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Multi-Criteria Analysis Approach for Potential Flood Areas Mapping in The Bedadung River Watershed, Jember Regency

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ABSTRACT

Flood disasters often result in negative impacts, including damage to property, infrastructure, and loss of human lives. Identifying flood-prone areas and implementing appropriate prevention measures can significantly reduce its adverse effects. Mapping potential flood plays a key role in land use planning, early warning systems, emergency response, and flood mitigation efforts. In recent years, the Bedadung Watershed has faced issues of fluctuations in water discharge and it has a potential to cause flooding in Jember regency. This study aims to assess the flood vulnerability level in the Bedadung Watershed using parameter's scoring and weighting methods, followed by an overlay or merging of each parameter. The research findings indicate that parameters influencing flood potential in the Bedadung Watershed are land use and land cover, slope and elevation area, and soil type. The results showed that the areas which are identified as vulnerable and highly vulnerable are mainly located at low elevations (0-500 m) with tend to be safe from occurring flood even though the level of rainfall is high. On the other side, the vegetation cover areas showed the low vulnerable from flood.

Keywords: Flood; Bedadung Watershed; Flood-prone map; Overlay, Vegetation cover

INTRODUCTION

Flood is a natural phenomenon involving a significant increase in water volume that cannot be accommodated by the drainage system of an area, resulting in detrimental water inundation (Paszkowski et al., 2021). This natural disaster often leads to negative impacts such as damage to property, infrastructure, and loss of human lives (Allafta & Opp, 2021). Identifying flood-prone areas and implementing appropriate preventive measures can mitigate its adverse effects (Bakhtiari et al., 2023). Mapping flood potential plays a crucial role in land use planning, early warning systems, emergency response, and flood mitigation efforts (Ghansah et al., 2021). Changes in weather patterns and rainfall due to global temperature rise increasing the risk of flooding (Abanda et al., 2022). The contributing factors to floods aree rainfall, land use, slope steepness, land elevation, and soil types. Floods can occur in various locations in Indonesia, both in urban and rural areas (Eliades et al., 2023). Information about the vulnerability to floods in a region is crucial for identifying at-risk areas and planning mitigation efforts (Ajtai et al., 2023).

Jember Regency, located in East Java, tends to be vulnerable to land movement, primarily due to its geographical and local environmental characteristics. These factors involve topography and soil properties that can increase the likelihood of land movement (Jiang et al., 2023). The Bedadung Watershed is located in three regencies, namely Jember Regency (94.89%), Bondowoso Regency (4.22%), and Probolinggo Regency (0.89%). In recent years, the Bedadung Watershed has faced issues of fluctuations in water discharge that may impact to the potential of flooding in Jember. The problem is suspected to be related to changes in land cover in the catchment area around the reservoir (Wolf et al., 2023). Information on land cover changes year by year is important for monitoring environment changes in the area (Nega & Balew, 2022). Changes in hydrological conditions in the Bedadung Watershed, Jember Regency, have led to drought and flash flood disasters throughout the year, mainly due to changes in land use and intensive farming in the upstream areas.

The study conducted by Andriyani et al, (2020) used the Revised Universal Soil Loss Equation (RUSLE) method to evaluate the erosion hazard level in the Bedadung Watershed (DAS Bedadung), Jember Regency. The results showed that the erosion rate in DAS Bedadung was 160.57 tons/ha/year, which falls into the moderate category. The study by Shekar & Mathew (2023) mapped flood vulnerability in the Peddavagu River Basin using GIS-AHP (Geographic Information System - Analytical Hierarchy Process) techniques. The research categorized flood-prone zones into very low hazard (30.98%), low hazard (14.42%), moderate hazard (12.58%), high hazard (12.58%), and very high hazard zones (29.45%). A significant portion of the area (42.02%) falls within highly vulnerable and very highly vulnerable zones.

Previous research emphasizes the significance of each parameter in flood vulnerability assessment. Rainfall data is crucial, as demonstrated by Hinge et al. (2022) in their assessment of flood prediction with meta-data analysis. Land use patterns also play a vital role, as shown by Nigatu et al. (2023) in their study of Ribb river, northwestern Ethiopia. Slope gradient and elevation are important factors as well, as highlighted by Wang et al. (2024) which stated that megafloods triggering sedimentary records in Eastern Himalaya since the Last Glacial Period, Shekar & Mathew (2023) in their study of the flood susceptibility mapping of the Peddavagu River Basin. Furthermore, Devanand & Kundapura (2021) emphasize the importance of soil type in their flood susceptibility mapping for the Harangi River Basin, Kodagu, India.

In Indonesia and globally, multi-criteria methods have been increasingly used to assess flood potential, combining various parameters to provide a more comprehensive analysis. These methods include Analytical Hierarchy Process (AHP), Geographic Information Systems (GIS), and Multi-Criteria Decision Analysis (MCDA). A global study Using GIS and multi-criteria decision analysis for flood vulnerability mapping provides a robust framework for assessing flood risk (Msabi & Makonyo., 2021; Ramadhani et al., 2022). Although there is existing studies on flood vulnerability in the Bedadung Watershed, few studies have employed a multi-criteria approach that incorporates all five parameters mentioned above. This study aims to address this gap by integrating these five parameters, developing a comprehensive framework, spatially mapping flood vulnerability, and identifying areas with high flood susceptibility to inform effective risk management strategies.

METHODS

Study Area

This study is located in the Bedadung Watershed, Jember Regency, that is geographically located between 07°57'11.96" - 08°25'3.14" South Latitude and 113°26'1.93" - 114°1'13.44" East Longitude. The data in this study consist of one year's duration of rainfall data from January 1, 2023, to December 31, 2023, DEMNAS (Digital Elevation Model National), land use and land cover data, and soil type data. The data were processed into maps using ArcGIS 10 software. Figure 1 depicts the watershed flow map of the Bedadung Watershed, where the river originates from the top of the map precisely on the western slopes of the Iyang Mountains around Rowosari Village, Sumberjambe District, known as the Sumberpakem River, and flows to the Indian Ocean, near Puger District at the bottom of the map. The Bedadung Watershed flow map illustrates evenly distributed and dense flow patterns in Jember Regency, considering that the Bedadung Watershed is one of the largest watersheds in the region. The watershed flow map shows elongated and widened characteristics in the upstream area. The presence of elongated watersheds can reduce the potential for downstream flooding during rainfall in the upstream area (Hairan et al., 2021). This phenomenon is caused by the time it takes for runoff water from the upstream to reach the outlet or downstream (Gosset et al., 2023). Additionally, it should be noted that rainwater also undergoes infiltration processes in green vegetation (Bodus et al., 2023).

