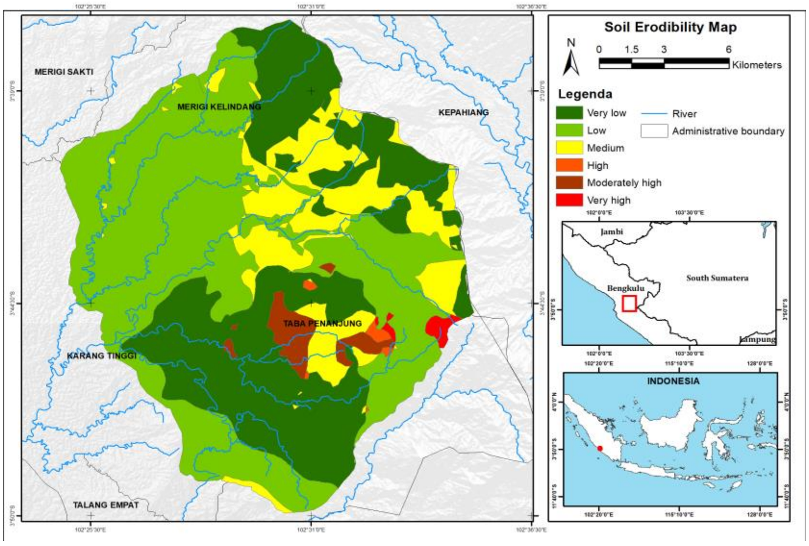

Figure 4. Flow diagram of the research

Data Collection

Soil sampling was conducted by purposive sampling, using Land Map Units obtained from overlaying slope maps, soil type maps and land cover maps. Soil samples were taken using ring samples (intact soil samples) for soil permeability analysis, while disturbed soil samples were taken for soil texture and organic matter analysis. Soil clods were sampled to analyze soil structure during the field survey. The research process consisted of the following stages: 1) preparation and map data collection, 2) field survey and soil sampling, 3) analysis of soil samples in the laboratory, 4) data analysis and mapping using *ArcGIS* 10.8, 5) providing soil conservation recommendations to mitigate the risk of erosion. These stages could be seen in the flow diagram (Figure 4).

Data Analysis

After carrying out laboratory analysis and obtaining soil organic matter, soil permeability and soil structure values, the soil erodibility value was determined using the reference formula from Hamer (1981), as followed:

K = {2.71 x 10^(-4) x (12 – OM) x M^1.14 + 4.20 x (s-2) + 3.23 x (p-3)} / 100

where:

K = soil erodibility factor
OM = percentage of organic matter,
s = soil structure class
P = soil permeability class
M = (% silt + % very fine sand) x (100 - % clay)

The soil permeability value was obtained using the Constant Head Permeability method, which was suitable for soils with granular structures and mixed with sand (Chibuzor, 2013). Furthermore, the determination of soil permeability values refers to the Ministry of Forestry Regulation (2009) could be seen in Table 1. The soil structure was observed in the field and the categorization of soil structure could be seen in Table 2, which refers to the result obtained from the formula processing were then divided into several erodibility classes based on the criteria from United States Department of Agriculture (1972) could be seen in Table 3.

After obtaining the distribution of erodibility values, the next step involves identifying erodibility values based on slope and land cover to analyze the interaction between slope and land cover on erodibility values. Conservation recommendations were provided based on slope, land cover and consideration of community aspects to reduce erodibility values and minimize the risk of erosion.

