Spatial Analysis of Flood Vulnerability Base on Biophysics Factor the Krueng Baro Watershed in Flood Mitigation Efforts at Aceh, Indonesia

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Abstract. Flooding in a watershed is caused by the disruption of hydrological functions and physical factors of the watershed, as well as human activities. In the Krueng Baro watershed, several sub-districts experience flooding twice a year. To mitigate this problem, a study was conducted to spatially analyze flood-prone areas based on biophysical factors. Primary data from Landsat imagery use for land cover/land use) and secondary data (rainfall, soil type, and slope, were analyzed using ArcGIS 10.8. Each parameter was scored, and the overlay analysis resulted in a distribution of flood susceptibility in the Krueng Baro watershed. River density was found to have a significant impact on flood susceptibility, and settlements, agricultural land, slopes, and low altitudes were identified as highly vulnerable areas. The distribution of flood susceptibility in the Krueng Baro watershed was classified as very high and high (38.35%), moderate (21.60%), and low/very low (39.86%). Flood control methods such as mechanical and vegetation conservation, and community involvement, must be implemented to mitigate flooding in the affected areas.

1 Introduction

Flood is the rise in the water level that exceeds the normal level in a river, typically causing it to flow over its banks and inundate a piece of land [1]. The condition of a flood is influenced by the physical conditions and characteristics of the area. Generally, floods are influenced by high rainfall intensity and drainage conditions. Floods are a natural phenomenon that occurs in areas with many river channels. According to [2], there are several natural factors that cause floods, such as rainfall intensity, river physiology, erosion and sedimentation, river

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capacity, drainage capacity, and the influence of high tides. Meanwhile, floods caused by human factors include changes in the river basin condition, slum areas, garbage, damage to flood control structures, and others.

Vulnerability is a condition determined by physical, social, economic, and environmental factors, which increase the propensity to hazards [3]. Flood vulnerability estimates areas that may be susceptible to flood events. Typically, flood-prone areas are those with flat topography, close proximity to rivers, located in basins, and in tidal coastal areas [4].

The Pidie Regency has several Watersheds that flow through it, one of which is the Krueng Baro Watershed. This watershed has a flow capacity of more than 250 liters per second [5]. The Krueng Baro Watershed is one of the watersheds located in the Pidie Regency, where the local population utilizes water from the Krueng Baro river for various needs. In a watershed, floods often occur in the downstream areas, which are typically flat. Flooding has occurred several times in the Pidie Regency, such as in 2021, affecting 11,731 people, and again in 2023, affecting 3,336 people. These floods are caused by high rainfall intensity, which increases the river's flow. According to [6] flooding is one of the major problems in the Pidie Regency. This flooding is caused by changes in land use due to illegal logging in the upstream forest, the physical condition of the river flow and irrigation, sedimentation in the Pidie Regency, leading to soil erosion and flooding in residential areas. Mapping flood-prone areas can utilize a geomorphological (landform) approach. Mapping flood-prone areas is one of the efforts to prevent losses caused by flooding. Geographic Information Systems (GIS) can be used to map flood-prone areas. The use of Geographic Information Systems can quickly and easily identify flood vulnerability in a specific region. Therefore, in this study, a Geographic Information System approach is employed to map flood-prone areas in the Krueng Baro Watershed.

2 Material and methods

2.1 Study area

This research was conducted in the Krueng Baro Watershed, which is geographically situated between the eastern longitude (EL) of 96º0’0”-96º21’20” and the northern latitude (NL) of 5º3’30”-5º21’20’’ (Figure 1). Administratively, the Krueng Baro Watershed, in accordance with the definitive boundaries set by the Ministry of Home Affairs in 2022 is located in Pidie Regency, with a small portion of the forest area falling under Aceh Besar Regency.

