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ANALYSIS OF THE NON-COMPATIBILITY OF GEOMORPHOLOGICAL CONDITIONS TOWARDS FLASH FLOOD VULNERABILITY IN ANAI VALLEY

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ABSTRACT: Flash floods are a hydrometeorological disaster that frequently occurs in mountainous watersheds, particularly in areas with land use that is not in accordance with its natural geomorphological conditions. This study aims to analyze the geomorphological characteristics of the Anai Valley, determine the level of flash flood vulnerability based on the integration of biophysical parameters, and assess the contribution of geomorphological mismatches to increasing flash flood vulnerability. This study uses a Geographic Information System (GIS) approach with a weighted overlay method through the integration of slope gradient, soil type, land use, river buffer, and rainfall parameters. The results show that the Anai Valley area is dominated by steep to very steep slopes, volcanic and alluvial soil types, and land use activities that develop along the Batang Anai River. High to very high flash flood vulnerability zones are concentrated in the valley plains and river corridors. Land use mismatches on steep slopes and river boundaries contribute significantly to increased surface runoff and environmental degradation.

Keywords: geomorphological incompatibility, flash flood vulnerability, watershed, Anai Valley, GIS

1. INTRODUCTION

Global climate change has an impact on the accumulation of high rainfall in a short time. Relatively similar annual rainfall, with a short duration, has an impact on increasing the intensity of flooding that occurs. Flash floods are inundation due to runoff from river channels because the river discharge suddenly increases beyond the flow capacity, occurring quickly in low-lying areas of the earth's surface, in river valleys and basins and usually carrying debris in their flow. The main causes of flash floods are high rainfall, steep topographic conditions and reduced vegetation in the location [1].

West Sumatra itself experiences high rainfall, varied topography, and demographic pressures and land conversion following the 2009 earthquake. These conditions were exacerbated by the eruption of Mount Merapi and the complex socio-cultural systems of the community, necessitating public policy in the field of water resources management. This disaster provides important lessons about disaster anticipation, long-term watershed management, and the need for technical and non-technical data. Post-disaster investigations found the Anai watershed in critical condition due to open land, reduced infiltration, and land conversion due to settlements and human activities [2].

Flooding is an event where river water overflows due to natural and anthropogenic factors, such as high rainfall, the inability of the river to accommodate the water discharge, and degradation of the river basin, resulting in inundation in the surrounding area and causing environmental damage, economic losses, and disruption to the social life of the community [3].

The flash floods of May 11, 2024, in the Anai Valley were one of the worst disasters in the last decade. The disaster was caused by extreme rainfall in the catchment areas of Mount Merapi and Mount Singgalang, which then triggered a torrential flow of water mixed with volcanic material downstream. The impact was significant, resulting in damage to vital infrastructure and settlements, as well as loss of life and public facilities [2-4].

The problem is becoming more complex due to the discrepancy between the Regional Spatial Planning (RTRW) and the use of existing space [4]. Many settlements, tourist facilities, and infrastructure are built along river banks, steep slopes, and areas that should be designated as green open spaces. This demonstrates weak spatial planning oversight and the low integration of geomorphological aspects into development policies [5].

Based on these conditions, this study aims to describe the geomorphological characteristics of the Anai Valley based on slope gradient, soil type, and proximity to the river; analyze the level of flash flood vulnerability in the Anai Valley based on the integration of biophysical parameters; and examine the incompatibility of geomorphological conditions with the increase in flash flood vulnerability in the area.

2. METHODS

2.1 Geomorphological Characteristics of the Anai Valley

The geomorphological characteristics of the Anai Valley were analyzed using a GIS-based spatial analysis approach. Parameters analyzed included slope gradient, soil type, and proximity to the river. Slope data was obtained from SRTM DEM processing and classified into specific slope classes. Soil type was analyzed based on soil maps and classified according to infiltration characteristics and erosion susceptibility. Proximity to the river was analyzed by creating buffers along the Batang Anai River at distances of 0–50 m, 50–100 m, 100–150 m, and 150–200 m. These three parameters were mapped to illustrate the geomorphological conditions of the study area.

2.2 Flash Flood Vulnerability Level in Anai Valley

Flash flood vulnerability was analyzed by integrating biophysical parameters including slope gradient, soil type, land use, river buffers, and rainfall. Each parameter was scored and weighted according to its influence on flash floods. All parameters were then overlaid using a weighted overlay method in GIS to produce a flash flood vulnerability index, which was further classified into low, medium, and high levels of vulnerability.

