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Mapping of landslide vulnerability in the build area based on Remote Sensing and GIS in Ambon City, Indonesia

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Abstract. *Landslides are natural hazards characterized by rock mass, debris, or soil movement on slopes under gravity. This study employed qualitative and quantitative methods with a spatial approach to analyze primary and secondary data obtained from satellite imagery, observations, and relevant institutions. Data were processed using Global Mapper 20, ArcGIS 10.8.1, and ER Mapper 8.1 Software. The results obtained from this study revealed that the majority of the Ambon City area (approximately 51.63%) was classified as having high landslide vulnerability. Meanwhile, only approximately 16.26% of the total area had very low or low landslide vulnerability. The same pattern is observed in built-up areas, where most landslide vulnerability falls under the high category (Z-4), at approximately 39.01%. In contrast, very low landslide vulnerability (Z-1) accounted for approximately 35.09%, and low vulnerability (Z-2) accounted for approximately 11.89%. The level of landslide vulnerability in the built-up areas also highlights that most of the Ambon City area, with mountainous terrain accounting for approximately 89% of the total area, experienced relatively high occurrences. In response, the government and relevant authorities must undertake careful spatial planning, direct development towards safer places, and implement policies that support sustainable development.*

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INTRODUCTION

In recent decades, landslides have received considerable attention as they are the most widespread disasters worldwide in terms of casualties and socioeconomic damage (Nefeslioglu et al. 2008; Shahabi et al. 2014; Benchelha et al. 2020). Physiographic conditions cause landslides that generally occur during the rainy season (Gorsevski et al. 2006) and high population growth (Lombardo et al. 2019), causing thousands of deaths and infrastructure damage every year worldwide (Juang et al. 2019). Landslides have caused many deaths beyond building damage and can potentially change the landscape. Regional topology, soil and vegetation composition, and land use in an area can affect and accelerate the occurrence of landslides (Lavan et al. 2021). Landslides are natural events occurring annually worldwide. There are 200 landslides in the Himalayan region every year, and the economic loss is more than US$ 1 billion (Tran et al. 2021). According to the National Geological Hazard Bulletin in China, from 2007 to 2016, an average of 762 people were reported dead or missing per year due to intense landslides (He et al. 2020).

Based on BPNB data from 2011 to 2015, there were 2,425 landslide events in Indonesia, with the location of the incident spread across the provinces of Central Java, West Java, East Java, West Sumatra, and East Kalimantan (ADPC 2021). The terms of natural hazards are related to dangerous phenomena within a specified space and time (Bhat et al. 2019). Landslides are natural hazards caused by the movement of rock mass, rock fragments (debris), or soil on a slope under the influence of gravity (Varnes 1978; Guzzetti et al. 2005; Benchelha et al. 2020). The mass displaced on hill slopes is often referred to as a landslide, a geological event where rocks, debris, or soil moves down a slope due to the force of gravity (Ahmed et al. 2020). Slope movements result from a complex force field that is active in the rock or soil mass on a slope (Cruden 2018). In contrast to soil erosion, movement occurs when shear stress exceeds the strength of the material (Devi 2020). This landslide concept is broader regarding the material moving down the slope (Enigda and Suryanarayana 2021).

In the last few decades, remote sensing techniques and Geographic Information Systems (GIS) have contributed significantly to determining the boundaries of areas prone to landslides, especially mountainous areas (Martensson 2011; Yadav et al. 2016; Tewari and Misra 2019). In addition, GIS provide spatial data processing, which can be used for landslide hazard inventories and zoning maps (Westen 1993; Singh 2013; Uvaraj and Neelakantan 2018). Landslide natural this part big has been researched using various analytical techniques and a different approach. Lavan et al. (2021) applied GIS to investigate the influence of rainfall runoff on landslides. Miura and Tanizaki (2022) used remote sensing and GIS combined with an Analytical Hierarchy Process (AHP). Tran et al (2021) have mapped landslide susceptibility using Naıve Bayes (NB), Multilayer Perceptron (MLP), and Alternating Decision Tree (ADT). Enigda and Suryanarayana (2021) used the Main Ethiopian Rift (MER) to assess slope instability problems. At the same time, Gong et al (2021) have developed a method for analyzing landslide stability from rainfall and vegetation roots. This study identified the spatial and terrestrial areas of landslide hazards in the research area based on remote sensing and GIS to assess vulnerability in built-up areas.

Based on its physiography, Ambon City consists mostly of hilly to mountainous areas, accounting for approximately 89% of its total area and is characterized by steep to very steep slope inclinations. In comparison, only approximately 11% comprised of flat regions. This physiographic condition triggers landslides, indirectly leading to landslide disasters during the rainy season if proper prevention and mitigation measures are not implemented. Landslides are natural geomorphic processes that evolve in mountainous landscapes (Wang and Li 2017). Meanwhile, the limited land availability in Ambon City has resulted in intensive land use conversion in hilly areas, which are essentially conservation areas, potentially leading to landslides. Several landslide incidents in Nusaniwe, Sirimau, and Baguala in 2020 caused damage to 56 houses at 17 landslide points (BPBD 2020).

METHODS

This study used qualitative and quantitative analytical methodologies using a spatial approach. This study includes interpretive and survey research based on analyzing primary and secondary data from satellite imagery, observations, and related agencies. A survey approach was used that emphasized the observation and measurement of the variables required for landslide analysis. The research was conducted from July to September 2022 in the Ambon City area, as a research location for observation and data collection activities. The area is divided into five administrative districts: Sirimau, Nusaniwe, South Leitimur, Ambon Bay, and Ambon Baguala Bay.

