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Analyzing Flood Disaster Risks in Senior High School: Envidence from Surakarta, Indonesia

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Abstract

Purpose: Flood disasters represent one of the most critical environmental challenges in Surakarta, particularly in areas along the Bengawan Solo River watershed, where high rainfall intensity and rapid land use changes substantially increase inundation risk. Educational facilities, especially Senior High Schools, are vulnerable due to their spatial distribution, physical conditions, and population characteristics. This study aims to analyze flood hazard, vulnerability, and risk levels of Senior High Schools in Surakarta as a scientific basis for strengthening disaster preparedness and risk reduction within school environments.
Methodology: This research employed a quantitative approach supported by spatial analysis. Flood hazard mapping was conducted using the Weighted Sum Method by integrating elevation, slope, rainfall, land use, and river proximity parameters. Vulnerability assessment was performed using physical and social indicators, including building condition, drainage, accessibility, population exposure, and institutional capacity, derived from secondary data and field surveys. Flood risk levels were identified through the integration of hazard and vulnerability components.
Results: The results indicate that flood hazard areas in Surakarta are dominated by high and moderate classes, particularly in Serengan, Pasar Kliwon, and parts of Jebres District. Vulnerability analysis shows that fifty seven schools have high physical vulnerability and sixty six schools exhibit high social vulnerability. Combined vulnerability classification identifies fifty seven schools as high, twenty seven as medium, and one as low. Flood risk analysis indicates that fifty one schools fall into the high risk category.
Applications/Originality/Value: This study provides an assessment of flood risk in educational facilities and supports School Based Disaster Preparedness Programs to enhance resilience.

Background

Flooding is a common problem in Indonesia, especially in densely populated areas, such as urban areas (Safitri et al., 2022). This condition can have devastating impacts on human life, the economy, and the environment (Ulum, 2013). Flooding generally occurs when water overflows from heavy rainfall, breaches river embankments or dams, rises due to rising sea levels, or melts from ice. A flash flood can be defined as a phenomenon in which water flows very rapidly and heavily, occurring suddenly and swiftly, and is accompanied by sediments, rock fragments, and soil (including pieces of wood), originating from the upstream area of a river (Widiyatmoko et al., 2015).

Floods can be considered a disaster when they occur in areas with human activity. Floods are divided into six types, including: 1.) Riverine Flooding, 2.) Urban Drainage Flooding, 3.) Flash Flooding, 4.) Structural Failure or Overtopping Floods, 5.) Mudflows, and 6.) Coastal Flooding and Erosion *)* (Arif, 2019). Human activities or environmental characteristics can also cause floods. In flood disaster management, it is essential to conduct a flood risk analysis (Aldiansyah et al., 2025). Flood disaster risk analysis requires assessing several variables, namely hazards and vulnerabilities. Some terms commonly used in disaster contexts include risk, vulnerability, susceptibility, and hazard (Duhamel et al., 2022).

A hazard is a condition in a community over a specific period of time that has the potential to cause casualties and damage. According to the Meteorology, Climatology, and Geophysics Agency (BMKG), a hazard is a hydrometeorological, geophysical, or human-induced element that poses a threat to life, property, or the environment (BMKG, 2023). Clarifying hazard sources helps readers understand their potential impacts and relevance to disaster risk. A hazard can be defined as any source, situation, or activity that has the potential to cause injury (work accidents) or occupational illness (Ramada, 2024). A hazard can also be defined as a condition, whether natural or caused by human activity, that has the potential to cause damage, loss, or loss of life (Yanuar Saifudin et al., 2021).Several indicators are used to analyze a disaster, particularly floods (Ni'matussyahara et al., 2022). Flood hazard indicators are usually determined by combining relevant flood parameters, particularly flood depth and flow velocity, flood arrival time, flood duration, sediment load or contamination, and so on (Maranzoni et al., 2023).

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Vulnerability is a condition of weakened resilience due to external factors that can endanger life, livelihoods, natural resources, infrastructure, economic productivity, and well-being in a community or society (Shah et al., 2020). The relationship between vulnerability and hazard can create a State of risk, in which the greater the vulnerability to disasters, the greater the risk posed by disasters (Mantika & Hidayati, 2020).Vulnerability can be divided into four categories: social, physical, economic, and environmental (Aisha et al., 2019). In this study, the risk components analyzed are those present in the school environment, focusing on two aspects: social and physical.

Risk refers to the possibility of a potential impact on achieving a goal. In the context of disaster management, disaster risk refers to the potential losses from a disaster within a specific area and time period (Lestari et al., 2018). These losses can include death, injury, illness, threat to life, loss of security, displacement, damage or loss of property, and disruption to community activities (Reppi et al., 2021). The disaster risk approach involves assessing the potential negative impacts, such as human casualties, property damage, and environmental degradation, based on the area's vulnerability and capacity. These impacts are evaluated using metrics such as affected populations, property losses, and environmental damage (BPBD, 2021).

In 1966, Surakarta experienced a major flood disaster, the peak of the Bengawan Solo River's flooding, which inundated nearly 75% of the city (Kholidah, 2022). Ecological changes contributed to the 1966 flooding in Surakarta (Prasetyo et al., 2020). The flooding in Surakarta was also caused by heavy rainfall over several consecutive days, which left the Bengawan Solo River unable to accommodate the volume of water, leading to it overflowing into residential areas. The flooding in Surakarta did not stop there; after this significant event, flooding occurred annually (Candraningtyas & Syahrani, 2023). Furthermore, in 2007, flooding in Surakarta City occurred again, causing roads in Surakarta City and the surrounding regencies of Sukoharjo and Karanganyar to malfunction (Muttaqin & Sibarani, 2015).