Table 1. Soil permeability class

Permeability Class	(cm/hour)	Score
Fast	>12.7	1
Rather Fast	6.3-12.7	2
Medium	2.0-6.3	3
Rather Slow	0.5-2.0	4
Slow	0.125-0.5	5
Very Slow	<0.125	6

Source: Ministry of Forestry, (2009)

Table 2. Score of soil structure

Soil Structure	Score
Very Fine Granular	1
Fine Granular	2
Coarse Granular	3
Granular, Platy, Massive	4

Source: Ministry of Forestry, (2009)

Table 3. Soil erodibility class criteria

Erodibility	Erodibility Class
0-0.10	Very Low
0.11-0.21	Low
0.22-0.32	Medium
0.33-0.44	Moderately High
0.45-0.55	High

Source: Pahlevi et al. (2018)

RESULTS

The results of laboratory analysis show that the erodibility values Upstream of Air Bengkulu Watershed were divided into six categories, namely very low, low, medium, moderately high, high and very high. The wide distribution and percentage of erodibility values could be seen in Table 4.

Based on the data presented in Table 4, the distribution erodibility values in the Upstream of Air Bengkulu watershed (Figure 5) was dominated by the low category with an area reaching 47.04%. Followed by a very low value with an area of 34.10%, the medium category had an area of 15.24%. Meanwhile, the moderately high category has an area of 2.66%, very high 0.59% and the high category has an area of 0.37%.There was a complex interaction between slope and land cover with varying erodibility values. The Upstream area of the Air Bengkulu Watershed was divided into five slope classes, namely: 0-3%, 3-8%, 8-15%, 15-25% and 25-45% with 13 different land covers. The distribution of erodibility values on slope and land cover could be seen in Figure 6.

The soil erodibility values tend to range from very low to low on slope with gradient of 0-3%. Meanwhile, on flat slope (3-8%), the soil erodibility values begin to increase compared to fla*t* slope classes. Areas with land cover such as rice fields, shrubs and mixed gardens, particularly those with dense and well-maintained vegetation, exhibit low to moderate erodibility values. However, in barren or uncultivated land areas, higher erodibility values were observed compared to flat slope classes.

Furthermore, in the slope class of 8-15% (sloping), areas of rice fields, shrubs and mixed gardens already exhibit higher erodibility values compared to flat slopes. The erodibility values range from 0.186 to 0.285. Meanwhile, moderately higher erodibility values of 0.285 were observed in cultivated or uncultivated land, or in areas with minimal vegetation cover, increasing further in mining areas with a value of 0.35 (moderately high). On *rather steep* (15-25%), there was variation in values, starting from the *low* category (0.186) in areas with shrubs, coffee plantations, forests and settlements, followed by cultivated land with minimal management at 0.28 (medium) and the *high* category (0.53) in mining areas. The erodibility values continue to rise to a very high category (0.704) in both mining areas and coffee plantations and forests in the steep slope class (25-45%).

Therefore, the conservation recommendations were necessary to reduce soil erodibility values and minimize erosion risk. The conservation recommendations were formulated based on slope classes, taking into the social and economic conditions of the community to ensure effective and sustainable implementation. The recommendations were presented in Table 5.

