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Flood Prone Area Analysis in the Wonosari Sub Watershed, Bondowoso Regency, East Java

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Abstract: Bondowoso Regency is known as a region highly susceptible to flood disasters. Factors contributing to the increased flood risk include the hydrological and topographical conditions present in the study area. Therefore, it is essential to identify and map areas that are vulnerable to flooding. Flood vulnerability is influenced by several parameters, including rainfall, soil type, land use, slope gradient, surface runoff, and elevation. The data used in this study were obtained from UPT PSDA WS Sampean, covering the period from 2013 to 2023. These parameters were processed using a weighting and scoring method. The assignment of scores and weights was based on the influence of each parameter on flood vulnerability, with each parameter assigned an equal value ranging from 1 to 5. An overlay analysis was then performed to generate a flood vulnerability map. The resulting vulnerability levels were classified into five categories: very low, low, moderate, high, and very high. The results show that the majority of flood-prone areas fall within the "high" vulnerability category, covering approximately 250.18 km² or about 41% of the total area of the Wonosari Sub-watershed. This finding can be validated by historical events in 2023, during which several flash floods were recorded.

Keywords: ArcSWAT; Flood; Wonosari Sub Watershed

Introduction

Indonesia as one of the developing countries continues to promote the development of physical infrastructure to support the improvement of social welfare for its population. Although this development is aimed at accelerating economic growth and ensuring equitable access to public services it has a direct impact on land use patterns across various regions (Igere et al., 2022). Uncontrolled land use changes can have negative impacts on environmental balance, including an increase in surface runoff volume that occurs annually. Excessive surface runoff may cause rivers to overflow leading to flood events (Nurcahyaningtyas et al., 2024).

Flooding is a condition in which the river discharge exceeds its normal capacity typically caused by high intensity rainfall occurring over an extended period, either in the upstream area or within the surrounding catchment. When the river channel can no longer accommodate the incomin water volume, the excess water overflows and inundates the surrounding areas (Asti & Mayasari, 2023). The occurrence of flooding is generally triggered by several factors, including the limited availability of water infiltration areas due to land use conversion, high rainfall intensity, and the reduction of vegetation cover, particularly in upstream regions. These conditions can accelerate surface runoff processes and reduce the land's capacity to absorb rainwater, thereby increasing the potential for flood events (Latue & Latue, 2023).

Flood prone areas are regions with a high potential for flood occurrences, either based on the historical frequency of past flood events or on physical parameters that reflect the environmental characteristics of the area. One of the key components in flood vulnerability analysis is surface runoff, as the volume of runoff

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significantly influences the likelihood of river overflow within the watershed (Darmawan et al., 2017). The process of mapping flood prone areas in the Wonosari Sub Watershed is conducted using a weighting and scoring approach. Weighting is applied to determine the level of influence each parameter has on the potential for flood occurrence; the greater the influence of a parameter, the higher the weight assigned to it. Meanwhile, scoring involves assigning values to each class within each parameter, where the assigned scores reflect the degree to which each class contributes to increasing flood risk (Sitorus et al., 2021).

Flood vulnerability mapping can be conducted by utilizing Geographic Information System (GIS) technology through an overlay process, which involves combining multiple spatial datasets, each containing distinct characteristics and information, into layered map compositions. Each land condition class integrated in the overlay process is assigned a specific value that reflects its contribution to flood potential. This process generates a composite value that represents the flood vulnerability level for each area within the study site. The subsequent step after the overlay is to calculate the total score, which is obtained by multiplying the class value by the assigned parameter weight. This cumulative score serves as the basis for classifying the flood vulnerability level at the research location (Fauzi et al., 2022).

Flood disasters continue to pose significant challenges to many regions in Indonesia, particularly in areas with dynamic land use changes and complex watershed conditions. The Wonosari Sub Watershed, located in Bondowoso Regency, East Java, is no exception. According to Asti & Mayasari (2023), effective flood management requires an understanding of local hydrological behavior and the integration of various risk factors. In the context of Wonosari, the combination of environmental degradation and rapid land-use transformation exacerbates flood susceptibility, as suggested by Latue & Latue (2023). Their review on urban environmental degradation highlights that unregulated land conversion significantly increases surface runoff, leading to frequent inundations.

