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RESEARCH ARTICLE

A Review of Critical Land in Areas Dominated by Volcanic Deposits to Support Local Ecosystem Rehabilitation Planning

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Abstract

Volcanic-derived Lithosol soils dominate North Bogor District and are inherently susceptible to erosion due to their shallow profiles and limited capacity to retain water. Combined with increasing urban land-use pressures, these conditions contribute to land degradation and the development of potentially critical land. This study aims to assess the spatial distribution of potentially critical land and formulate ecosystem-based rehabilitation strategies for sustainable land management in North Bogor District. The assessment followed a GIS-based critical land evaluation framework adapted from the national guideline for critical land assessment. GIS overlay analysis was applied to integrate land cover, soil characteristics, and land management parameters, while erosion susceptibility was evaluated using the Universal Soil Loss Equation (USLE) approach. The results indicate that potentially critical land is primarily associated with volcanic-derived Lithosol soils and areas experiencing moderate to very slight erosion hazards. These areas represent priority zones for rehabilitation because their geological characteristics increase vulnerability to ongoing land degradation. Ecosystem-based rehabilitation strategies, including the establishment of locally adapted vegetation species and the implementation of contour terracing, are recommended to reduce erosion risks, improve environmental resilience, and restore land functions. This study provides an integrated framework that links geological vulnerability, erosion susceptibility, and ecosystem-based rehabilitation for prioritizing land restoration efforts, thereby supporting sustainable land management and urban environmental planning in volcanic landscapes.

Keywords: Critical Land; Volcanic Deposit; Local Ecosystem; Rehabilitation

1. Introduction

Land degradation has become one of the most significant environmental challenges threatening ecosystem sustainability, land productivity, and environmental quality in both rural and urban areas. Among various forms of land degradation, soil erosion is considered one of the dominant processes because it removes fertile topsoil, reduces land productivity, disrupts hydrological functions, and increases sedimentation in downstream environments (Borrelli et al., 2017). In tropical regions, erosion is controlled by a complex interaction among rainfall intensity, soil properties, slope characteristics, vegetation cover, and human activities that alter land surface conditions (Panagos et al., 2015). Uncontrolled land-use changes, particularly those associated with urbanization, have been shown to increase erosion susceptibility and accelerate environmental degradation (Keesstra et al., 2018; Schillaci et al., 2023).

In Indonesia, land degradation and the expansion of critical land remain major challenges for sustainable land resource management. The conversion of agricultural land, green open spaces, and vegetated areas into residential, commercial, and infrastructure developments has altered land capability and reduced ecological functions. Previous studies have demonstrated that inappropriate land utilization and land-cover changes can increase erosion susceptibility, reduce environmental quality, and promote the development of critical land (Putera et al., 2019; Iskandar et al., 2023, Li et al, 2025). Furthermore, land-cover changes within watershed systems contribute to increased surface runoff, sedimentation, and ecosystem degradation (Ramsof et al., 2025). The integration of GIS-based spatial analysis with environmental variables provides a more comprehensive understanding of the interactions among geological conditions, land cover dynamics, erosion processes, and land degradation. Such an approach improves the identification of degradation hotspots and supports the development of ecosystem-based rehabilitation strategies through spatially explicit decision-making (Wu et al., 2024; Wang et al., 2023; Al-Quraishi, 2024). These conditions highlight the importance of periodically assessing critical land conditions as a basis for sustainable land management and environmental rehabilitation planning.

Bogor City is one of the fastest-growing urban areas in West Java Province. Continuous urban expansion has reduced agricultural land and green open spaces that naturally function as regulators of surface runoff and soil erosion. Geologically, the city is dominated by volcanic deposits derived from Mount Pangrango and Mount Salak, consisting of lava, lahar, and volcaniclastic materials (Effendi et al., 1998). Volcanic materials not only influence the physical characteristics of soils but also affect their biological properties, including microbial activity and biological fertility, which are important indicators of soil quality and ecosystem recovery following environmental disturbances (Setiawati et al., 2026). Weathering of these volcanic deposits has produced residual soils predominantly classified as Lithosols. These soils are generally characterized by shallow soil profiles, abundant rock fragments, and limited pedogenic development. Under conditions of high rainfall intensity and disturbed land cover, Lithosols tend to have limited water-holding capacity, which increases surface runoff and erosion susceptibility. This condition indicates that geological and soil characteristics play an important role in controlling land degradation processes in urban environments dominated by volcanic deposits.

The impacts of land degradation in Bogor City have become increasingly evident through the occurrence of erosion, sedimentation, and landslide events. According to data from the Regional Disaster Management Agency (BPBD) of Bogor City, landslides remain one of the most frequent natural hazards affecting the area. Pamungkas et al. (2022) reported that spatial planning inconsistencies contribute significantly to increased landslide susceptibility and environmental degradation in Bogor City. In addition, Pamungkas et al. (2023) demonstrated that critical land in urban areas continues to expand due to land-use changes and increasing development pressures. These findings suggest that critical land development in urban environments is influenced not only by land-use dynamics but also by the underlying geological and geomorphological conditions.

