ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of Geography Vol 54, No 3 (2022): 463-470
DOI: 10.22146/ijg.69879 website: htps://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY

ARTICLE REVIEW

Flood Risk Mapping Using GIS and Multi-Criteria Analysis at Nanga Pinoh West Kalimantan Area

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Received: 2021-12-22
Accepted: 2022-10-13

Keywords:
Flood Risk; GIS, Multi-Criteria Analysis; Nanga Pinoh

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Abstract. Flood is one of the disasters that often hit various regions in Indonesia, specifically in West Kalimantan. The floods in Nanga Pinoh District, Melawi Regency, submerged 18 villages and thousands of houses. Therefore, this study aimed to map flood risk areas in Nanga Pinoh and their environmental impact. Secondary data on the slope, total rainfall, flow density, soil type, and land cover analyzed with the multi-criteria GIS analysis were used. The results showed that the location had low, medium, and high risks. It was found that areas with high, prone, medium, and low risk class are 1,515.95 ha, 30,194.92 ha, 21,953.80 ha, and 3.14 ha, respectively. These findings implied that the GIS approach and multi-criteria analysis are effective tools for flood risk maps and helpful in anticipating greater losses and mitigating the disasters.

1. Introductin

Floods occur when a river exceeds its storage capacity, forcing the excess water to overflow the banks and fill the adjacent low-lying lands. This phenomenon represents the most frequent disasters affecting a majority of countries worldwide (Rincón et al., 2018; Zwenzner & Voigt, 2009), specifically Indonesia. Flooding is one of the most devastating disasters that yearly damage natural and man-made features (Du et al., 2013; Falguni & Singh, 2020; Tehrany et al., 2013; Youssef et al., 2011).

There are flood risks in many regions resulting in great damage (Alfieri et al., 2016; Mahmoud & Gan, 2018) with significant social, economic, and environmental impacts (Falguni & Singh, 2020; Geographic, 2019; Komolafe et al., 2020; Rincón et al., 2018; Skilodimou et al., 2019). The effects include loss of human life, adverse impacts on the population, damage to the infrastructure, essential services, crops, and animals, the spread of diseases, and water contamination (Rincón et al., 2018).

Food accounts for 34% and 40% of global natural disasters in quantity and losses, respectively (Lyu et al., 2019; Petit-Boix et al., 2017), with the occurrence increasing significantly worldwide in the last three decades (Komolafe et al., 2020; Rozalis et al., 2010). The factors causing floods include climate change (Ozkan & Tarhan, 2016; Zhou et al., 2021), land structure (Jha et al., 2011; Zwenzner & Voigt, 2009), and vegetation, inclination, and humans (Curebal et al., 2016). Other causes are land-use change, such as deforestation and urbanization (Huong & Pathirana, 2013; Rincón et al., 2018; N. Zhang et al., 2018; Zhou et al., 2021).

The high rainfall in the last few months has caused much flooding in the sub-districts of the West Kalimantan region. Thousands of houses in 18 villages in Melawi Regency have been flooded in the past week due to increased rainfall intensity in the upstream areas of West Kalimantan. This occurred within the Nanga Pinoh Police jurisdiction, including Tanjung Lay Village, Tembawang Panjang, Pal Village, Tanjung Niaga, Kenual, Baru and Sidomulyo Village in Nanga Pinoh Spectacle, Melawi Regency (Supriyadi, 2020).

The flood disaster in Melawi Regency should be mitigated to minimize future consequences by mapping the risk. Various technologies such as Remote Sensing and Geographic Information Systems have been developed for monitoring flood disasters. This technology has significantly contributed to flood monitoring and damage assessment helpful for the disaster management authorities (Biswajeet & Mardiana, 2009; Haq et al., 2012; Pradhan et al., 2009). Furthermore, techniques have been developed to map flood vulnerability and extent and assess the damage. These techniques guide the operation of Remote Sensing (RS) and Geographic Information Systems (GIS) to improve the efficiency of monitoring and managing flood disasters (Haq et al., 2012).

In the age of modern technology, integrating information extracted through Geographical Information System (GIS) and Remote Sensing (RS) into other datasets provides tremendous potential for identifying, monitoring, and assessing flood disasters (Biswajeet & Mardiana, 2009; Haq et al., 2012; Pradhan et al., 2009). Understanding the causes of flooding is essential in making a comprehensive mitigation model. Different flood hazard prevention strategies have been developed, such as risk mapping to identify vulnerable areas' flooding risk. These mapping processes are important for the early warning systems, emergency services, preventing and mitigating future floods, and implementing flood management strategies (Bubeck et al., 2012; Falguni & Singh, 2020; Mandal & Chakrabarty, 2016; Shafapour Tehrany et al., 2017).