Other evidence was obtained from media reports, such as those presented by detikJateng on February 25, 2025, that the overflowing Bengawan Solo River inundated hundreds of houses in Jebres and Pasar Kliwon Districts. Heavy rain that occurred in Solo City for a long duration caused an increase in the water discharge in the Bengawan Solo River. As a result, the river overflowed, causing flooding that inundated residents' homes in several locations (NV, 2025). In 2024, precisely on December 22, Sambirejo Village RW 01, Banjarsari District, Solo City, experienced flooding after heavy rain. The flood that hit Sambirejo Village, Banjarsari District, also inundated the Simpang Joglo project and several residents' homes (NV, 2024). In early 2023, heavy rains also occurred, resulting in flooding in Surakarta City, inundating four sub-districts and 17 villages as the Bengawan Solo River overflowed. The worst-affected area was Serengan District, Joyotakan Village. Approximately 1,700 residents were affected in Joyotakan (BPBD, 2023a).

Figure 1. List of historical flood events in Surakarta City in 1966, 2023, 2024, 2025 as reported by the mass media

Heavy rainfall distributed throughout the Bengawan Solo River Basin (DAS) has caused flooding in Surakarta City. The environmental change, such as the Conversion of riverbanks into residential areas driven by population growth, exacerbates flood risks. Modifying riverbank functions can increase the likelihood of flooding in surrounding areas (Winata et al., 2025).

The impacts of floods can include environmental damage, loss of valuables, and even disruptions to human activities such as the inability to go to work and school (Findayani, 2015). According to the Regional Disaster Management Agency (BPBD), floods have significant impacts, including fatalities and serious injuries. They can also cause significant economic losses due to damage and disruption to economic activities. They can also pollute drinking water, leading to a clean water crisis (BPBD, 2023b). Floods can also lead to the spread of various diseases that threaten public health, such as diarrhea, dengue fever, leptospirosis, acute respiratory infections (ARI), skin diseases, and gastrointestinal illnesses like typhoid fever. Additionally, prolonged rainy seasons can weaken immune systems, worsening chronic health conditions (Christian et al., 2023).

Floods can also impact schools, damaging buildings, disrupting the learning process, causing the loss of student materials, and affecting student well-being (Eny Junyanti, 2024). Schools in Solo, such as SMPN 6 Surakarta, experienced flooding that damaged infrastructure, led to the loss of learning materials, and hindered student education. This flood occurred on February 16, 2023 (Alfarizi et al., 2024a).

Not much research has been conducted on flood risk analysis in Surakarta City, especially in high schools. For example, research conducted by (Noviani et al., 2021) in Surakarta City discussed the mapping of disaster-prepared high schools. Furthermore, research conducted by (Dahlia & Fadiarman, 2020) in Jakarta City used flood risk and educational facilities as variables. A different approach was taken by (Herdiana et al., 2024), who conducted a study on risk analysis, vulnerability, impact, and school-based disaster risk management efforts in East Java Province. Furthermore, research by (Septiningrum et al., 2022) examined the vulnerability of elementary schools in flood-prone areas of Sukoharjo Regency. Another study by (Mukaroma et al., 2022a) examined the vulnerability of junior high schools in disaster-prone areas of Sukoharjo Regency. These two studies analyzed only the vulnerability of schools in flood-prone areas in Sukoharjo Regency, not the flood risk. This study analyzed flood hazard levels in Surakarta City and conducted a flood risk analysis for high schools in the city. The results can be used to recommend SPAB policies in Surakarta City.

Method

1. Location

This research was conducted at all high schools in Surakarta City. Surakarta City is located between 110° 45` 15”–110° 45` 35” East Longitude and 70` 36”–70` 56” South Latitude (Kristiawan, 2025). The city of Surakarta is a lowland area with an average elevation of 97 meters above sea level, forming a basin located between two volcanic mountain ranges—Mount Lawu to the east and Mount Merapi and Mount Merbabu to the west (Alfarizi et al., 2024b). Surakarta City is crossed by the Bengawan Solo River and several tributaries, including the Pepe River, which are potentially affected by flooding when river discharge increases (Pramitha et al., 2020). Furthermore, Surakarta City’s geological condition, located between several volcanoes, including Mount Lawu, Merapi, and Merbabu, makes it a fluvial sediment area and a flood-prone zone. This research is a quantitative study. This method was used to obtain information regarding the level of flood risk among high schools in Surakarta City.

2. Data Collection Techniques

This study used primary and secondary data. Primary data, generated from field observations and interviews, were collected directly using instruments explicitly developed for this study and used to validate the flood hazard map of Surakarta City. Secondary data were obtained from the Basic Data for Elementary and Secondary Education (DAPODIKDASMEN) website to determine the level of flood vulnerability in senior high schools in Surakarta City.

Table 1. List of Primary Data and Secondary Data

Primary Data	Hazard Variables	Description	Source
	Interview data	Information obtained directly from respondents (residents around the flood-affected area).	Interview
	Flood Validation Points	Locations that have experienced flooding and those that have not experienced flooding.	Field Survey
	Vulverability Variables	Description	Source
	School Room Structural Condition Data	Information related to the physical condition of school buildings, such as materials, drainage conditions, building age, foundation, wall materials, and roof materials.	Field Survey
Secondary	Hazard Variables	Description	Source

Data	Flood Hazard Map Data	A map that shows areas prone to flood hazards based on spatial analysis.	InaRISK (https://inarisk.bnpb.go.id/)
	DEM Raster Data	Raster spatial data used to analyze slope gradients.	Ina-Geoportal (https://tanahair.indonesia.go.id/portal-web/)
	Land Use Raster Data	Raster spatial data used to analyze land-use patterns.	ESRI Land Cover https://livingatlas.arcgis.com/landcover/
	Rainfall Raster Data	Raster spatial data used to analyze rainfall levels.	CHIRPS : Rainfall Estimates from Rain Gauge and Satellite Observations https://www.chc.ucsb.edu/data/chirps
	Vulverability Variables	Description	Source
	School Location Data	Information related to the administrative identification of school locations.	Google Maps
	Number of Students	Information related to the number of students in the school.	Data Pokok Pendidikan (DAPODIK) https://dapo.kemendikdasmen.go.id/
	Number of Teachers and Staff	Information related to the number of teachers and school staff.	
	Number of School Rooms	Information related to the number of rooms in the school.	