This research begins by collecting data in the form of shapefiles (SHP) for land cover, rainfall, soil types, and slope. The process of creating flood-prone area maps in the Krueng Baro Watershed area is carried out using ArcGIS software, version 10.8, following these steps:

2.2 Collection of relevant data

In the initial stage of this research, relevant data such as rainfall data, land elevation, land use, river data, slope, and flood history data need to be collected. This data can take the form of tabular data or spatial data in map format. It is essential to ensure that all acquired data has predefined geographical coordinates so that it can be used in spatial analysis using ArcGIS.

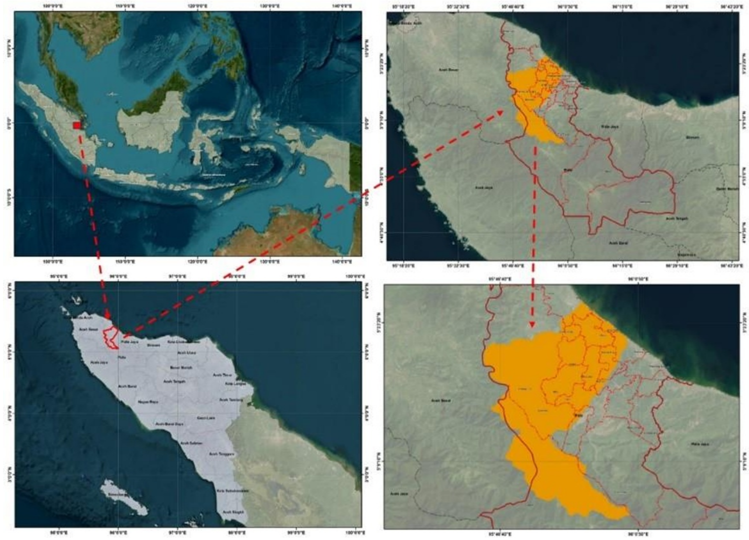

Fig. 1. The location of the Krueng Baro Watershed.

2.3 Rectification of spatial data

The data that has been acquired, whether in the form of maps or tabular data, needs to be rectified to make it usable in GIS software, such as ArcGIS. Rectification is the process of transforming non-geographic data into spatial data by attaching the relevant geographic coordinate information. This process must ensure that the data has an appropriate and compatible coordinate system for use in subsequent analyses.

2.4 Analysis of the identification of factors contributing to flood vulnerability

After the data has been prepared and rectified, the next analysis is to identify factors that contribute to the level of flood vulnerability in the Krueng Baro watershed area. Factors such as low land elevation, distance to rivers, soil type, and high rainfall may have a significant role in determining the level of flood vulnerability. Identifying these factors is an important step in understanding flooding in the region.

2.5 The allocation of criteria and weights

Once the contributing factors have been identified, criteria and weights need to be determined. Criteria are parameters used to assess the level of flood vulnerability, while weights are values used to assign the importance of each criterion in the analysis. For example, in the case of lower ground elevation, higher weights can be assigned because this factor is considered to have a greater impact on flood vulnerability.

To assign scores to each factor at each location and generate flood vulnerability values, you can use the "Weighted Overlay" tool available in the ArcGIS software. This tool allows you to combine predefined criteria and weights to create a map depicting flood vulnerability distribution across the entire Krueng Baro Watershed area.

Overlay is a technique used to combine information from various layers of spatial data in GIS (Geographic Information System). In the context of flood vulnerability, various data layers, such as ground elevation, river networks, rainfall, land use, and other factors can be merged to determine the most flood-prone areas. The overlay process generates a new map that identifies areas with a combination of specific vulnerability factors.