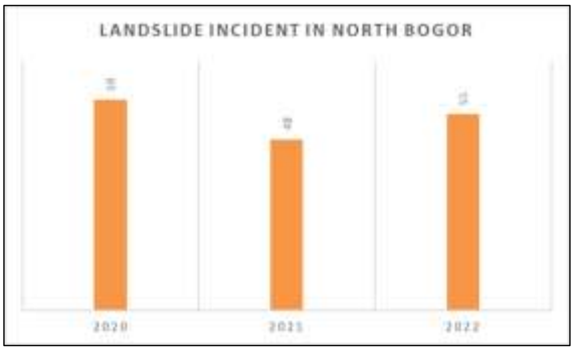


Fig. 1. Trend of landslide occurrence in North Bogor. *Source: BPBD Bogor City (2023)*

Although previous studies have investigated land-use change, land capability, critical land mapping, and landslide mitigation in Bogor City and other regions (Putera et al., 2019; Pamungkas et al., 2022; Iskandar et al., 2023; Pamungkas et al., 2023), most of them focused on land condition assessment or hazard evaluation separately. Critical land inventories conducted in 2012, 2016, and 2023 primarily emphasized the identification of critical land extent and spatial distribution without explicitly examining the relationships among volcanic-derived soils, erosion hazards, urban land-use dynamics, and ecosystem-based rehabilitation priorities. Furthermore, differences in assessment methodologies applied during each inventory period have limited the interpretation of temporal land degradation patterns and reduced their effectiveness in supporting rehabilitation planning.

This limitation reveals an important research gap because effective rehabilitation planning requires not only information regarding the spatial distribution of critical land but also a comprehensive understanding of the environmental processes controlling land degradation. In volcanic urban environments such as North Bogor District, the relationships among volcanic-derived Lithosol soils, erosion susceptibility, land-cover changes, and critical land development remain insufficiently understood. Such information is essential for determining rehabilitation priorities that are compatible with local environmental characteristics and for supporting long-term ecosystem recovery (Keesstra et al., 2018; Arneth et al., 2021; Schillaci et al., 2023).

Therefore, this study aims to: (1) evaluate the current critical land condition in North Bogor District using the latest critical land assessment framework; (2) analyze the relationships among volcanic-derived Lithosol soils, erosion susceptibility, and land degradation in an urban environment; and (3) formulate ecosystem-based rehabilitation recommendations that are compatible with local environmental characteristics. The novelty of this study lies in the integration of critical land assessment, erosion hazard evaluation, and ecosystem-based rehabilitation planning within an urban area dominated by volcanic deposits. This integrated approach is expected to provide a scientific basis for sustainable land management and support more resilient urban environmental planning in areas vulnerable to land degradation.

2. Material and Methods

The integration of GIS-based spatial analysis with environmental variables provides a more comprehensive understanding of the interactions among geological conditions, land-cover dynamics, erosion processes, and land degradation. Such an approach enables the identification of dominant driving factors controlling land degradation and supports more effective ecosystem-based rehabilitation planning (Wu et al., 2024). The inventory of critical land in North Bogor Sub-district was conducted with reference to the Regulation of the Director General of Watershed and Protected Forest Management No. P.3/PDASHL/SET/KUM.1/7/2018 concerning the technical guidelines for the preparation of critical land spatial data. The preparation of such spatial data requires several supporting components, including hardware, software, and data materials.

2.1 Material

The hardware and software used in this study included up-to-date Geographic Information System (GIS) software and a personal computer with a minimum specification of 16 GB RAM, a 1 TB hard drive, and access to a plotter.

The data materials required for the preparation of critical land spatial data consisted of: (1) the most recent land cover data issued by the Directorate General of Forestry Planning and Environmental Management, Ministry of Environment and Forestry; (2) a forest area map obtained from the same institution; (3) a slope map derived from the Indonesian Base Map (RBI) and aerial photographs at a scale of 1:25,000 provided by the Geospatial Information Agency in 2014; and (4) an erosion susceptibility map analyzed in accordance with the Regulation of the Director General of PDASHL No. P.10/PDASHL/SET/KUM.1/8/2017.

2.2 Procedure

The critical land assessment was conducted through a GIS-based spatial analysis using thematic spatial datasets derived from land cover, slope, erosion hazard level, and area function maps. Each parameter was assigned a score and weight according to the PDASHL guideline, and the resulting thematic layers were integrated through a GIS overlay process to generate a composite critical land index. Based on the total score obtained, the study area was classified into five critical land categories: Not Critical, Potentially Critical, Rather Critical, Critical, and Very Critical. The overall analytical workflow is presented in Figure 2.

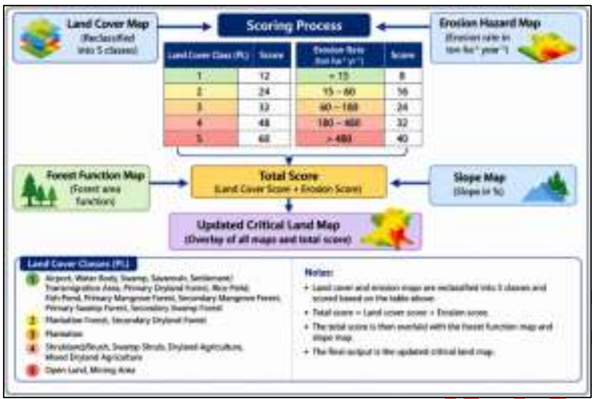


Fig. 2. Procedures for the preparation of technical guidelines for the preparation of spatial data on critical land in North Bogor Sub-district

a) Map Attribute Preparation Process

This stage was carried out to prepare the attributes of each parameter represented in the thematic maps. Proper attribute preparation facilitates the subsequent analysis process after map overlay, particularly through the application of logical expressions.