In-depth spatial analysis is crucial to mapping flood-prone zones, and the use of Geographic Information Systems (GIS) has become a standard tool. Darmawan et al. (2017) emphasize that GIS-based overlay techniques can systematically quantify flood vulnerability, making it possible to prioritize intervention areas. Similarly, Fauzi et al. (2022) demonstrated how GIS modeling facilitates urban flood potential assessments, offering a methodological framework applicable to Wonosari's case. Moreover, Kurnia et al. (2019) used GIS for flood hazard mapping in Pontianak, indicating the adaptability of such techniques to varying geographical contexts.

Land use changes, notably deforestation and agricultural expansion, significantly influence runoff patterns. Swallow et al. (2002) illustrated that upstream land clearing without proper conservation practices increases downstream flood risks. As pointed out by Pujiono et al. (2025), mapping flood-prone areas requires an understanding of these land-use dynamics over time. Integrating satellite imagery, as conducted by Vivinia et al. (2023), helps track changes that influence watershed hydrology. Studies by Zhou et al. (2019) also confirm that urban expansion without appropriate drainage planning leads to higher flood incidents. This situation resonates with the conditions in Bondowoso, where agricultural practices often replace natural vegetation without strategic planning.

Hydrological modeling techniques such as the Soil and Water Assessment Tool (SWAT) provide reliable simulations for flood risk analysis. Sukmayu et al. (2022) employed Arc-SWAT for flood discharge estimation in Cimandiri Watershed, illustrating the benefits of using integrated hydrological models. Similarly, Samaniyatul Aliyah et al. (2024) utilized SWAT modeling to evaluate erosion rates and suggest conservation measures, a practice highly relevant for Wonosari's sediment-prone sub-watersheds. Nurcahyaningtyas et al. (2024) demonstrated how SWAT modeling based on surface runoff analysis can enhance flood-prone mapping, emphasizing its utility in upper Brantas regions, a model that Wonosari could adopt.

Environmental factors such as soil type, slope, and rainfall intensity are pivotal in flood hazard assessments. Syamsidik et al. (2019) detailed the significance of topographic factors in flood mapping. These findings are consistent with Umar et al. (2017) discussions on land evaluation, which stress the necessity of integrating physical land characteristics into flood risk analysis. Moreover, studies by Guan et al. (2016) highlight that rainfall intensity directly correlates with runoff volumes, underlining the need for localized climate data integration in Wonosari's flood models.

Bacterial contamination due to flooding poses secondary public health risks. Igere et al. (2022) warn that floods can spread antibiotic-resistant bacteria through contaminated wastewater, a concern that should be factored into flood response strategies in Bondowoso. Similarly, Sitorus et al. (2021) recommend that flood risk mapping must consider not only physical hazards but also socio-environmental vulnerabilities, advocating for a multi-dimensional approach.

Community involvement is critical in building resilience against flood risks. Research by Onyeagoziri et al. (2021) shows that participatory disaster risk mapping increases community preparedness and awareness. This approach is mirrored in the findings of Lassa et al. (2019), who underscore the importance of incorporating local knowledge into early warning systems. In Wonosari, leveraging community insights could enhance the relevance and accuracy of flood-prone area analyses.

Policy interventions that integrate sustainable watershed management are necessary to achieve long-term flood mitigation. Ward et al. (2013) emphasized that integrated flood management, combining structural and non-structural measures, yields better results than reactive, single-sector responses. In addition, Ariyaningsih et al. (2024) advocate for green infrastructure developments, such as infiltration wells and biopores, to manage urban floods. Lessons from these studies suggest that similar infrastructural and policy efforts must be strengthened in Wonosari to ensure sustainable flood risk reduction.

The economic impact of floods cannot be overlooked. Dewi & Putra (2022) discuss the significant losses suffered by agricultural communities due to floods, which is particularly relevant for Wonosari, where agriculture is a major economic sector. Integrating disaster risk reduction strategies into regional development planning, as suggested by Novita et al. (2023), could minimize such losses and enhance economic resilience.

Several studies have shown that restoration of river corridors and floodplains can significantly mitigate flood risks. Research by Marfai & King (2008) emphasized the need to protect natural buffers, which absorb excess runoff during peak rainfall events. The Wonosari watershed, characterized by river systems and riparian zones, would benefit greatly from such conservation efforts.

Furthermore, accurate and updated flood hazard maps are essential tools for planners and decision-makers. Purwasih & Wilujeng (2023) demonstrated the effectiveness of updated flood mapping in improving disaster management outcomes. Similarly, Zaafrano et al. (2023) stressed that GIS-based erosion hazard indexing can complement flood hazard mapping efforts by identifying vulnerable soil zones contributing to sediment-laden floods.