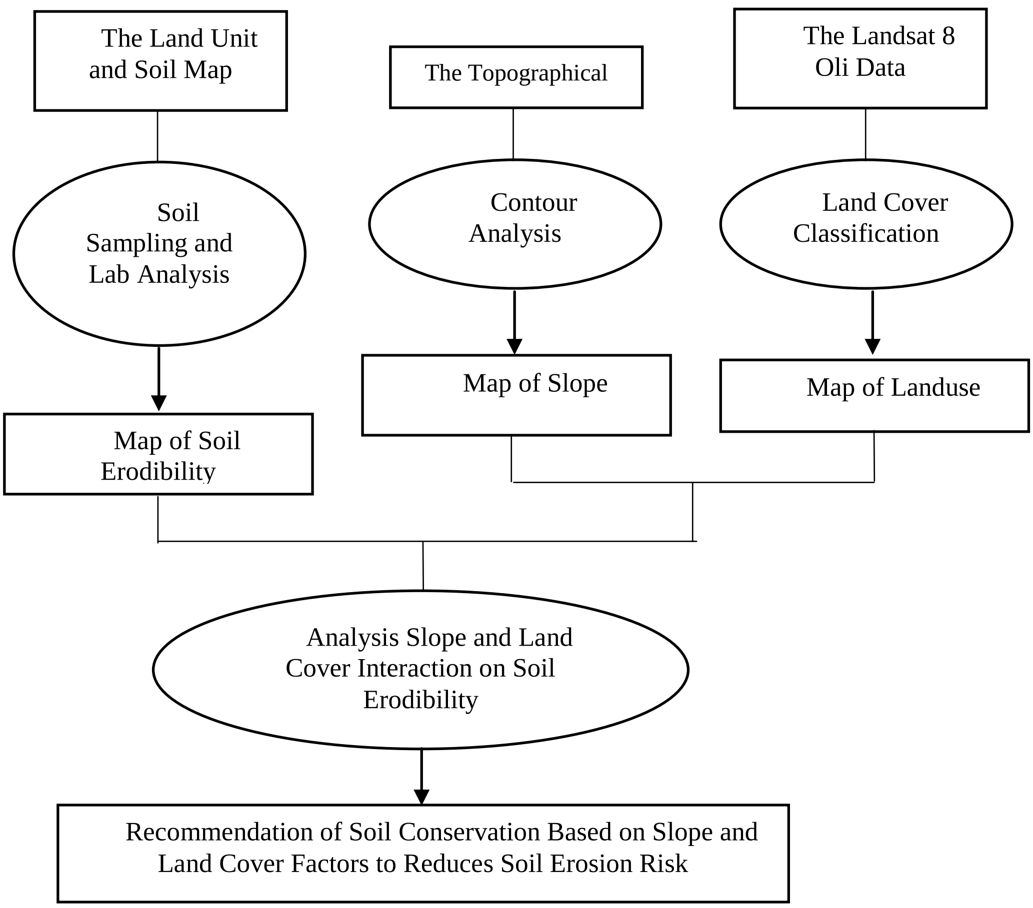

Figure 5. Soil erodibility map of the upstream of Air Bengkulu Watershed

Table 4. The distribution area of erodibility classes Upstream of Air Bengkulu

Erodibility Class	Area (ha)	Area (%)
Very low	9,923.33	34.10
Low	13,685.92	47.04
Medium	4,434.74	15.24
Moderately high	774.72	2.66
High	107.78	0.37
Very high	170.76	0.59
Total	20,097	100

Table 5. Recommendation of conservation in the Upstream of Air Bengkulu Watershed

Slope	Conservation Recommendation
0-3% (*flat*)	1. Vegetative Conservation • Cover crops that could be used as forage grasses, such as *Pennisetum purpureum*, *Imperata cylindrica*, *Vetiveria*, *Indigofera zollingeriana* (Erfandi, 2016; Rinaldi & Basri, 2012; Sri et al., 2023) • Ricefield • Legume plants, such as peanuts, soybeans and *hahapaan* (Ishak, 2016; Kusumastuti et al., 2018; Noywuli, 2023), • Vegetables 2. Mechanical Conservation • Arrangement of water drainage channels, • Construction of embankments and • Ridge Construction
3-8% (*gentle slope*)	1. Vegetative Conservation • Forage grass, such as *Pennisetum purpereum*, *Imperata cylindrica*, *Vetivera*, *Indigofera zollingeriana* (Erfandi, 2016; Rinaldi & Basri, 2012; Sri et al., 2023) • Cover crops, such as *Centrosema pubescens* and *Mucuna* (Perkasa et al., 2023; Pitaloka, 2020) • Mixed gardens with perennial crops, such as bananas, cassava, cloves and mangoes (Naharuddin, 2018) 2. Mechanical Conservation • Construction of ridge terraces, and • Construction of infiltration trench • Arrangement of water drainage channels
8-15% (*undulating*)	1. Vegetative Conservation • Perennial crops, such as coffee, cocoa, eucalyptus, mango and banana (Anna et al., 2024; Rizki et al., 2016) • Shrubs, such as *Gliricidia* and *Calliandra calothyrsus* (Maulana et al., 2021; Sayfulloh et al., 2020) • Legume plants, such as peanuts, soybeans, *Desmodium rensonii* (Suherman & Herdiawan, 2015) 2. Mechanical Conservation • Construction of bench terrace, • Earth embankment construction, and • Arrangement of water drainage *channels*
15-25% (*hilly*)	1. Vegetative Conservation • Forest plants, such as mahogany, sengon, damar and acacia (Rajagukguk et al., 2018) • Coffee and cacao plantations (Anna et al., 2024; Rizki et al., 2016) • Shrubs, such as *Gliricidia* and *Calliandra calothyrsus* (Maulana et al., 2021; Sayfulloh et al., 2020) 2. Mechanical Conservation • Stone terrace construction, • Bench terrace construction, and • Constructing ridges with vegetation such as shrubs and forage grass (*rumput gajah*) (Erfandi, 2016)
25-45% (*steep*)	1. Vegetative Conservation • Hardwood trees such as teak, mahogany, pine and fir, combined with ground cover grass such as *Vetiveria* 2. Mechanical Conservation • Stone terrace construction, • Individual terrace construction, • Constructing gabions, and • Stone steep slope stabilization