The materials in this research are Landsat imagery and Shuttle Radar Topography Mission (SRTM), imagery for making slope maps, soil map, geological map, land form map at 1: 50,000 scale, and rainfall maps. In addition, it was obtained from Development Planning Agency at Sub-National Level, Central Bureau of Statistics and the Public Works Department. The research tools included 1 Global Mapper 20 and ER Mapper v. 8.1, ArcGIS 10.8.1, GPS, and digital cameras. All land in the Ambon City area was used as the research population, and the research sample consisted of land units obtained using the overlay approach. The land units in this study were obtained from an overlay of land use maps, landforms, and slopes.

The analysis was based on adding the variable values to produce class intervals of five so that the classification of landslide vulnerability levels could be made. The data analysis was performed in several stages. The preparation stage was carried out in various ways with data processing, starting with the data analysis of land-use maps, soil types, landforms, and geology. Furthermore, SRTM image data processing was used to create slope maps. In contrast, Landsat images include image splicing, geometric correction, radiometric correction, and image sharpening, which are then interpreted and delineated on the screen. Observations were made in the field during the implementation phase to verify that the image interpretation accurately reflected the reality of the field and to measure any parameters that could not be determined from the image. The survey was carried out throughout the research area, focusing on areas where the density of land use or other weather factors, in this case, the presence of clouds, hindered accurate image interpretation of the appearance of objects.

The interpretation accuracy test checks the validity of the interpretation results from the image, and then compares them with the results of the field checks. Field test activities to improve the interpretation results and mapping accuracy tests were conducted through sampling. Processing Landsat satellite image data with layer stacking is crucial because it contains eleven different channels. Layer stacking is necessary to combine image data into a single dataset, making it easier to analyze and interpret all information contained within it. Radiometric correction was performed to reduce errors caused by the recording system and the propagation of sunlight passing through the objects to the recording camera. Radiometric accuracy describes the ability of a system to differentiate or perceive differences in electromagnetic energy. This accuracy depends on the signal-to-noise ratio of the detector and is limited by its ability to convert continuous electromagnetic signals into digital signals. The higher the bit value used by the sensor, the higher the radiometric accuracy level.

The radiometric correction used in Landsat 8 images was atmospheric reflectance correction or called Top of Atmosphere (ToA). ToA aims to adjust images by compensating for radiometric distortions resulting from the sun's position. The sun's position relative to the Earth varies based on the time of acquisition and the object's location. ToA correction involves converting the digital number values to reflectance values. This research focuses on assessing the reflectance properties of Landsat-8 imagery concerning different terrains such as vegetation (forests and rice fields), open spaces (barren land and settlements), and bodies of water. The ToA reflectance correction has been used to convert digital values into reflectance values (Nugroho et al. 2017). Radiometric correction aims to remove radiometric distortions from images. Radiometric distortions are errors that occur in recorded pixel intensity values and can be caused by various factors during data collection, transmission, and recording. The most influential factors causing radiometric distortions in Landsat images are detector failures and scattering appearances. The final step in pre-processing the image is image cropping. Image cropping aims to create an area of interest (AOI) to focus the analysis on specific geospatial phenomena and limit the discussion to relevant study areas.

The data collection at this post-stage is suitable for use as material for analysis, and the overall data compilation is carried out by grouping the data and analyzing it quantitatively and deductively. Spatial patterns were identified using spatial analysis. For the mapping activity, each indicator was based on the 2004 Puslittanak estimation model. Puslittanak is a research institution under the Indonesian Agency for Agricultural Research and Development that focuses on studying aspects of soil resilience and climatology in Indonesian agriculture. From this model, the parameters are classified based on the scores obtained for each parameter, and the results are summed based on the suitability of their geographical location by assigning 5 classes of landslide vulnerability which include very low, low, moderate, high, very high.

RESULTS AND DISCUSSION

Built-Up Area Development Analysis

An analysis of the development of built-up areas was conducted to determine the increase and distribution of built-up areas in Ambon between 2012 and 2021. The data used in this analysis included land cover data from 2012, sourced from the results of the image classification on Landsat 7, and land cover data from 2019, sourced from the results of the Landsat 8 image classification. The accuracy level of the Landsat 7 classification in 2012 was 0.9251 (92.51%), whereas that of the Landsat 8 classification in 2021 was 0.9108 (91.08%). Therefore, with a coefficient value of 0.81–1.00 (81–100%), Cohen's Kappa coefficient, as interpreted by Altman (1991), is categorized as a very strong level of closeness, and can be used in the analysis.

Based on the analysis of Landsat images from 2012 and 2022, an increase in the area and distribution of built-up land in Ambon City was observed (Table 1). Table 1 shows that there was an increase in the built-up area of Ambon City between 2012 and 2022. In 2012, the built-up area reached 4,527,424, while in 2022, the built-up area increased to 5,707,990. The expansion of the built-up area indicates the development and urbanization of Ambon City during this period. The increase in built-up areas can be influenced by factors such as population growth, urbanization, and development activities in various sectors. The increase in built-up areas also has the potential to affect spatial planning and the environment. Proper management is needed to ensure sustainable development and minimize negative impacts on ecosystems and natural resources. In this context, careful spatial monitoring, planning, and policies focusing on sustainable development are crucial. Furthermore, an increase in built-up areas should be viewed in the context of landslide vulnerability and disaster potential. The distribution and extent of built-up areas within landslide vulnerability classes can provide important information for risk assessment and handling of potential landslide disasters in the region.