GIS and remote sensing technologies map the spatial variability of flooding events and the resulting hazards

(Elkhrachy, 2015; Greene & Cruise, 1995; Ozkan & Tarhan, 2016; Paudyal, 1996; Shafapour Tehrany et al., 2017). This study adopted a multilayered flood mapping approach to improving the accuracy of coarse grid modeling with an insignificant increase in the computing cost (Chen et al., 2012; Zhou et al., 2021).

The cellular automata (CA) approach using regular grid cells and generic rules was employed to simulate the spatiotemporal evolution of pluvial flooding, greatly reducing the computation time (Chen et al., 2010; Ghimire et al., 2013). This study also developed an urban storm-inundation simulation method (USISM) using GIS-based simplified distributed hydrological models with DEM inputs (S. Zhang & Pan, 2014). An urban pluvial flood model was presented by integrating a 1D hydraulic drainage network model and GIS technology to rapidly estimate the flood extent, depth, and damage (Jamali et al., 2018).

Floods should be mitigated to reduce the resultant risks, necessitating creating a flood risk map of the physical, social, and economic vulnerabilities. Studies using Geographic Information Systems and Remote Sensing techniques are a novelty because there is no analysis of the topographic conditions in many areas of West Kalimantan, where heavy floods have hit in the last two years. Therefore, this study aimed to determine the flood risk and its environmental impact in Nanga Pinoh, Melawi Regency.

2. Methods

Study Area

This study was carried out in the Sengah Temila District, Landak Regency, West Borneo province, Indonesia, located between longitude 111°40’30”E to 111°58’30”E and latitude 0°13’30”N to 0°31’30”N (Figure 1). The area is approximately 45.448,72 ha (454,4873 km²). The Nanga Pinoh Watershed covers Tengkaju, Nanga Blimbing, Batu Buil Baru, Tekelak, Manding, Sidomulyo,Tanjung Niaga, Paal, Nanga Kebebu, Nanga Man, Engurai, Nanga Tebedak, Tanjungsari, Tembawang Panjang, Tanjung Pauh, poring, Sungai Pinang, Bina Jaya, Landau Garong, and Nangkalan Villages.

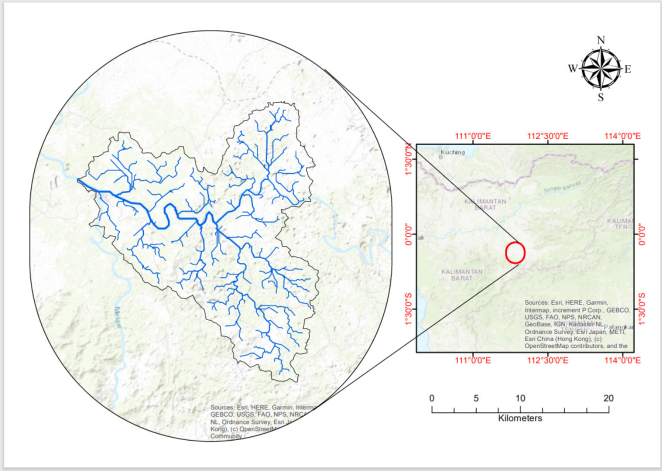

Figure 1. Study Area

The Method

A GIS-based weighted multi-criteria analysis (MCA) (Nagu et al., 2021; Roy et al., 2021) was used to determine flood risk areas in Nanga Pinoh Watershed, West Kalimantan. The method involved integrating five flood conditioning factors, including slope (S), soil type (ST), total precipitation (TP), drainage density (DD), and land use land cover (LULC). These geo-rectified maps were digitized in the GIS to produce thematic soil layers, drainage network or density, contour lines to generate slope, land use and cover (Chauhan et al., 2016), and total precipitation.

This study was conducted in three stages (Rincón et al., 2018):

- The first stage involved determining the weight and impact score of the five determined flood-causing factors on a 1 to 5 scale. Scores of 1 and 5 were given to impact factors with low and high contributions to flooding, respectively.
- In the second stage, all maps were reclassified on a scale from 1 to 5 using the Reclassify Tool in ArcMap, where 1 referred to very low and 5 implied a very high flood risk.