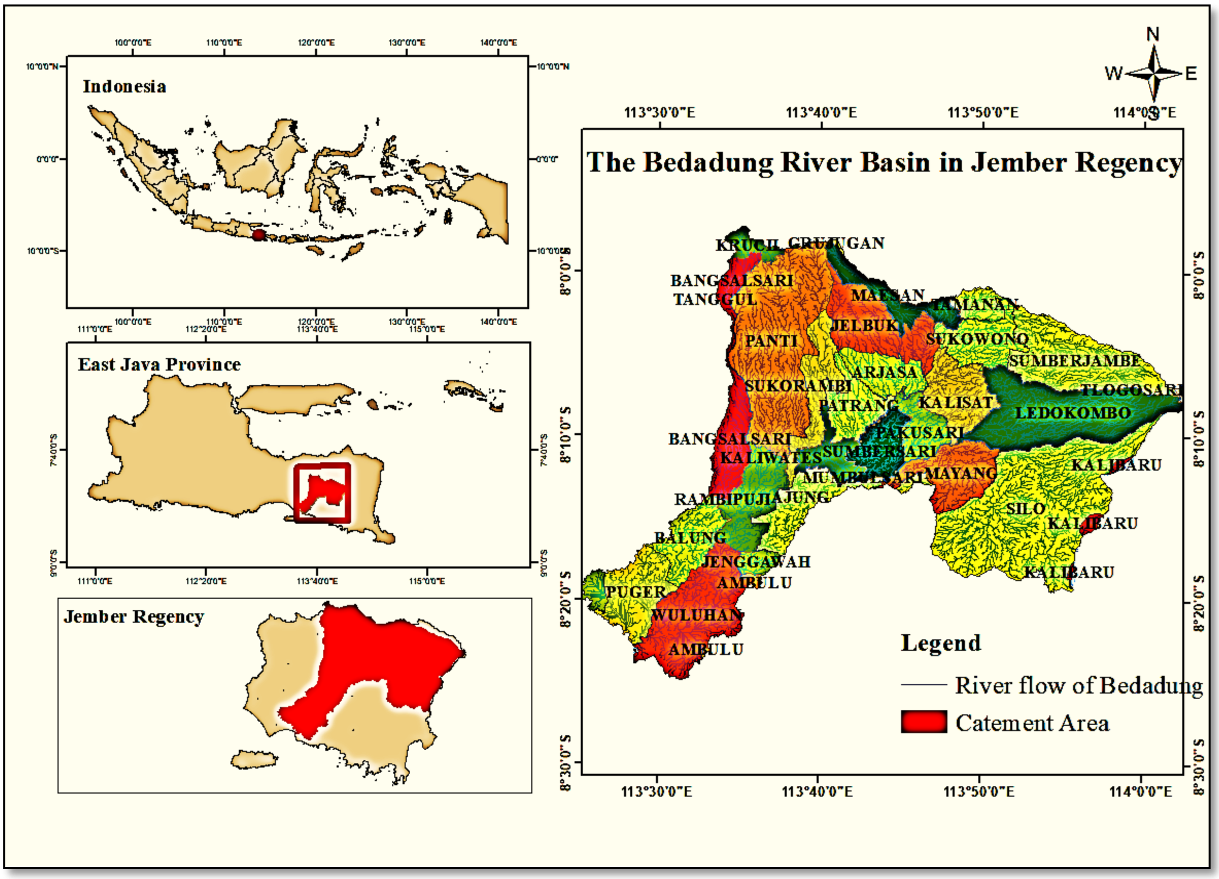

Figure 1. Study Area

To obtain land use and land cover data from Landsat 8 imagery with accuracy using a confusion matrix, the steps involved include downloading and pre-processing Landsat 8 imagery from official sources such as USGS Earth Explorer. The imagery is then processed for classification using techniques such as Maximum Likelihood or Support Vector Machine (SVM), employing training and validation datasets to compute the confusion matrix. Meanwhile, soil data is obtained from FAO soils portal, which is then mapped in the Bedadung watershed.

We used Digital Elevation Model (DEMNAS) data from the Indonesia Geospatial Portal to obtain topography data (Indonesian Geospatial Agency, 2023). The DEMNAS data was processed using ArcGIS 10 software with the primary goal of forming a river flow pattern. The formed river flow is selected and cut to include only the part that constitutes the Bedadung Watershed. The identified Bedadung river basin area was used as the basis for data processing for each flood parameter. The extent boundaries of each flood parameter are adjusted according to the predetermined river basin area, ensuring that data processing aligns with the Bedadung Watershed boundaries.

Data Processing

The flowchart of data processing is illustrated in Figure 1. Data processing in this research aims to obtain flood vulnerability levels in the Bedadung Watershed area. Parameters used to determine flood vulnerability levels include rainfall, land use and land cover (LULC), slope, elevation, and soil type. The formulation to calculate the flood vulnerability index is provided in Equation 1.

$$K = \sum_{i=1}^{n}(W_i \; x \; X_i) \quad (1)$$

Where K is vulnerability value, W_i is weight of parameter i, X_i is score on parameter i (Feng et al., 2023). The values of K are considered to classify the flood vulnerability level values. There are 4 classes of flood vulnerability level namely safe, low vulnerable, vulnerable, and high vulnerable. These four categories are obtained after determining the class interval of flood vulnerability, where the interval for each class category is calculated based on equation 2.

$$i = \frac{R}{n} \quad (2)$$

where i is interval width, R is difference between the maximum and minimum flood vulnerability values, and n is a number of flood vulnerability classes.