Table 1 Area of Ambon City Built-in 2012 and 2022

No	Land use	Area (ha)
1.	The built-up area in 2012	4,527,424
2.	The built-up area in 2022	5,707,990

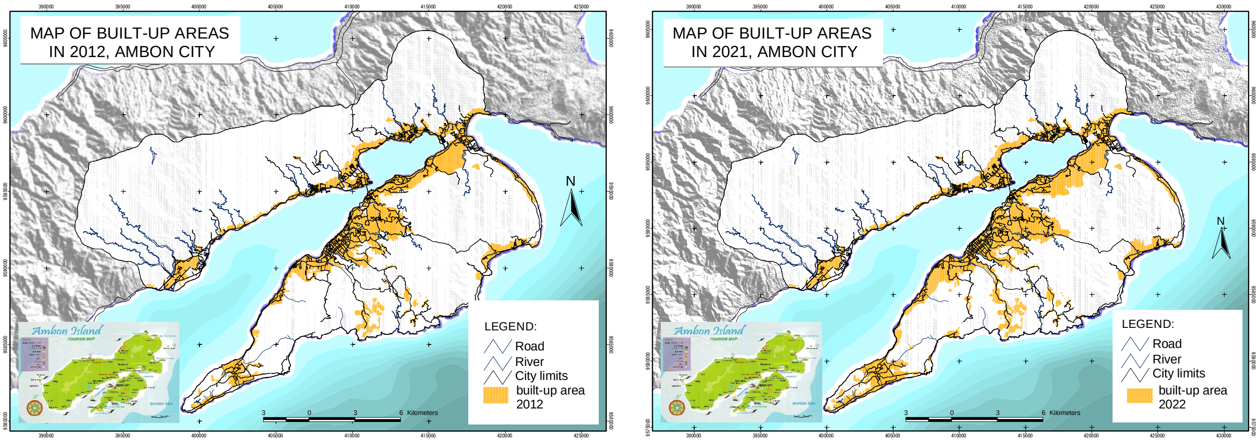


Figure 1 Map of Ambon City built area in 2012 (a) and 2022 (b)

Figure 1 illustrates the development of built-up areas spreading towards the northeast of Ambon city. This pattern of development appears to follow existing road infrastructure, resulting in a linear expansion of built-up areas along the main transportation routes. Moreover, the expansion into hilly areas indicates that previously remote or less accessible regions are now becoming part of the city's growth, signaling urban expansion into surrounding areas. This could be due to the increasing need for space and land as the population and economic activities in Ambon continue to grow.

Landslide Factors Analysis

Rainfall

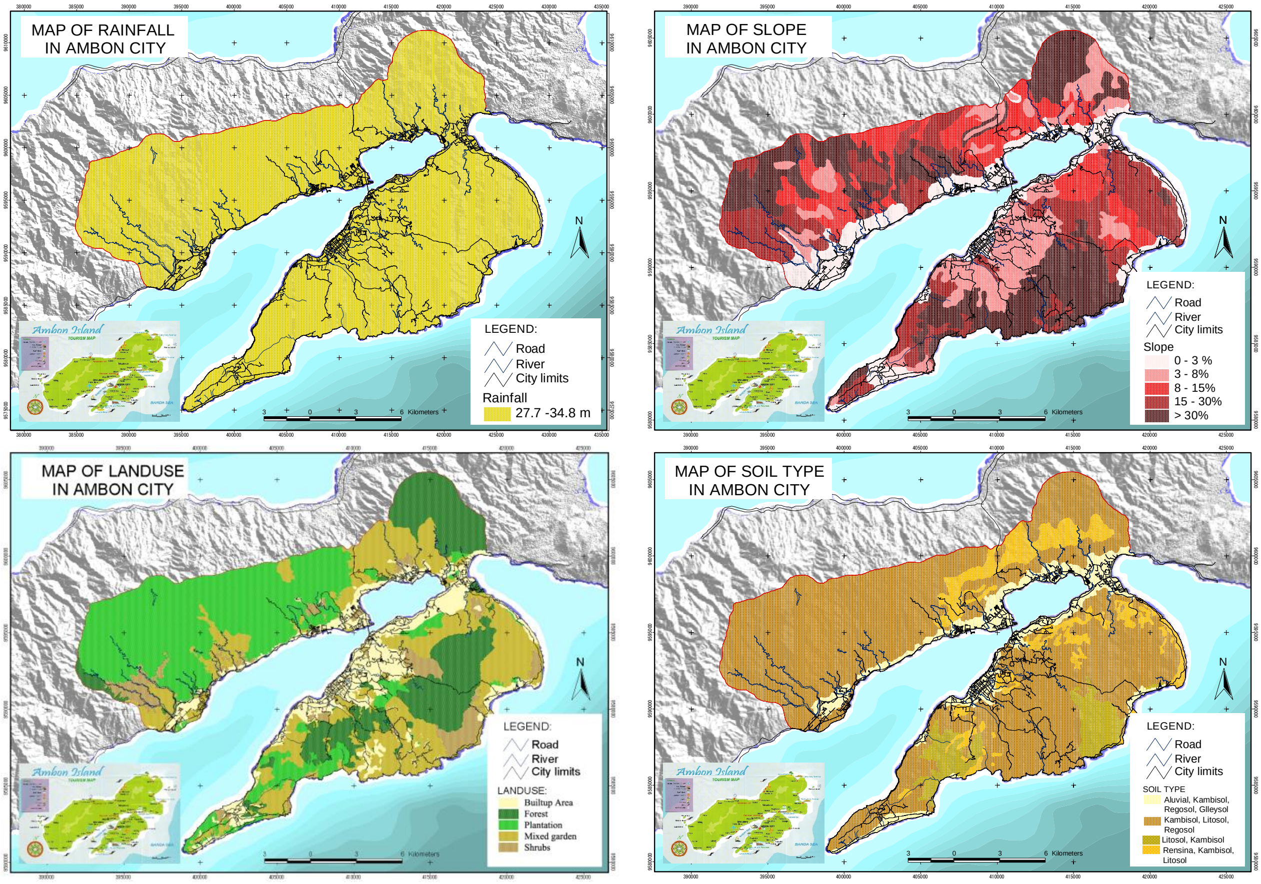
Rainfall is an indicator of landslide occurrence. Rainfall, which has a wet tropical climate, is the main determinant of the temperature. Rainfall is an external variable outside the body of a slope that can cause landslides because of its intensity that flows somewhere (Handoko and Ikaputra 2019). The rainfall intensity values are listed in Table 2.

