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Research article

Utilization of Digital Elevation Models in Slope Morphology Analysis for Landslide Identification in Ternate City, Indonesia

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Abstract: Ternate City, located in the North Maluku archipelago, Indonesia, has hilly geographical and morphological conditions that make it vulnerable to landslides. This research aims to identify potential landslide risks by utilizing the Digital Elevation Model and slope morphology analysis and provide recommendations for disaster mitigation. This study used Digital Elevation Model (DEM) data obtained from the Indonesian Geospatial Information Agency, as well as land use data extracted from Sentinel 2 satellite imagery. The Slope Morphology (SMORPH) method was applied to analyze the shape and slope, which was then used to generate a landslide potential map. The analysis results show that 1,391.72 hectares of area in Ternate City have a high risk of landslides, with factors such as slope, slope shape, and land use conditions contributing to soil stability. The study also identified the importance of risk mapping and socialization to the community on early signs of landslides to improve preparedness. This research confirms the need for comprehensive and sustainable mitigation efforts to reduce the impact of landslides in Ternate City. Recommendations include infrastructure strengthening, drainage channel construction, and reforestation in critical areas. The results of this study are expected to serve as a basis for policymakers to formulate more effective disaster mitigation strategies and increase public awareness of the importance of wise environmental management.

Keywords: Digital elevation model, SMORPH, landslide, Ternate

1. Introduction

Landslides are a natural disaster that often occurs in various regions, including Indonesia [1]. This phenomenon can cause significant damage to infrastructure and the environment and even threaten the safety of human life. Ternate City, located in the North Maluku archipelago, has hilly geographical and morphological conditions that make it vulnerable to landslides [2]. In 2024, Ternate City experienced landslides and flash floods caused by a combination of interacting geological and meteorological factors [3]. High and prolonged rainfall causes soil saturation, reducing cohesion and slope stability, especially in areas with steep slopes. Ternate's hilly topography and the presence of uncompacted volcanic material exacerbate these conditions, as loose soils are more prone to movement. In addition, deforestation and vegetation degradation in upstream areas reduce the soil's ability to absorb water, thereby increasing surface flow and landslide risk. The presence of alluvial fan plain morphology and the soluble nature of alluvium lithology also create ideal conditions for debris flow, known as debris flow. All these factors contributed to the occurrence of significant landslides in Ternate City, resulting in loss of life and damage to infrastructure.

Therefore, it is important to identify and analyze the landslide potential in this area in order to minimize the impact. Modern technology, such as Digital Elevation Models (DEMs), has become an effective tool in the analysis of slope morphology [4]. DEMs provide accurate and detailed topographic information, which is very useful in understanding the physical characteristics of an area [5]. By utilizing DEMs, researchers can analyze slope gradients, slope shapes, and other factors that contribute to the potential for landslides [6]. This allows for more precise and efficient identification of landslide-prone areas. One method that can be used in this analysis is the SMORPH (Slope Morphology) method. This method integrates slope and slope shape data to produce a classification of landslide potential [7]. By using SMORPH, researchers can identify areas that have a high risk of landslides based on slope morphology characteristics [8]. The application of this method in Ternate City is expected to provide a clear picture of the areas that need more attention in disaster mitigation efforts. In addition, land cover change is also an important factor affecting slope stability. Rapid urbanization and land conversion for development purposes often result in the reduction of vegetation that functions as a soil barrier [9]. Therefore, it is necessary to analyze land cover change in Ternate City to understand its impact on landslide potential. By combining the analysis of slope morphology and land cover change, this research aims to provide more comprehensive recommendations for landslide risk management.