Research Framework

Figure 2 shows research framework as a technical guide for researchers in carrying out a series of research activities. We used various data to determine flood hazard, where each data was processed by considering region perspective.

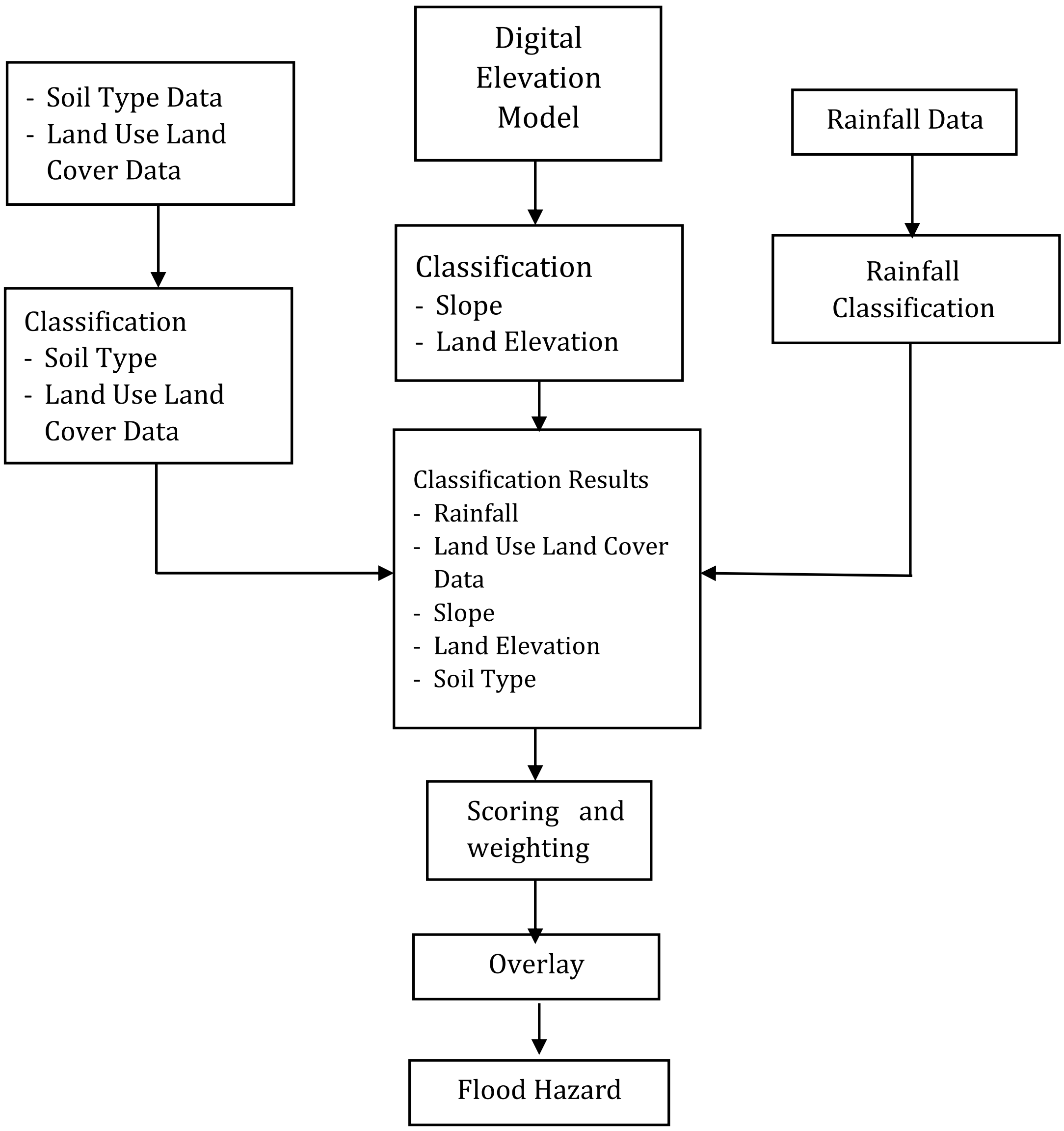

Figure 2. Research Framework

RESULTS AND DISCUSSION

Parameters Constituting the Flood Vulnerability Map of the Bedadung Watershed

In the process of creating the flood-prone map of the Bedadung Watershed, several parameters are employed, including rainfall, land use and land cover, slope, elevation, and soil type parameters.

Rainfall

Rainfall information is obtained through the processing of CHIRPS rainfall image or raster data for the year 2023. The collected rainfall data is in the form of monthly raster images, so a total aggregation is performed over the 12-months period. Subsequently, the images are cropped according to the boundaries of the Bedadung Watershed area.