Table 2 Rain intensity class criteria

No	Class	Rainfall intensity	Description	Score
1	I	0 – 13.6	Very low	1
2	II	13.6 – 20.7	Low	2
3	III	20.7 – 27.7	Moderate	3
4	IV	27.7 – 34.8	High	4
5	V	> 34.8	Very high	5

Source: BMKG (2022)

The rainfall in the study area was based on data from the Ambon Pattimura Meteorological Station. The average annual rainfall has been relatively high over the last 10 years (2013–2022), with an average of approximately 27,862 m. This condition resulted in a relatively high annual rainfall intensity. Based on this, Table 2 shows the criteria for the class of rainfall intensity and the area that is spread in Ambon City, which ranges from 27.7 to 34.8 m, then and is at high rainfall intensity (Class IV). Figure 2 shows the spatial distribution of the rainfall in the study area.



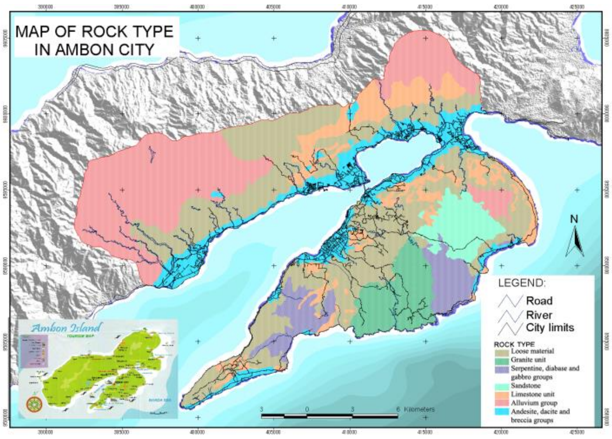


Figure 2 a) Rainfall Intensity Map, b) slope map, c) land use map, d) soil type maps, and e) map of rock types

Slope

Slope inclination is a crucial factor influencing the risk of landslides. This factor is closely related to the topographic characteristics of an area. When a slope has a steep inclination, the pressure on the soil tends to increase, enlarging the likelihood of soil mass movement. Additionally, slope inclination also affects the distribution of rainfall. Steep slopes tend to struggle to retain rain, which, in turn, can seep into the soil, increasing the soil's density and exacerbating conditions that support landslides. The gravitational gradient concept measures the soil surface's stability against the force of gravity. It refers to a surface's ability to withstand gravitational pull that can impact slope stability (Fransiska et al. 2017). The slopes are listed in Table 3.

Table 3 Class and slope area

No	**Class**	**Criteria**		**Area (ha)**	**%**	**Score**
		Slope description	**Slope (%)**			
1.	I	Flat to sloping	0 – 8	5,087.65	15.80	1
2.	II	Slightly tilted	8 – 15	6,974.29	21.66	2
3.	III	Crooked	15 – 30	9,380.68	29.14	3
4.	IV	Very tilted	> 30	10,750.05	33.39	4
		Total area		32,068,753	100.00	

Based on Table 3, Ambon City has a slope that varies and is mostly on a hill of > 30% and 15–30%, with an area of 10,750.05 ha and 9,380.68 ha. Meanwhile, flat to sloping (0–8%) and slightly tilted (8–15%), with an area of 6,974.29 ha and 5,087.65 ha. Landslides can occur because of the terrain conditions of Ambon City, which are mainly sloping sites spread at values 3 and 4, or have a high percentage of slopes (Figure 2).

Land Use

Regarding plant forms and rock structures covering the soil surface, land use refers to human activities on and around land. According to Nugroho et al. (2017), various types of land use significantly affect slope stability. Land use is an element that is triggered externally or originates from outside the slope. Ambon City covers an area of 32,068,753 ha and consists of five services: forests, mixed gardens, shrubs, built spaces, and plantations. The determination of the value of land use is presented in Table 4.

Table 4 Land use class and area

No	Class	Land use	Area (ha)	%	Score
1.	I	Forest	7,875,105	24.46	1
2.	II	Plantation	6,132,103	19.05	2
3.	III	A built area	5,707,990	18.40	3
4.	IV	Mixed garden	10,832,291	33.65	4
5.	V	Shrubs	1,428,821	4.44	5
		Total area	32,068,753	100.00	

Based on Table 4, mixed garden land use, with a total area of 10,832,291 ha and a value of 4, dominates the Ambon City area. With a total area of 5,923,844 ha and a value of 3, land use in the built area was evenly distributed throughout Ambon City. Shrubs are land uses with the smallest size (1,428,821 ha) and have a value of 5, whereas plantations, with a total area of 6,132,103 ha, have a value of 2. The spatial distribution of land use indicated that mixed gardens and dryland farming techniques constituted the majority. Land use in Ambon City. Shrub had the highest score among several types of land cover in Ambon City, meaning that it significantly affects the frequency of landslides (Figure 2).

Soil Type

Soil factors are closely related to landslide levels. The soil types in Ambon City consist of four soil units: 1) alluvial, cambisol, regosol, and gleysol; 2) cambisol, latosol, and regosol; 3) latosol and cambisol; and 4) rendzina, cambisol, and litosol. The values for these soil types are listed in Table 5. Table 5 shows that the soil types in Ambon City are mostly distributed in cambisol, latosol, and regosol soil units with a land area of 23,599,715 ha. Latosol and cambisol soil units cover only 6.12% of the total area of Ambon City (1,699,064 ha), which is a very small landform. On the other hand, the Latosol soil type differs significantly because it can be found in almost all locations in Ambon City. The spatial distribution of this soil type is shown in Figure 2.

