




ISSN: 2785-2997

Journal of Human, Earth, and Future

Vol. 7, No. 2, June, 2026



Flood Risk Mapping Based on Vulnerability Factors Assessment and Raster Analysis

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Received 01 August 2025; Revised 30 March 2026; Accepted 11 May 2026; Published 01 June 2026

Abstract

This study aims to assess and map flood disaster risk in Central and North Jakarta, Indonesia, by integrating spatial analysis and vulnerability-based flood risk modeling. The objective is to identify vulnerability levels and the spatial probability of flood occurrence to support risk-based decision-making and mitigation planning. The analysis incorporates four vulnerability components (social, economic, physical, and environmental), combined with flood vulnerability raster data derived from spatial overlays. A multi-criteria spatial classification and weighted scoring approach was applied to determine vulnerability levels and categorize flood risk zones. The findings revealed that Central Jakarta has a spatial vulnerability score of 2.5, while North Jakarta has a score of 2.6, indicating high vulnerability in both regions. Component scores for Central Jakarta were social (2–moderate), economic (3–high), physical (3–high), and environmental (2–moderate). In comparison, North Jakarta demonstrated higher environmental vulnerability (3–high), with other components showing similar levels. Approximately 90.69% of Central Jakarta and 85.82% of North Jakarta lie within high vulnerability zones, resulting in spatial flood probabilities of 0.999 and 0.931, respectively. The novelty of this research lies in integrating multi-dimensional vulnerability factors with raster-based spatial probability modeling, providing comprehensive flood risk mapping for urban coastal regions.

Keywords: Flood; Spatial Analysis; Raster; Vulnerability; Disaster; Mapping.

1. Introduction

Flood disasters are among the most destructive natural hazards worldwide, affecting multiple sectors and emphasizing the need for comprehensive risk assessment and coordinated mitigation strategies [1, 2]. Indonesia is highly susceptible to flooding, with recurring events occurring in major cities, including Jakarta. According to the Jakarta Regional Disaster Management Agency (BPBD), extreme rainfall intensity largely triggered recent flood events in Jakarta [3]. This trend is intensified by climate change, where extreme rainfall events increase in intensity and frequency, thereby amplifying flood hazards [4-6]. However, hazard alone is insufficient; therefore, regional vulnerability and spatial conditions must also be considered in flood risk assessments [7]. While floods are challenging to predict and prevent, GIS-based spatial analysis provides a valuable tool for identifying and mapping areas at risk of flooding, thereby supporting more effective mitigation and management efforts [8-10].

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 <https://doi.org/10.28991/HEF-2026-07-02-07>

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Indonesia's disaster risk paradigm recognizes that flood risk is shaped not only by hazard but also by social, economic, physical, and environmental vulnerability components, as stated by the National Disaster Management Agency (BNPB) [11, 12] and international disaster risk frameworks, such as the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Office for Disaster Risk Reduction (UNDRR) [4, 13, 14]. Vulnerability is highly dependent on the hazard context, as it is shaped by individual factors and behavior within that context, history, socio-political-cultural factors, and natural processes. This includes land use, public infrastructure, population damage, and economic losses. The factors that make someone vulnerable are complex, and vulnerability can be both a risk factor and an impact of a disaster [15]. Social vulnerability leverages various vulnerabilities at the individual and community levels, including population density, resource access, and socio-cultural conditions, that increase susceptibility to flood impacts [16-21]. Economic vulnerability reflects a community's capacity to absorb financial losses arising from disasters [12, 22, 23]. Physical vulnerability assesses the susceptibility of built assets and infrastructure to damage under flood hazard [12, 19, 24, 25]. Land cover change and ecosystem degradation drive environmental vulnerability, which can intensify flood impacts by reducing natural buffering capacity [12, 26].

According to the National Disaster Management Agency of Indonesia, the vulnerability analysis of flood disasters can be conducted using four vulnerability factors: social (e.g., population density and vulnerable groups), economic (e.g., productive land value and gross regional domestic product), physical (e.g., residential buildings, public facilities, and critical facilities), and environmental (e.g., land cover) factors [22]. However, existing studies on flood risk in Jakarta have rarely integrated these four vulnerability dimensions within a unified spatial modeling framework, and most have not incorporated refined topographic parameters, such as elevation and slope, to strengthen physical vulnerability assessment [27, 28]. Furthermore, previous research has typically focused on either hazard mapping or single-dimension vulnerability analysis, resulting in limited understanding of probabilistic spatial flood risk patterns in densely populated coastal areas such as Central and North Jakarta.