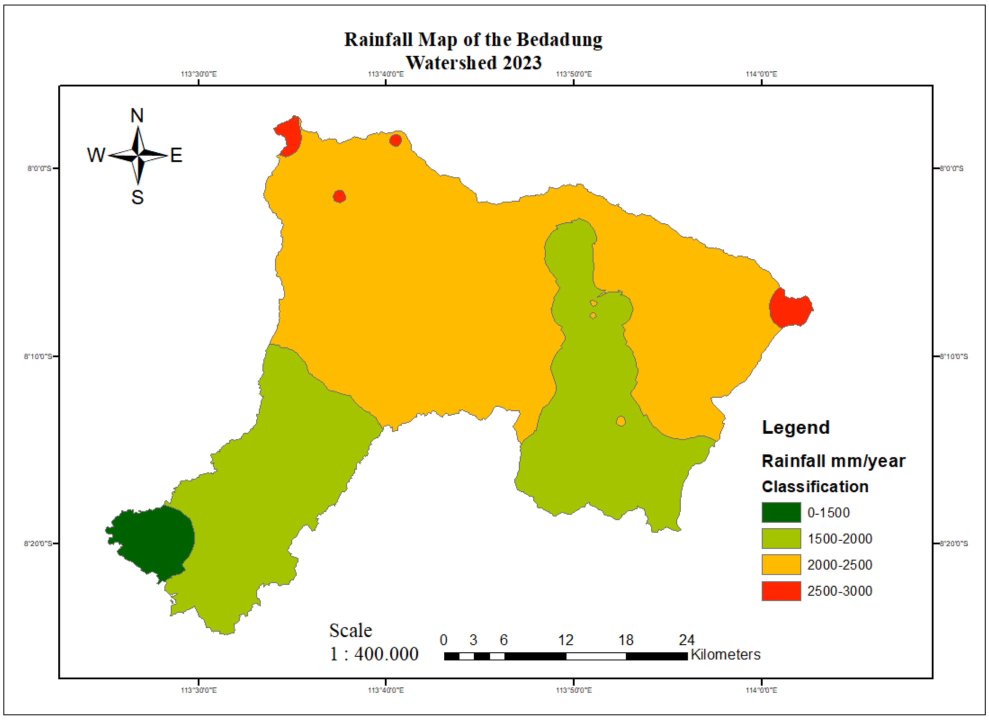

Figure 3. Rainfall Map of the Bedadung Watershed

Table 2. Rainfall Parameters

Rainfall (mm/year)	Area (Ha)	Score	Weight
<1500	4364.08	1	
1500 – 2000	56073.79	3	
2000 - 2500	91923.82	5	0.3
2500 - 3000	1990.82	7	
>3000	0	9	

The classification results of the 2023 rainfall in the Bedadung Watershed show a relatively high level of rainfall. In Figure 3, most of the Bedadung Watershed indicates rainfall in the range of 2000-2500 mm/year, which can increase the potential risk of flooding. Although high rainfall covers a small area with an area of about 1990.82 hectares, there is no area experiencing very high rainfall (>3000 mm/year) in the Bedadung Watershed in 2023.

Land Use and Land Cover

Maps of land use and cover were obtained from Landsat 8 satellite imagery at the Bedadung watershed location. The land use and cover obtained were then carried out for accuracy using the confusion matrix. The accuracy value obtained was 98%. The results of land use and cover classification are shown in Figure 4, and the area and its weight can be seen in Table 3.

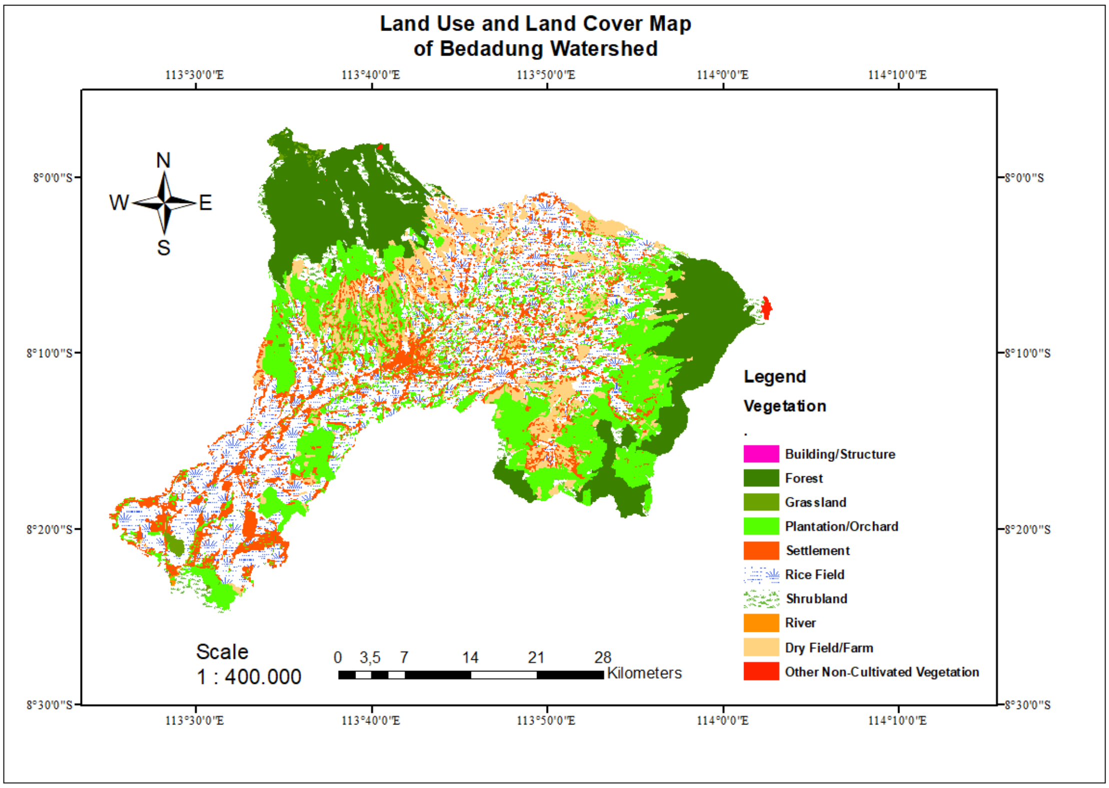

Figure 4. Land Use and Land Cover Map of Bedadung Watershed

Table 3. Land Use and Land Cover Parameter

Vegetation	Area (Ha)	Score	Weight
Building/Structure	37.26	7	
Forest	30672.16	1	
Grassland	825.89	5	
Plantation/Orchard	34100.95	3	
Settlement	20764.08	7	
Rice Field	47212.60	9	0.25
Shrubland	5542.94	5	
River	490.71	5	
Dry Field/Farm	14984.23	3	
Other Non-Cultivated Vegetation	197.58	5	

The analysis results indicate that the land cover dominance in DAS Bedadung is characterized by the symbol of rice fields, covering an area of 47,212.60 hectares. Rice fields have a score of 9, indicating that rice field vegetation has the potential flood risk. In addition to rice fields, there are also forest and plantation vegetation, each covering an area of 30,672.16 hectares and 34,100.95 hectares, respectively. Forest and plantation vegetation have good ability to retain rainwater and facilitate the infiltration process, thus reducing surface water runoff caused by rain (Dowtin et al., 2023).