Table 5 Class and area of soil types

No	Class	Land unit	Area (ha)	%	Score
1	I	Alluvial, Cambisol, Regosol, Gleysol	3,300,144	10.25	1
2	III	Cambisol, Latosol, Regosol	23,599,715	73.31	2
3	II	Latosol, Cambisol	1,969,064	6.12	3
4	IV	Rendzina, Cambisol, Litosol	3,323,746	10.32	4
		Total area	32,068,753	100.00	

Source: Soil Survey Institute (1985)

Rock Type

The rock types in Ambon City include sandstone, serpentine, diabase, gabbro groups, andesite groups, breccias, loose materials, granite units, limestone units, and alluvial deposits. The determination of rock type values is presented in Table 6. The area of rock types in Ambon City area has the widest rock types, namely loose material covering an area of 14,490.24 ha or 45.01%, and the Andesite, Dacite, and Breccia groups with an area of 5,684.05 ha. The smallest size is sandstone, covering an area of 1,524.21 ha or 4.73%. Thus, the distribution of loose material and the Andesite, Dacite, and Breccia groups is the widest type of rock in Ambon City, resulting from the Ambon volcanic deposits in the Pliocene era.

Table 6 Broad class of rock types

No		Rock type	Area (ha)	%	Score
1.	I	Alluvial deposit	4,402.08	13.67	1
2.	I	Sandstone	1,298.61	4.03	1
3.	II	Serpentine group, diabase, and gabbro	2,293.32	7.12	2
4.	III	Granite unit	2,099.98	6.52	3
5.	III	Limestone unit	1,924.40	5.98	3
6.	IV	Andesite group, dacite, breccia	5,684.05	17.66	4
7.	V	Loose materials	14,490.24	45.01	5
		Total area	32,068,753	100	

Source: Ministry of Public Works and Housing (2014)

Landslide Vulnerability Analysis

The landslide hazard zoning in Ambon City was determined by grouping it into five risk classes, namely very low, low, moderate, high, and very high, based on the landslide hazard analysis design. The degree of vulnerability or the possibility of landslides can be calculated by summing (scoring) the factors in each field unit. Five (5) interval classes consisting of the number of variables and their weights are listed in Table 7.

Table 7 Scoring and area of landslide vulnerability

No	Vulnerability class	Score	Area (ha)	Large (%)
1.	Very low	19 – 21	2,641,019	8.21
2.	Low	7 – 9	2,591,553	8.05
3.	Moderate	10 – 12	8,992,736	27.94
4.	Hight	13 – 15	16,619,011	51.63
5.	Very high	16 – 18	1,341,312	4.17
	Total area		32,185,631	100.00

Based on Table 7, it can be observed that the distribution of built-up land in Ambon City varies in terms of landslide vulnerability. Only approximately 8.21% (2,641,019 ha) of the total area of Ambon City was classified as having very low landslide vulnerability (class Z-1). Areas with low landslide vulnerability (class Z-2) accounted for approximately 8.05% (2,591,553 ha) of the total area. Furthermore, approximately 28.02% (8,992,736 ha) of the total area was classified as moderately vulnerable to landslides (class Z-3). However, it is important to note that the majority of the area in Ambon City, approximately 51.63% (16,619,011 ha), falls under the category of high landslide vulnerability (class Z-4). Additionally, approximately 4.17% (1,341,312 ha) of the total area was classified as having very high landslide vulnerability (class Z-5). This indicates that a significant portion of the built-up land in Ambon City is situated in areas of high or very high landslide vulnerability. These areas are prone to landslide hazards and require serious attention for risk management and mitigation. The spatial distribution of landslide vulnerability is shown in Figure 3.

Figure 3 illustrates the location of the landslides in the study area, which damaged several residential buildings. According to the *Badan Penanggulangan Bencanan Daerah* (BPBD) of Ambon City, at least 56 houses have been destroyed by 17 landslides. The four sub-districts are Teluk Ambon, Nusaniwe, Sirimau, and Baguala, with 17 landslide points. There are three landslide points in Nusaniwe District: Kudamati, Benteng, and Amahusu. The remaining four locations are Batu Gajah, Amantelu, Batu Meja, Waihoka, and Soya, scattered in Sirimau District. Landslides occurred in the Tawiri, Poka, and Tihu areas of Teluk Ambon District. The Baguala sub-districts are located at Negeri Lama, Lateri, Halong, and Passo.

It is crucial for the government and relevant authorities to implement effective measures to reduce the risk of landslide disasters in areas of high and very high vulnerability. This may involve developing stricter policies regarding development in these areas, conducting more intensive monitoring and supervision of construction activities, and implementing appropriate engineering techniques and mitigation measures to reduce the landslide potential. Furthermore, efforts should be made to direct the development of built-up land in areas with low-to-moderate landslide vulnerability. This can help reduce the potential for landslide disasters in the future and enhance the sustainability of development in Ambon City.