Ternate City has a long history of natural disasters, including landslides. Several landslides that have occurred in this region have caused significant losses. In 2024, the landslide caused 19 deaths, while eight injured victims are still being intensively treated in several hospitals in Ternate. There were 25 houses and places of worship destroyed, and one bridge connecting the highway between villages on Pulau Ternate was broken. Approximately 60 families or hundreds of people were evacuated to a number of safe places in Rua Village, Ternate City [10]. In response, the Ternate City Government issued a 14-day Disaster Emergency Response status, mobilized a Joint SAR Team with 400 personnel to search for missing victims, and planned post-disaster rehabilitation and reconstruction, including possible relocation of residents from high-risk areas [11]. Therefore, efforts to increase public and government awareness of this potential disaster are very important. This research is expected to be a useful source of information for policymakers in formulating more effective disaster mitigation strategies. In this context, the utilization of GIS (Geographic Information System) technology also becomes very relevant. GIS allows the integration of various spatial and non-spatial data, thus facilitating the analysis and visualization of landslide potential [12]. By using GIS, researchers can produce landslide vulnerability maps that can be used as a tool in spatial planning and disaster risk management [13].

Analysis of landslide-prone areas using the Slope Morphology Method is very effective, as this method utilizes Digital Elevation Model (DEM) data to evaluate the shape and slope, which are key factors in determining landslide potential. With a simple and Geographic Information System (GIS)-based approach, SMORPH enables quick and accurate identification of landslide-prone areas. Many previous studies have used this method, such as Ramdhoni et al. used SMORPH method to identify landslides in Kebumen region [6], Ristya et al. used this method to analyze landslide-prone areas in Pelabuhanratu [8], Latue et al. used this method to identify landslide-prone areas in Leihitu Barat sub-district [14]. These studies show that SMORPH can produce informative landslide potential maps, supporting disaster mitigation efforts by providing data needed for planning and preventive actions in landslide-prone areas.

Through this research, it is expected to identify landslide-prone areas in Ternate City as well as factors that influence the occurrence of landslides. The results of this research are expected to contribute to disaster mitigation efforts, as well as increase public understanding of the importance of preserving the environment and managing land use wisely. Overall, this research aims to provide a clearer picture of landslide potential in Ternate City by utilizing the Digital Elevation Model and slope morphology analysis. Thus, it is expected that this research can be the first step in landslide risk reduction efforts in the region.

2. Methods

This research was conducted in Ternate City, North Maluku Province, Indonesia. The data used is the Indonesian National Digital Elevation Model, which has a resolution of 8 meters. The data is obtained from the official Indonesian government agency, the Geospatial Information Agency. This data is used to process slope and slope shape variables to produce a landslide potential map. Land use data was obtained from Sentinel 2 satellite image extraction, which was then classified into five classes, namely built-up area, agriculture, forest, open land, and water body. The whole data processing was done using ArcGIS Pro software and Microsoft Office 365. This research uses the Slope Morphology method.

Table 1. Slope morphology matrix [6], [8], [9], [14].

Slope shape	Slope gradient					
	0–8 %	8–15 %	15–25 %	25–45 %	45–65 %	>65 %
Concave	Very Low	Low	Low	Low	Low	Medium
Flat	Very Low	Low	Low	Low	Medium	High
Convex	Very Low	Low	Medium	High	High	High

DEM data is processed using slope tools in ArcGIS Pro to produce slope data in percent and slope shape using curvature tools to produce slope shape classification (concave, flat, convex) and classification based on Table 1. After that, an overlay between slope and slope shape data was conducted to determine the landslide potential class. This process uses the SMORPH matrix developed by Shaw and Johnson to identify landslide potential based on a combination of slope and slope shape [15]. The results of the Landslide Potential analysis were then calcified into four hazard classes: very low, low, medium, and high. These results were then overlaid with population settlements to produce a map of predicted landslide affected areas in Ternate City, Indonesia.

3. Results and Discussion

3.1. Slope

The results showed significant variations in slope, which could potentially affect the risk of landslides. From the data obtained, areas with slopes between 0-8% cover 1,043.50 hectares, indicating that most of these areas have relatively flat slopes and may be more stable against landslides. However, as the slope increases, areas with slopes of 8-15% and 15-25% cover 1,768.99 hectares and 2,070.44 hectares, respectively. These areas, although still in the moderate slope category, show a higher potential to experience landslides, especially in the event of heavy rainfall or land use change. Furthermore, areas with steeper slopes, such as 25-45% and 45-65%, cover 2,925.12 hectares and 1,850.58 hectares, respectively, indicating that almost half of the total analyzed area has a significant slope, which may increase the risk of landslides, as seen in Figure 1. Moreover, areas with more than 65% slope covering 501.49 hectares show a very high potential for landslides, especially in areas exposed to erosion or other environmental disturbances [16]. Therefore, an in-depth understanding of the distribution of these slopes is crucial for spatial planning and disaster risk mitigation in Ternate so that preventive measures can be taken to protect communities and infrastructure from the threat of landslides.