Technological advancements, such as remote sensing and spatial modeling, have revolutionized flood risk assessments. Supriatna et al. (2023) utilized high-resolution imagery to monitor changes in watershed conditions, an approach that could enhance Wonosari's flood analysis. Remote sensing integration, as proposed by Raharjo (2023), allows for near-real-time monitoring, ensuring that flood-prone mapping remains dynamic and responsive to environmental changes.

Ultimately, an interdisciplinary and multi-sectoral approach is indispensable in flood-prone area analysis. The watershed management must involve ecological, social, and economic dimensions to achieve holistic outcomes. Supporting this emphasized the necessity for collaborative governance models, particularly in watershed conservation efforts under national disaster risk reduction programs.

Flood-prone area analysis in the Wonosari Sub Watershed must integrate hydrological modeling, land-use analysis, community participation, technological tools, and policy interventions. Drawing insights from the extensive body of literature, including studies by (Darmawan et al., 2017; Fauzi et al., 2022; Ward et al., 2013), and many others, it becomes evident that a comprehensive and adaptive strategy is essential for reducing flood risks in Wonosari. Future research should continue to explore innovative methods for enhancing flood resilience, while policy frameworks must support sustainable watershed management and community empowerment in flood mitigation efforts. The availability of a flood vulnerability map enables the identification of areas with the highest levels of flood risk.

Method

This study was conducted in the Wonosari Sub-watershed, which is located in Bondowoso Regency and covers an area of approximately 619 km². Geographically, it lies between 7°50'10" – 7°56'41" South Latitude and 113°48'10" – 113°48'26" East Longitude. The Sub Watershed is bordered by Situbondo Regency to the north, Jember Regency to the south, Situbondo and Banyuwangi Regencies to the east, and Situbondo and Probolinggo Regencies to the west. The Wonosari Sub-watershed is equipped with 17 rainfall stations and a river discharge monitoring post (AWLR). The study area location, specifically the Wonosari Sub-watershed in Bondowoso Regency, is presented in Figure 1.