3. *Population, Sample, Sampling*

The population in this study was all 81 high schools in Surakarta City, located in flood-prone areas. Two sampling techniques were used in this study: Cluster Random Sampling to determine the locations for the flood hazard validation survey, and Stratified Random Sampling to select schools based on their level of vulnerability and risk to flooding. Cluster random sampling involves selecting groups/clusters and then drawing individual samples from them (Fajrin & Leonardi, 2019). Stratified random sampling, meanwhile, is a sampling technique that divides the population into smaller groups. The formation must be such that each stratum is homogeneous with respect to one or more specific criteria. A random sample is then drawn from each stratum (Ulya et al., 2018). The sample in this study comprised 29 locations across high-, medium-, and low-flood potential areas, as well as 81 high schools (SMA) at risk of flooding in Surakarta City, divided into three strata.

Table 1. Stratified Random Sampling Calculation Results

No	Strata	Sample
1.	Low	19
2.	Moderate	25
3.	High	37
	Total	81

Table 2. Cluster Random Sampling Calculation Results

No	Strata	Sample
1.	Low	5
2.	Moderate	9
3.	High	15
	Total	29

4. *Instruments*

Instruments are crucial data-collection tools for field data collection. These instruments are one method used to obtain information regarding building vulnerability to flooding and flood hazards in the area by conducting interviews with residents living near the flooded area. The instruments used in this study include a flood hazard validation instrument, a school condition instrument, and an interview guide.

a. The Flood Hazard Validation Instrument used in this study was a flood validation observation sheet for senior high schools in Surakarta City.

Table 4. Field Observation Sheet

No	Indicator	Description
1.	Drainage Condition	To assess the ability of drainage channels to carry rainfall and prevent flooding.
2.	Slope/Topography Condition	To identify potential surface runoff and determine areas prone to water accumulation or flooding.
3.	Land Use Condition	To analyze the influence of human activities on increased surface runoff and flood risk, especially in built-up areas.

b. The School Vulnerability Sheet was used to determine the structural conditions of senior high schools in Surakarta City.

Table 5. School Vulnerability Observation Sheet

Variable	Parameter	Unit	Weight	Description	Source
Social Vulnerability (0,6)	a) School Community	People	0,6	The larger the school community (students, teachers, and staff), the higher the exposure to disaster risks.	Data Pokok Pendidikan (DAPODIK)
	b) Gender Ratio of Teachers & Staff	People	0,1	Imbalance in gender ratios may affect the ability to respond to disasters.	Data Pokok Pendidikan (DAPODIK)
	c) Gender Ratio of Students	People	0,3	Imbalanced gender ratios may indicate certain groups being more socially and psychologically vulnerable during disasters.	Data Pokok Pendidikan (DAPODIK)
Physical Vulnerability (0,4)	a) Buildings Located in Flood Area		0,4	The more school buildings located in flood-prone areas, the higher the potential exposure and damage.	Field Validation
	b) Drainage			Poor drainage conditions hinder water flow and increase flooding risk in school areas.	Field Validation
	c) Building Materials			Low-quality building materials increase vulnerability to flood damage.	Field Validation
	d) Building Age			Older buildings are more structurally vulnerable to flood impacts.	Field Validation
	e) Floor Height Above Ground			Lower floor elevations have higher risk of inundation and damage.	Field Validation
	f) Foundation			Shallow or weak foundations increase structural vulnerability during flooding or erosion.	Field Validation

	g) Roof Materials			Lightweight or non-water-resistant roofing increases damage potential during flooding or strong winds.	Field Validation
	h) Wall Materials			Non-permanent wall materials are more prone to flood-induced damage.	Field Validation

c. The Interview Guide was used to conduct interviews with informants regarding flood disaster risk in schools.

Table 6. List of Flood Validation Test Interview Questions

No	Indicator
1.	History of flood events.
2.	Duration of flood events.
3.	Water depth during flooding.
4.	Time of flood occurrence.
5.	Causes of flood events.

5. *Data Analysis Techniques*

Data analysis techniques were used to obtain data in this study to achieve the research objectives. Three analysis techniques were used:

a. *Flood Hazard Analysis*

The flood hazard analysis in this study was conducted using the Weighted Sum method. The Weighted Sum method is a spatial analysis technique found in ArcGIS that combines multiple spatial data layers into a single layer by assigning weights to each layer. This technique can be used to create multi-criteria models by combining several factors or spatial variables in a single analysis. The result of the Weighted Sum process will be a flood hazard map derived from weighting existing parameters (Libora & Saputra, 2023). In this study, five variables will be used to produce a flood hazard map: Digital Elevation Model (DEM), Slope, Distance from the nearest river, Land Use Data, and Rainfall. DEM data can be obtained from the Ina-Geoportal website, slope can be obtained from the results of slope processing in the ArcGIS application, the distance of the flow to the nearest river can also be obtained through flow accumulation processing, land use data is obtained from the Ina-Geoportal website, and rainfall data is obtained from the CHIRPS website: Rainfall Estimates from Rain Gauge and Satellite Observations. After obtaining all variables, the value of each raster is reclassified, and the weight settings are set on "Weighted Sum (Spatial Analyst)" by classifying it into three classes, namely high, medium, and low, so that a flood hazard map is obtained (Fristyananda & Hertiari Idajati, 2017).

b. *Flood Vulnerability Analysis*

The vulnerability analysis begins by grouping vulnerability parameters into their respective categories or classes. Each parameter within this variable is categorized into three levels: low, medium, and high. These categories are determined through statistical processing that uses the mean and standard deviation to ensure objective, measurable classification (Wibowo et al., 2022). Furthermore, this analysis assigns a value or score to each vulnerability parameter. The scoring system is hierarchical, with a maximum score of 3 for "high," 2 for "medium," and 1 for "low".