According to the Regulation of the Director General of Watershed and Protected Forest Management No. P.3/PDASHL/SET/KUM.1/7/2018, the classification of area function types is based on the authority of the government, particularly the Ministry of Environment and Forestry, in relation to its roles and responsibilities in forest area management. This classification refers to the area function data provided in the thematic map of area functions issued by the Directorate General of Forest Planning and Environmental Management, Ministry of Environment and Forestry. In the spatial planning area of Bogor City, especially North Bogor Sub-district, no forest area function is designated; instead, the area is classified as other use areas or areas outside the forest estate.

Under the same regulation, forest area functions are classified into several categories, including protected forest, conservation forest, production forest, limited production forest, conversion production forest, terrestrial nature park, nature reserve, botanical forest park, marine wildlife reserve, terrestrial wildlife reserve, terrestrial nature tourism park, marine nature tourism park, hunting park, marine nature park, marine nature reserve, terrestrial national park, and marine national park.

The land cover map used in this study consists of 23 land cover types obtained from the Directorate General of Forest Planning and Environmental Management, which are published annually. The scoring system was determined by multiplying the parameter weight assigned to land cover, which is 60, by the land cover class value and then dividing the result by the total number of classes established, namely five, as presented in Table 1.

Table 1. Land Cover Score (Weight = 60%)

Number	Symbol	Note	Class	Score
1	A	Aiport	1	12
2	WB	Water Body		
3	SW	Swamp		
4	SV	Savannah		
5	S/T	Settlement/Transmigration		
6	PDF	Primary Dryland Forest		
7	RC	Rice Fields		
8	PDF	Ponds		
9	PMF	Primary Mangrove Forest		
10	SMF	Secondary Mangrove Forest		
11	PSF	Primary Swamp Forest		
12	SSF	Secondary Swamp Forest		
13	SDF	Secondary Dryland Forest	2	24
14	PF	Plantation Forest		
15	P	Plantation	3	36
16	S	Shrubs/Shrubs	4	48
17	SC	Swamp Scrub		
18	DA	Dryland Agriculture		
19	DMF	Dryland Mixed Farming		
20	OL	Open Land	5	60
21	M	Mining		
22	C	Clouds	0	0
23	NN	No data		

The erosion susceptibility map is divided into five erosion hazard classes expressed in tons per hectare per year, based on the thematic erosion hazard map prepared in accordance with the Regulation of the Director General of PDASHL No. P.10/PDASHL/SET/KUM.1/8/2017. The score for this parameter was calculated by multiplying the erosion weight, which is 40, by the class order number and dividing the result by the total number of erosion classes, namely five, as shown in Table 2.

Table 2. Erosion Class Data Attributes

Number	Erosion Class	Score
1	<=15	8
2	>15-60	16
3	>60-180	24
4	>180-480	32
5	>480	40

The area function map was derived from the thematic map of area functions issued by the Directorate General of Forest Planning and Environmental Management, Ministry of Environment and Forestry. The attribute indicating whether an area lies inside or outside the forest estate represents the classification of area function types based on the authority of the government, particularly the Ministry of Environment and Forestry, in carrying out forest area management. This classification is based on the area function data contained in the official thematic map, as shown in Table 3.

Table 3. Data Attributes Inside and Outside the Forest Area

Number	Function Area	In and Out
1	Protection Forest	Within Forest Area
2	Conservation Forest	
3	Production Forest	
4	Limited Production Forest	
5	Convertible Production Forest	
6	Land Nature Park	
7	Nature Reserve Area	
8	Marine Wildlife Sanctuary	
9	Land Nature Reserve	
10	Botanical Forest Park	
11	Nature Conservation Area	
12	Land-based Nature Reserve and Tourism Forest	
13	Marine Nature Reserve and Tourism Forest	
14	Hunting Park	
15	Marine Nature Park	
16	Marine Nature Reserve	
17	Land Wildlife Sanctuary	
18	Land National Park	
19	Marine National Park	
20	Other Use Areas	Outside Forest Area
21	Water Body	Water Body

For the slope map, the required fields and attributes were prepared in the thematic database. The slope class attributes, expressed as percentages, were derived from contour data from the Indonesian Base Map at a scale of 1:50,000 published by the Geospatial Information Agency, as presented in Table 4.

Table 4. Slope Class Data

Number	Slope
1	0-8%
2	>8-15%
3	>15-25%
4	>25-40%
5	>40%

b) Critical Land Analysis Process

Critical land assessment was performed through a GIS overlay analysis integrating four principal thematic layers: land cover, erosion hazard level, area function, and slope gradient. Each parameter was assigned a score according to the PDASHL guideline and subsequently combined through a weighted scoring approach. The resulting composite score was used to classify land into five categories: Not Critical, Potentially Critical, Rather Critical, Critical, and Very Critical.