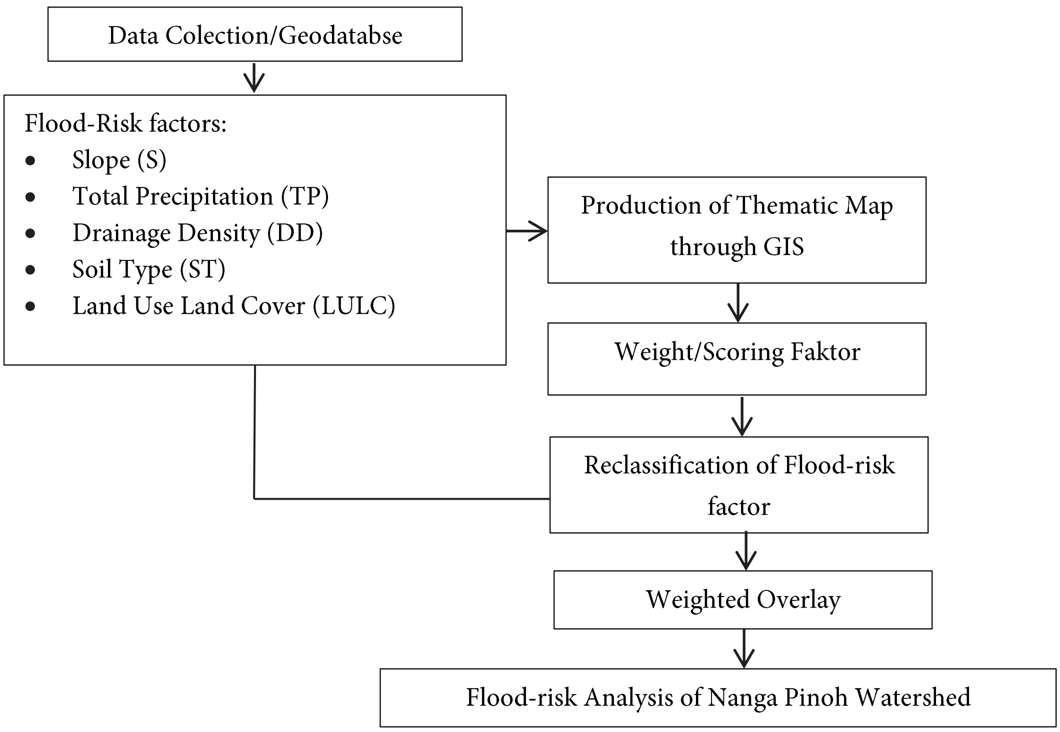

Figure 2. Study Method

- The third stage employed the Weighted Overlay Tool of ArcMap to carry out the maps' spatial overlay.

3. Result and Discussion

Slope (S)

The gradient slope strongly influences river flow velocity through drainage channels and watersheds. A steeper slope causes high runoff, increasing peak discharge (Rincón et al., 2018). In line with this, previous studies found that a lower slope gradient has more chances of flooding (Khosravi et al., 2018; Radmehr & Araghinejad, 2015; Ullah & Zhang, 2020).

This study derived the slope from the DEM, with a resolution of 30 m, to determine the slope map using the Slope tool in ArcMap10.8. It was reclassified on a scale from 1 to 5, where 5 and 1 were assigned to lower and higher slopes, respectively, as shown in Table 1.

Total Precipitation (TP)

Precipitation is a major cause of floods, where heavy rainfall and runoff make streams unable to hold the excess water. High rainfall increases runoff, meaning increased precipitation leads to higher flood risk. Many previous studies established a relationship between rainfall and flooding (Das, 2019; Sahana & Patel, 2019; Ullah & Zhang, 2020; J. Zhang & Chen, 2019). This study created a map by interpolating the monthly average precipitation data for the wet season (January to December 2020) using the inverse distance weighted (IDW) interpolation method. The total precipitation (TP) map was reclassified on a scale from 1 to 5 for low and high TP values, respectively, as shown in Table 1.

Drainage Density

Drainage density significantly influences flood vulnerability and surface runoff. The water that cannot be accommodated in the river overflows from various drainage channels and gathers into puddles or floods (Das, 2019; Ullah & Zhang, 2020). The flooding probability increases with drainage density (Ullah & Zhang, 2020). This study derived drainage density from the DEM with a resolution of 30 m using the line density tool in ArcMap10.8. Drainage density was reclassified on a scale from 1 to 5, where 5 and 1 were assigned to higher and lower density values, respectively, as shown in Table 1.