Slope

The slope of the land plays a crucial role in determining the potential flood risk as it influences the speed of runoff (Dung et al., 2022). Information about the slope of the land in the DAS Bedadung area was obtained through the processing of DEMNAS data, which was then clipped according to the boundaries of the DAS Bedadung area. Details regarding the slope of the land were generated by analyzing the slope in the DEMNAS data, adapted to fit the boundaries of the DAS Bedadung area using ArcGIS software. The analysis results provide percentage values for the slope of the land, which are subsequently categorized into classes according to the classification table in Table 4.

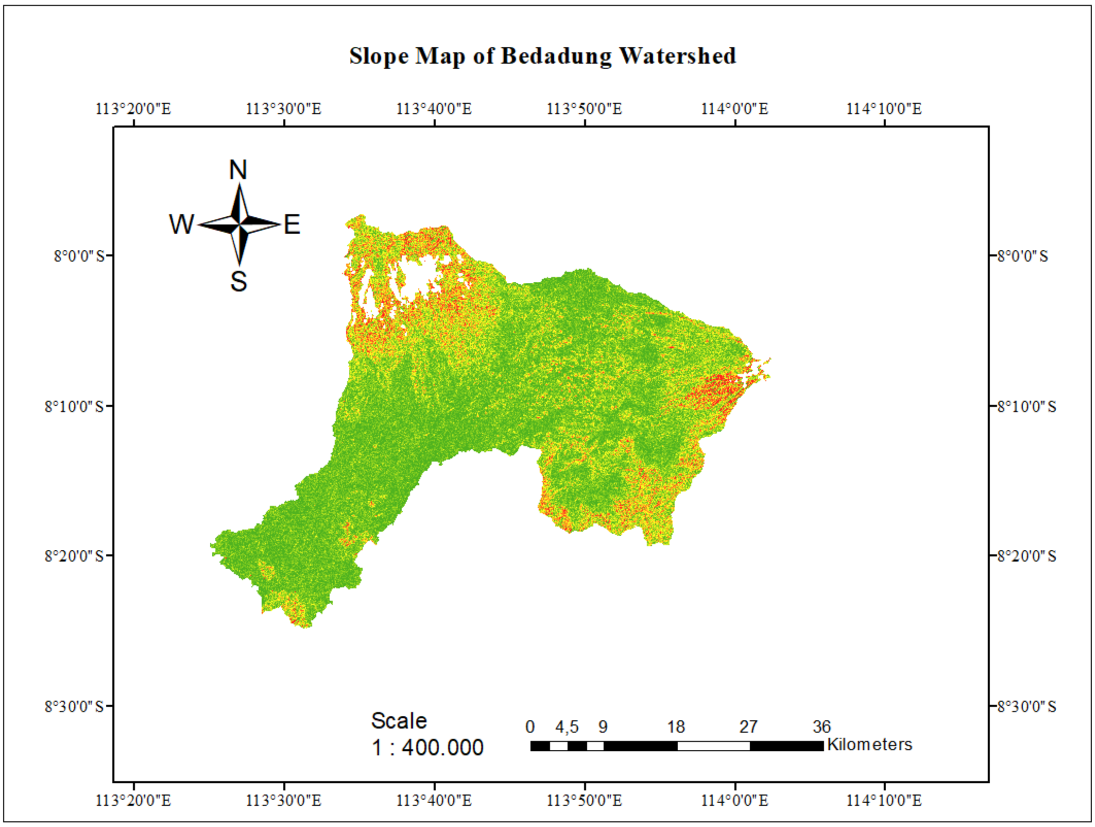

Figure 5. Slope Map of Bedadung Watershed

Table 4. Slope Inclination Parameter

Slope (%)	Area (Ha)	Score	Weight
0-8	291.67	9	
8-15	149327.71	7	
15-25	0.23	5	0.25
25-40	1.86	3	
>40	0.85	1	

Table 4 presents the results of slope classification into 5 classes in the Bedadung Watershed. Slopes ranging from (0-8)% are categorized as flat with a score of 9 and an area of 291.67 hectares. Slopes ranging from (8-15)% are classified as gentle with a score of 7, involving an area of 149,327.71 hectares. Slopes ranging from (15-25)% are considered moderately steep with a score of 5 and have an area of about 0.23 hectares. Slopes ranging from (25-40)% are classified as steep with a score of 3, covering an area of 0.23 hectares. Meanwhile, slopes exceeding 40% are classified as very steep with a score of 1 and an area of up to 0.85 hectares. Analysis of the table indicates that the majority of the Bedadung Watershed falls into the gentle slope category. However, the area with very steep slopes is only a small portion.

Elevation

Land elevation is one of the key parameters in creating flood vulnerability maps as it has a significant impact on the susceptibility to floods (Membele et al., 2022). Areas with high topography tend to have lower flood vulnerability (Ha et al., 2023), while areas with low topography have a higher likelihood of experiencing floods (Merz et al., 2021). Scores are assigned based on land elevation, with areas at elevations of 0-500 m receiving a score of 9, while areas at elevations >2000 m receive a low score of 1.

The land elevation map is generated through the processing of DEMNAS data, and the results are displayed in Figure 6. Subsequently, classification is carried out for each land elevation class to support the creation of the flood vulnerability map.