First, the land cover map was overlaid with the erosion map. This process produced Overlay Map 1, in which the attributes of the two thematic maps were combined into a single layer. A new field, TOTAL_SCORE, was then added to Overlay Map 1 to calculate the sum of the land cover score (SCORE_KLSPL) and the erosion score (SCORE_EROSION). As a result, each polygon generated from the overlay process had a total score ranging from 20 to 100, as presented in Table 5.

The total score range, from the minimum value of 20 to the maximum value of 100, is 80. This range was then divided into five classes, resulting in an interval of 16 for each class. Subsequently, an additional field, SCORE_CRIT, was created to classify the total score values into five criticality classes, as shown in Table 6.

Table 5. Score of Land Cover and Erosion Map

Land Cover	CLS_LC	Score_CLSLC	Erosion	Score_erosion	Total Score
Swamp Savannah Primary Dryland Forest	1	12	>=15	8	20
Secondary Dryland Forest Plantation Forest	2	24	>15-60	16	40
Plantation	3	36	>60-180	24	60
Shrubs/Brush Mixed Dryland Agriculture	4	48	>180-480	32	80
Open land Mining	5	60	>480	40	100

Table 6. Land Criticality Score

Number	Critical Score
1	20-36
2	>36-52
3	>52-68
4	>68-84
5	>84-100

Next, Overlay Map 1 was overlaid with the area function map and the slope map. This step produced Overlay Map 2, which may be referred to as the draft critical land map. The attributes of this map represent a combination of the four thematic maps used in the analysis, namely the land cover map, erosion map, area function map, and slope map. An additional field, L_CRITICAL, was then added to store the results of the logical expression analysis based on the attributes of these four thematic maps. The L_CRITICAL field contains five classes of critical land, namely Not Critical, Potentially Critical, Slightly Critical, Critical, and Very Critical.

The logical expressions used to determine the critical land classes are presented in Table 7. Since North Bogor is located outside the forest estate, the analysis applied in this study was limited to the critical land assessment scheme for areas outside forest zones.

Table 7. Analysis Score of Critical Land Outside Forest Area

Slope	Critical Score				
	0-36	>36-52	>52-68	>68-84	>84-100
0-8	NC	NC	PC	RC	RC
>8-15	NC	PC	RC	RC	RC
>15-25	PC	RC	RC	C	VC
>25-40	RC	RC	RC	C	VC
>40	RC	RC	RC	C	VC

Note: NC = Not Critical, PC = Potential Critical, RC= Rather Critical, C = Critical, VC = Very Critical

Field verification was conducted to validate the results of the GIS-based critical land assessment and to ensure the reliability of the spatial classification. Validation activities included direct observations of land cover conditions, evidence of surface erosion, slope characteristics, soil conditions, and existing land management practices at selected observation points. The interpreted critical land classes were compared with actual field conditions to evaluate the accuracy of the GIS analysis and image interpretation. High-resolution satellite imagery obtained from LAPAN was also used to support the verification process and refine the delineation of critical land boundaries. Where discrepancies were identified between field observations and the preliminary classification, the draft critical land map was revised through additional spatial analysis or manual delineation. Following the completion of the validation and revision processes, the final critical land map was produced. The validation process was intended to minimize classification errors and improve the accuracy of the final critical land inventory.

c. Erosion Susceptibility Map Analysis Process

The preparation of the erosion susceptibility map followed the procedure specified in the Regulation of the Director General of PDASHL No. P.10/PDASHL/SET/KUM.1/8/2017. The procedure involves determining the level of erosion hazard by calculating the ratio between the predicted soil erosion rate and the tolerable soil loss rate. The general workflow is presented in Figure 3.

The erosion susceptibility map was developed in accordance with the procedure stipulated in the Regulation of the Director General of PDASHL No. P.10/PDASHL/SET/KUM.1/8/2017. The analysis was based on the integration of supporting spatial and environmental datasets, including base maps, remote sensing imagery, geomorphological maps, slope maps, soil maps, land cover data, and rainfall records obtained from relevant government institutions. These datasets were used to delineate land units according to their geomorphological, slope, soil, and land cover characteristics, followed by soil sampling and laboratory analysis.

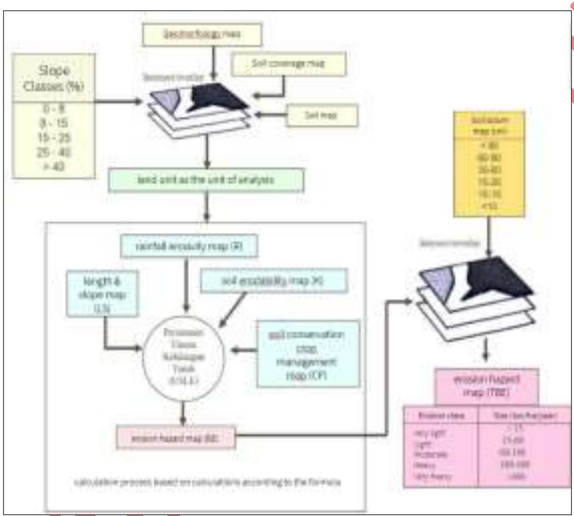


Fig. 3. Procedure for preparing the erosion susceptibility map. (Source: Regulation of the Director General of PDASHL No. P.10/PDASHL/SET/KUM.1/8/2017.)