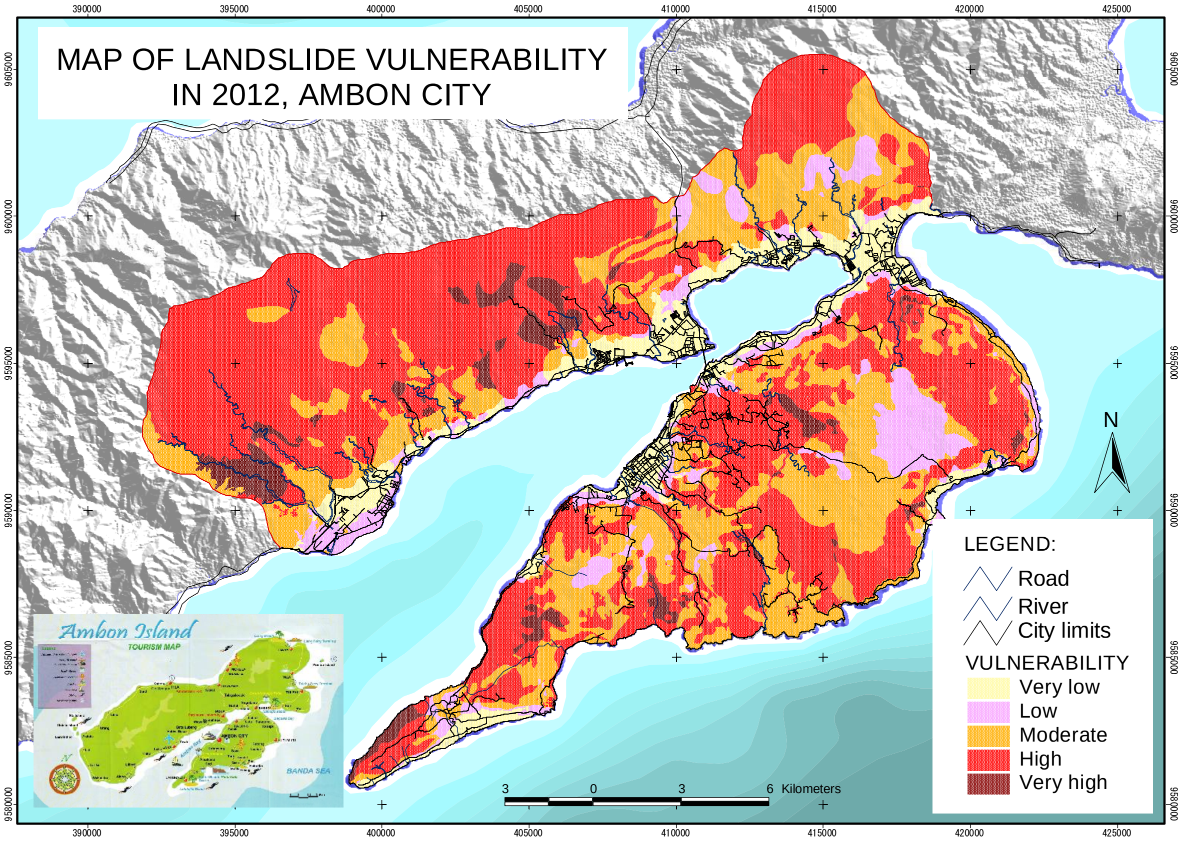


Figure 3 Map of landslide vulnerability in Ambon City

Analysis of Built-up Land in Landslide Disaster Area

This study was obtained from the analysis of the development of built-up land and the analysis of landslide vulnerability to Ambon City, which was used as an input for the survey of built-up land in landslide-vulnerable areas. The distribution of built-up land in each class of landslide vulnerability was determined by overlaying the results of the two analyses and performing an overlay intersection analysis. This process is known as zoning and is shown in Table 8.

Table 8 Area of built-up land in landslide disaster area

Zone	Information	Area (ha)	%
Z - 1	Built-up land on very low landslide hazard class	2,000,913	35.09
Z - 2	Built-up land on low landslide hazard class	678,094	11.89
Z - 3	Built-up land on moderate landslide vulnerability class	777,107	13.63
Z - 4	Built-up land on high landslide vulnerability class	2,224,549	39.01
Z - 5	built-up land on very high landslide vulnerability class	21,691	0.38
	Total area	5,702,356	100.00

The distribution of built-up land in various landslide vulnerability classes in Ambon City is important for assessing risk and addressing potential landslide disasters. Based on the data presented in Figure 4 and Table 8, the extent of built-up land varies in each landslide vulnerability class. In the very low landslide vulnerability class (Z-1), the total built-up land area was 2,000,913 ha (35.09%). This zone represents areas with a very low landslide risk. This was attributed to the relatively flat to moderately steep slope conditions.

The built-up land in this zone exhibited good stability and tended to have low vulnerability to landslide disasters. The low landslide vulnerability class (Z-2) had a built-up land area of 678,094 ha (11.89%). This zone indicates a low landslide risk. The slope gradient in this zone is moderately steep but still meets the safety criteria for residential development through specific engineering measures. Although it carries a higher risk than Z-1, built-up land in this zone can still be effectively managed to reduce the potential for landslides. The moderate landslide vulnerability class (Z-3) had a built-up land area of 777,107 ha (13.63%). This zone represents a moderate landslide risk. The slope gradient in this zone is steep and requires intensive monitoring and management. Appropriate engineering construction and mitigation measures are necessary to reduce the risk of landslide disasters.

The high landslide vulnerability class (Z-4) had a built-up land area of 2,224,549 ha (39.01%). This zone indicates a high landslide risk. The slope gradient in this zone ranges from 25 to over 40%, with rock types having a high degree of weathering. These conditions render this zone highly susceptible to landslides. Strong mitigation efforts and management are required to reduce disaster risk in this zone. The very high landslide vulnerability class (Z-5) had the smallest built-up land area of 21,691 ha (0.38%). This zone represents a very high landslide risk. The slope gradient in this zone is steep, with rock types that have a high degree of weathering.

Additionally, the built-up land in this zone adds weight to the slopes and has a low soil-holding capacity, making it highly vulnerable to erosion. Intensive risk management and mitigation efforts are required to address risks in this zone. The distribution and extent of built-up land in different landslide vulnerability classes highlights the varying levels of risk and the need for appropriate measures to mitigate the potential for landslide disasters. It is crucial to implement effective land management strategies, engineering interventions, and continuous monitoring to minimize the impact of landslides and ensure the safety of the population in Ambon City.