An example of using overlay in flood vulnerability analysis is by combining elevation data layers (identifying low-lying areas susceptible to flooding), river network data layers (identifying areas near rivers), and land use data layers (identifying areas that become flooded during specific times). The results of this overlay can be used to determine priority areas for flood mitigation measures. The equation used in the overlay process, based on the research by [7] using the arithmetic method, is as follows:

$$FV = (1 \times R) + (2 \times S) + (3 \times ST) + (4 \times LU) \quad (1)$$

Where, FV (Flood Vulnerability): the level of vulnerability to floods that is being calculated or assessed. The result of this formula will provide an overview of how vulnerable a location is to flooding.
ST (Soil Type): the type of soil in the location being assessed. Different soils have different characteristics in terms of water absorption, and this factor is assigned a weight of 3 in the equation
S (Slope): the incline or slope of the land in the location being assessed. The slope of the land can affect water flow and the level of flood risk. This factor is given a weight of 2 in the formula.
R (Rainfall): the amount of rainfall in the location being assessed. High rainfall can increase the risk of flooding, and this factor is given a weight of 1 in the equation.
LU (Land Use): Land use in the assessed location. Certain types of land use, such as urban or densely populated areas, tend to have a higher risk of flooding. This factor is assigned a weight of 4 in the equation.

3 Result and discussion

3.1 Land use

Land cover plays a role in the magnitude of rainwater runoff [8]. Areas with good vegetation cover will have difficulty in discharging rainwater runoff due to the high infiltration capacity provided by the trees, and runoff will flow slowly due to the presence of plant roots [9]. In areas with good vegetation, rainwater will infiltrate effectively, increasing the travel time for runoff to reach the river, thus reducing the likelihood of flooding.

Changes in land use in river watershed areas are expected to have a significant impact on flood inundation. Prolonged significant land use changes, along with a sharp increase in built-up areas combined with a reduction in agriculture and green areas, are the primary causes of the increased occurrences of flood inundation [10]. The land cover image within the Krueng Baro Watershed can be observed in Figure 2.

Based on the land use map obtained from the Basic Map (RTRW) of Pidie Regency for the year 2022, in the Krueng Krueng Baro Watershed, there are several types of land use, as indicated in Table 1.

Table 1. Land Use in the Krueng Baro Watershed

Land use	Scoring	Area (Ha)
Forest	1	23,197
Swamp	3	44
Underbrush	3	15

Land use	Scoring	Area (Ha)
Plantation	5	14,119
Wetland Farming	7	11,957
Build up Area	7	5,710
Pond	9	1,813
Water Body	9	357
Total		**57,211**

Source: Analysis Results, 2023

Land with forest land cover can be more effective in reducing the risk of flood vulnerability [11]. Dense population settlements contribute to flooding because the land cover in these areas consists of hard materials like concrete and stone, which can slow down the process of water infiltration or absorption into the ground. Open land can also lead to flooding because there is no proper land management in those areas [4]. Another cause of flooding is the change in land use from agricultural land to built-up land, such as industrial factories, which certainly affects the water management in the region [12].