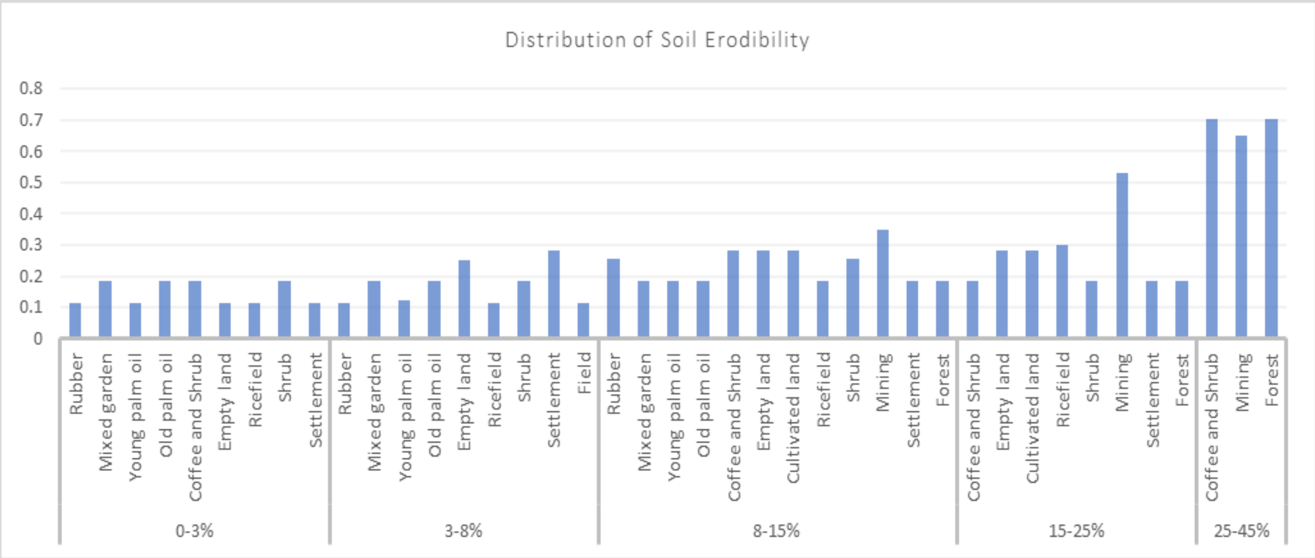

Figure 6. Distribution of soil erodibility on different land covers and slopes

DISCUSSION

Relationship between soil erodibility values and soil erosion hazard levels

Soil erodibility value is a critical component and has a direct relationship with determining soil susceptibility to erosion (Liu et al., 2025; Peng et al., 2024). A high soil erodibility value indicates that the soil is more susceptible to erosion, conversely, a low soil erodibility value suggests greater resistance to erosion. Furthermore, in calculating erosion hazard levels based on the Universal Soil Loss Equation (USLE), other factors can significantly contribute to erosion estimation, including the rainfall erosivity factor, slope length and steepness factor, and land use and management factor. Even if the soil has a low erodibility value, prolonged high-intensity rainfall can significantly increase surface runoff and the risk of erosion (Mohamadi & Kavian, 2015).