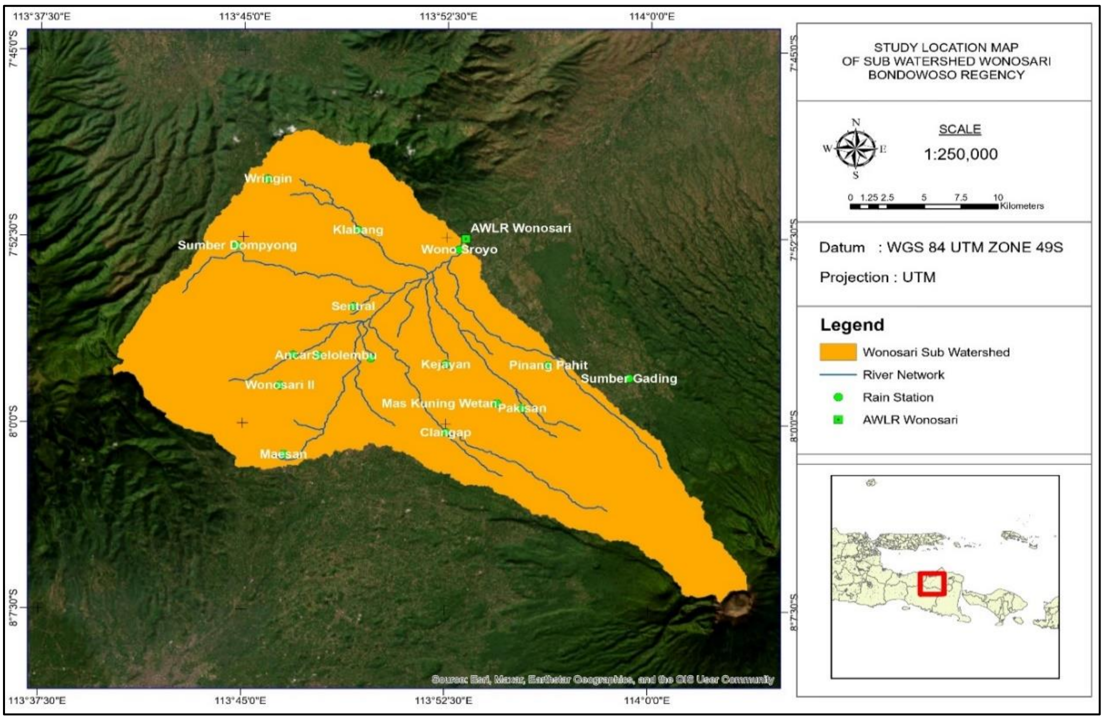

Figure 1. Study Area Location Map of Wonosari Sub Watershed, Bondowoso Regency

Research Data

The data needs in this study are: Daily rainfall data derived from 17 rainfall stations with a time span of 10 years (2013-2023) obtained from UPT PSDA WS Sampean; Daily climatological data (wind speed, temperature, solar radiation and humidity) with a span of 10 years (2013-2023) obtained from Meteorology, Climatology, and Geophysical Agency; Discharge data derived from river water level recording with AWLR with a span of 10 years (2013-2023) obtained from UPT PSDA WS Sampean; Soil type map from FAO/UNESCO The Soil Map of the World in 1981; and National digital elevation model with 30 meter resolution was processed to produce the 2023 land use map, the slope gradient map, and the elevation map.

Surface runoff map

The first step undertaken in this study was the collection of both non-spatial and spatial data. The non-spatial data included rainfall records, climate information, and meteorological data, while the spatial data encompassed soil type, land use, slope, and elevation.

After data collection, a series of statistical tests were conducted to assess the quality and reliability of the data. These tests included consistency testing using the double mass curve method and stationarity testing (F-test and t-test), which were performed exclusively on rainfall data. In the stationarity test, the null hypothesis (H_0) tested was that the rainfall data remained stationary throughout the observation period. The tests were conducted at a 5% (0.05) level of significance. Once the data were validated and deemed satisfactory, model simulation was carried out using ArcSWAT for the period from January 1, 2013, to December 31, 2023.

The modeling process in ArcSWAT was carried out through several stages, including automatic watershed delineation using the national digital elevation model (DEM) with a 30-meter resolution, and HRU (Hydrologic Response Unit) analysis with a 10% threshold for soil type, land use, and slope. Rainfall station data and weather data—including rainfall, relative humidity, wind speed, solar radiation, and temperature—covering a ten-year period from 2013 to 2023 were input into the model. The selection of this time period was based on the occurrence of several flash flood events during those years.

After all necessary data were entered, the SWAT simulation was conducted, and the desired model outputs were configured. The simulation results were produced on a monthly timescale. Following the simulation, model calibration was performed to ensure the model's accuracy. The calibration utilized monthly river discharge data at the Sub-watershed outlet. Calibration performance was evaluated using three criteria: the coefficient of determination (R^2), Percent Bias (PBIAS), and the index of agreement (d). The calibration process is crucial for assessing the model's reliability by estimating the actual field parameter values. Performance criteria for the SWAT model are presented in Table 1.

Table 1. ArcSWAT Model Performance Criteria

Measure	Temporal Scale	Very Good	Good	Satisfactory	Not Satisfactory
R^2	Monthly	$0.70 < R^2 < 1$	$0.60 < R^2 < 0.70$	$0.50 < R^2 < 60$	$R^2 < 0.5$
Pbias	Monthly	Pbias < ±10	±10 ≤ Pbias < ±15	±15 ≤ Pbias < ±25	Pbias > ±25
d	Monthly	d > 0.90	0.85 ≤ d ≤ 0.90	0.75 ≤ d ≤ 0.85	d ≤ 0.75

Subsequently, a surface runoff map was generated using the annual surface runoff simulation output (SURQ). The surface runoff outputs can be accessed via Scenarios > Tables > SWAT Output folder. Upon opening the file, the Sub section should be consulted to view various surface runoff (SURQ) values. These surface runoff outputs were then incorporated into the attribute table of the delineated Sub-watershed data to produce a surface runoff map. The process was then continued with the scoring and weighting analysis.

Scoring and weighting process was applied to each parameter, including the rainfall map, land use map, soil type map, slope map, surface runoff map, and elevation map. Scoring and weighting involved assigning values to each class within each parameter. The basis for assigning values was determined by the degree of influence each class had on flood occurrence; the greater the influence, the higher the assigned value. Scores were then multiplied by their respective weights to obtain a total value. Results of the scoring and weighting process are presented in Table 2.