To address this research gap, this study aims to develop a comprehensive spatial flood risk assessment model that integrates multi-dimensional vulnerability indicators with spatial physical parameters and flood-vulnerability raster datasets. The model produces spatial vulnerability scores, classifies flood risk zones, and estimates probabilistic flood occurrence at high spatial detail. The novelty of this research lies in its combination of multi-criteria vulnerability assessment and raster-based overlay modeling to generate data-driven, location-specific flood risk outputs tailored for urban coastal planning and mitigation. This approach provides actionable insights to support evidence-based decision-making for flood risk reduction in Jakarta, especially Central and North Jakarta.

The remainder of this article is structured as follows: Section 2 describes the study area; Section 3 presents the literature review, including some recent works about flood risk analysis, flood vulnerability factors, and raster data in spatial analysis; Section 4 discusses the data sources and methodology; Section 5 discusses the findings; and Section 6 concludes with key implications and recommendations for flood risk management.

2. Study Area

This study was conducted in Central Jakarta (*longitude* 106.83; *latitude* -6.18) and North Jakarta (*longitude* 106.87; *latitude* -6.13), Jakarta, Indonesia. Jakarta is a region in Indonesia that frequently experiences flood disasters [29, 30]. The geographical and environmental characteristics of Jakarta contribute significantly to its flood vulnerability, as the city is located on a low-lying coastal plain with an average elevation of less than 10 m above sea level and is traversed by 13 major rivers that discharge through the metropolitan area before flowing into Jakarta Bay [31].

This study area was selected according to previous studies about flood disasters in Jakarta, which resulted in high susceptibility to flooding in Central and North Jakarta [3, 32-34]. Additionally, these districts hold strategic economic importance, characterized by high population density and critical infrastructure, making flood risk assessment essential for disaster resilience planning [34]. Figure 1 presents the study area.

3. Literature Review

3.1. Recent Flood Risk Assessment Studies in Jakarta

In recent years, flood risk assessment in Jakarta has received increasing attention due to the city's high vulnerability to frequent urban and coastal flooding. Various methodological approaches, including GIS-based spatial analysis, multi-criteria evaluation, hydrological and hydraulic modeling, remote sensing, and vulnerability assessment, have been applied to understand the dynamics of flood hazard, exposure, and vulnerability across different areas of the city [27, 28, 35]. Although these studies provide valuable insights into specific aspects of flood risk, such as social vulnerability, land-use change, or hydrodynamic behavior, they are often fragmented and focus on one or two dimensions. Consequently, a comprehensive understanding of the flood risk in Jakarta, such as the integration of social, economic, physical, and environmental dimensions of vulnerability with spatially refined hazard and topographic parameters, remains limited. Table 1 summarizes selected recent studies, highlighting the methods, study areas, and key findings.



Figure 1. The Study Area: a) North Jakarta, b) Central Jakarta

Table 1. Recent Studies on Flood Risk and Vulnerability in Jakarta

Year	Authors	Methods	Study Area	Key Finding
2024	Gunandar et al. [28]	Quantitative assessment of coastal-settlement vulnerability (social, settlement data)	Kalibaru Subdistrict, North Jakarta	Identifies high vulnerability in coastal settlement due to social and adaptive-capacity factors
	Ariyani et al. [36]	GIS and MCDA to produce flood hazard maps	Ciliwung watershed, Jakarta	Mapped and validated hazard zones with historical flood incidents; shows an increase in hazard area over time
	Juliastuti et al. [37]	Hydrological modelling and GIS floodplain analysis	East Sunter Polder System, located in the north and east of Jakarta	Demonstrates polder system insufficient; proposes green-infrastructure solutions
2025	Pindarwati et al. [38]	Satellite imagery + MCDA for high-resolution flood vulnerability mapping	Jakarta	Offers a vulnerability map at fine spatial resolution combining environmental/spatial factors
	Amiruddin et al. [39]	Qualitative assessment: interviews, policy & institutional analysis, early-warning, community preparedness	Jakarta	Highlights governance gaps, community awareness, weaknesses in risk reduction strategies
	Muhammad et al. [40]	GIS and weighted-overlay method	Greater Jakarta	More than 60% of study area is classified as high to very high flood hazard; identified hazard zones with five hazard levels.