Soil erosion rates were estimated using the Universal Soil Loss Equation (USLE), incorporating rainfall erosivity, soil properties, slope length and steepness, crop management, and soil conservation practices. The USLE model estimates annual soil loss (A) as a function of rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover-management factor (C), and conservation practice factor (P). These parameters were derived from rainfall records, soil characteristics, topographic conditions, land cover data, and existing conservation practices within the study area. The Erosion Hazard Level (TBE) was subsequently determined based on erosion rates and soil depth, and the preliminary results were verified through field surveys and map revision. The final output of this procedure was an Erosion Hazard Level map. In this study, the analysis employed 10 years of rainfall data from 2013 to 2022, with an average annual rainfall of 3,605.25 mm/year, obtained from the West Java Meteorological Station (WMO ID 96753).

3. Result and Discussion

Based on the analysis carried out in accordance with the Regulation of the Director General of Watershed and Protected Forest Management No. P.3/PDASHL/SET/KUM.1/7/2018, the critical land condition in North Bogor District is classified into two categories, namely potentially critical and non-critical, as shown in Table 8. The spatial distribution of critical land is predominantly characterized by potentially critical areas, which are represented by green on the map in Figure 4. The most extensive potentially critical land occurs in the urban villages of Ciluar and Kedunghalang, while non-critical land is also identified in Kedunghalang. This pattern is closely associated with the ongoing conversion of cultivated land into residential areas.

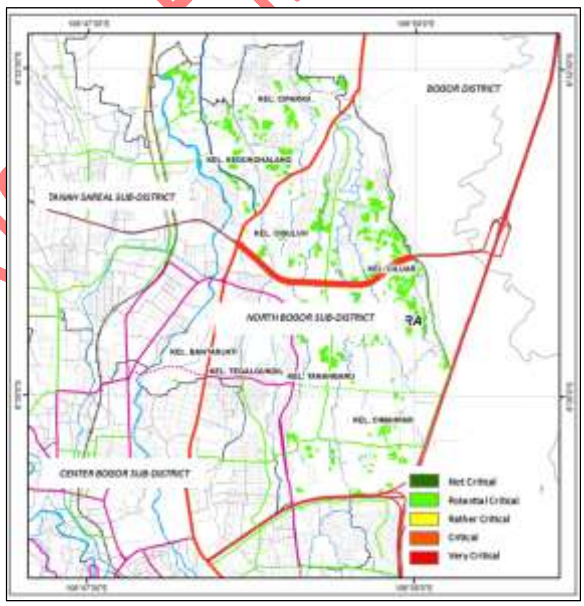


Fig. 4. Map of Critical Land in North Bogor Sub-district, Bogor City

Field observations indicate that the morphology of North Bogor Sub-district is generally characterized by gently undulating hills and lowland plains. From a geomorphological perspective, the area is composed of volcanic hill units and alluvial fan units. The bedrock identified in the study area consists predominantly of conglomerate with a tuffaceous base and an andesitic matrix, as reported by Effendi et al. (1998). From a geological perspective, the soils in this area are residual soils derived from the weathering of the underlying bedrock. Based on the 1:50,000 scale soil map issued by the Soil Research Institute (n.d.), the dominant soil type in North Bogor is Lithosol. Therefore, the critical land in North Bogor Sub-district is primarily associated with Lithosol soils.

Geologically, the occurrence of potentially critical land in North Bogor District is closely related to the characteristics of Lithosol soils developed from the weathering of volcanic deposits derived from Mount Salak and Mount Pangrango. Lithosols are generally characterized by shallow soil profiles, abundant coarse fragments, limited soil development, and relatively low water-holding capacity. Although volcanic parent materials commonly contain relatively high mineral nutrients, the shallow soil depth reduces the ability of the soil to retain water and resist erosion processes under intensive rainfall conditions (Alewell et al., 2019; Schillaci et al., 2023).

Under the humid tropical climate of Bogor, where annual rainfall exceeds 3,500 mm, these soil characteristics promote the generation of surface runoff, particularly in areas with disturbed vegetation cover. Continuous runoff removes fertile topsoil, decreases soil organic matter, and accelerates land degradation processes. Consequently, the development of potentially critical land in North Bogor is controlled not only by land-use practices but also by the inherent geological and pedological characteristics of volcanic-derived Lithosols (Borrelli et al., 2023; Panagos et al., 2024).

These findings indicate that Lithosol soils act as a predisposing factor for erosion susceptibility, whereas land-cover changes associated with urban expansion function as triggering factors that accelerate land degradation. Therefore, understanding the interaction between volcanic-derived soil properties and land-use dynamics is essential for developing effective rehabilitation strategies in urban environments dominated by volcanic deposits (Keesstra et al., 2021; Schillaci et al., 2023).