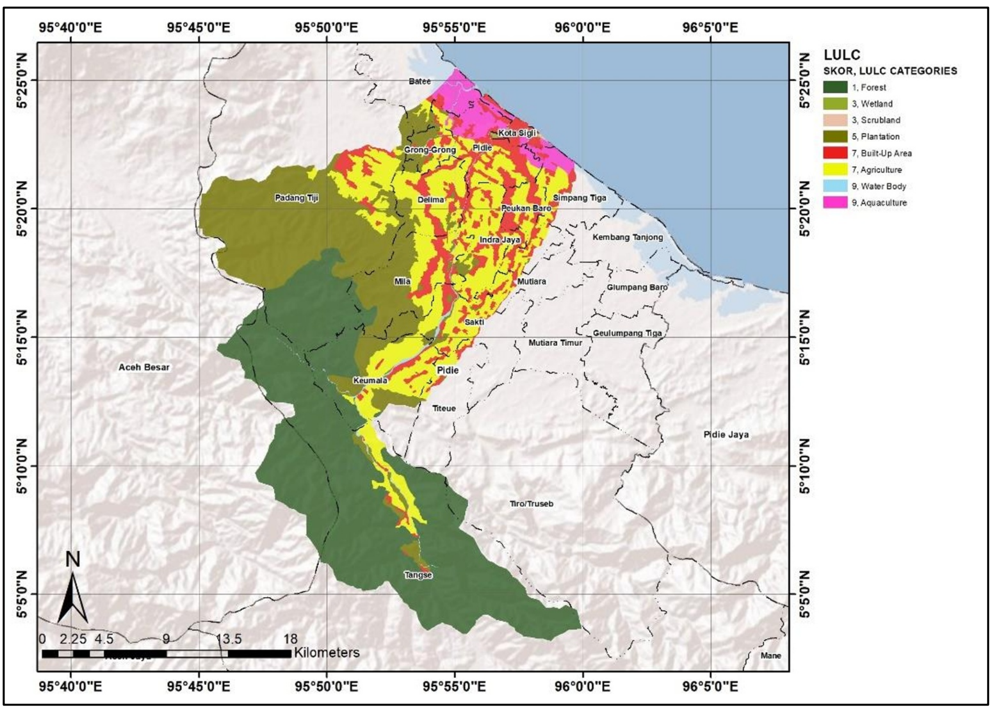

Fig. 2. Land cover in the Krueng Baro Watershed

3.2. Rainfall

Areas with high rainfall levels have a more significant impact on flood events and climate change [13]. The higher the amount of rainfall in an area, the greater the potential for flooding. For this research, the rainfall data for the Krueng Baro river basin was collected from the nearest stations, namely Sarah Mane, Tangse, and Tiro stations, for the period between 2012 – 2021. The average rainfall data collected from Sarah Mane Rainfall Station, Tangse Station, and Tiro Station were respectively 1,586-1,907.3 mm/yr, 2,135.4 -2,479.0 mm/yr, and 2,908.4 mm/yr. The data was obtained from the Meteorology, Climatology and Geophysics Agency (BMKG) Indrapuri, Aceh Besar District. Based on the rainfall data in the Krueng Baro Watershed area, the rainfall data is categorized into three (3) classes. In determining the rainfall classes, the key factors considered are the monthly and annual rainfall amounts. Rainfall above 3000 mm receives the highest score of 9, while rainfall below 1500 mm is scored (Table 2).

The higher the rainfall intensity, the greater the potential for flooding in the area [14]. According to [15], high rainfall intensity and unpredictable weather changes lead to river overflow. Rainfall is a crucial component of data often required for hydrological and ecological modeling [16]. The flood flow patterns in the Watershed are heavily influenced by variables such as land use, flow duration, rainfall intensity, and the volume of rain that falls within the Watershed [17].

Table 2. Rainfall of the Krueng Baro Watershed

Rainfall (mm/year)	Classification	Scoring	Area (Ha)
1500-2000	Moderate	5	32,147
2000-2500	High	7	24,708
2500-3000	Quite high	9	355
Total			**57,211**

Based on the rainfall data and in accordance with the scoring in Table 2. Calculating the weight of each station which represents the surrounding area is done using the Thiessen Polygon Method. This method is used to expand data from the point data type to the polygon data type. The polygon shape is obtained based on data from measurement points. Next, through the ArcGIS application program, the distribution of rainfall is mapped which can provide a distribution pattern of location points which contains information in the form of a map layout (Figure 3).