Soil Type

Soil greatly influences flooding due to its water absorption ability, known as infiltration. Studies examined the factors influencing infiltration, including in the province of Aceh, Indonesia (Basri & Chandra, 2021; Silalahi et al., 2019; Suryadi & Riduansyah, 2021). It was found that soil types have different infiltration rates based on their characteristics. The physical factors include soil texture, structure, and density. Ultisol soil has a clay texture that makes it easily flooded (Y. Liu et al., 2019) due to the low ability to pass water. Table 1 shows the soil criteria used in the flood risk assessment.

Land Use Land Cover (LULC)

Land use and land cover (LULC) also greatly affects an area's flood susceptibility and determines the amount of runoff, the rainwater exceeding the infiltration rate. Expensive land is planted with vegetation, increasing the rainwater infiltration and time taken by runoff to get to the river. This reduces the possibility of flooding compared to areas not covered with vegetation. Therefore, this study analyzed the effect of settlement and mining on runoff in impervious soil (Ullah & Zhang, 2020). It also analyzed the relationship between runoff and land without plants to prevent water flow to the soil surface (J. Liu et al., 2018; Ullah & Zhang, 2020). Table 1 shows the land use criteria used in the flood risk assessment.

GIS approach and multi-criteria analysis are effective tools for flood risk mapping. The weighted overlay method showed that the study location has low, medium, and high risks. Low-risk areas are 990,88 ha, while medium and high regions cover 35.294,35 ha and 8.601,70 ha, respectively. Figure 8 shows flood risks at Nanga Pinoh Watershed.

Slope affects the velocity of water flowing through drainage channels and watersheds. Steeper slopes result in higher runoff and peak discharges. The 0–8% slope classes occupied most of the basin, implying a higher susceptibility to flooding hazards. This is because steeper slopes are more susceptible to surface runoff, while flat terrains are vulnerable to waterlogging, accumulating over time and becoming floods. Therefore, efforts should be made to minimize the inundation by ensuring drainage channels facilitate smooth water flow.

Rainfall is spatially distributed, ranging from 3.684 to 3.858 mm. The rainfall map shows that heavy rainfall is observed in the top and middle areas. Since rainfall is a natural factor that cannot be controlled, it is necessary to minimize its impact. The high rainfall in the upper and middle regions significantly contributed to flooding in the lower regions. Almost the entire basin is susceptible to flooding due to high-intensity rainfall.

Drainage density significantly influences vulnerability and flood risk. The potential for flooding increases with the drainage density. The volume of water that cannot be accommodated in the river overflow into drainage channels and gathers into puddles or floods (Das, 2019; Ullah & Zhang, 2020).

The relationship between soil and flooding is the ability to absorb water, a process known as infiltration. The physical factors affecting infiltration include soil texture, structure, and density. In this situation, coarse-textured soils have a greater infiltration capacity than fine-textured soils. Soils with low structure and density have a faster infiltration than those with high structure and density. Rapid infiltration reduces the flooding risk because the stagnant soil above flows more quickly vertically. The predominant soil in the study area is

Table 1. Criteria that contribute to flood risk. S: Slope, TP: Total Precipitation, DD: Drainage Density: TS: Type of Soil, LULC: Land Use Land Cover

Class	Level	Criteria for Flood prone				
		S (%)	TP (mm)	DD (km)	TS	LULC
1	Very low	> 45	3.684-3.723	>174,9	-	Primer Forest
2	Low	25-45	3.723-3.751	120,4-174,9	Inseptisol	Sekunder Forest
3	Medium	15-25	3.751-3.801	72,3-120,4	Oxisol, Ultisol	Plantation
4	High	8-15	3.801-3.858	25,4-72,3	-	Farming
5	Very high	0-8	> 3.858	0-25,4	-	Mining, Settlement