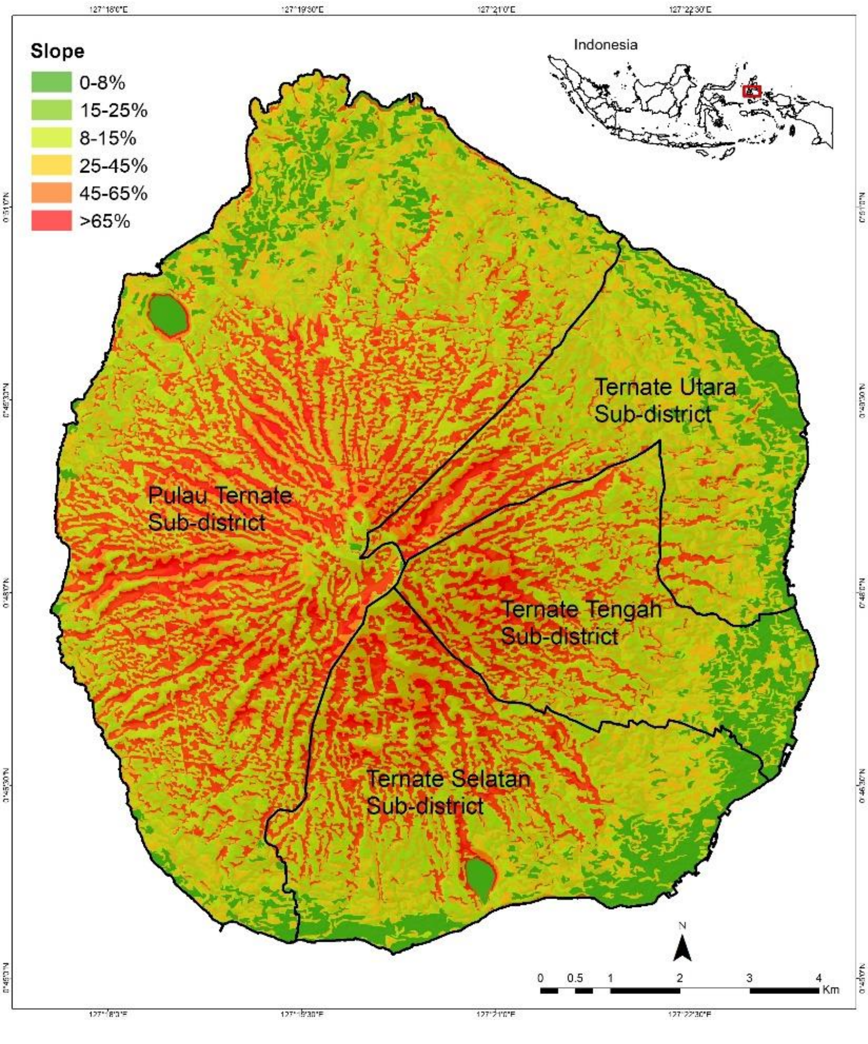
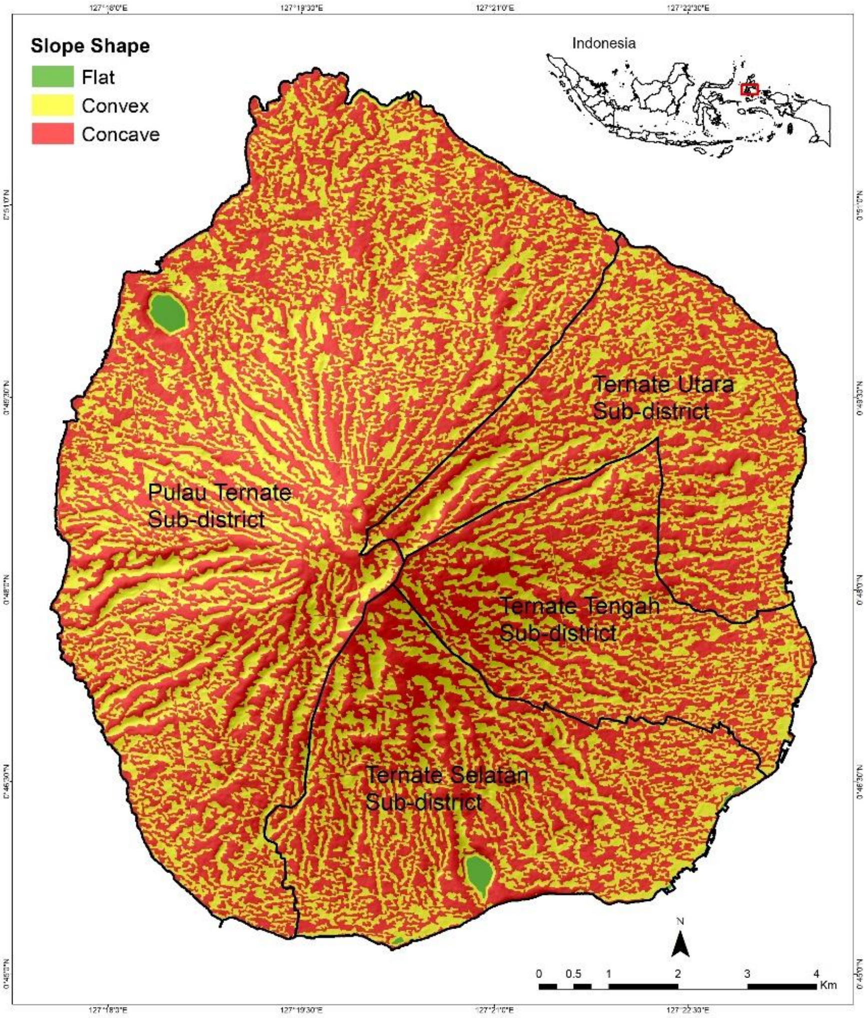