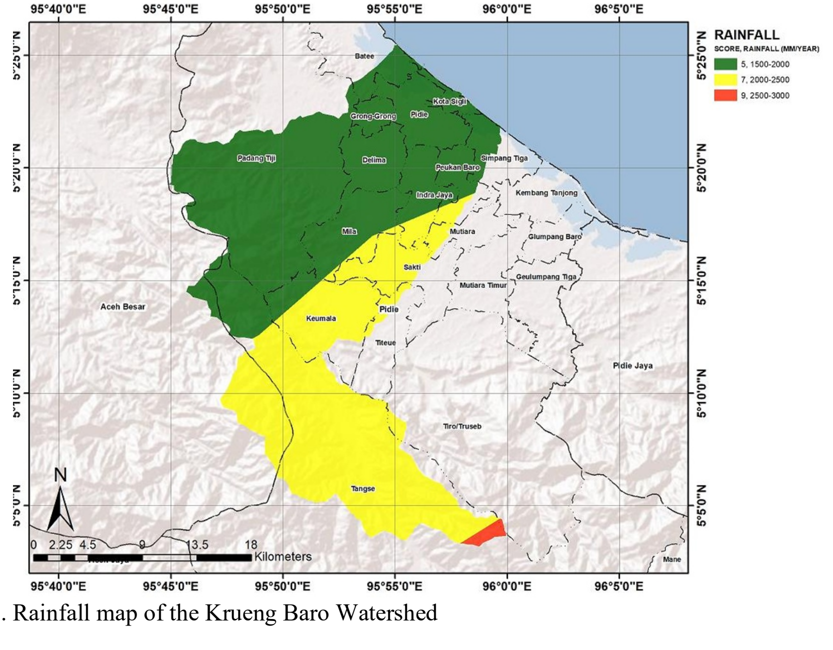

Fig. 3. Rainfall map of the Krueng Baro Watershed

3.3. Soil types

Soil with a very fine texture has a high potential for flooding, whereas coarse-textured soil has a low potential for flooding. The type of soil has an impact on the level of water infiltration capacity. Soil texture is determined by its grains; if the grain size is coarse, there are larger spaces between the grains or soil pores, which increases the opportunity for water infiltration into the soil. The more significant the presence of large pores, the greater the soil's capacity for water infiltration. On the other hand, soils with clayey or silty textures tend to have a smaller potential for soil infiltration, similar to clay soils, which have numerous fine pores and few large ones [18]. The description of soil types in the Krueng Baro Watershed can be seen in the Table 3.

Table 3. Soil types in the Krueng Baro Watershed

Soil type	Classification	Scoring	Area (Ha)
Entisol	Rather sensitive	3	963
Entisol – Inceptisol	Moderate	5	18,182
Inceptisol	Sensitive	5	23,048
Ultisol	Very sensitive	7	15,018
Total			**57,211**