Table 2. Flood Vulnerability Parameters

Parameter	Indicator	Score	Weight	Total Value
Rainfall (mm)	< 1500	1	0.15	0.15
	1500 – 2000	2		0.30
	2000 – 2500	3		0.45
	2500 – 3000	4		0.60
	> 3000	5		0.75
Land Use	Shrubs	2	0.15	0.30
	Secondary Dryland Forest	1		0.15
	Plantation Forest	1		0.15
	Settlement	5		0.75
	Plantation	3		0.45
	Dryland Agriculture	4		0.60
	Mixed Dryland Agriculture	4		0.60
	Rice Field	4		0.60
	Open Land	4		0.60
Soil Type	Vertic Luvisols (Lv)	2	0.20	0.40
	Vitric Andosols (Tv)	2		0.40
	Ochric Andosols (To)	2		0.40
	Mollic Andosols (Tm)	2		0.40
	Eutric Gleysols (Re)	5		1.00
Land Slope (%)	0 – 8	5	0.20	1.00
	8 – 15	4		0.80
	15 – 25	3		0.60
	25 – 45	2		0.40
	> 45	1		0.20
Surface Runoff (mm)	< 350	1	0.15	0.15
	351 – 415	2		0.30
	416 – 480	3		0.45
	481 – 545	4		0.60
	> 546	5		0.75
Elevation (m)	< 500	5	0.15	0.75
	500 – 1000	4		0.60
	1000 – 1500	3		0.45
	1500 – 2000	2		0.30
	> 2000	1		0.15

The next stage, after performing the overlay, was to sum the total values (the result of multiplying scores by weights) to generate interval values for flood vulnerability classes. Flood vulnerability levels were subsequently classified into five categories: very low, low, moderate, high, and very high. The equation used to establish the interval values for flood vulnerability classes following (Kurnia et al., 2019) is as follows:

$$\text{Ki} = \frac{(Xt - Xr)}{K} \quad (1)$$

Information:
Ki = Interval Class
Xt = Highest Data
Xr = Lowest Data
K = Interval Class desired

Result and Discussion

Hydrological analysis is a crucial step prior to proceeding with further analyses. The hydrological analysis was conducted through statistical testing of rainfall data, as presented in Table 3. The statistical tests performed include consistency testing and stationarity testing (F-test and T-test). The results of these tests indicate that the rainfall data meet the requirements of each respective test, and thus, the data are deemed valid for use in subsequent analyses.

Table 3. Recapitulation of Statistical Tests

Rainfall Station	Hydrological statistical tests		
	Consistency Test	Stationary Test (Test-F)	Stationary Test (Test-T)
Wonosari II	Consistent	Stable	Stable
Sentral	Consistent	Stable	Stable
Selolembu	Consistent	Stable	Stable
Ancar	Consistent	Stable	Stable
Grujugan Lor	Consistent	Stable	Stable
Klabang	Consistent	Stable	Stable
Maesan	Consistent	Stable	Stable
Kejayan	Consistent	Stable	Stable
Mas Kuning Wetan	Consistent	Stable	Stable
Clangap	Consistent	Stable	Stable
Pinang Pahit	Consistent	Stable	Stable
Sumber Dompyong	Consistent	Stable	Stable
Sumber Gading	Consistent	Stable	Stable
Pakisan	Consistent	Stable	Stable
Wringin	Consistent	Stable	Stable
Sukokerto	Consistent	Stable	Stable
Wonosroyo	Consistent	Stable	Stable

Delineation of Sub Watershed Boundaries

Sub Watershed delineation process was carried out by selecting the Watershed Delineator menu and proceeding with the Automatic Watershed Delineation submenu. Several steps were involved in the delineation process, including importing the DEM map, defining the river network, specifying the outlet point, and finally generating the desired sub-watershed boundary (Sukmayu et al., 2022). Delineated Sub Watershed covers an area of approximately 619 km² and is divided into 35 sub-basins. The results obtained from the ArcSWAT modeling require calibration using field observation data from the Automatic Water Level Recorder (AWLR), in which several parameters can be adjusted to reflect actual field conditions (Zaafrano et al., 2023).

Simulation Results

After the required data were inputted, the next step was to conduct the simulation. In this simulation, the parameters used were initially set according to the default conditions in ArcSWAT. If the simulation results did not correspond with the field observation data recorded by the Automatic Water Level Recorder (AWLR), the parameters influencing streamflow were adjusted accordingly (Samaniyatul Aliyah et al., 2024). The calibration utilized monthly river discharge data at the Sub-watershed outlet. Calibration performance was evaluated using three criteria: the coefficient of determination (R^2), Percent Bias (PBIAS), and the index of agreement (d). The calibration process is crucial for assessing the model's reliability by estimating the actual field parameter values. calibration process must ensure the accuracy and precision of the parameters used in the model, as well as consider the sensitivity of each parameter to the simulation results. Parameters such as CN2, ALPHA_BF, SOL_AWC, GWQMN, ESCO, GW_DELAY, GW_REVAP, and REVAPMN have been identified in several studies as significantly influencing surface runoff.