Figure 1. Slope map of Ternate City.

3.2. Slope Shape

The analysis results show a varied distribution between concave, flat, and convex shapes. From the data obtained, areas with concave slope shapes cover 4,495.59 hectares, indicating that most areas have concave characteristics. This concave shape often serves as a water accumulation area, which can increase the risk of landslides, especially during high rainfall [17]. This is due to the potential for water accumulation that can reduce soil stability, making it important to pay attention to these areas in disaster mitigation planning. Meanwhile, areas with convex slope shapes cover 5,624.32 hectares, making it the most dominant shape in the area. Convex shapes tend to have faster surface flow, which can reduce water accumulation as well as increase erosion at the top of the slope. The flat area, which covers only 41.19 hectares, indicates that this area is very limited and may not contribute significantly to landslide risk. Thus, an understanding of the distribution of these slope shapes is crucial for identifying potential landslides and planning appropriate mitigation measures, especially in concave areas that are more prone to water accumulation and landslides. Slope shape map of Ternate city is shown in Figure 2.

Figure 2. Slope shape map of Ternate City.



3.3. Landslide Prone and Affected Areas

Analysis of landslide potential in Ternate City shows significant variation in the level of landslide vulnerability in each sub-district. On Pulau Ternate, areas with very low risk cover 323.97 hectares, while areas with low risk reach 2,364.97 hectares. Interestingly, however, 1,391.72 hectares were identified as high-risk areas, suggesting that although most areas are low risk, there are areas that are highly vulnerable to landslides. This indicates the need for special attention in spatial management and planning in Pulau Ternate, especially in high-risk areas, to prevent disasters that can harm the community. In other sub-districts, such as Ternate Tengah, Ternate Utara, and Ternate Selatan, similar patterns are also seen. Central Ternate has 160.80 hectares with very low risk and 326.47 hectares with high risk, while North Ternate shows 199.13 hectares with high risk, although the area with low risk is quite significant. South Ternate, with 442.59 hectares in the high risk category, shows that while there are safer areas, there are also highly vulnerable areas, as seen in Figure 3. This overall data emphasizes the importance of monitoring and mitigating landslide risk across all sub-districts, focusing on areas identified as high risk to protect communities and infrastructure from potential disasters.