Table 7. Vulnerability Level

Value	Class	Score	Interval
3	High	2,3	1,9 – 2,3
2	Medium	1,8	1,5 – 1,8
1	Low	1,4	<1,4

The scores are then multiplied by the weights assigned to each risk component within the vulnerability variables, based on their importance or impact on the total risk. Furthermore, the multiplication of the scores and weights for each parameter is summed to produce a total score for each vulnerability variable, encompassing both social and physical aspects. This total reflects each variable's contribution to the overall level of vulnerability. Once the total score for the four variables is obtained, a regrouping is performed to determine the final vulnerability class. This overall vulnerability class is calculated using similar statistical methods, based on the mean and standard deviation, as in the initial classification stage. This method produces a comprehensive, measurable vulnerability map that can serve as a basis for overall risk analysis and for establishing disaster risk reduction strategies.

c. *Risk Analysis*

The previously created hazard and vulnerability maps for flood disasters are further analyzed to gain a comprehensive understanding of the disaster risk level. The next stage is validation using a three-class matrix. This matrix combines two main elements: hazard level and vulnerability level, to determine the risk category arising from the combination of these two components that determine flood risk. This matrix generally consists of three risk categories: high risk, moderate risk, and low risk, each reflecting the level of threat to the area or object being analyzed based on the combination of its hazard and vulnerability values.

At this stage, each area, mapped according to its hazard and vulnerability levels, is aligned with or remapped into a risk category, in accordance with the guidelines in the three-class disaster risk analysis matrix. For example, an area with high hazard and high vulnerability would be classified as high risk, while one with moderate hazard and low vulnerability would be classified as low risk. This process is carried out in a comprehensive and structured manner to ensure that the risk-mapping results reflect actual conditions on the ground and serve as a basis for formulating effective flood disaster risk reduction and mitigation strategies.

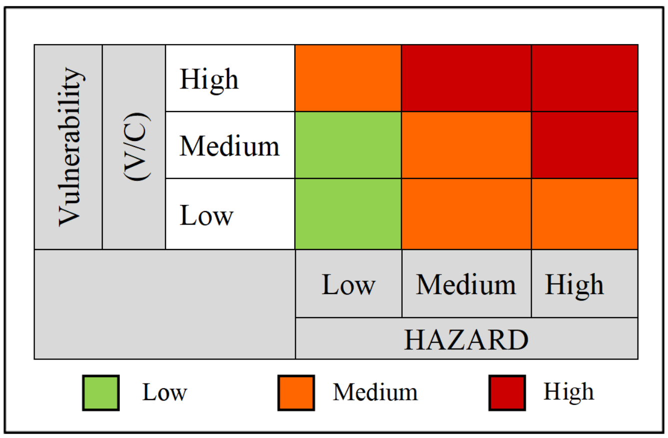

Figure 2. Flood Risk Matrix

Result and Disscussion

1. *Result*

a. *Hazard*

1) *Hazard Class Area*

The spatial analysis results show that the hazard level in Surakarta City is divided into three classes: high, medium, and low. The high hazard class area covers 18 km², generally located in low-lying areas and adjacent to major rivers. Furthermore, the medium hazard class area covers 19 km², spread across transitional areas from the lowlands with relatively better drainage systems. Meanwhile, the low-hazard class area covers 8 km², is located at higher elevations than the medium- and low-hazard classes, and has a more optimal drainage system.

2) *Map Per Parameter*

a) *Slope Map*

The spatial analysis results displayed on this map categorize Surakarta City's slope gradients into three groups: steep, moderately steep, and gentle. The city is mainly characterized by gentle slopes, which pose a high flood risk during heavy rainfall. Steep and moderately steep zones are primarily located on the outskirts, especially in Jebres District, and serve as catchment areas that affect flood susceptibility.

b) *Rainfall Map*

The spatial analysis results on this map illustrate rainfall levels in Surakarta City into three categories: high, moderate, and low. Areas with high rainfall potential can increase river discharge, thereby increasing the risk of flooding in Surakarta City. Furthermore, areas with low rainfall tend to be safer from potential flooding, but can still be affected if they are located along watercourses.

c) *River Network Map*

The results of a spatial analysis of the river network map highlight how the water flow system in Surakarta City, including small streams, tributaries, and large rivers, is essential for effective urban management. Large rivers such as the Bengawan Solo are central to this system, with tributaries reaching various sub-districts, underscoring their significance for city planning and safety.

d) *Land Use Map*

The spatial analysis results on this map illustrate the distribution of land use in Surakarta City. Land use categories in Surakarta City include residential areas, scrubland, and freshwater bodies. The map interpretation reveals that most areas in Surakarta City are dominated by residential areas, indicating that the city is densely populated. Areas with scrubland are fewer and likely located on the outskirts of Surakarta City, while freshwater bodies occur around rivers.

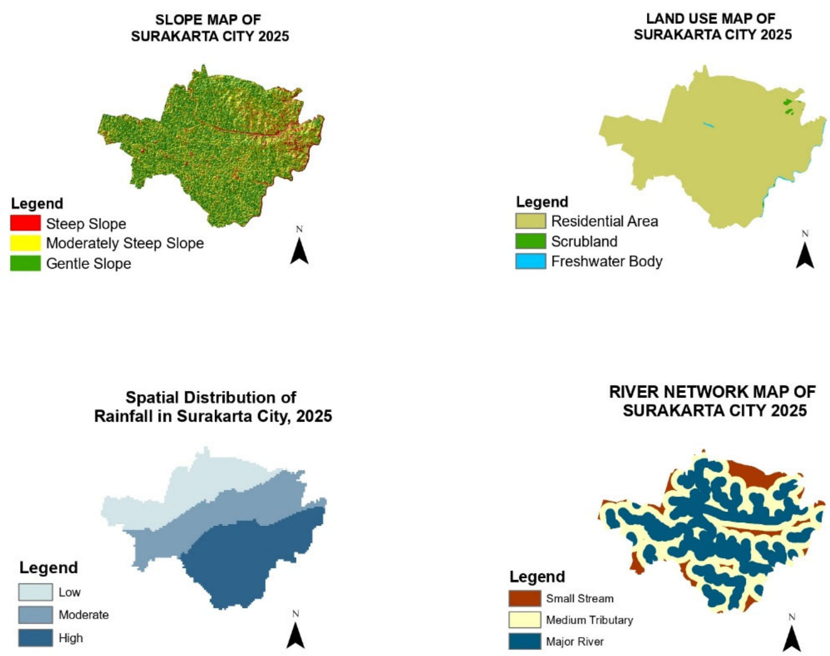

Figure 3. Flood Hazard Parameter Map

3) *Flood Hazard Map*

The results of the spatial analysis of the flood hazard map show that the flood threat level in Surakarta City is divided into three categories: high, medium, and low. Areas with a high hazard category are located around the main rivers that cross the city, particularly in Serengan, Pasar Kliwon, and parts of the Jebres District. Furthermore, areas with a moderate hazard level are found in parts of Laweyan, Banjarsari, and Jebres Districts. Areas with a relatively low hazard level are found in parts of Laweyan District and Banjarsari District.