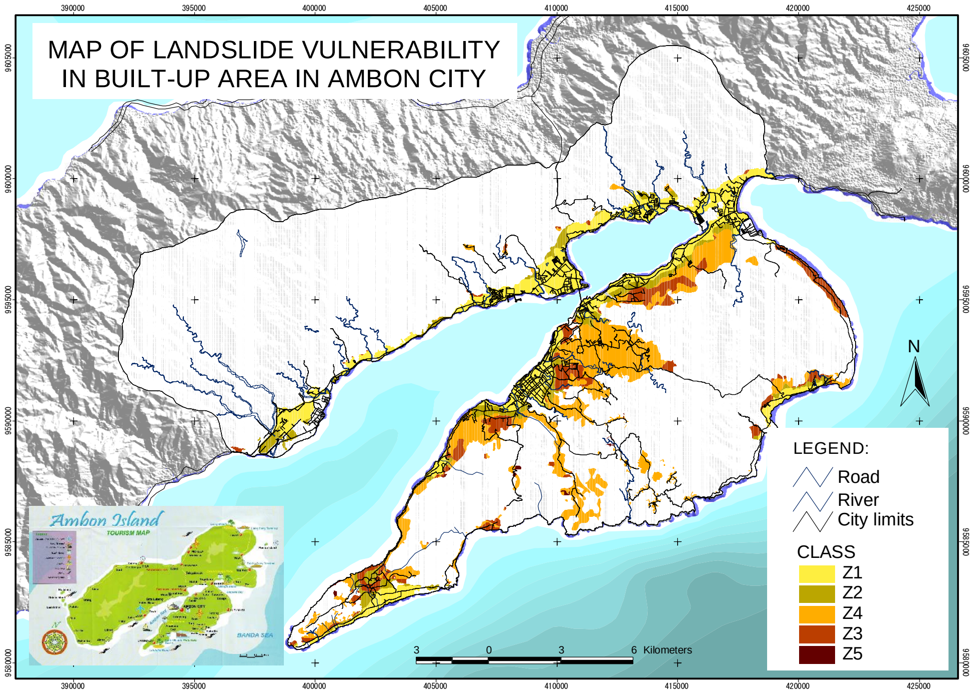


Figure 4 Map of landslide vulnerability in built-up areas in Ambon City

Discussion

Rainfall is a natural phenomenon that occurs worldwide and is crucial to various aspects of life. Indonesia, a country with a tropical wet climate, often experiences heavy rainfall. High rainfall can increase the surface water flow, leading to significant soil erosion. Strong water flow can erode the top layer of the soil, displace soil material, and reduce slope stability. In this situation, slopes disturbed by erosion are more vulnerable to landslides (Handoko and Ikaputra 2019). Rainfall in Ambon City, which is intensive even during the dry season, can cause landslides. This is in accordance with Arsyad et al. (2018), who found that the amount of rain that falls on a slope increases with altitude. If there is no vegetation or impermeable layer, heavy rains can cause landslides (Rienzi et al. 2013). The amount of rainfall affects the distribution strength, carrying capacity, and soil damage (Hutapea 2020). Andriawan and Sarya (2014) found that rainfall intensities of more than 50 mm/h result in shallow landslides. Hidayat and Zahro (2018) identified rainfall data as a catalyst for landslides in the Banjarnegara Region. The maximum rainfall per day that could cause landslides was 56 mm. Gemilang et al. (2017) reveal that the Bungus Hills area has a high level of landslide hazard with an average rainfall of over 200 mm.

Slope inclination is a critical factor that plays a role in landslide occurrence. In various regions worldwide, including Indonesia, landslides frequently occur because of the instability of steep or excessively steep slope inclinations (Fransiska et al. 2017). Rompon and Almulqu (2018) asserted that landslides usually occur in sloping areas as the slope of land increases. Slope is one of the factors that can reduce the shear strength of the soil, making it vulnerable to collapse (Akbar et al. 2022). The slope affects the volume of landslides. The higher the slope value, the larger the landslide volume. Çellek (2020) showed that there is an increase in the volume of soil mass movement with an increase in the slope, which is caused by the gravitational thrust and shear stresses that increase. Nengsih (2015) also demonstrated that the stability of a slope is affected by the shear strength and shear stress of the soil. If the value of shear stress exceeds the shear strength of the soil, the soil collapses.

Land use changes from natural conditions to agriculture, housing, or industrial purposes can alter soil and vegetation characteristics, resulting in the removal of soil-bound roots, increased erosion, and reduced slope stability. Inappropriate land-use choices that do not align with environmental conditions can increase the risk of landslides (Nugroho et al. 2017). According to Ritung et al (2007), landslides often occur in locations with steep slopes and land use, such as moors and scrubs. The potential for decreasing slope stability can cause landslides to increase as the intensity of land use increases (Hasibuan and Rahayu 2017; Soewandita (2018). Areas of high landslide vulnerability are found in mixed gardens, where land management still needs to implement appropriate planting methods based on land conservation rules. Suwarsito et al (2020), perennial plants with deep root systems need to be placed on sloping areas to reduce the occurrence of landslides.

Landslides can occur in this type of soil, particularly after rain. The occurrence of landslides is strongly influenced by the smooth texture of the soil, such as clay texture. According to Harjadi and Paimin (2013), the finer the soil texture class, the more likely it is to shrivel, be unstable, or move. According to Heradian and Arman (2015), clay composed of clay and has water content is a type of soil that becomes a landslide area because it has the lowest resistivity value. Soewandita (2018), a thick soil solum with a porous structure, is located on a sloped area that is very vulnerable to landslides. Hadiyanto (2011) reported that cytosol and regosol soil types are very sensitive to water. On the other hand, soil types in the form of alluvial, gleysol, planosol, laterite, and hydromorphone are soil types that are less sensitive to water, so landslides occur during the rainy season.