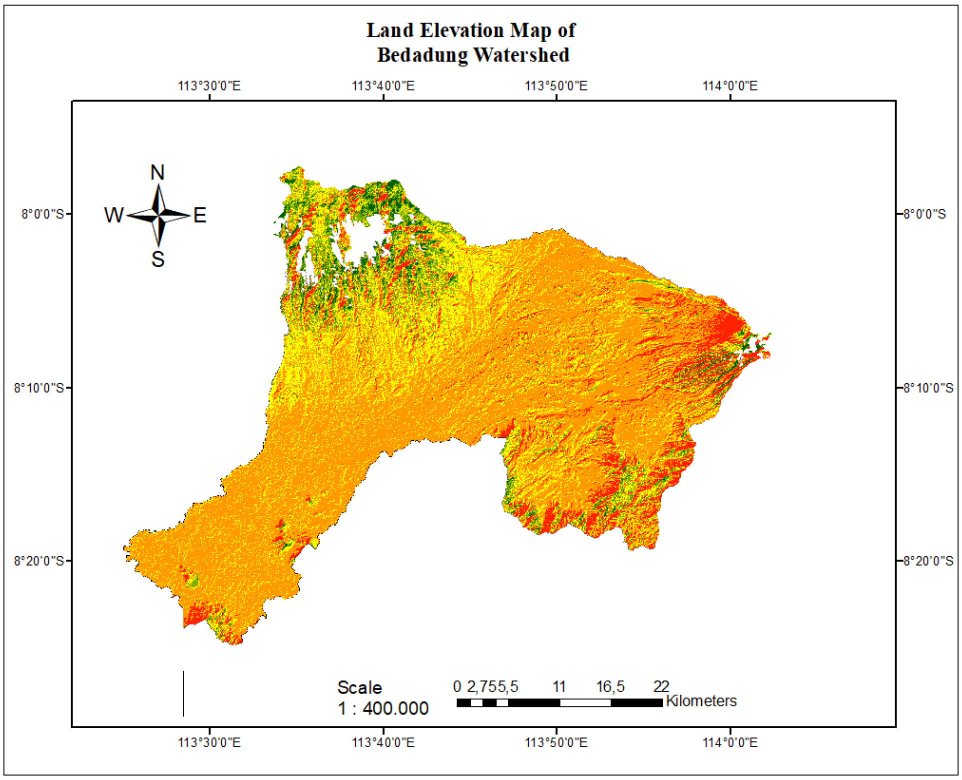

Figure 6 Elevation Map of Bedadung Watershed

Table 5. Elevation Parameter

Elevation (m)	Area (Ha)	Score	Weight
0 - 500	105879.41	9	
500 - 1000	28722.13	7	
1000 - 1500	7583.03	5	0.1
1500 - 2000	4608.28	3	
>2000	4624.64	1	

The elevation map of DAS Bedadung in Figure 6 shows that the area is classified as low elevation, ranging from 0-500 m with an area of 105,879.41 hectares. Furthermore, at an elevation of 500-1000 m, it covers an area of 28,722.13 hectares, 1000-1500 m with an area of 28,722.13 hectares, 1500-2000 m with an area of 4,608.28 hectares, and elevation >2000 m with an area of 4,624.64 hectares. From Table 5, it can be concluded that the higher the elevation of an area in DAS Bedadung, the smaller its area tends to be.

Soil Type

Soil type map is one of the parameters in assessing flood vulnerability because soil type has a significant impact on the water infiltration capacity (Alam et al., 2021). Less permeable soils tend to cause most water to become surface runoff, while soils sensitive to infiltration can absorb water better, reducing the potential for flooding (Rajbanshi et al., 2023). The soil type map is obtained through the processing of soil type data, where the soil type shapefile (.shp) data is processed by classification in the Bedadung Watershed area. Information about soil types was obtained from the FAO SOILS PORTAL (FAO, 2024). The map result of soil type classification can be seen in Figure 7.

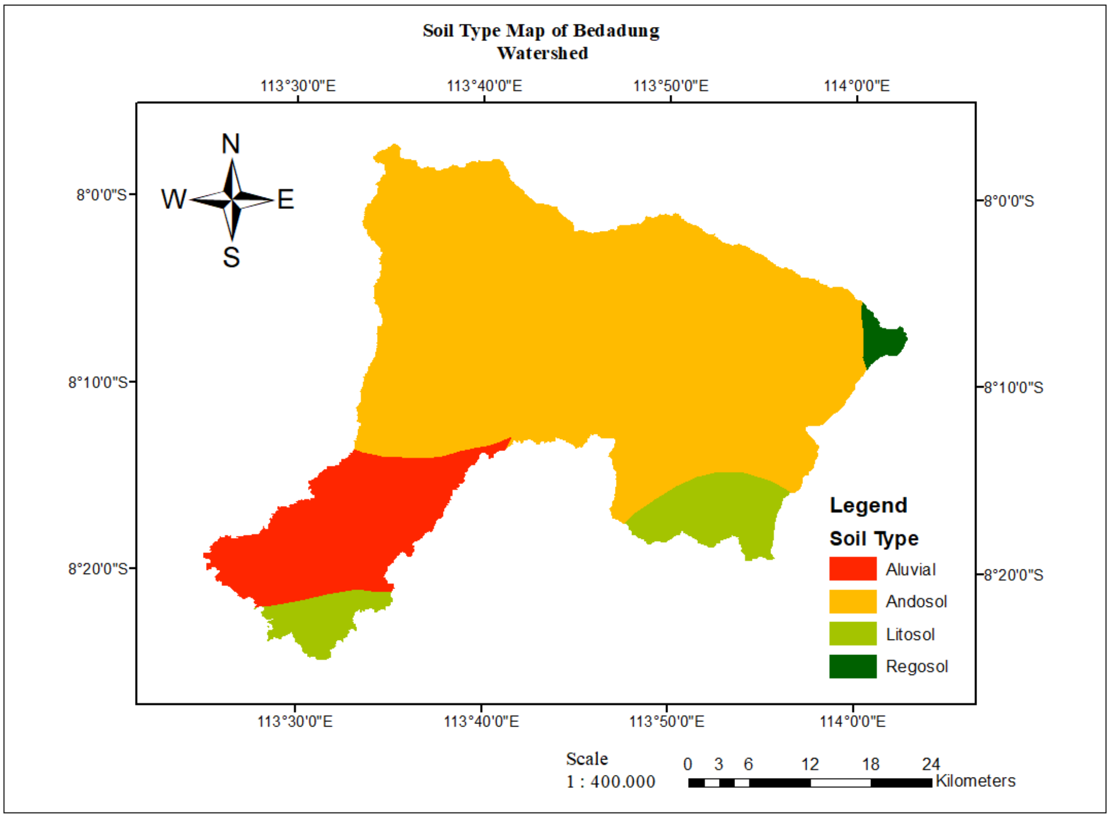

Figure 7. Soil Type Map of Bedadung Watershed

Table 6. Soil Type Parameter

Soil Type	Area (Ha)	Score	Weight
Aluvial	23169.58	9	0.1
Andosol	116262.92	3	
Litosol	13424.40	1	
Regosol	1496.39	1	