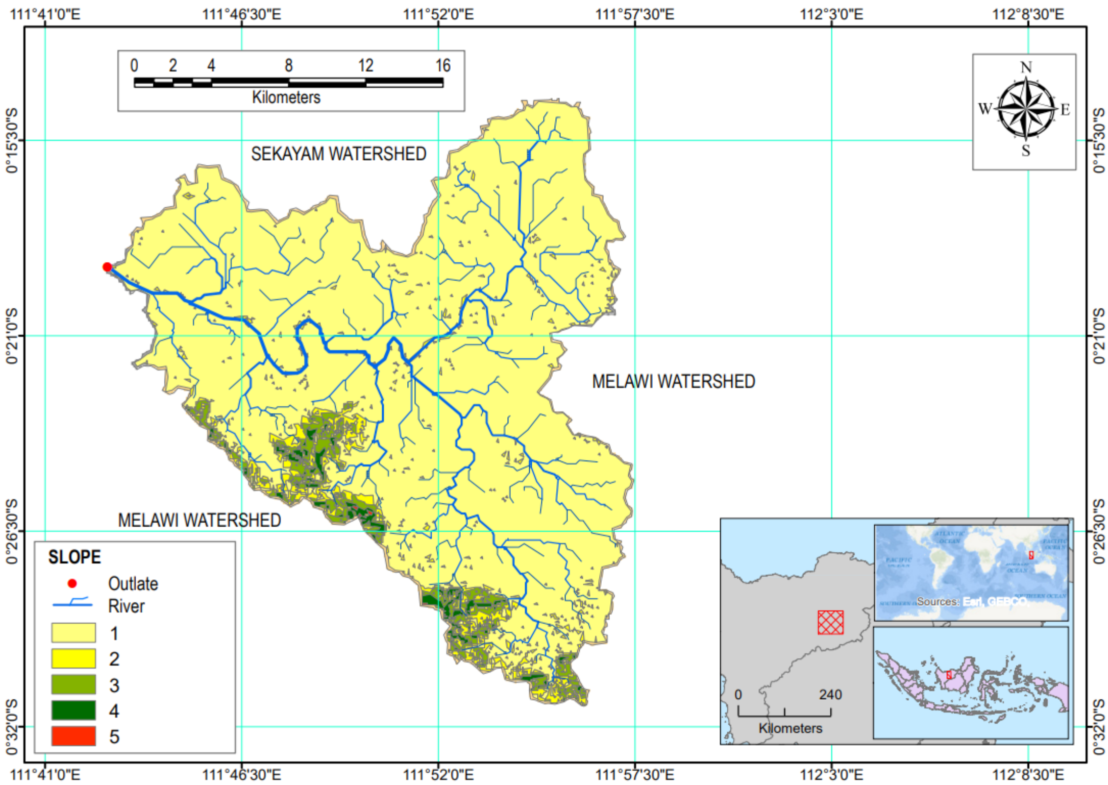

Figure 3. Flood Risk Criteria Reclassified Slope

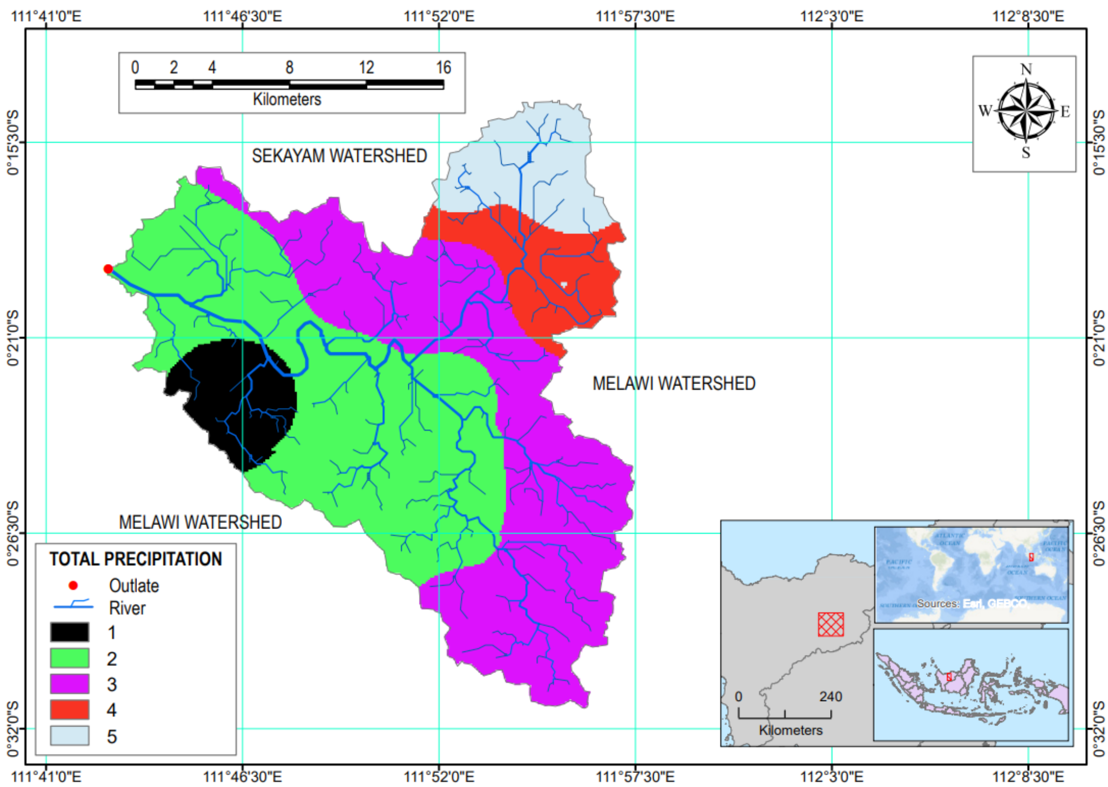

Figure 4. Flood Risk Criteria Reclassified Total Precipitation

ultisol soil, which has a clay texture. This soil is also easily flooded due to its low ability to pass water (Y. Liu et al., 2019).