2.3 Contribution of Geomorphological Unsuitability to Flash Flood Vulnerability

The analysis of the contribution of geomorphological mismatches was conducted using a comparative spatial approach, comparing natural geomorphological conditions with existing land use. Areas with inappropriate land use, such as activities on steep slopes, river buffer zones, and areas with low vegetation cover, were identified as mismatch zones. These areas were then analyzed for their relationship to flash flood vulnerability maps to assess their contribution to increased vulnerability.

3. RESULTS AND DISCUSSION

3.1 Geomorphological Characteristics of Anai Valley

Geomorphological analysis results indicate that the Anai Valley area is dominated by steep to very steep slopes, especially in the upstream and downstream areas. This steep slope directly increases surface flow velocity and the potential for erosion. The soil types developing in the study area are predominantly volcanic, such as andosols and regosols, which are easily saturated and susceptible to erosion if vegetation cover is reduced.

River buffer analysis indicates that some human activity areas are located very close to the Batang Anai River channel. This situation increases the potential impact of peak flows during high-intensity rainfall events. The combination of steep slopes, vulnerable soil types, and proximity to the river creates a geomorphological character that is naturally highly susceptible to flash floods.

Tabel 1. Anai Valley slope class

Kelas Lereng	Kemiringan (%)	Skor	Bobot	Skor × Bobot
Datar	0–8%	1	0,1	0,1
Landai	8–15%	2	0,15	0,3
Agak Curam	15–25%	3	0,2	0,6
Curam	25–45%	4	0,25	1
Sangat Curam	>45%	5	0,3	1,5

Source: Results of data analysis, 2025.

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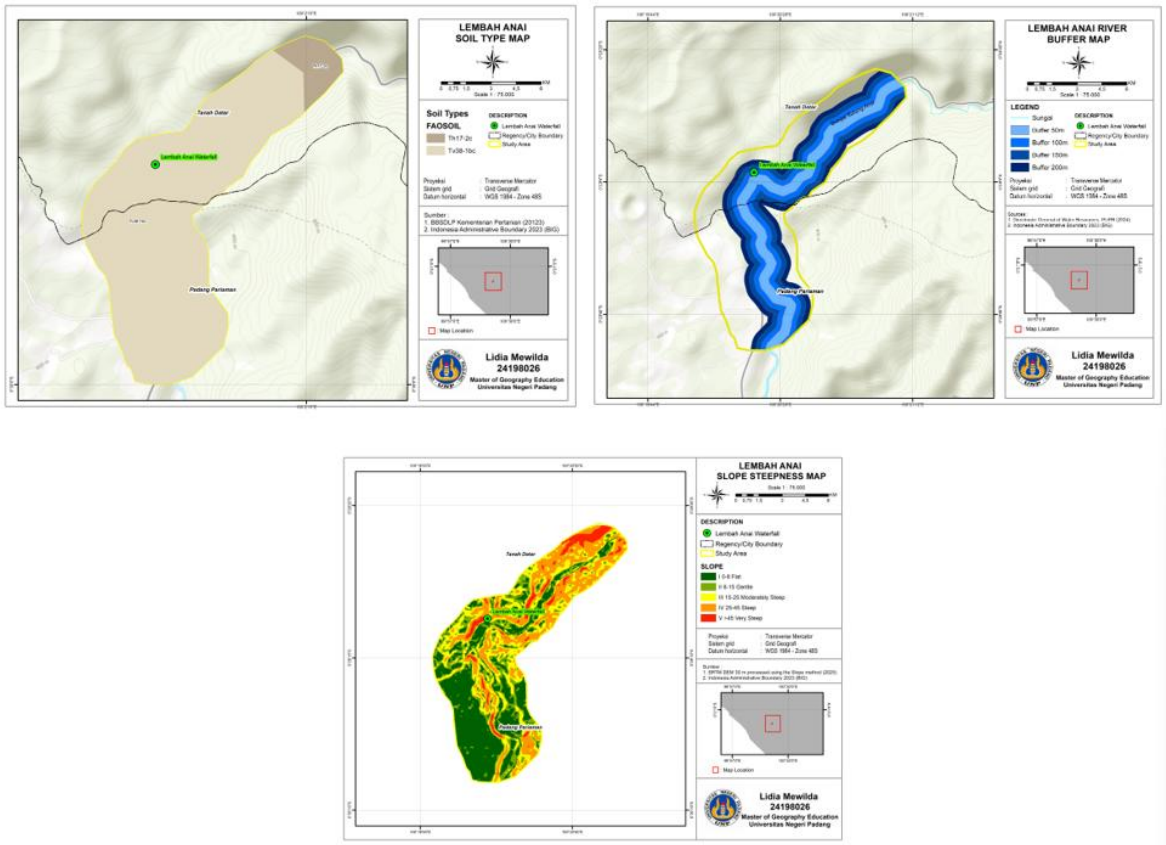

Fig 1. Map of The Volcano Eruption Risk Level of Sinabung.