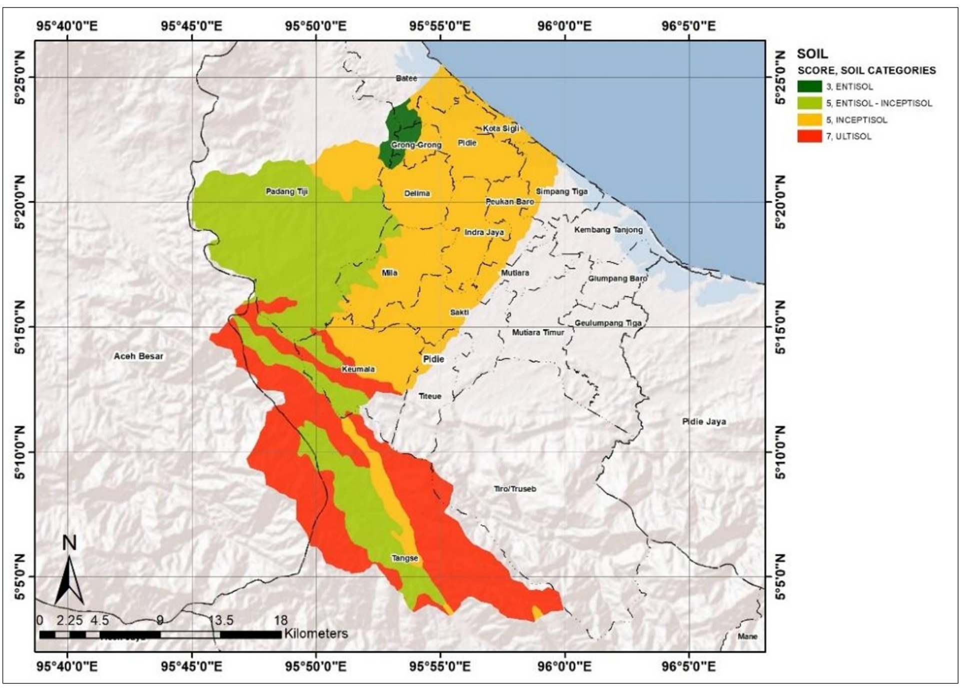

Fig. 4. Map of soil types in the Krueng Baro Watershed

Entisol soil has low permeability, making it less capable of retaining water. Therefore, entisol soil requires a significant amount of water because the water lost due to infiltration is substantial [19]. Inceptisol soil is susceptible to flooding because, according to [20], inceptisol is soil with a coarse texture and relatively high clay content (35-78%), with some having low clay content (18-35%). Ultisol soil has slow to moderate permeability and low aggregate stability, so most of this soil has a low water-holding capacity [21].

3.4. Slope

The slope gradient has a significant impact on floods because it is related to the natural flow of water, which moves from higher areas to lower ones. Areas with higher elevations have a lower potential for flooding, while areas with lower elevations are more prone to floods. As indicated by [22] in general, the flatter the slope, the more vulnerable the area is to flooding. The data on slope gradient in the Krueng Baro Watershed can be seen in Figure 5 and Table 4.

Table 4. Slope type and skoring in the Krueng Baro Watershed

Slope type	Classification	Scoring	Area (Ha)
0-8%	Flat	9	27,758
8-15%	Slightly tilted	7	9,684
15-25%	Crooked	5	12,360
25-45%	A bit steep	3	7,365
>45%	Steep	1	43
Total			**57,211**