Table 6 presents the results of soil types in the Bedadung Watershed, with the majority of the area classified as andosol soil covering an area of up to 116,262.92 hectares, indicated by the yellow color in Figure 7. Andosol soil is known to be sensitive to water infiltration (Patiño et al., 2021), thus capable of absorbing flowing water effectively. Furthermore, there is alluvial soil covering an area of 23,169.58 hectares. Alluvial soil is a type of soil less sensitive to water infiltration (Moragoda et al., 2022), hence absorbing water minimally and posing flood potential in the Bedadung Watershed. Litosol and regosol soil types have respective areas of 13,424.40 hectares and 1,496.39 hectares. Both of these soil types are highly sensitive to water infiltration, allowing for efficient water absorption (Jiménez de Cisneros et al., 2021).

Flood Vulnerability Map of the Bedadung River Watershed

The flood vulnerability map in the Bedadung Watershed is obtained through an overlay or combination process of all previously processed flood vulnerability parameters. This includes rainfall maps, land use and land cover maps, slope maps, elevation maps, and soil type maps. To combine all these flood vulnerability parameters, the Union tool in ArcGIS (Zhu & Wu, 2022). This process aims to obtain new classes and features by merging all features and attributes from each flood vulnerability parameter.

The combined parameters are further assessed by multiplying the score and weight, as per equation 1. Then, to determine the flood vulnerability class intervals, calculations are conducted using equation 2. In this study, it is identified that the maximum flood vulnerability value reaches 7.80, while the minimum value is 0.1. The difference between the maximum and minimum flood vulnerability values is then divided into 4, considering that this study classifies flood vulnerability into 4 classes. Thus, the interval value for flood vulnerability classes in this study is 1.93. After obtaining the interval value, classification is performed according to the flood vulnerability classes, as shown in Table 7.

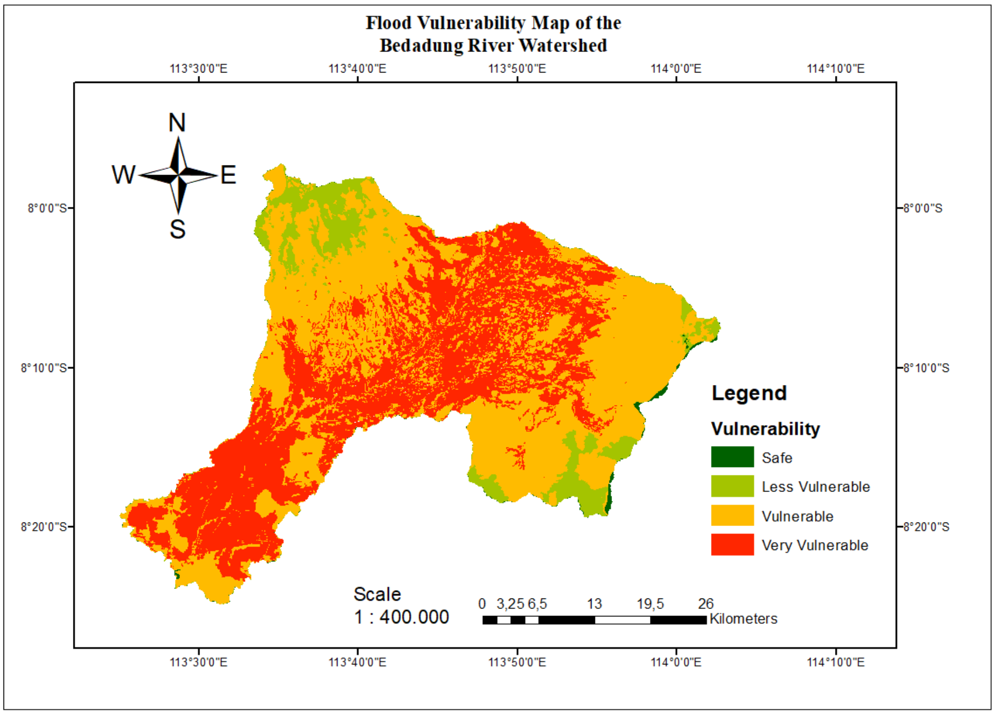

Figure 8. Flood Vulnerability Map of the Bedadung River Watershed

Table 7. Flood Vulnerability Levels

Flood Vulnerability Levels	Area (Ha)	Interval Weight
Safe	701.00	0.10-2.03
Less Vulnerable	11850.93	2.03-3.95
Vulnerable	80782.40	3.95-5.88
Highly Vulnerable	61620.01	5.88-7.80

The classification results of flood vulnerability levels in this study are shown in Figure 8, and the associated data for each flood vulnerability class can be found in Table 7. Table 7 categorizes the flood vulnerability levels into 4 classes: "safe," "less vulnerable," "vulnerable," and "highly vulnerable." From the table, it can be concluded that the Bedadung Watershed falls into the "Vulnerable" and "Highly Vulnerable" classes with the largest areas, amounting to 80,782.40 hectares and 61,620.01 hectares, respectively. Meanwhile, the area of the Bedadung Watershed classified as "safe" is the smallest, totaling only 701.00 hectares.

The flood vulnerability map indicates that areas with elevations ranging from 0-500 meters are predominantly categorized as "vulnerable" or "highly vulnerable." This observation aligns with established hydrological principles that highlight the propensity for low-lying areas to experience higher flood risks due to the natural flow of rainwater from higher elevations to lower plains (Huq et al., 2007). The concentration of flood-prone zones in these low-lying areas underscores the need for targeted flood mitigation measures in such regions.