Slope gradiant

The results of the slope weighting in the Anai Valley as presented in Figure 1 show that the study area is dominated by slope classes of 0–8% (flat) to 8–15% (sloping) which generally develop in the valley and along the main river channel. Meanwhile, slope classes of 15–25% (slightly steep) to >45% (very steep) are spread across the valley cliffs and surrounding hilly areas. Based on the slope parameters, the topographic conditions of the Anai Valley generally support the accumulation of surface flow, especially in flat and sloping zones, thus contributing to the high potential for flash flood vulnerability, especially in areas adjacent to the river. This is in accordance with what was stated by [6] that most of the land is flat with a slope of 0–8%. Based on the slope parameters, it can be concluded that the Samin Sub-watershed has a high level of flood vulnerability.

Soil type

Soil characteristics reflect the ease with which rainfall infiltrates into the soil (infiltration). This is closely related to the physical properties of the soil, namely texture and permeability. Soil texture is used to describe the soil's ability to absorb rainwater. Permeability is used to determine the rate at which rainwater infiltrates (cm/hour) [6].

The results of the analysis of soil type characteristics in the Anai Valley, as presented in Figure X, show that the research area is dominated by alluvial soil which develops mainly in the valley plains and along the Anai River. In addition, brown andosol and latosol soils are also found, distributed over relatively small areas, generally in the upstream areas and hilly areas surrounding the valley. This diversity of soil types reflects differences in physical properties, particularly in terms of texture and permeability. In general, the soil in the Anai Valley has a water permeability that varies from slow to moderately fast, with permeability values ranging from 0.01 to 10.94 cm/hour. This indicates that areas dominated by low-permeability soils, particularly alluvial soils, have a relatively greater potential for flooding and increased surface runoff.

River buffer

The scoring of the River Buffer class is based on the proximity to the river. The closer the area is to the river, the higher the score assigned to that class. This disrupts the flow of rainwater into the river [7].

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Based on the Anai Valley River Buffer Map, most of the study area is located within the buffer zone 0–200 m from the Batang Anai River channel. The closest buffer zone (0–100 m) generally develops in valley plains that are geomorphologically associated with alluvial soils. This type of soil has a relatively fine texture and tends to have low to moderate permeability, thus limiting water infiltration capacity [8]. These conditions cause areas within river buffer zones, particularly those ⩽100 m away, to have the potential for high surface runoff accumulation during high-intensity rainfall. Conversely, in more distant buffer zones (150 – 200 m away), although the direct influence of river overflows begins to diminish, soil characteristics still play a role in controlling infiltration and water movement toward the river.

Thus, the relationship between proximity to the river and the dominance of alluvial soil types makes the Batang Anai River buffer zone the area most vulnerable to flash floods, especially in the Anai Valley plains.

3.2 Flash flood vulnerability level in Anai Valley based on integration of biophysical parameters.

As part of the analysis of flash flood vulnerability in the Anai Valley, the following discussion focuses on land cover conditions and rainfall characteristics. These two parameters play a crucial role in controlling the magnitude of surface runoff and the region's hydrological dynamics. Land cover and rainfall maps are presented to illustrate the spatial distribution of each parameter as a basis for assessing flash flood vulnerability.

Land use

Land use is a form of human intervention in utilizing natural resources to support well-being. This is usually done without regard for environmental aspects, resulting in disasters due to the impacts of improper management [7]. Land use patterns in the Anai Valley indicate that although the study area is still dominated by forest cover, land use changes, particularly in the form of open land and settlements, have developed in the valley plains and along the Batang Anai River. These areas are largely located within the river's buffer zone, thus directly interacting with the dynamics of river flow.

The presence of open land and settlements in the river buffer zone has the potential to reduce infiltration capacity and increase the amount of surface flow, especially when it rains. [9] High intensity. This condition increases the potential for river overflows and increases the vulnerability to flash floods in valley areas.