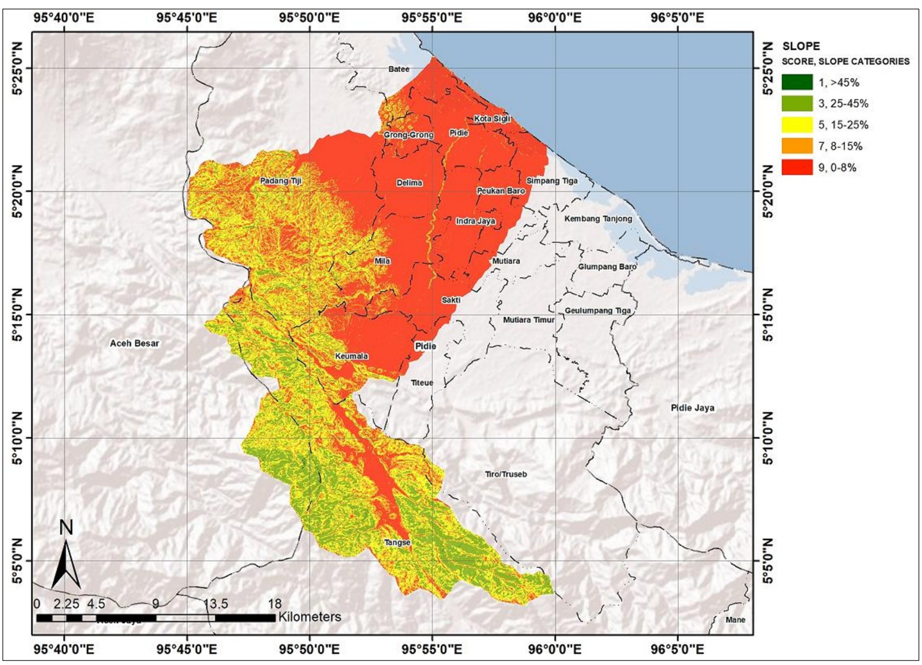

Fig. 5. Slope map of the Krueng Baro Watershed

3.5. Flood vulnerability in the Krueng Baro watershed

Based on the map analysis and scoring of flood vulnerability parameters (Table 5), an overlay of the parameter maps was conducted. The highest weight is given to the land use parameter because flood vulnerability in an area is largely determined by the land use in that location, the more open the land, the higher the potential for flooding. The elevation parameter shows that the lower the elevation of an area and the closer the area is to the river, the greater the potential for flooding. The weight of rainfall is not too high but it is quite influential in flooding problems, where the higher the rainfall the higher the possibility of flooding, but the effect of the amount of rainfall on flooding will not apply to highland areas because it is less likely to cause flooding so the weight is not too high. Soil type also has a lesser influence on flooding due to the absorption of water into the soil.

Table 5. Weighting of Flood Vulnerability Parameters

No.	Parameter	Bobot (%)
1.	Rainfall	10
2.	Slope	20
3.	Soil Type	30
4.	Land Use	40

After overlaying the land cover map, rainfall, soil type, and slope of the Krueng Baro Watershed, five vulnerability classes were identified: very low, low, moderate, high, and very high. The majority of this watershed is in a highly vulnerable condition to flooding, covering an area of 21,940 km2 or 38.35% (High and vey high). The results of the Flood Vulnerability Analysis in the Krueng Baro Watershed can be seen in the following Table 6.

Table 6. The flood vulnerability of the Krueng Baro Watershed.

Description	Low	Very Low	Moderate	High	Very High	Total Overall
Aceh Besar Regency	2,748	415	92			3,255
Batee Subdistrict	28		227	145	647	1,048
Delima Subdistrict	0		504	1,984	0	2,489
Grong-Grong Subdistrict	11		342	447	2	803
Indra Jaya Subdistrict	0		115	1,754	517	2,385
Keumala Subdistrict	901	514	134	1,071	1,854	4,473
Kota Sigli Subdistrict	9		54	486	689	1,238
Mila Subdistrict	164	129	1,662	1,395	270	3,621
Mutiara Subdistrict				1	350	351
Padang Tiji Subdistrict	1,050	2,556	8,404	1,845		13,855
Peukan Baro			3	1,116	347	1,466
Pidie Subdistrict	0		65	1,918	194	2,178
Sakti Subdistrict			12	528	1,538	2,078
Simpang Tiga Subdistrict	0		5	687	313	1,005
Tangse Subdistrict	11,406	2,651	800	679	756	16,292
Tiro/Truseb Subdistrict	217	0	47			265
Titeue Subdistrict	3		3	19	387	411
Overall Total	**16,538**	**6,265**	**12,468**	**14,076**	**7,864**	57,211

Based on the flood vulnerability map in the Krueng Baro Watershed in Figure 6, it is observed that the highly vulnerable and moderately vulnerable classes are found in areas with flat elevation, characterized by entisol and inceptisol soil types, low rainfall, and various land cover types. The overlay of the map results in five classes: very low, low, moderate, high, and very high.

The most dominant factor causing floods is changes in land cover, the amount of rainfall, drainage density, and other contributing factors to flood vulnerability such as ground surface subsidence [23]. Areas with a high flood vulnerability level are located in low-lying areas near major rivers, which are the primary contributors of water during floods and are directly related to rainfall intensity. Agricultural land use is also a factor contributing to flood vulnerability [24].

According to the analysis of the Flood Vulnerability Map in the Krueng Baro Watershed, there are areas with the lowest and low flood vulnerability risk in the Tangse Subdistrict, covering an area of 14,057 hectares. The majority of this area is covered by forests. Areas with a moderate flood risk are located in the Padang Tiji Subdistrict, covering an area of 8,404 hectares. Meanwhile, areas with a high flood risk are found in the Delima Subdistrict, covering an area of 1,984 hectares, and areas with a very high flood risk are present in the Keumala Subdistrict, covering an area of 1,854 hectares.