The analysis demonstrates that land use and land cover significantly impact flood vulnerability. The areas classified as "vulnerable" and "highly vulnerable" predominantly include rice fields, settlements, and residential areas. These land cover types have high scores on the flood vulnerability scale due to their inherent characteristics. For instance, rice fields, typically situated in low-lying areas, are designed to retain water, thereby increasing susceptibility to flooding. Similarly, densely populated residential areas often lack adequate drainage systems, exacerbating flood risks. This finding is consistent with previous studies (Merz et al., 2021; Azadi et al., 2022; Mfon et al., 2022) which also identified agricultural and residential land use as critical factors contributing to increased flood vulnerability.

Interestingly, regions with high precipitation levels, particularly those at elevations >2000 meters, do not correspond to the highest flood vulnerability levels. Instead, these areas are classified as "moderately vulnerable" to "vulnerable." This counterintuitive result can be attributed to the efficient natural drainage systems in high-altitude regions, which facilitate the rapid runoff of rainwater to lower elevations (Li et al., 2021). Consequently, high precipitation alone does not directly translate to high flood risk, emphasizing the importance of considering multiple parameters in flood risk assessments.

Soil type is another critical factor influencing flood susceptibility. The study reveals that alluvial soils, which are prevalent in low-lying areas, exhibit high flood vulnerability due to their poor infiltration capabilities. This finding aligns with the research by Li et al., (2021), which highlights the heightened flood risk associated with alluvial soils. Conversely, soils such as andosol, litosol, and regosol, which possess better infiltration properties, are less susceptible to flooding. However, it is noteworthy that andosol soils, despite their generally favorable infiltration characteristics, still show moderate to high flood vulnerability in certain areas. This suggests that soil type, while influential, interacts with other factors such as topography and land use to determine overall flood risk.

The slope gradient parameter in the Bedadung Watershed predominantly shows gentle slopes, particularly within the range of 8 to 15%. This gentle gradient suggests that slope alone is not a significant determinant of flood risk in this region. The relatively flat terrain allows for the accumulation of surface water, which, when combined with other factors like poor drainage and specific soil types, can lead to flooding. This finding indicates that in regions with gentle slopes, other parameters such as land use and soil type may play a more critical role in influencing flood vulnerability.

The findings from this study provide valuable insights for flood management and mitigation strategies in the Bedadung Watershed. The identification of high-risk areas, particularly low-lying regions with specific land use and soil characteristics, can inform targeted interventions. For instance, improving drainage systems in residential areas and implementing land management practices that enhance soil infiltration in agricultural fields could significantly reduce flood risks.

The findings of this study on flood vulnerability in the Bedadung Watershed provide valuable insights for flood mitigation strategies and land-use planning in the region. Here are some key points to consider:

- **Prioritizing vulnerable areas:** The study identifies areas classified as "vulnerable" and "highly vulnerable" as priorities for implementing flood mitigation measures. These areas, encompassing a significant portion of the watershed (80,782.40 ha and 61,620.01 ha, respectively), require specific attention to minimize potential flood damage.
- **Addressing land-use and land-cover factors:** The research highlights the influence of land use and land cover on flood vulnerability. Areas covered by rice fields, settlements, and residential areas exhibit high flood potential due to factors like limited infiltration capacity and potential flow obstructions. Therefore, implementing land-use regulations and promoting flood-resilient practices in these areas are crucial aspects of mitigation strategies.
- **Considering the role of elevation:** The study suggests that low-lying areas (0-500 m elevation) are particularly susceptible to flooding due to water accumulation from higher elevations. This emphasizes the importance of prioritizing flood protection measures in low-lying regions.

- **Understanding soil type influence:** The findings indicate that alluvial soil, with its low infiltration capacity, contributes significantly to flood vulnerability. Conversely, other soil types like andosol, litosol, and regosol offer better infiltration and demonstrate lower flood susceptibility. This knowledge can inform land-use planning and guide the selection of appropriate mitigation strategies in different areas based on soil characteristics.
- **Slope gradient as a secondary factor:** While the study acknowledges the role of slope gradient in flood potential, it suggests that the Bedadung Watershed's predominantly gentle slopes (8-15%) make this parameter a less significant factor compared to land use, elevation, and soil type.
- **Limitations and future research:** It is important to acknowledge that this study might have limitations, such as the use of specific datasets or methodologies. Future research could involve:

- Expanding the study area to encompass a broader region for comparative analysis.
- Incorporating additional parameters, such as historical flood data, drainage patterns, and infrastructure development, to refine the flood vulnerability assessment.
- Employing advanced modeling techniques to simulate flood scenarios and assess the effectiveness of potential mitigation strategies.

By considering the findings and limitations of this study, relevant authorities and stakeholders can make informed decisions regarding flood mitigation strategies, land-use planning, and sustainable development practices in the Bedadung Watershed and beyond.

CONCLUSION

Based on this research on this study, it is could be concluded that potential flood areas were influenced by rainfall, land use and land cover, slope area, elevation and soil type. There are 4 vulnerability category that are safe, low vulnerable, vulnerable, and high vulnerable. The areas that are identified as vulnerable and highly vulnerable are mainly located at low elevations (0-500 m) with tend to be safe from occurring flood even though the level of rainfall is high. On the other side, the vegetation cover areas showed the low vulnerable from flood as the rain water is not directly flow on the land surface and flooding the low altitude areas. This research provides insights into the factors influencing flood vulnerability in the Bedadung Watershed area and it can serve as a basis for planning and mitigating flood disasters in the future.

ACKNOWLEDGMENTS

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DECLARATIONS

Conflict of Interest

We declare no conflict of interest, financial or otherwise.

Ethical Approval

On behalf of all authors, the corresponding author states that the paper satisfies Ethical Standards conditions, no human participants, or animals are involved in the research.

Informed Consent

On behalf of all authors, the corresponding author states that no human participants are involved in the research and, therefore, informed consent is not required by them.

DATA AVAILABILITY

Data used to support the findings of this study are available from the corresponding author upon request.

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