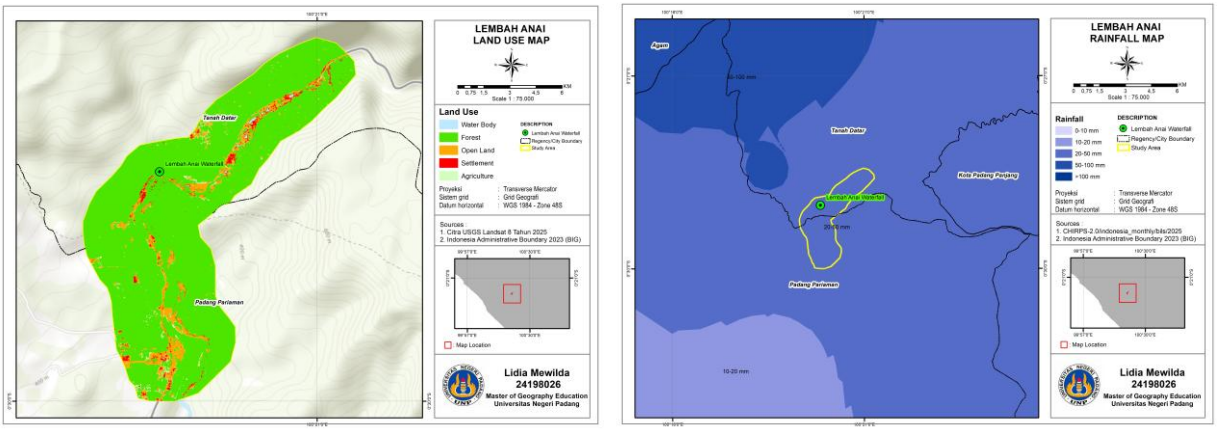

Fig. 2 Map of land use and rainfall of the Anai Valley.

Rainfall

Rainfall is the measurement of rainwater that accumulates in a flat, non-absorbent, and non-flowing area. The unit of rainfall is millimeters (mm). The higher the rainfall, the higher the potential for flooding. Conversely, if the rainfall is low, the potential for flooding is lower [10]. Based on the Anai Valley Rainfall Map, the study area generally falls within the 20–50 mm rainfall range, indicating medium to high rainfall intensity. A small area around Anai Valley is also affected by a higher rainfall zone, at 50–100 mm, particularly in the upstream area bordering Agam Regency.

The Head of the BMKG Weather Prediction and Early Warning Working Team stated that the weather conditions that caused the hydrometeorological disaster were the impact of cyclonic circulation around the western waters of Aceh in the last few days, causing the formation of wind turns and convergence in North Sumatra, active Equatorial Rossby atmospheric waves causing the accumulation of air masses and

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triggering the growth of rain clouds in West Sumatra [10].

Vulnerability level

The resulting vulnerability map depicts spatial variations in vulnerability levels, ranging from very low to very high. Zones with high and very high vulnerability levels generally develop in the valley plains and along the Batang Anai River, influenced by a combination of flat slopes, dominant alluvial soils, proximity to the river, land-use changes, and relatively high rainfall. Conversely, areas with low to very low vulnerability levels are more commonly found in hilly areas with better forest cover and relatively steep slopes, which reduce runoff accumulation. These results indicate that interactions between biophysical parameters play a significant role in determining flash flood vulnerability in the Anai Valley.

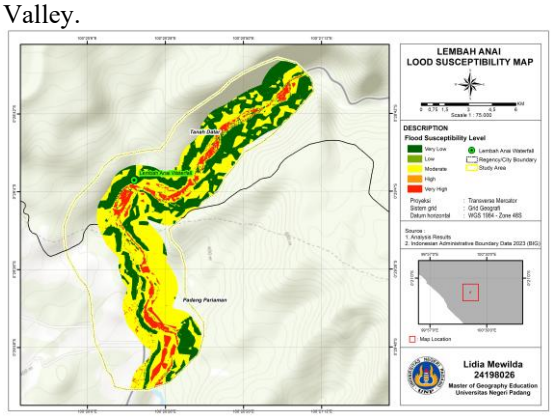

Fig.3 Anai Valley Flood Hazard Map

Based on the integration of five biophysical parameters: slope gradient, soil type, land cover, river buffer, and rainfall, a flash flood vulnerability map for the Anai Valley was generated, classified as very low to very high. High and very high vulnerability zones are generally concentrated along river channels, influenced by relatively gentle slopes, fine-textured soil types, built-up or open land cover, proximity to rivers, and high rainfall intensity [11]. Meanwhile, areas with low to very low vulnerability are predominantly located in the upstream and hilly areas, characterized by steeper slopes, good vegetation cover, and greater distance from the river, thus having a greater capacity to reduce surface runoff. These results indicate that a combination of spatial biophysical conditions plays a significant role in determining the level of flash flood vulnerability in the Anai Valley.