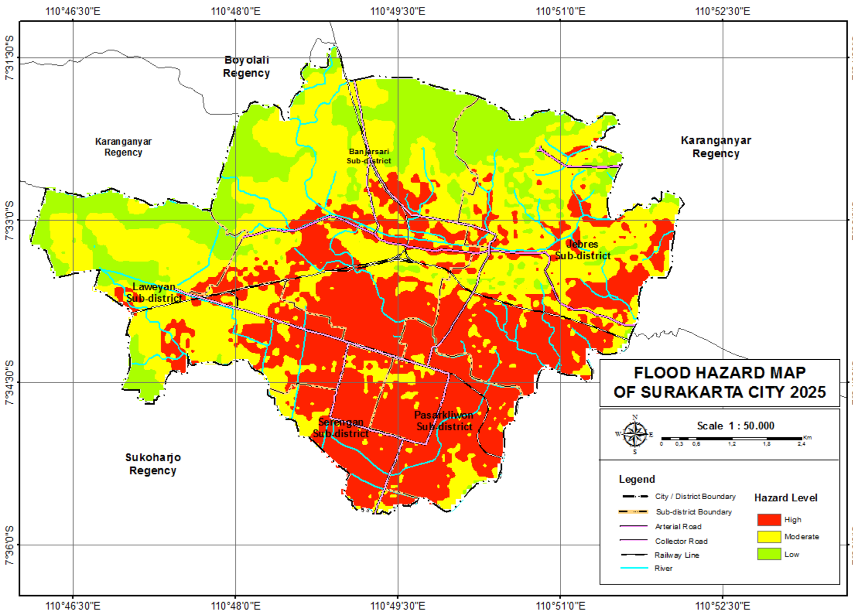

Figure 4. Flood Hazard Map

4) Validation

Based on field validation of the hazard map in Surakarta City in 2025, it was found that in areas with a high flood hazard class, 12 points experienced flooding, and 3 did not. Therefore, areas in the high-hazard class had an 80% accuracy rate for flooding and a 20% rate for non-flooding. Meanwhile, in areas with a low hazard class, 4 points experienced flooding, while 10 did not. It indicates that areas in the low hazard class had an accuracy rate of 28.57% for flooding and 71.43% for non-flooding.

b. Vulnerability

1) Social Vulnerability

Based on the spatial analysis of the physical vulnerability map of Surakarta City Senior High Schools in 2025, there are 57 red points with high vulnerability, 21 yellow points with moderate vulnerability, and 3 green points with low vulnerability. The high category dominates the physical vulnerability level of Surakarta City Senior High Schools. It indicates that the physical components are at relatively high risk of disasters.

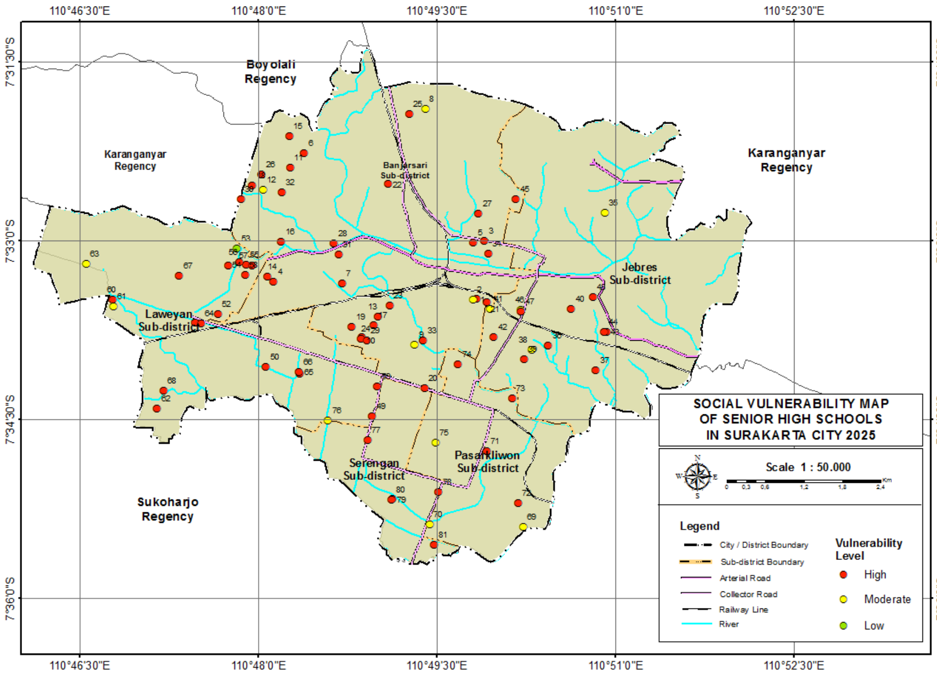

Figure 5. Social Vulnerability Map

2) *Physical Vulnerability*

Based on the spatial analysis of the social vulnerability map of Surakarta City Senior High Schools in 2025, schools with high vulnerability dominate, totaling 66 schools. Furthermore, 14 schools with moderate vulnerability are symbolized by yellow dots. A green dot symbolizes one school with low vulnerability. This high level of social vulnerability is related to the size of the school community, the teacher-to-student gender ratio, and the still-low level of disaster knowledge.