Recent studies on flood risk assessment in Jakarta (2024–2025) revealed that while a variety of methods, including GIS-based spatial analysis, multi-criteria evaluation, hydrodynamic modeling, remote sensing, and governance assessments, have been applied, most studies focus on only one or two dimensions of flood risk, such as social vulnerability, land-use change, or hazard mapping. Although high-resolution spatial analyses and probabilistic hazard modeling exist, they rarely integrate all four key vulnerability dimensions (social, economic, physical, and environmental) within a unified framework. Consequently, a comprehensive, spatially explicit understanding of flood risk in densely populated coastal areas, such as Central and North Jakarta, remains limited. This fragmented evidence underscores the need for an integrated approach that combines multi-dimensional vulnerability assessment with refined topographic parameters and probabilistic flood mapping.

3.2. Flood Vulnerability Factors

The National Disaster Management Agency (BNPB) of Indonesia states that there are four vulnerability factors of disasters: social, economic, physical, and environmental factors [11, 12]. Each vulnerability factor has contributing parameters [33-36]. The four factors determine the vulnerability factors of flood disasters, as illustrated in the diagram presented in Figure 2.

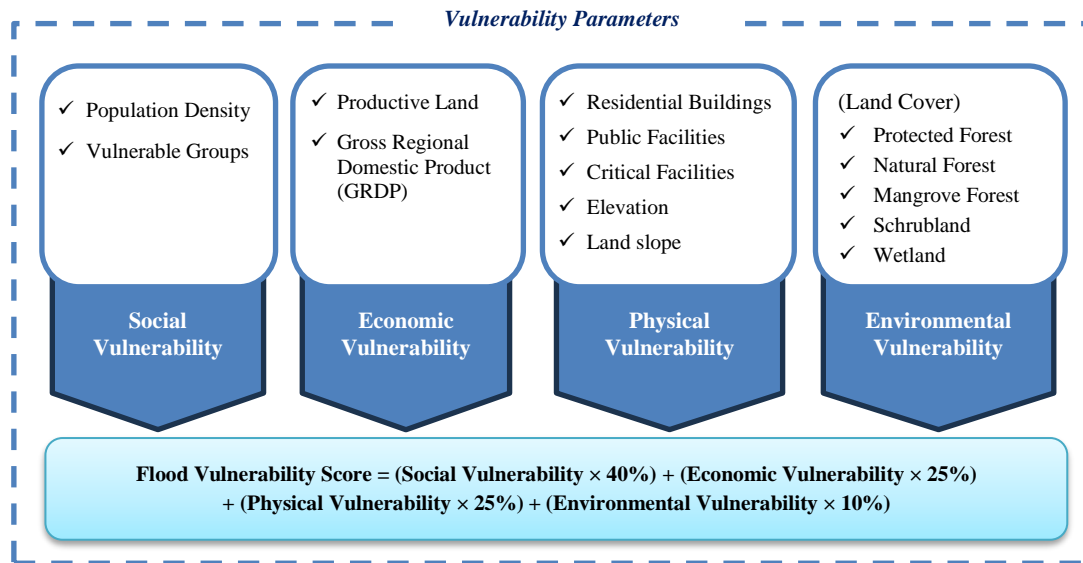


Figure 2. Structure Diagram of Flood Vulnerability

• Social Vulnerability

Social vulnerability, also known as the potential population exposure, contains information about community groups that are more susceptible to negative impacts, such as death, injury, loss of livelihoods, or disruption, in the event of a disaster [10, 19]. Social vulnerability consists of the population density and vulnerable groups contributing parameters. The social vulnerability score is determined based on the scoring system outlined in BNPB Regulation No. 2 of 2012 [41], as shown in Table 2.