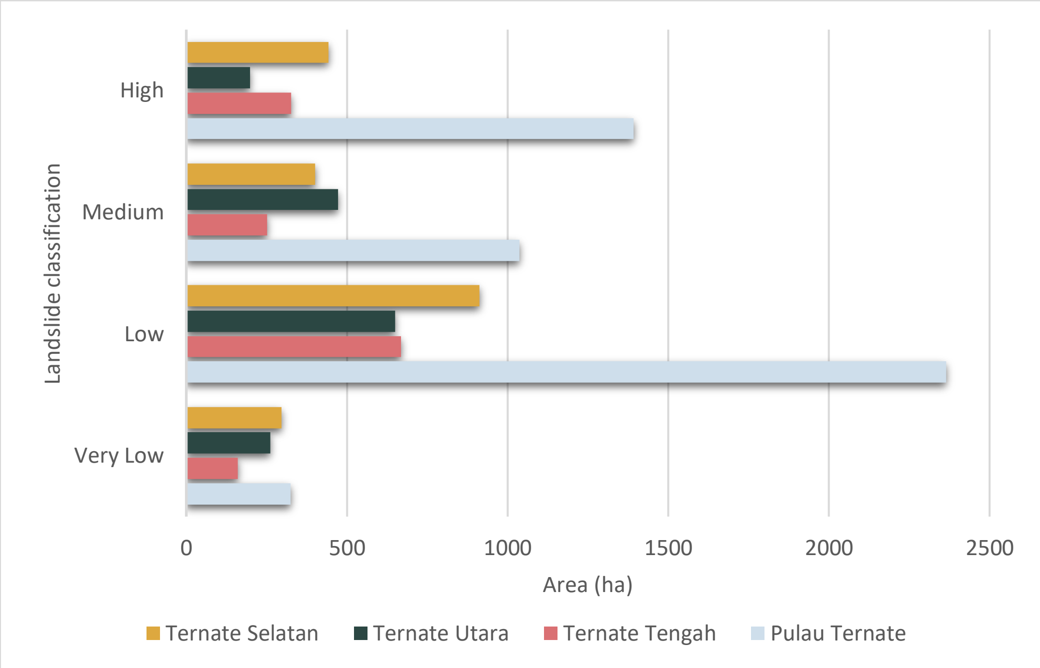


Figure 3. Diagram of landslide-prone areas per sub-district.

Analysis of the impact of settlements on landslide potential in Ternate City shows that although there are areas with low risk, there are still a number of settlements located in the risk zone. On Pulau Ternate, only 14.86 hectares of the total area were identified as very high landslide risk, while 70.93 hectares were in the very low category. This shows that most settlements in Pulau Ternate are in relatively safe areas but still need to be vigilant due to the potential for landslides that could affect infrastructure and the safety of residents. Therefore, it is important to conduct regular monitoring and risk assessments to ensure that settlements remain safe from disaster threats [18]. In other sub-districts, such as Ternate Tengah and Ternate Utara, although there are larger areas of low risk, the number of settlements exposed to high risk remains significant. Ternate Tengah has 239.69 hectares in the very low category but only 7.10 hectares in the high risk category. The same is also seen in North Ternate and South Ternate, where although the area with low risk is quite large, the number of settlements exposed to high risk remains noteworthy.

The area affected by landslides in 2024 in Ternate City, Ruha Village, is 2.7 ha. The impact of this disaster was significant, with 19 people reported dead due to being buried by landslide material, while eight others were injured. In addition, dozens of housing units suffered heavy damage due to being dragged and buried by landslide material. There were 25 houses and places of worship destroyed, and one bridge on the highway between villages on Pulau Ternate was broken. Approximately 60 families or hundreds of people were evacuated to a number of safe places in Rua Village, Ternate City.