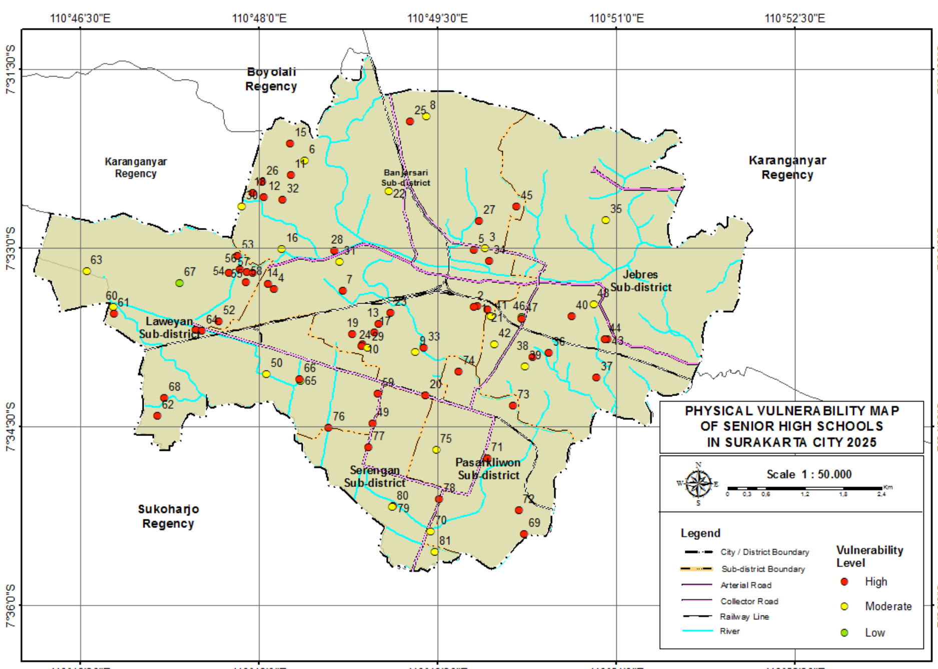

Figure 6. Physical Vulnerability Map

3) *Total Vulnerability*

Based on the results of the spatial analysis of the total vulnerability map, which combines the physical and social vulnerability of Surakarta City Senior High Schools in 2025, 57 schools (symbolized by red dots) are classified as having a high level of vulnerability. Furthermore, 27 schools, symbolized by yellow dots, are classified as having a moderate level of vulnerability. Meanwhile, one school, symbolized by a green dot, is classified as having a low level of vulnerability.

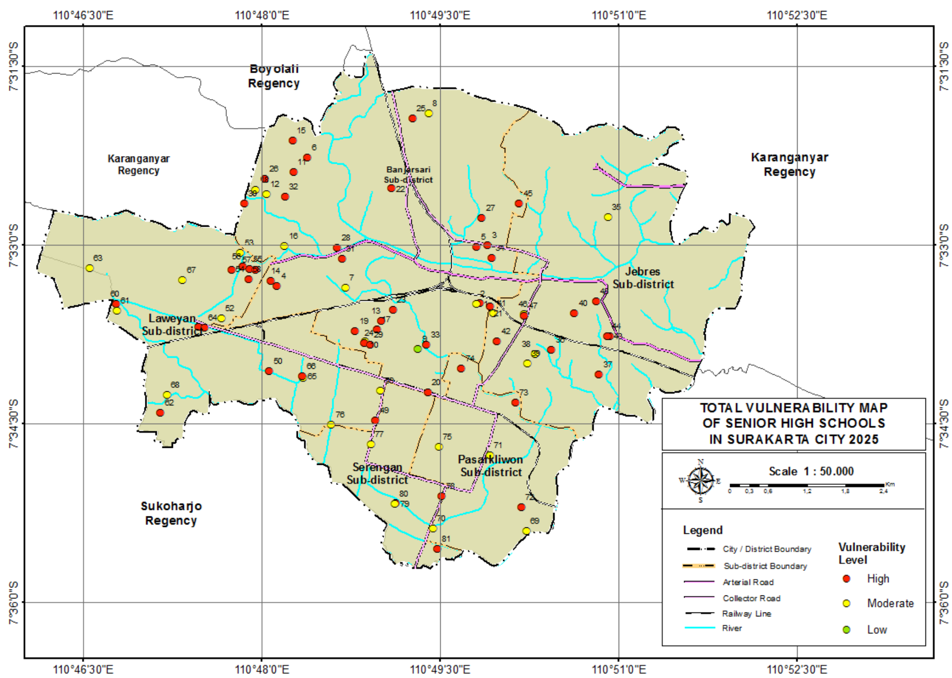

Figure 7. Total Vulnerability Map

c. *Risk*

Based on the spatial analysis of the flood risk map for Surakarta City Senior High Schools in 2025, it is evident that each school has a different level of flood risk. 51 schools are classified as having a high level of flood risk, 25 as having a moderate level of Risk, and 5 as having a low level of Risk.