Calibration results indicated that the coefficient of determination (R^2) was 0.65, which is classified as good because it falls within the range of $0.6 < R^2 < 0.7$. The Percent Bias (PBIAS) value was 14.44, also categorized as good, as it lies within the range of $\pm 10 \leq \text{PBIAS} < \pm 15$. The index of agreement (d) was 0.89, meeting the criteria for a good model, as it falls within the range of $0.85 \leq d < 0.90$. These results demonstrate that the SWAT model exhibited good performance based on the calibration criteria. Therefore, parameters such as CN2, ALPHA_BF, SOL_AWC, GWQMN, ESCO, GW_DELAY, GW_REVAP, and REVAPMN did not require further adjustment and could be maintained at their default values in ArcSWAT. Moreover, the statistical tests confirmed that the simulated streamflow had a strong correlation with the observed discharge data, suggesting that the SWAT model is reliable for simulating surface runoff in the Wonosari Sub-watershed.

Surface Runoff Results

Surface runoff data utilized in this study were obtained from the 2023 ArcSWAT simulation. The spatial map illustrating the annual surface runoff distribution within the Wonosari Sub-watershed displays a range of measured values. This map was generated based on the classification of runoff levels, arranged from the highest to the lowest values, and distributed across 35 sub-basins. The surface runoff classes were visualized using a color symbology, where red indicates areas with high runoff values and green represents areas with low runoff values are presented in Figure 2. The surface runoff simulation results are presented in Table 4.

Table 4. Recapitulation of Surface Runoff Results

Subbasin	Area (km²)	Annual Surface Runoff (mm)	Subbasin	Area (km²)	Annual Suface Runoff (mm)
1	27.76	774.68	20	18.38	699.39
2	25.96	878.15	21	18.03	633.52
3	1.46	886.89	22	20.33	874.16
4	16.72	492.48	23	1.45	629.78
5	4.90	833.05	24	12.44	555.50
6	2.70	894.30	25	26.12	440.79
7	35.81	489.03	26	24.02	769.47
8	0.19	870.97	27	22.97	815.56
9	0.15	905.64	28	13.88	628.95
10	0.32	854.12	29	24.65	457.54
11	68.72	428.52	30	15.04	803.23
12	0.98	648.27	31	62.03	605.45
13	1.26	648.12	32	22.06	516.92
14	16.77	779.42	33	40.37	680.28
15	2.16	599.90	34	25.10	705.40
16	6.18	873.90	35	19.68	642.74
17	24.57	730.51		Average	695.28
18	0.66	589.72		Minimum	428.52
19	5.80	698.64		Maximum	905.64