In North Bogor Sub-district, the largest area of critical land is located in Ciluar Village, covering 31.89 ha. This critical land is mainly associated with plantation/garden land cover and low erosion susceptibility.

Table 8. Area of critical land in non-forest land area in North Bogor Sub-district.

Urban Village	Critical Class (ha)		Grand Total	%
	Critical Potential	Non-Critical		
Bantarjati	0.16		0.16	0.15
Cibuluh	5.99		5.99	5.36
Ciluar	31.89		31.89	28.52
Cimahpar	19.89		19.89	17.79
Ciparigi	11.82		11.82	10.57
Kedunghalang	23.57	0.36	23.92	21.08
Tanahbaru	16.05		16.05	14.36
Tegalgundil	2.43		2.43	2.18
Grand Total	111.81	0.36	112.16	100.00

The classification of land criticality outside forest areas can be described as follows.

a) Potentially Critical Land

The level of land criticality has a value of 56 and is therefore classified as potentially critical. The dominant land cover types in this category are plantations/gardens and swamps or open fields. The vegetation is predominantly composed of perennial plants and bamboo. The slope class ranges from gentle to steep, while the erosion rate is classified as very low. An example of potentially critical land is shown in Figure 5.

The criticality level of the land has a value of 20, which is included in the non-critical category. The land cover is in the form of rice fields, but is covered by vegetation. The dominant vegetation is perennial and bamboo. The slope class of the non-critical land is flat. The erosion rate is very low. An example of non-critical land is shown in Figure 6.

Fig 5. Potentially critical land condition in gardens in Cimahpar Urban Village

Fig. 6. Non-critical land condition in RW 13 Kedunghalang garden

The Erosion Hazard Level map in North Bogor was validated by field indications of sediment deposition transported by runoff during flood events, for example along Tumenggung Wiradiredja Street in Tanah Baru Village (Figure 7). The dispersive nature of the soil makes it highly vulnerable to erosion, especially where land cover is open, such as in dryland agriculture or recently cultivated intercropping areas. Therefore, the area is classified as having a high Erosion Hazard Level. The Erosion Hazard Level in each urban village is presented in Table 9, and its spatial distribution is illustrated in Figure 8.

Table 9. Level of Erosion Hazard North Bogor

Urban village	Level of Erosion Hazard				Grand Total
	0 - SR	II - S	III - B	IV - SB	
Bantarjati		0.16			0.16
Cibuluh		2.89	3.10		5.99
Ciluar		18.73		13.16	31.89
Cimahpar		5.60	11.10	3.19	19.89
Ciparigi		7.80	3.13	0.89	11.82
Kedunghalang	0.36	19.85	3.71		23.92
Tanahbaru		3.64	9.86	2.56	16.05
Tegalgundil		1.11	1.00	0.32	2.43
Grand Total	0.36	59.79	31.90	20.12	112.16

Fig. 7. Photo of heavy erosion at an open land site in Cimahpar

In the case of Jalan Tumenggung, it is open land, with no retaining wall, irregular soil, hollow topography, and no sodetan to the main drainage that flows into the drainage on Jalan Pandu Raya as shown in Figure 7, so the flood hit Jalan Tumenggung Wiradiredja, North Bogor, Bogor City. This flood picture was taken on Radar Bogor (2023).

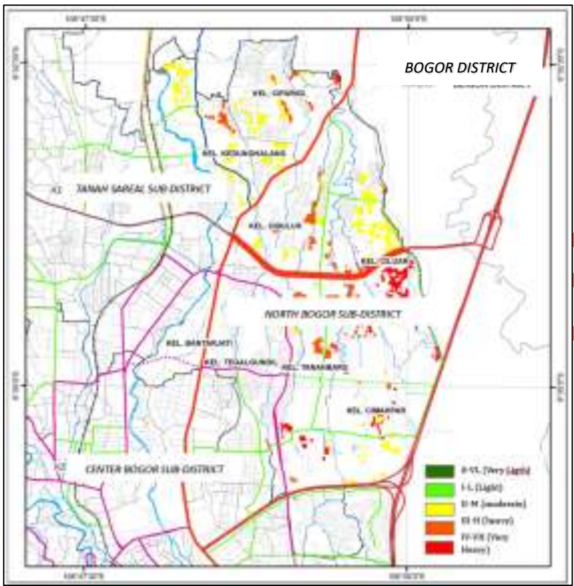


Fig 8. Map of Erosion Hazard Level in North Bogor Sub-district, Bogor City

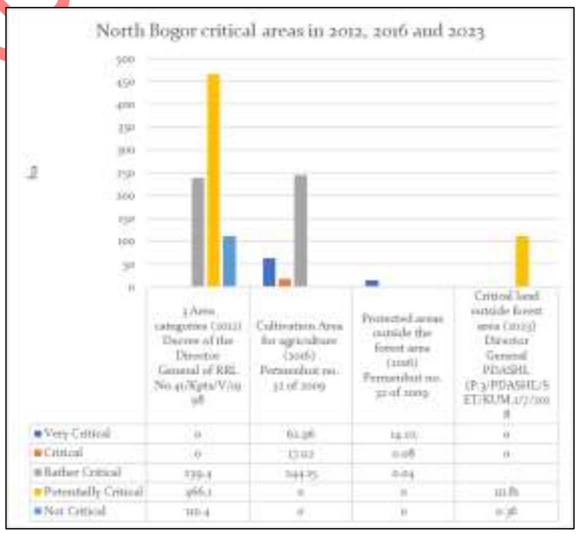
b) Relationship Between Land Cover, Slope Conditions, and Erosion Hazard