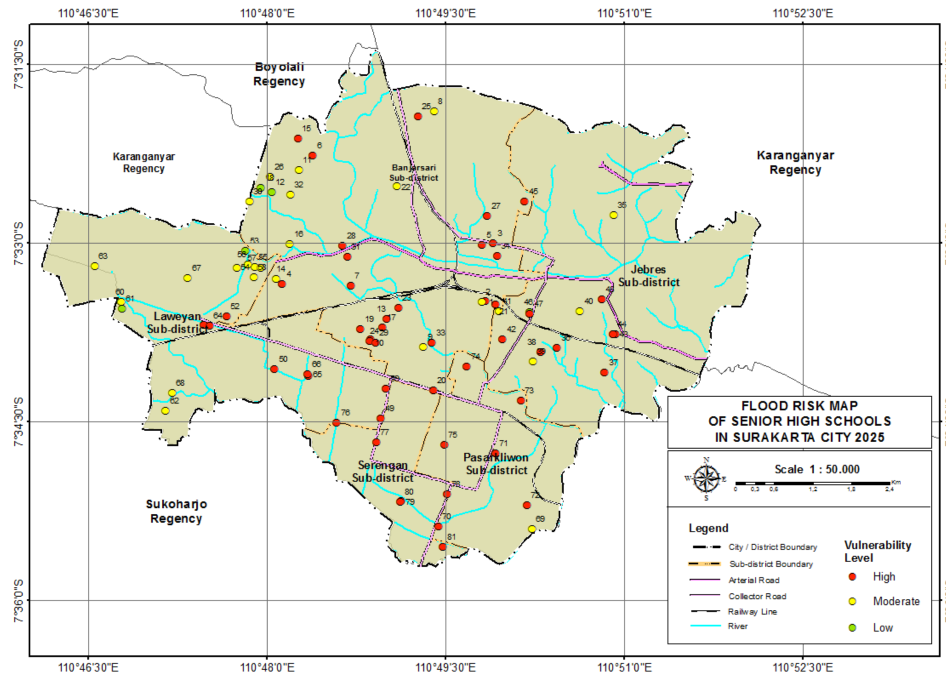

Figure 8. Flood Risk Map

2. Disscusion

a. Hazard

A hazard is a potential source of damage or a condition that can harm humans by disrupting safety and health (Nando & Yuamita, 2021). Hazards encompass not only natural phenomena but also biological processes, technology, and potentially harmful human activities. Flood hazard indicators are usually determined by combining flood hazard parameters. The parameters used for flood hazard mapping in Surakarta City are slope gradient, rainfall, river network, and land use. It aligns with the research by (Husein et al., 2025) on assessing flood hazard and risk in the Ziway Lake Watershed, Ethiopia, which integrated GIS, remote sensing, and the Analytic Hierarchy Process (AHP). This approach is relevant for urban areas, including Surakarta City. This study shares similar conditions, including increased settlement in lowlands and changes in land cover. The flood parameters in this study used eleven parameters, such as elevation, slope gradient, drainage density, rainfall, distance from rivers and roads, lithology, NDVI, TWI, soil texture, and land use.

Meanwhile, research conducted by (Chen et al., 2025) measured flood risk in the Jinsha Watershed using the Pressure-State-Response (PSR) and Weighted Frequency Ratio (WFR) models, integrated with Grey Relation Analysis (GRA). The flood hazard parameters in this study were rainfall, topography, slope gradient, river network density, land use, vegetation, and soil type. In contrast to the research by (Li et al., 2025), this study combined remote sensing (Sentinel-1 SAR) with explainable machine learning (XGBoost + SHAP) within the Hazard-Exposure-Vulnerability (HEV) framework to map flood risk in the Beijing, Tianjin, and Hebei regions. The flood hazard parameters in this study used rainfall, elevation, slope gradient, soil moisture, and topography. Furthermore, a study conducted by (Singha et al., 2025) used a hybrid Fuzzy-AHP method with six machine learning algorithms (RF, XGB, GBM, avNNet, AdaBoost, PLS) for flood hazard mapping in the Mahananda River watershed, India. The integrative approach combining subjective (AHP) and objective (ML) methods achieved high accuracy and flexibility for long-term spatial predictions. The flood hazard parameters in this study used elevation, slope gradient, soil type, soil moisture, rainfall, land use, vegetation index, geomorphology, drainage density, surface flow, and wind speed. Another study by (Shirzadi et al., 2025) measured urban flood vulnerability in Sanandaj City (Iran) using the Deep Abstract Network (DANet) algorithm and compared it with ANN, CNN, SVM, and LR models across 19 environmental and urban planning parameters. This study confirms that deep learning methods are highly effective for complex data in urban environments. The flood hazard parameters used in this study were elevation, slope gradient, distance to the river, distance from the river bed, rainfall, vegetation index (NDVI), land use, and soil type. These parameters influence the level of flood hazard, including rainfall. Almost everyone uses rainfall as a flood-hazard parameter because it is the primary factor triggering river flooding.

Based on the analysis, one of the parameters used to determine flood hazard is slope data. Slopes in Surakarta City are divided into three categories: steep, moderately steep, and gentle. Low-lying areas dominate Surakarta City, making it highly prone to flooding during heavy rainfall. It is in line with research conducted by (Seprianto et al., 2024), which revealed that the Andoolo District has a potential for flooding, especially in areas with low slopes, approximately 47% of the area. Low landforms can cause pooling at several points, leading to flooding.

Furthermore, research by (Jiang et al., 2025) indicates that slope is a significant factor influencing water flow energy and sediment distribution along rivers. On steep slopes, high flow energy narrows the river's path. Meanwhile, on gentle slopes, flow energy is lower, forming a branching river pattern with a wider sediment distribution. These differences in conditions result in significant variations in water flow capacity and the potential for inundation across slope types. The research conducted by (Musiyam, 2020), which examines areas affected by flooding due to extreme weather, states that regions with a slope of 0–7% are the most prone to flooding or can be considered to have a high level of flood hazard.

Based on field validation of the flood hazard map in Surakarta City, areas with a high flood hazard class show a relatively high level of accuracy relative to on-the-ground conditions. The field validation results showed that 12 points in the high-hazard class experienced flooding, while 3 points in the high-hazard class did not. Therefore, the high-hazard class map's accuracy was 80%, indicating that most areas were correctly categorized as high hazard based on on-the-ground conditions. Only 20% did not show flooding despite being spatially identified as high risk. Furthermore, in areas with a low flood hazard class, the validation results showed that 4 points experienced flooding and 10 did not. Therefore, the low-hazard class map's accuracy reached 28.57% for areas experiencing flooding and 71.43% for areas not experiencing flooding. It shows that most areas in the low-hazard category are relatively safe from flooding, though several points remain at risk.

b. Vulnerability

Vulnerability, a key aspect of disaster risk, assesses a community or region's susceptibility to hazards. It encompasses social, physical, economic, and environmental factors that influence disaster impacts.