Landslide-prone areas in Ternate City can be seen in Figure 4. Analysis of the impact of settlements on landslide potential in Ternate City shows that although there are areas with low risk, there are still a number of settlements located in the risk zone. On Pulau Ternate, only 14.86 hectares of the total area were identified as very high landslide risk, while 70.93 hectares were in the very low category. This shows that most settlements in

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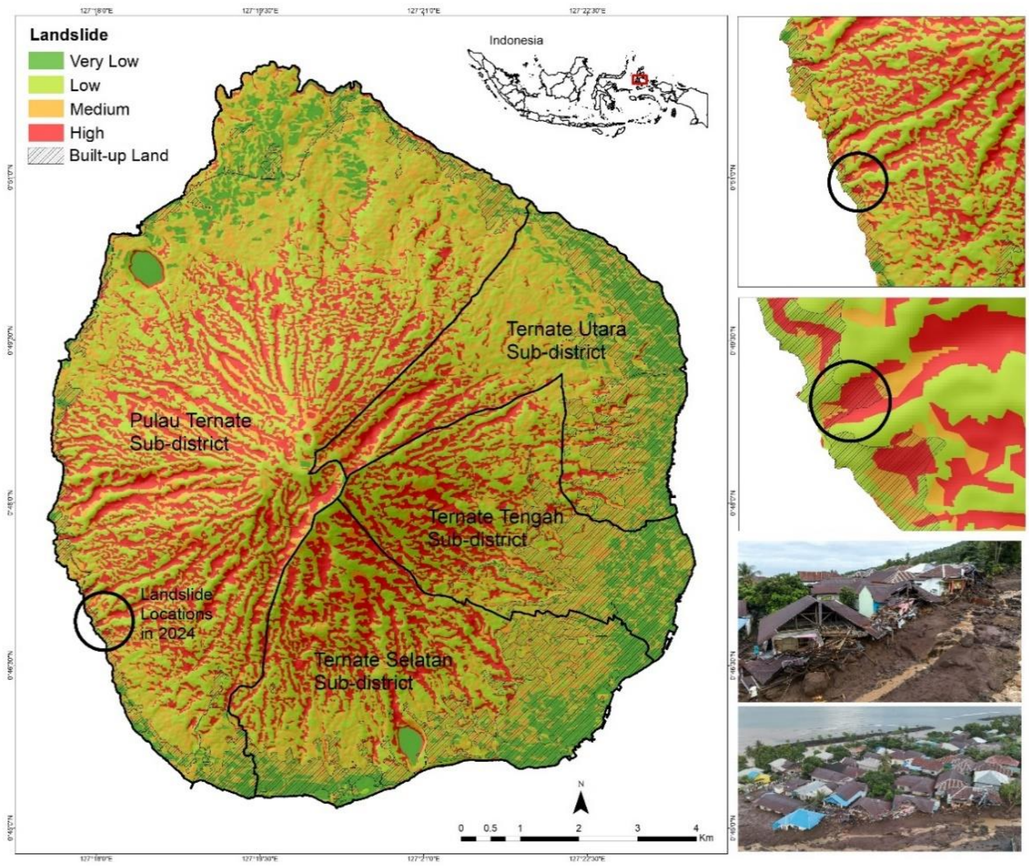

Figure 4. Landslide hazard map in Ternate City.

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4. Conclusions

This research shows that Ternate City has significant potential landslide risk, with 1,391.72 hectares of area identified as high risk, although most areas have low risk. Through the use of the Digital Elevation Model and slope morphology analysis, this research successfully mapped landslide-prone areas and factors affecting slope stability.

The results of this study emphasize the importance of comprehensive and sustainable mitigation efforts, including risk mapping, community socialization, infrastructure strengthening, and reforestation, to reduce disaster impacts and protect communities and infrastructure in Ternate City. Thus, this research is expected to serve as a basis for policymakers in formulating more effective disaster mitigation strategies and raising awareness of the importance of wise environmental management.

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