Land use plays a role in determining the amount of runoff and the rainwater exceeding the infiltration rate. Land covered with vegetation is less vulnerable to flooding because the runoff takes longer to get to the river, allowing more time for infiltration (Y. Liu et al., 2019; Ullah & Zhang, 2020). Therefore, settlement, mining, and land without plants are highly discouraged.

The floods in Tanjung Lay Village, Tembawang Panjang, Pal Village, Tanjung Niaga, Kenual, Baru, and Sidomulyo Village in the last few months were indeed caused because they were included in medium and high-risk areas. The risk mapping showed that future developments could consider mitigating the flooding possibility to minimize losses and social, economic, and physical damage (Meyer et al., 2009; Rincón et al., 2018). Therefore, mapping flood risk areas could be used in making policies regarding possible flood risks.

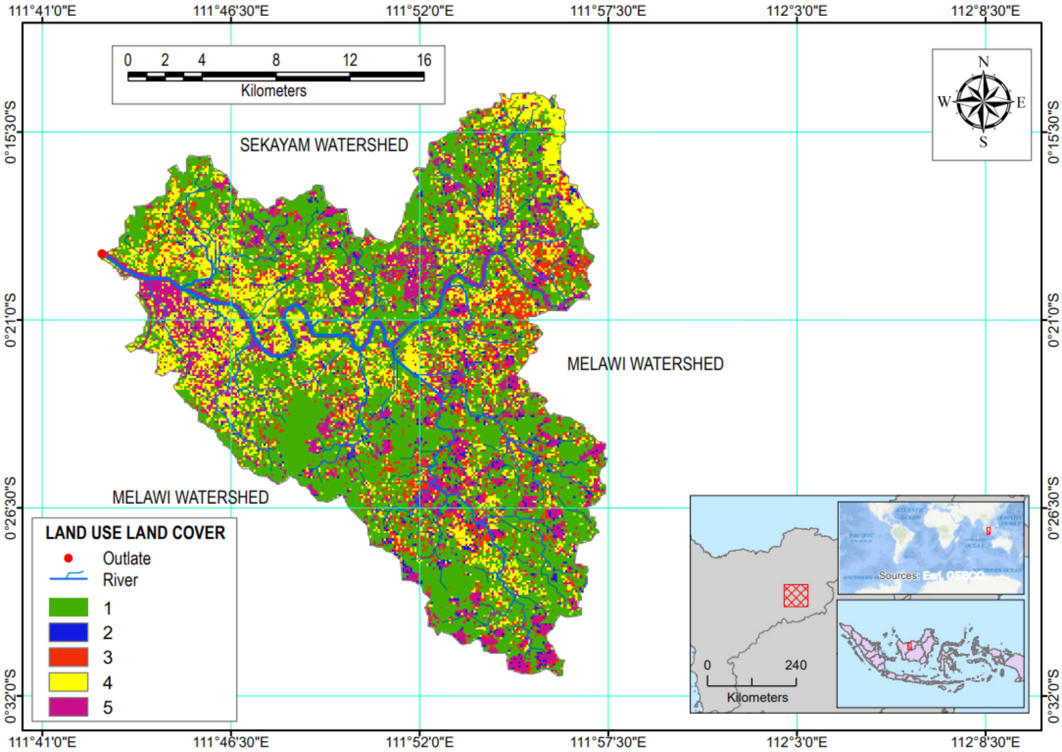

Figure 5. Flood Risk Criteria Reclassified Land Use Land Cover