The geological structures found in Ambon City are down (normal) and joint faults. The developing fault structure extends northeast to the southwest, intersecting granite rock units and groups of serpentine, diabase, and gabbro units found on the headlands of Seri Village and Hukurila Village. The findings of this study support the statement of Rahman (2010) that the landslide-vulnerable location has a rock dome exposed to flow and soil structure with older Andesite and Andesite Breccia formations penetrated by many faults. These rocks are easily weathered into soil, and if they are on slopes that experience landslides, they are often vulnerable to landslides (Putra et al. 2020). Volcanic sedimentary rocks, sedimentary rocks with sand-sized grains, and combinations of gravel, sand, and clay is often weak. If the rock experiences weather, it will quickly turn into soil, and if it is on a steep slope, it is often vulnerable to landslides (Darmawan et al. 2021).

In addition, the middle area of the landslide vulnerability map tended to have a vulnerability level that ranged from moderate to high, which was dominant in the hilly and mountainous areas of Ambon City, followed by areas with high slopes. This study is based on the results of research conducted in the Ponorogo Regency by Yuniarta et al. (2015) and Naryanto et al. (2019), which is a location that has the potential to experience landslides because most of its morphological forms are hills. The same problem has also been investigated by Fitrianingrum and Ruslanjari (2012) in the Kulonprogo Regency, Menoreh Hills area, which is geomorphologically vulnerable to landslides mostly caused by high and rapid rainfall.

In the development of settlements in the research location, considering the vulnerability to landslide disasters, the basis is the Minister of Public Works Regulation No. 22/PRT/M/2007, which is an essential guideline concerning the management of landslide-prone areas in Indonesia. This document provides a framework and technical guidance for relevant parties to identify, categorize, and manage areas susceptible to landslide disasters. The regulation emphasizes the importance of early identification of regions with high landslide potential, devising risk mitigation plans, and implementing preventive and adaptive measures to reduce landslide risks. Additionally, this regulation encourages cross-sectoral cooperation and community participation in efforts to prevent and manage landslide disasters, as part of the endeavor to enhance resilience and safety in areas exposed to such risks. Based on this regulation, settlement development is only recommended for slopes ranging from 0 to 15% (flat to slightly tilted). Therefore, the zoning considered suitable and safe for built-up land use is zones Z-1, Z-2, and Z-3. Housing development is directed towards slopes with a maximum inclination of 25% (moderately steep to steep), but with certain criteria, such as implementing construction engineering in the area, which can include retaining walls to maintain slope stability. The site also prohibits excessive construction loads that can endanger slope stability, among other important requirements that must be considered. The recent experience of extreme climate change will affect the resilience of construction engineering, and some of these criteria and engineering designs will inevitably incur high handling costs.

Most of the built-up areas in zones Z-4 and Z-5 were constructed by communities with high or very high vulnerability to landslides and could not be relocated easily. The built-up areas located in the high landslide vulnerability class (Z-4), covering an area of 2,224,549 ha (39.01%), and a very high landslide vulnerability class (Z-5), covering an area of 21,691 ha (0.38%), are due to the limited availability of flat land in Ambon City, which only accounts for approximately 11% of the total area. As a result, the population is forced to develop in hilly areas that are at high risk of landslides. The available land for development in flat areas is extremely limited, with approximately 89% of the area consisting of hilly terrains. This leads the population to seek locations in hilly areas to build settlements and infrastructure. However, hilly areas tend to have steep slopes and vulnerable rock types, which are prone to landslides.

The limited availability of flat land in Ambon City compels the population to take risks and build in areas with a high landslide risk. This complicates the management of landslide disaster risks and necessitates more intensive mitigation measures to protect the population and infrastructure from potential disasters. In response to this situation, it is important for the government and relevant authorities to engage in careful spatial planning, direct development towards safer areas, and implement policies that support sustainable development. These measures can help reduce landslide disaster risks and protect the population and the environment of Ambon City. In the future, the government must be more proactive in controlling the growth of built-up land in zones Z-4 and Z-5, as policymakers and authorities are responsible for spatial planning. The government should also direct the development of built-up land in areas with low to moderate landslide vulnerability, such as Z-1, Z-2, and Z-3 in Ambon City, and educate the public about the consequences of development activities that can lead to landslide disasters due to their high and very high vulnerability.

CONCLUSION

The description of land units in the research area was arranged based on rainfall, soil type, land use, landforms, geology, slope, and landslide hazard. The triggering factor for landslides in the study area was caused by high rainfall intensity ranging from 27.7 to 34.8 m, the extent of the slopes from steep to very steep (62.53%), the use of mixed garden land, and built-up areas that dominate the area (52.05%), as well as cambisol, latosol, and regosol soil types and loose material rock, which cover an area of approximately 73.31% and 45.01%.

The distribution of built-up land in Ambon City across various landslide vulnerability classes provides an overview of the risk level of the area and potential landslide disasters. Zone Z-1 (very low landslide vulnerability) has the largest area of built-up land, followed by Z-4 (high landslide vulnerability). Zone Z-5 (very high landslide vulnerability) has the smallest built-up land area. Zones Z-1 and Z-2 (very low and low landslide vulnerability, respectively) indicate a low risk of landslides. The built-up land in these zones tends to be stable, with relatively flat to moderately steep slopes, and meets safety criteria through specific construction engineering measures. Zone Z-3 (moderate landslide vulnerability) requires more intensive monitoring and handling.

Zones Z-4 and Z-5 (high and very high landslide vulnerability, respectively) exhibited a relatively high risk of landslides. These zones are highly susceptible to erosion and require intensive risk management and mitigation efforts to reduce landslide risks. The importance of the government and relevant authorities controls the growth of built-up land in zones with high and very high landslide vulnerability (Z-4 and Z-5) while directing the development of built-up land in zones with low to moderate landslide vulnerability (Z-1, Z-2, and Z-3).

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