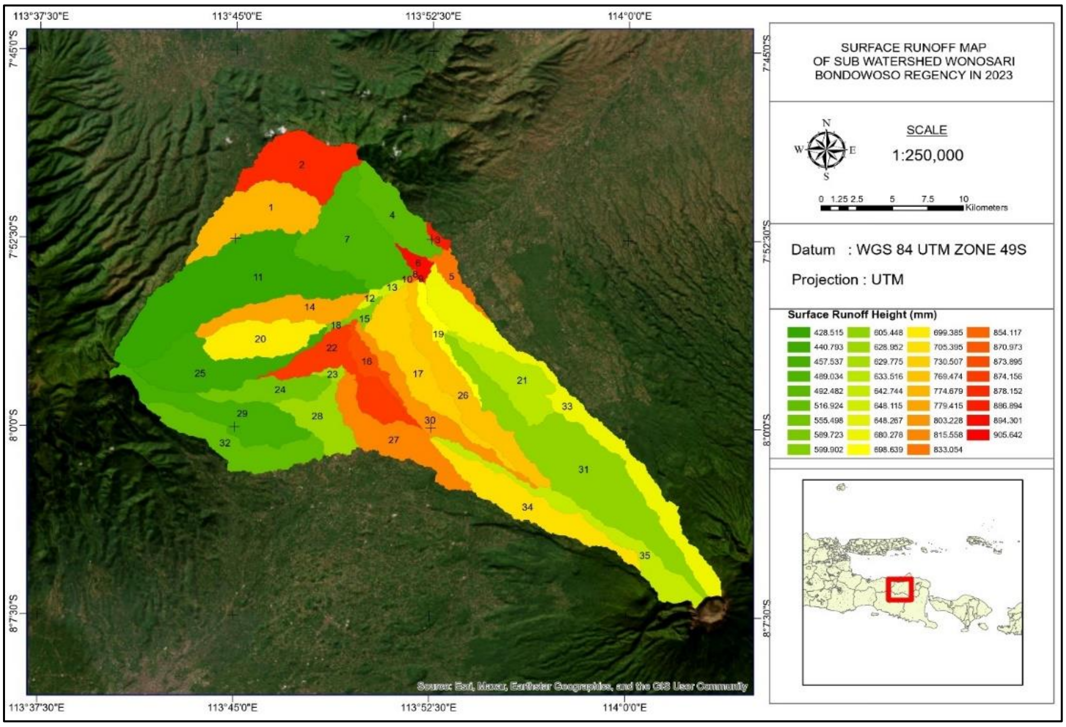

Figure 2. Surface Runoff Map

As shown in Table 4, the distribution of surface runoff depths in the Wonosari Sub Watershed indicates that the average runoff in 2023 reached 695.28 mm. The highest surface runoff was recorded in Sub-basin 9, with a value of 905.64 mm, while the lowest surface runoff occurred in Sub-basin 11, with a depth of 428.52 mm.

Flood Prone Area Analysis

Level of flood vulnerability is a measure of how susceptible an area or region is to flood disasters. It reflects the potential of a region to experience flooding, the frequency of flood occurrences, and the resulting impacts on the surrounding environment (Nurdiawan &

Putri, 2021). Flood vulnerability mapping was carried out by overlaying all relevant parameters, including rainfall, soil type, land use, slope, surface runoff, and elevation. These predefined parameters were combined by summing their respective scores and weights using the Field Calculator tool in ArcGIS. The classification of flood vulnerability levels can be conducted by determining data intervals using the following method:

$$Ki = \frac{(Xt - Xr)}{K} \quad (2)$$

$$= \frac{(3.85 - 1.25)}{5} = 0.52 \quad (3)$$

Table 5. Flood Vulnerability Levels

Level of Vulnerability	Data Intervals
Very Low	1.25 – 1.77
Low	1.77 – 2.29
Medium	2.29 – 2.81
High	2.81 – 3.33
Very High	3.33 – 3.85

The results of the flood vulnerability mapping in the Wonosari Sub-watershed are presented in Figure 3. Based on Figure 3, it can be observed that areas classified as highly vulnerable to flooding are located in lowland regions, where land use is predominantly residential. In contrast, areas with low flood vulnerability are situated in highland regions, particularly in mountainous areas.