Rainfall contributes to the disintegration of soil aggregates through raindrops with varying kinetic energies and plays a significant role in surface runoff. High rainfall intensity and erosivity were key factors driving erosion and influencing slope morphology. These processes were closely associated with infiltration, surface runoff, and subsurface flow (Alewell et al., 2019; Gil et al., 2021). Under the same rainfall intensity, surface runoff can vary across different slope (Zhang & Dai, 2022). On steep slopes, rainfall tends to flow downward more rapidly, and infiltration occurs within a shorter time frame, resulting in higher surface runoff. Furthermore, the rate of surface runoff decreases on gentle slopes, particularly when accompanied by dense and tall vegetation cover (Mu et al., 2015).

The interaction between land cover and slope on soil erodibility values

Slope significantly influences the occurrence of erosion and the acceleration of surface water flow (Feng et al., 2016). The observation indicates that the steeper slope corresponds to higher soil erodibility values. As the slope increases, rainfall is more likely to flow, thereby intensifying the erosion process. Land cover and slope show an interrelated relationship in determining soil erodibility values. Areas with steep slopes, lacking adequate land cover or proper land management, were more susceptible to elevated soil erodibility. Conversely, even areas with a flat slopes may experience increased soil erodibility if land cover is inadequate or vegetation is insufficient to protect the soil surface. A decline in vegetation cover or suboptimal land management can exacerbate soil vulnerability to erosion (Lech-hab et al., 2015). For example, on bare land, whether cultivated or uncultivated, soil erodibility values tend to fall within the medium category, even in areas with flat slopes. This is because the rainfall directly impacts the soil without the protection of vegetation (Liu et al., 2025).

The vegetation plays a crucial role in preventing soil particles from being carried away by surface water flow and in reducing the kinetic energy of rain that breaks soil aggregates (Jin et al., 2021; Zhang et al., 2016). This is achieved through the plant canopy and the composition of litter. Litter, such as fallen leaves and twigs, serves as a natural barrier and provides time for rainwater before it reaches the soil surface. The thickness of the litter layer is also a key factor in controlling erosion by increasing soil shear strength and creating permeation space to minimize surface water runoff (Zhou et al., 2016).

Plant roots can also contribute to strengthening soil structure, thereby increasing soil resistance to erosion. Poor infiltration conditions on open land or in the spaces between trees, particularly on slopes with gradients greater than 8-15%, can lead to surface water runoff. High rainfall volumes can amplify runoff concentration, potentially causing splash erosion and even rill erosion. The vegetation plays a significant role in regulating infiltration. For instance, the infiltration rate increased by 155% when agricultural land was converted to shrubland, while forest areas and grasslands also showed significant increases in soil infiltration rates (Guo et al., 2022; Qiu et al., 2023).

Rainfall, slope and land cover were the primary factors influencing the erosion process (Li et al., 2024). Land cover is more dominant than rainfall and slope gradient (Babiarz et al., 2012). This is due to the greater kinetic energy of rainfall, which, when combined with minimal land cover and steep slopes, facilitates sediment transport. Areas with flat slopes have a lower risk of erosion, but good land management is essential to maintain soil productivity. Meanwhile, on steeper slopes, the risk of erosion increases significantly, particularly in areas with minimum of vegetation. Land cover such as shrubs and mixed plantations across all slope classes demonstrates potential for minimizing erosion if managed optimally.