Table 2. Parameters and Scoring of Social Vulnerability

Parameter	Weight (%)	Class		
		Low	Moderate	High
Population Density	60	<5 people/ha	5-10 people/ha	>10 people/ha
Vulnerability Groups:				
Gender Ratio (10%)		>40	20-40	<20
Ratio of Vulnerable Age Groups (10%)	40			
Ratio of Poor Population (10%)		<20	20-40	>40
Ratio of Disabled Population (10%)				

Note:

1. The vulnerability class scores are categorized as follows: 1 = Low, 2 = Moderate, and 3 = High [35,37,38]
2. The gender ratio is the comparison between the number of male and female residents.
3. The ratio of vulnerable age groups is the proportion of the population aged 0–4 years and over 60 years to the total population.

The social vulnerability score is calculated based on BNPB Regulation No. 2 of 2012 concerning the General Guidelines for Disaster Risk Assessment, using the formula in Equation 1 as follows:

$$\begin{aligned}
 \text{Social vulnerability score} &= (0.6 \times \text{population density score}) + (0.1 \times \text{gender ratio score}) \\
 &+ (0.1 \times \text{ratio of vulnerable age groups score}) + (0.1 \times \text{ratio of poor population score}) \\
 &+ (0.1 \times \text{ratio of disabled population})
 \end{aligned}
 \tag{1}$$

• Economic Vulnerability

Economic vulnerability to disasters indicates the ability of a region or community group to bear the impact of losses and economic condition resulting from the disaster [12, 22, 23]. Economic vulnerability consists of two parameters: productive land and Gross Regional Domestic Product (GRDP). The monetary value of productive land is calculated based on the GRDP contribution from sectors related to productive land, which can be classified according to land use data. Each parameter is analyzed using a scoring method to obtain the economic vulnerability score, as shown in Table 3 [41].

Table 3. Parameters and Scoring of Economic Vulnerability

Parameter	Weight (%)	Class		
		Low	Moderate	High
Productive Land	60	< IDR 50 million	IDR 50-200 million	> IDR 200 million
Gross Regional Domestic Product (GRDP)	40	< IDR 100 million	IDR 100-300 million	> IDR 300 million

Note: The vulnerability class scores are categorized as: 1 = Low, 2 = Moderate, 3 = High [35, 37, 38].

The economic vulnerability score is calculated based on BNPB Regulation No. 2 of 2012 using the formula in Equation 2 as follows:

$$Economic\ vulnerability\ score = (0.6 \times productive\ land\ score) + (0.4 \times GRDP\ score) \tag{2}$$

• **Physical Vulnerability**

Physical vulnerability to disasters measures the vulnerability of an area or structure to the negative impacts of a disaster. Physical vulnerability has the potential to damage physical structures during a disaster. Physical vulnerability can also be defined as the extent of loss to elements at risk [12, 18, 24, 26]. Physical vulnerability consists of three parameters: residential buildings, public facilities, and critical facilities. The values in Table 4 for each class represent the justified monetary value (in IDR) of each parameter in the event of damage. The parameters and scoring of physical vulnerability [41] are adjusted as shown in Table 4:

Table 4. Parameters and Scoring of Physical Vulnerability

Parameter	Weight (%)	Class		
		Low	Moderate	High
Residential Buildings	40	< IDR 400 million	IDR 400-800 million	> IDR 800 million
Public Facilities	30	< IDR 500 million	IDR 500 million – 1 billion	> IDR 1 billion
Critical Facilities	30	< IDR 500 million	IDR 500 million – 1 billion	> IDR 1 billion

The calculation of physical vulnerability for all parameters (except residential buildings) is based on the following hazard class influences: low, moderate, and high hazard classes have 0%, 50%, and 100% impact, respectively. For the residential buildings parameter: in the low hazard class, the number of affected residential buildings is multiplied by IDR 5 million; in the moderate hazard class, it is multiplied by IDR 10 million; and in the high hazard class, it is multiplied by IDR 15 million.