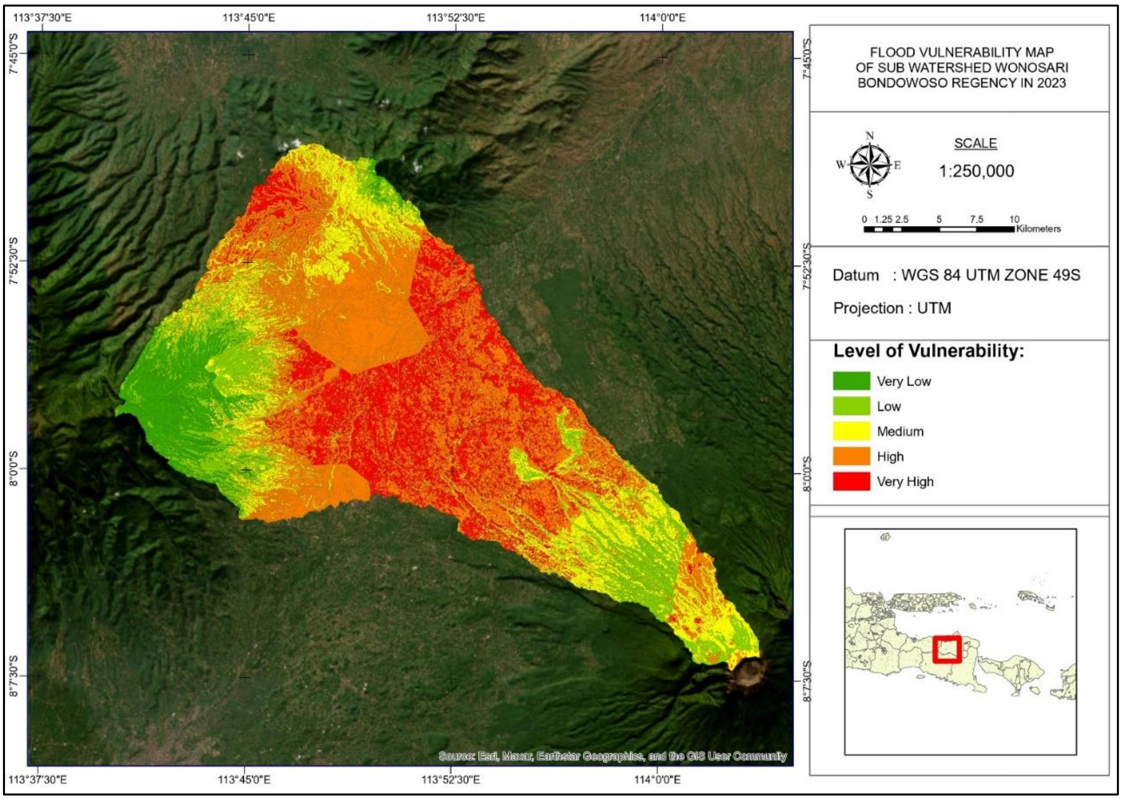

Figure 3. Flood Vulnerability Map in 2023

Based on the results of the flood vulnerability mapping in the Wonosari Sub-watershed, it was found that 26 villages are located in areas classified as very low vulnerability, 81 villages in low vulnerability areas, 148 villages in medium vulnerability areas, 152 villages in high vulnerability areas, and 117 villages in very high vulnerability areas. Following the identification of the number of affected villages through the overlay analysis, the spatial extent of each flood vulnerability level was calculated. The largest flood-prone area in the Wonosari Sub-watershed falls under the high vulnerability category, covering an area of 250.18 km². The very high vulnerability area covers 120.06 km², the medium vulnerability area covers 128.69 km², the low vulnerability area covers 69.12 km², and the very low vulnerability area covers 41.54 km².

Conclusion

This research demonstrates that physical development in Indonesia, particularly in the Wonosari Sub-watershed, has led to changes in land use patterns that have increased the risk of flooding due to enhanced surface runoff. Through modeling using ArcSWAT and

GIS-based spatial analysis, a flood vulnerability map was produced by integrating parameters such as rainfall, land use, soil type, slope gradient, surface runoff, and elevation. The model calibration results indicated good performance, with an R^2 value of 0.65, a PBIAS of 14.44, and a index of agreement (d) of 0.89. The average annual surface runoff in the Wonosari Sub-watershed in 2023 was 695.28 mm, with a maximum value reaching 905.64 mm. Based on the flood vulnerability mapping results in the Wonosari Sub-watershed, it was found that 26 villages were located in areas classified as very low vulnerability, 81 villages were located in low vulnerability areas, 148 villages in medium vulnerability areas, 152 villages in high vulnerability areas, and 117 villages in very high vulnerability areas. Following the identification of the number of affected villages through overlay analysis, the spatial extent of each flood vulnerability level was calculated. The largest flood-prone area in the Wonosari Sub-watershed falls under the high vulnerability category, covering an area of 250.18 km^2. The very high vulnerability area covers 120.06 km^2, the medium vulnerability area covers 128.69 km^2, the low vulnerability area covers 69.12 km^2, and the very low vulnerability area covers 41.54 km^2. The resulting flood vulnerability map successfully identifies areas with the highest flood risk and is expected to be utilized as an early warning system as well as a basis for flood mitigation policy planning in the region. This research has several limitations, including a spatial scope restricted to the Wonosari Sub-watershed, the use of land cover data derived from Landsat 8 imagery with a 30-meter spatial resolution, and the classification of land cover into only nine categories. Furthermore, the ArcSWAT model employed in the analysis considered only biophysical factors and did not integrate local socio-economic dynamics, which could significantly influence flood vulnerability levels. The policy implications derived from this research suggest that areas along riverbanks and lowland regions in the central and southern parts of the Wonosari Sub-watershed should be prioritized for flood mitigation interventions. Recommended interventions include land conservation and rehabilitation through reforestation of critical lands, control of residential development in flood-prone zones, and the implementation of sustainable agricultural practices in mixed and dryland farming areas. The resulting flood vulnerability map could be integrated into existing flood early warning systems to strengthen the region's early disaster response capacity based on spatial data. To support further development, this research recommends integrating socio-economic factors into flood vulnerability analyses, utilizing higher-resolution imagery such as Sentinel-2 or drone data to enhance mapping accuracy, and developing advanced hydrological models that incorporate future climate change scenarios and human activities. In addition, involving local communities in field validation and in the formulation of community-based mitigation strategies is highly encouraged to enhance the effectiveness of the implementation of the study's findings.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

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