The spatial distribution of erosion hazard levels in North Bogor demonstrates a strong relationship among land cover conditions, slope gradients, and soil characteristics. Areas with permanent vegetation cover, such as mixed gardens and densely vegetated lands, generally exhibit lower erosion hazard levels because plant canopies reduce rainfall impact while root systems improve soil structure and increase infiltration capacity. In contrast, open land and recently cultivated agricultural areas are more susceptible to erosion because rainfall directly impacts the soil surface, increasing soil particle detachment and runoff generation (Panagos et al., 2015; Panagos et al., 2024).

Slope gradient also plays an important role in controlling erosion intensity. Steeper slopes increase runoff velocity and erosive power, resulting in higher rates of soil particle transport. Although much of North Bogor is characterized by gentle to moderately steep slopes, erosion hazards become more pronounced where steep slopes coincide with inadequate vegetation cover. This explains why several areas classified as potentially critical land are associated with garden land, shrubland, or partially open land cover despite being located in areas with relatively low to moderate erosion classes.

The interaction between slope conditions and land cover indicates that erosion hazard is not controlled by a single factor but rather by the combined influence of topography, vegetation cover, and soil properties. Therefore, maintaining adequate vegetation cover is essential for reducing runoff and minimizing erosion risks in volcanic urban environments (Schillaci et al., 2023; Borrelli et al., 2023).

Figure 9 presents a summary of the results reported by BPLHD in 2012 and 2016, together with a comparison to the 2023 analysis. According to the 2012 critical land inventory data for North Bogor, which were prepared using the method set out in the Decree of the Director General of Reforestation and Land Rehabilitation No. 41/Kpts/V/1998, critical land was classified into four categories: non-critical, covering 110.4 ha (6.2%); potentially critical, covering 466.1 ha (23.6%); moderately critical, covering 239.4 ha (13.5%); and critical, covering 7.6 ha (0.4%). However, the report does not clearly indicate the area classification used in the assessment. It may therefore be inferred that the 2012 inventory in North Bogor considered three area function categories, namely protected areas, agricultural cultivation areas, and protected areas outside the forest estate.



** North Bogor Critical Land Inventory Report (2012) by BPLHD Bogor City; ** Tanah Sareal and North Bogor Critical Land Inventory Report by BPLHD Bogor City (2016).*

Fig 9. North Bogor critical land area in 2012, 2016, and 2023

In the 2016 critical land assessment, the method applied referred to Minister of Forestry Regulation No. 32 of 2009. The same method was also used by Pamungkas et al. (2023) in East Bogor. According to BPLHD (2016), critical land in North Bogor District was identified in protected areas outside the forest estate and in agricultural cultivation areas. Protected areas outside the forest estate were classified into three categories: very critical, critical, and moderately critical. In these areas, critical land cover included public cemeteries, parks, road corridors, and riparian zones along the Ciliwung, Ciluar, Ciparigi, Cibuluh, and Cilimus rivers. The total area of critical land in riparian zones was 0.38 ha. In addition, protected areas outside the forest estate also included residential yards, parking areas, office green spaces, sports facilities, green belts along highways, green spaces along primary and secondary collector roads, home gardens, swamps, and shrubland. Among the non-forest protected areas, Cimahpar Urban Village had the largest extent of very critical land, covering 4.6 ha.

In the agricultural area, land use consisted of irrigated paddy fields, rainfed paddy fields, swamps or gardens, fish ponds, temporarily uncultivated land, and livestock areas. This classification is consistent with the land-use grouping used by the Bogor City Agriculture Office (2016). Based on data from the Bogor City Agriculture Office, the area of agricultural cultivation land in North Bogor Sub-district in 2016 reached 262.69 ha, while non-agricultural land covered 1,501.12 ha. In the 2016 inventory, private gardens, which were generally planted with mixed crops, were also included. Agricultural land was classified into very critical, critical, and moderately critical categories. Tanah Baru Urban Village had the largest area of very critical agricultural land in 2016, reaching 19.79 ha. The occurrence of critical land in agricultural areas was likely related to poor land management practices, including inadequate irrigation performance. Cultivated land planted with cassava was particularly susceptible to erosion. The erosion class in North Bogor ranged from moderate to severe, and severe erosion has contributed to sedimentation problems, including the siltation of drainage channels in the area.