Research indicates that physical vulnerability in senior high schools (SMA) in Surakarta City includes 57 schools with high vulnerability, 21 with moderate vulnerability, and 3 with low vulnerability. It indicates that most senior high schools in Surakarta are highly vulnerable to flooding. It indicates that the physical component has a relatively high risk of potential disasters. It is in line with what was done by (D'Ayala et al., 2020), who stated that public schools in developing countries are often in a State of high vulnerability to disaster hazards due to factors such as building designs that are not always resistant to earthquakes or floods, inadequate materials, lack of maintenance, and locations close to rivers or vulnerable areas. Furthermore, in contrast to research conducted by (Dahlia & Fadiarman, 2020) in Jakarta City, which stated that the vulnerability assessment resulted in 8 schools being non-vulnerable, 22 schools with a low level of vulnerability, 16 schools with a moderate level of vulnerability, and 4 schools with a high level of vulnerability. It indicates that most high schools in Jakarta have a low level of vulnerability. The research conducted by (Mukaroma et al., 2022b) in Sukoharjo states that the analysis of physical vulnerability was carried out using building structure, facilities, and the number of classrooms. The study found that there are two schools with medium vulnerability, namely SMPN 1 Grogol and SMPN 2 Grogol, while one school has low vulnerability, namely SMP Tahfidz Azzayadiy.

Based on the study's results, social vulnerability in Senior High Schools (SMA) in Surakarta City included 66 school points with high vulnerability, 14 with medium vulnerability, and 1 with low vulnerability. Based on this, it is known that Senior High Schools in Surakarta City have a dominantly high level of social vulnerability to flood hazards. Various factors, including the school community, the student gender ratio, and the teacher gender ratio, can contribute to this high level of social vulnerability. Thus, it can be seen that senior high schools in Surakarta City are still not sufficiently resilient to withstand potential flood hazards. In contrast, research by (Yousefi et al., 2020a) found that 492 schools in rural areas and 147 in urban areas are located in the very high vulnerability zone. The percentage of students in these very vulnerable schools is 54% in rural areas and 8% in urban areas.

Furthermore, research conducted by (Septiningrum et al., 2022) in Sukoharjo Regency identified three schools with very high social vulnerability, one with high, and one with low social vulnerability. The schools with very high social vulnerability were SDN 1 Madegondo, SDN 1 Pandeyan, and SDN 1 Kadokan. The school with high social vulnerability was SDN 2 Pandeyan, and the school with low social vulnerability was SDN 3 Madegondo.

Based on the research results, the total vulnerability level, a combination of social and physical vulnerability, in high schools in Surakarta City showed a very significant result. 57 schools were found to be highly vulnerable, meaning their buildings and social infrastructure were less prepared to withstand flooding. Furthermore, 27 schools were at a moderate level of vulnerability, indicating that they still had vulnerability components and could be considered somewhat safe but still moderate. Meanwhile, only one school is classified as low vulnerability, indicating that most schools in Surakarta City have preparedness levels that need improvement in the face of disasters, especially floods. In contrast, research by (Aisha et al., 2019) in the Pepe Hilir Watershed, Surakarta, found that flood vulnerability was assessed using 3 factors: physical, social, and economic vulnerability. The analysis of these three aspects indicates that most of the research area falls within the low vulnerability classification, meaning that if a flood occurs, the Pepe Hilir Watershed research area is less likely to suffer losses.

In contrast to research conducted by (Guillard-Gonçalves & Zêzere, 2018) in Loures, Portugal. This research develops an integrative approach to analyzing landslide risk at the City/Regency level by combining social vulnerability and physical vulnerability. Social vulnerability is calculated based on sensitivity (population density, youth/old age, gender, and illiteracy) and lack of resilience (unemployment, dependency, housing conditions, rental status, and accessibility). Meanwhile, physical vulnerability is determined based on building structures. The results show that 0.9% of the population and 0.8% of buildings in Loures are located in high-risk landslide zones.

c. Risk

Risk is the result of the interaction between hazard, vulnerability, and capacity throughout all phases of the disaster management cycle (Slotsvik et al., 2025). Risk is the consequence of uncertainty about things considered valuable to humans. Disaster risk refers to the potential loss caused by a disaster in a specific area and time period.

Based on the research results, high schools in Surakarta City showed very significant differences in flood risk levels. 51 schools were classified as high risk, meaning they could be severely impacted in the event of a flood. Meanwhile, 25 schools were classified as medium-risk, meaning they could be affected by flooding but with a lower level of threat. Furthermore, five schools were classified as low risk, indicating they were relatively safe from the potential impacts of flooding. It aligns with research by (Yousefi et al., 2020b), which found that 1,622 schools in Iran are vulnerable to flooding. However, not all schools are at high risk of flooding; 492 are in rural areas, and 147 are in urban areas. The results of this study found that more than 30% of schools are in high-risk zones, indicating that schools are public facilities that are highly at risk of flooding, especially in densely populated areas. It contrasts with research by (Grant et al., 2024) on flood risk analysis of essential facilities in Iowa using the HAZUS-FEMA approach, considering flood depth, loss of function, and facility recovery time. The results of this study showed that 39% of schools were at risk of flooding.

Conclusion

Based on the research findings, this study highlights the importance of flood risk analysis in Surakarta City, particularly in high schools (SMA) that are at risk of flooding. Surakarta City is highly vulnerable to flooding due to its gently sloping topography, increased rainfall, and changes in land use resulting in increasingly dense settlements around the Bengawan Solo River Basin. Using the Weighted Sum Method and field validation, spatial analysis yielded flood hazard, vulnerability, and risk maps, indicating that most areas of Surakarta fall into the high-hazard and high-vulnerability categories. The results showed that areas with a high hazard class achieved up to 80% accuracy in predicting actual field flood events, while areas with a low hazard class achieved only 28.57%. In terms of vulnerability, 57 schools had high physical vulnerability, 21 had moderate, and 3 had low. Regarding social aspects, 66 schools were classified as very vulnerable, 14 as moderately vulnerable, and 1 as lowly vulnerable. Combining these two aspects yields 57 schools with high vulnerability, 27 with moderate vulnerability, and 1 with low vulnerability. Further risk analysis reveals 51 schools with high flood risk, 25 with moderate vulnerability, and only 5 with low vulnerability, meaning that the majority of high schools in Surakarta City are at high risk of flooding. Overall, the results of this study confirm that schools in Surakarta City require special attention in flood risk mitigation. This study also provides a scientific basis for the government and relevant parties to strengthen the Disaster-Safe Education Unit (SPAB) policy and implement spatial planning that is more adaptive to environmental changes. Therefore, this flood risk analysis is expected to serve as a strategic reference in efforts to increase school and community resilience to future flood threats.

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