3.3. Contribution of Geomorphological Incompatibility to Flash Flood Vulnerability

Based on the analysis of slope gradient, soil type, river buffers, land use, and rainfall, several areas appear to be inconsistent with their natural geomorphological conditions. These inconsistencies primarily occur in: (1) Land use on steep to very steep slopes, (2) Use of low-infiltration soils, (3) Activities very close to rivers (0–100 m), and (4) Vegetation clearing in steep slope zones. This combination of factors causes accelerated runoff, increased erosion, and the accumulation of water discharge toward the river valley.

This condition indicates that spatial use patterns in several areas of the Anai Watershed have not fully considered the environmental carrying capacity and capacity [12]. Construction activities and land clearing in steep to very steep slope zones have the potential to disrupt slope stability and reduce the land's ability to absorb rainwater [13]. In addition, land use on soil with low infiltration characteristics and proximity to river channels increases the risk of surface runoff and rapid accumulation of water flow towards the river body.

This mismatch in spatial patterns has direct implications for increasing the vulnerability of the Anai watershed area to flash floods and environmental degradation [14]. Therefore, the spatial pattern map displayed is important as a basis for evaluating the suitability of land use [15]. As well as considerations in spatial control, especially in protected areas, river boundaries and disaster-prone zones in Tanah Datar Regency [8].

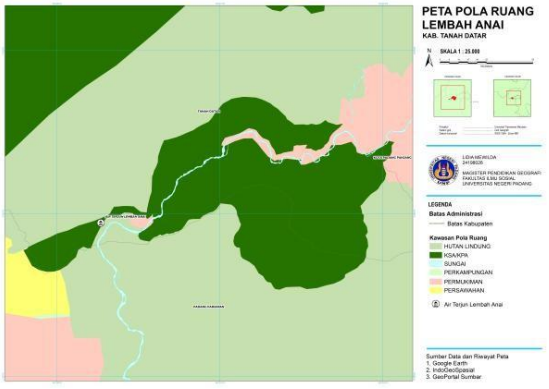

Fig.4 Anai Valley spatial pattern map

Based on the 1:25,000 scale Anai Valley Spatial Pattern Map of Tanah Datar Regency, it can be seen that the study area is dominated by protected areas and nature reserves/nature conservation areas (KSA/KPA) that stretch following the morphology

of the valley and hill slopes along the Anai Watershed. This area functions as a water catchment area and controls hydrological balance, especially in the upstream and middle of the valley [1].

Along the main river corridor of the Anai Watershed, residential and village zones have developed following the river's course and regional accessibility, particularly in the relatively gentle valley areas. The presence of settlements adjacent to the river indicates pressure on land use in the riparian zone, which geomorphologically increases vulnerability to flash floods.

Land use, including rice paddies, has been identified in the downstream and transitional areas leading to Padang Pariaman Regency, which generally occur on alluvial plains with low slopes. This pattern reflects land use that adapts to the flat topography and availability of surface water, but remains at risk of river overflows during periods of heavy rainfall.

4. CONCLUSION

The results of the study indicate that the Anai Valley is geomorphologically highly vulnerable to flash floods, characterized by the dominance of flat to gentle slopes on the valley plains, fine-textured soil types with low infiltration, and the proximity of human activity areas to the Batang Anai River channel. The integration of biophysical parameters such as slope gradient, soil type, land use, river buffers, and rainfall produces a flash flood vulnerability map with high to very high vulnerability zones concentrated along the river channel and valley plains. The mismatch between natural geomorphological conditions and spatial utilization, particularly development on river banks [16], steep slopes, and land clearing on low-infiltration soils, contribute significantly to increasing the vulnerability to flash floods. Therefore, the integration of geomorphological aspects in spatial planning and management of the Anai Watershed is important as a basis for controlling land utilization and formulating sustainable flash flood mitigation strategies in Tanah Datar Regency.

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