The differences observed among the critical land inventories conducted in 2012, 2016, and 2023 should be interpreted carefully because they were produced using different assessment frameworks. The 2012 inventory referred to the Decree of the Director General of Reforestation and Land Rehabilitation No. 41/Kpts/V/1998, while the 2016 inventory adopted the Minister of Forestry Regulation No. P.32/Menhut-II/2009. The present study employs the more recent framework established by the Regulation of the Director General of PDASHL No. P.3/PDASHL/SET/KUM.1/7/2018. Differences in classification systems, parameter weighting, land function criteria, and assessment procedures may therefore influence the resulting critical land extent and category distribution

Besides methodological differences, land-use dynamics have also contributed to temporal variations in critical land conditions. Rapid urban expansion in Bogor City has converted agricultural land, mixed gardens, and open green spaces into residential and commercial areas. Such land-use transformations alter hydrological responses, reduce infiltration capacity, and increase surface runoff, thereby modifying erosion susceptibility patterns. Consequently, changes in critical land extent over time reflect not only environmental degradation processes but also differences in assessment methods and urban development pressures.

These findings suggest that long-term monitoring of critical land should employ standardized assessment procedures to ensure consistency and improve the reliability of temporal comparisons. Standardized methodologies would provide a stronger basis for evaluating land degradation trends and prioritizing rehabilitation programs in rapidly developing urban environments.

c) Critical Land Rehabilitation Recommendations

The rehabilitation strategy proposed in this study is based on ecosystem-based rehabilitation principles that integrate vegetation establishment and soil conservation measures. The recommended plant species, including breadfruit (*Artocarpus altilis*), jackfruit (*Artocarpus heterophyllus*), mango (*Mangifera indica*), leucaena (*Leucaena leucocephala*), calliandra (*Calliandra calothyrsus*), albizia (*Falcataria moluccana*), and Indian coral tree (*Erythrina variegata*), were selected because they are well adapted to volcanic soils and tropical climatic conditions. These species possess extensive root systems capable of improving soil aggregation, enhancing infiltration capacity, and increasing slope stability.

Fast-growing species such as albizia, calliandra, and leucaena are particularly effective for erosion control because they rapidly establish canopy cover and reduce the kinetic energy of raindrop impact on the soil surface. In addition, leucaena and calliandra contribute to soil fertility improvement through biological nitrogen fixation. Fruit-bearing species such as breadfruit, jackfruit, and mango provide additional socio-economic benefits to local communities while maintaining vegetation cover. Therefore, the proposed rehabilitation strategy not only addresses erosion control but also supports sustainable land management and community-based ecosystem restoration.

Mechanical conservation measures, particularly contour terracing, are recommended in areas with moderate to steep slopes. Contour terraces reduce slope length, decrease runoff velocity, increase infiltration, and minimize soil loss. The integration of vegetative and mechanical approaches is therefore expected to provide more effective and sustainable erosion control in volcanic urban environments.

Critical land rehabilitation through mechanical and vegetative approaches was tailored to land characteristics and to local plant species that are well adapted to the soil conditions volcanic product of North Bogor. Table 6 indicates that 111.8 ha of potentially critical land are recommended for combined vegetative and mechanical rehabilitation, whereas 0.4 ha are classified as non-critical land.

Table 10**.** Recommendations for mechanical and vegetative treatments on critical land

Urban Village	Critical Class		Critical land restoration	
	Potential Critical	Not Critical	Vegetative	Mechanics
Bantarjati	0.2			
Cibuluh	6.0			
Ciluar	31.9			
Cimahpar	19.9			
Ciparigi	11.8			
Kedunghalang	23.6	0.36	Breadfruit, Jackfruit, Mango, lead tree, Calliandra, Albazia, and Indian coral tree	contour terrace
Tanahbaru	16.1			
Tegalgundil	2.4			
Grand Total	**111.8**	**0.36**		

4. Conclussion

This study demonstrates that land degradation in North Bogor District is strongly influenced by the interaction between volcanic-derived Lithosol soils, erosion susceptibility, and increasing urban land-use pressures. The findings indicate that areas classified as potentially critical require special attention in land management because their inherent soil characteristics increase vulnerability to surface erosion and environmental degradation.

The results highlight the importance of ecosystem-based rehabilitation strategies as an effective approach for managing potentially critical land in volcanic urban environments. Integrating locally adapted vegetation with soil and water conservation measures, such as contour terracing, can reduce erosion risks, improve slope stability, and enhance long-term ecosystem resilience. These measures provide practical guidance for mitigating land degradation while maintaining ecological functions in rapidly urbanizing areas.

This study contributes to sustainable land management by proposing an integrated spatial framework that combines volcanic-derived Lithosol soil characteristics, erosion susceptibility, and ecosystem-based rehabilitation strategies for assessing potentially critical land. Unlike conventional critical land assessments that primarily emphasize land cover and erosion indicators, the proposed framework explicitly incorporates geological vulnerability as a key factor controlling land degradation. The study further extends the application of critical land assessment to volcanic urban environments, where geological conditions interact with rapid urban expansion and land-use change. By linking geological characteristics, erosion susceptibility, and rehabilitation planning within a single framework, this approach provides a scientific basis for prioritizing rehabilitation efforts, supporting urban environmental planning, and fostering more resilient volcanic urban landscapes.

The framework may also be adapted to other volcanic regions experiencing rapid urbanization, thereby supporting broader efforts toward sustainable land management and ecosystem restoration in tropical volcanic landscapes.

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