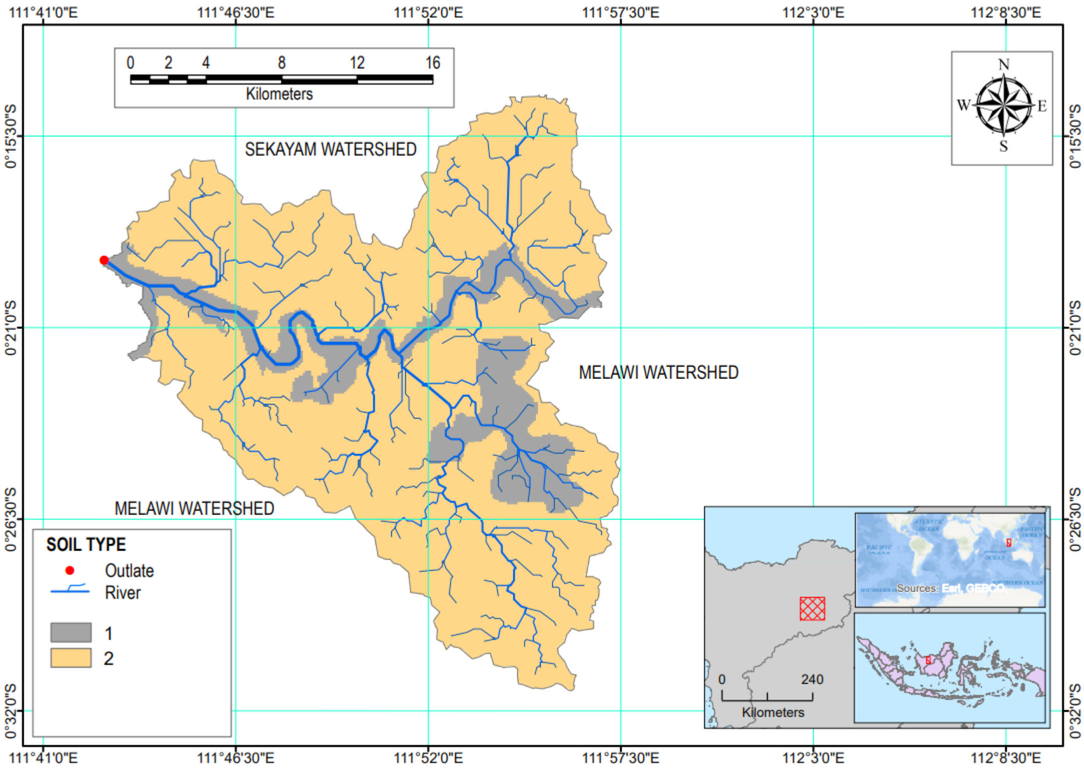

Figure 6. Flood Risk Criteria Reclassified Soil Type

4. Conclusion

GIS approach and multi-criteria analysis are effective tools for flood risk mapping. It could help estimate areas prone to flood risk and assist water resources planners and decision-makers in focusing on specific areas to perform a further detailed assessment. Consequently, this simplified but reliable methodology could help reduce resource requirements for accurate flood risk assessments. The GIS approach is flexible, easy to handle, and inexpensive, making it applicable to areas lacking detailed information. The method helps obtain large-scale flood risk maps or a rapid assessment.

The flood risk maps generated in this study could help Nanga Pinoh District and Melawi Regency implement mitigation measures for insurance purposes, disaster response, and land. The results showed that criteria of slope, total rainfall, drainage density, soil type, and land use are sufficient to obtain a reliable map.