The interaction between slope gradient and rainfall plays a critical role in accelerating water flow and increasing erosion volumes. In areas with low soil erodibility values, steep slopes and rapid surface water flow can increase the kinetic energy of water, enabling it to transport more sediment. Furthermore, land cover types and land management practices play a critical role in determining erosion hazard levels (Maximus, 2025; Senanayake et al., 2020). Studies conducted in the upper watershed of the Air Bengkulu revealed that, despite low soil erodibility values, other contributing factors can significantly exacerbate erosion risks (Barchia et al., 2020). Consequently, implementing effective conservation measures and environmental management strategies is essential to mitigate erosion.

Conservation Recommendations in the Upstream of Air Bengkulu Watershed

The recommended conservation efforts were divided into two categories: vegetative conservation and mechanical conservation. These efforts aim to transform the area into productive land, improving soil and water quality (Lal, 2014), preserving the soil, and enhancing crop yields (Xin et al., 2019), improving soil stability, reducing surface runoff, and potentially minimizing erosion by up to 80% (Wang et al., 2024). The implementation of the recommended conservation methods takes into account environmental conditions, slope, existing vegetation, as well as the social and economic context of the community. The variation in land cover types recommended has the potential to influence erosion and sedimentation patterns.

Flat to gentle slopes generally have a lower risk of erosion, so conservation techniques were more focused on optimizing agricultural land with crops that have economic value for the community. Cover crops that can serve as forage grasses include Pennisetum purpereum, Imperata cylindrica, Vetivera, Indigofera zollingeriana. Leguminous plants such as peanuts, soybeans and hahapaan not only function as ground cover and livestock feed but also improve soil fertility, soil quality and productivity (Ishak, 2016; Kusumastuti et al., 2018; Noywuli, 2023). Planting cover crops can influence the microclimate by reducing light intensity and air temperature while increasing humidity (Perkasa et al., 2023). On gentle slopes (8-15%) to the steep slope (25-45%) with higher erodibility values, particularly in mining areas, agroforestry practices can be developed using multi-strata canopies to produce dense vegetation.

The implementation of agroforestry systems across all slope classes can enhance natural resource management, increase crop diversification and improve ecosystems. Agroforestry defined as a system that combines woody vegetation with perennial crops or livestock production, beneficial for ecology, economy and conservation (Torralba et al., 2016; Tropenbos, 2023). Agroforestry is the most efficient system for erosion control (Atangana, et al., 2014). In addition to promoting sustainable economic development for communities (Wu et al., 2019), agroforestry can also improve soil properties such as soil aggregation, infiltration and bulk density, while enhancing soil organic matter and overall soil quality (Ketema & Yimer, 2014).

Mechanical conservation practices are designed to complement vegetative efforts in controlling water flow and improving soil structure. Constructing ridges or infiltration can optimize water infiltration, reducing the risk of significant surface runoff on flat to gentle slopes. On the steeper slopes, bench terraces, stone terraces and gabions are effective options for holding water flow, and preventing erosion and landslides. The combination of vegetative and mechanical conservation practices is expected to maintain slope stability and minimize erosion risks (Lovita et al., 2022; Sulistyo et al., 2020). Additionally, soil conservation offers long-term benefits for environmental sustainability and community welfare. Implementing both mechanical and vegetative conservation practices requires technical support from the government and stakeholders to ensure the recommendations are effectively applied.

CONCLUSSION

The erodibility values in the Upstream of Air Bengkulu watershed were influenced by the interaction between land cover and slope. Areas with dense land cover on flat to hilly slopes exhibit low erodibility values, while steep slope, especially those with minimal vegetation cover, showed high erodibility values. Conservation recommendations, incorporating both vegetative and mechanical practices, have been tailored to the slopes gradients and the socio-economic needs of the local community. Therefore, the proposed management strategies aim to reduce erodibility values, minimize erosion risks, enhance land productivity and quality, and support ecosystem sustainability in the upper Air Bengkulu watershed.

ACKNOWLEDGEMENTS

The authors would like to thank the University of Bengkulu Research Institute for partially funding this research through the University of Bengkulu Superior Research Scheme for the 2020 Fiscal Year, Contract Number 1990/UN30.15/PG/2020.

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