Changes in land use related to urban development also impact flood risk and influence on rainfall [25]. In urban areas, much of the permeable land is replaced by waterproof infrastructure such as roads and buildings, reducing its capacity to absorb rainfall and water [8] ; [26]. Increased residential and developmental activities along river channels will result in higher exposure to flood hazards [14].

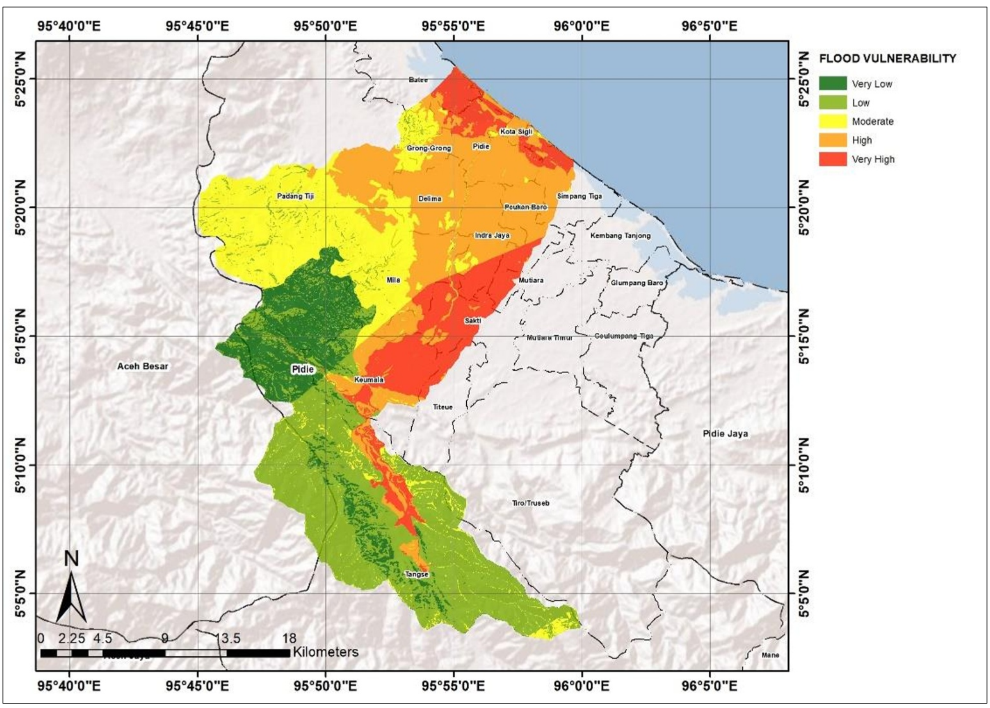

Fig. 6. Flood Vulnerability in the Krueng Baro Watershed

4. Conclusion

The highly vulnerable and moderately vulnerable classes are found in areas with flat elevation, characterized by entisol and inceptisol soil types, low rainfall, and various land cover types. There are areas with the lowest and low flood vulnerability risk in the Tangse Subdistrict, covering an area of 14,057 hectares. Areas with a moderate flood risk are located in the Padang Tiji Subdistrict, covering an area of 8,404 hectares. Meanwhile, areas with a high flood risk are found in the Delima Subdistrict, covering an area of 1,984 hectares, and areas with a very high flood risk are present in the Keumala Subdistrict, covering an area of 1,854 hectares. In general, flood vulnerability in the Krueng Baro watershed is classified as very high and high at 38.35%, moderate (21.60%), and low/very low (39.86%). Areas with a high flood vulnerability level are located in low-lying areas near major rivers, which are the primary contributors of water during floods and are directly related to rainfall intensity.

The acknowledgements: We hereby would thanks to Syiah Kuala University and the Ministry of Education, Culture, Research, and Technology, Republic of Indonesia, in supporting and funding this research well accomplished. Contract No. 652/UN11.2.1/PT.01.03/DPRM/2023.

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