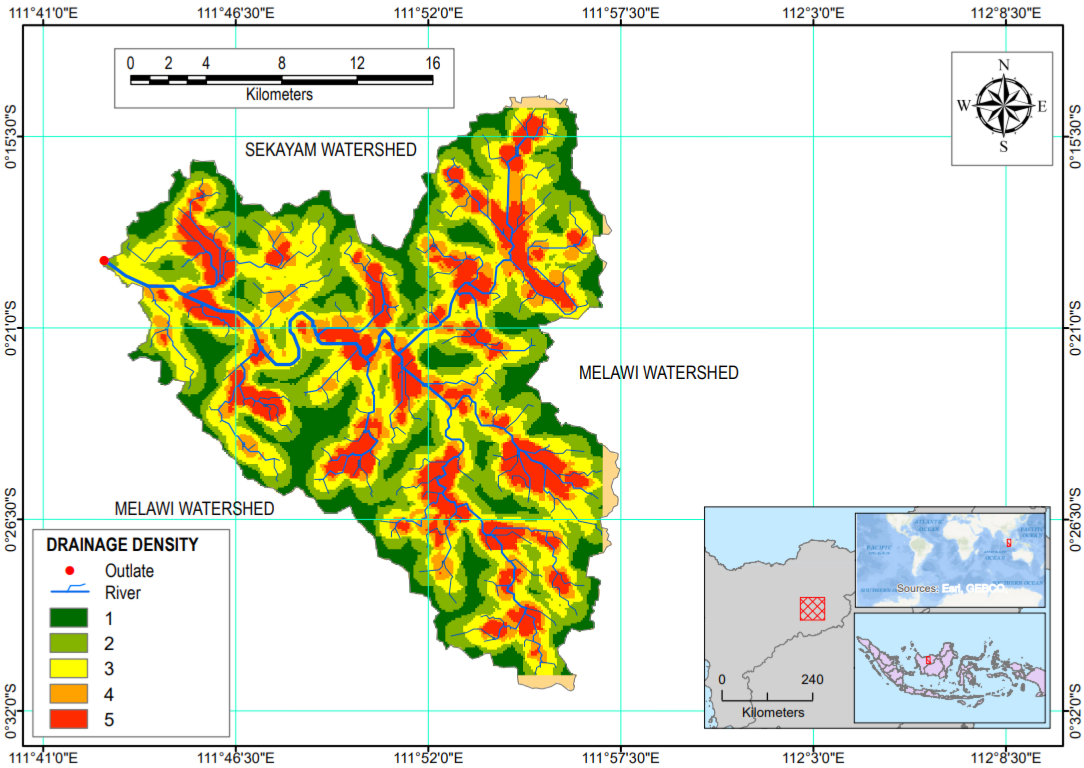

Figure 7. Flood Risk criteria reclassified Drainage Density

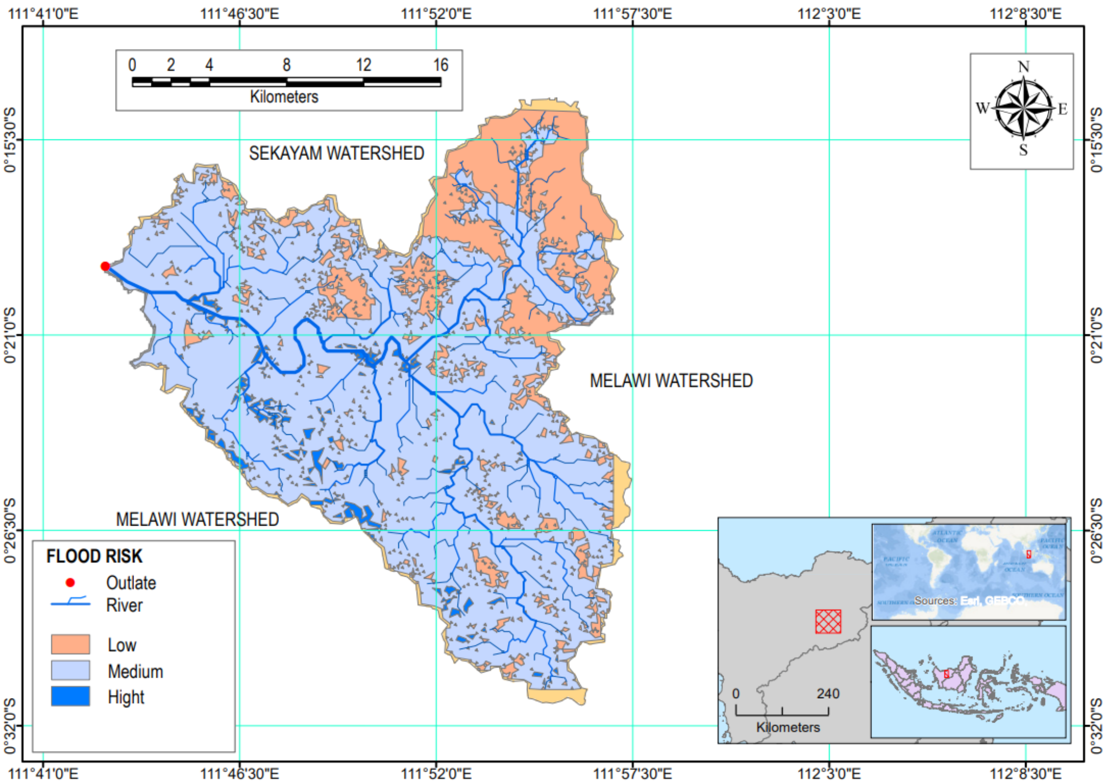

Figure 8. Flood Risk Map Nanga Pinoh Watershed

Acknowledgments: The authors are grateful to Land Rehabilitation and Soil Conservation (Forestry Service) and Disaster Management Service West Kalimantan Province for providing the data on land use and other facilities.

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