The physical vulnerability score is calculated based on BNPB Regulation No. 2 of 2012 using the following formula in Equation 3:

$$Physical\ vulnerability\ score\ (BNPB) = (0.4 \times housing\ score) + (0.3 \times public\ facilities\ score) + (0.3 \times critical\ facilities\ score) \tag{3}$$

Given the various available parameters to assess physical vulnerability to flooding, additional parameters such as elevation and land slope were incorporated to enhance the determination of the flood vulnerability score [42-44]. The class scores for elevation and land slope are based on previous studies regarding flood causative factors [44], with adjustments made by the researcher to maintain a three-class vulnerability scoring system, as specified in Table 5:

Table 5. Class Scores for Elevation and Land Slope in Physical Vulnerability

Parameter	Class Score
Elevation:	
< 75 m.a.s.l.	3
75 – 250 m.a.s.l.	2
> 250 m.a.s.l.	1
Land Slope:	
< 8%	3
8 – 30%	2
> 30%	1

Equation 4 presents the calculation of the physical vulnerability score based on elevation and land slope parameters, while Equation 5 shows the total physical vulnerability score.

$$\text{Physical vulnerability score (additional parameters)} = (0.5 \times \text{elevation score}) + (0.5 \times \text{land slope score}) \tag{4}$$

$$\text{Physical vulnerability score (total)} = (0.5 \times \text{physical vulnerability score(BNPB)}) + (0.5 \times \text{physical vulnerability score(additional parameters)}) \tag{5}$$

• **Environmental Vulnerability**

Exacerbation of environmental vulnerability by land cover change and climate change amplifies the impacts of disasters. In essence, disasters disrupt in environmental conditions [12, 26]. Environmental vulnerability consists of parameters such as protected forest, natural forest, mangrove forest, shrubland, and wetlands. Each of these parameters can be identified using land cover data. In this study, environmental vulnerability classes were scored using the Land Cover Quality Index (LCQI), as defined by the Ministry of Environment and Forestry of Indonesia (KLHK) and Jakarta Environmental Agency [45]. The index is calculated based on the area of forest vegetation (protected forest, natural forest, and mangrove) and non-forest vegetation (shrubland and wetlands). Land Cover (LC) is calculated as shown in Equation 6, while the calculation of Land Cover Quality Index (LCQI) is presented in Equation 7. The environmental vulnerability score is shown in Table 6.

$$LC = \frac{\text{forest vegetation area} + (\text{non - forest vegetation area} \times 0.6)}{\text{total area}} \tag{6}$$

$$LCQI = 100 - \left((84.3 - (LC \times 100)) \times \frac{50}{54.3} \right) \tag{7}$$

Table 6. The Classification of Environmental Vulnerability Score

LCQI Value	Land Cover Condition	Environmental Vulnerability Score	Environmental Vulnerability Class
> 80	Excellent	0	Not Vulnerable
50 – 80	Good	1	Low
26 – 50	Moderate	2	Moderate
0 – 26	Poor	3	High

The classification of vulnerability scores into four vulnerability class is based on three categories of vulnerability [38]:

$$\begin{aligned} \text{low class: } & 1 \leq \text{vulnerability score} \leq 1.6 \\ \text{medium class: } & 1.7 \leq \text{vulnerability score} \leq 2.3 \\ \text{high class: } & 2.4 \leq \text{vulnerability score} \leq 3 \end{aligned} \tag{8}$$

3.3. Raster Data in Spatial Analysis

Spatial analysis is a fundamental capability that involves structuring or processing spatial data to derive enhanced or novel interpretations [46]. In this study, spatial analysis is employed to analyze raster data derived from regional maps containing flood vulnerability indices using ArcGIS software. Raster data is one of the commonly used data types in Geographic Information Systems (GIS) and digital mapping. It represents geographic information as a grid comprising small cells known as pixels. Each pixel holds a value that corresponds to specific information, such as color intensity, elevation, or land use classification [47]. GIS serves as a powerful tool for efficiently processing, managing, and analyzing diverse data models and types [48]. Raster data is structured in a grid format, where each cell (pixel) within the grid represents a specific geographic area and stores a data value. The size of the cells in the grid determines the resolution of raster data; smaller cell sizes indicate higher resolution. Each pixel contains a value that can be numerical or categorical, representing attributes of the mapped area, such as temperature, elevation, or land use. Figure 3 presents the raster data illustration.

Raster-based spatial statistics refer to analytical methods applied to each cell within a raster dataset. This type of analysis involves the calculation of statistical measures for individual pixels or groups of pixels to identify patterns and distributions of spatial phenomena [46]. The raster stores one or more values at each grid cell. A high-resolution raster has more grid cells that are closer together than a low-resolution raster; thus, it requires more memory to store data [49].

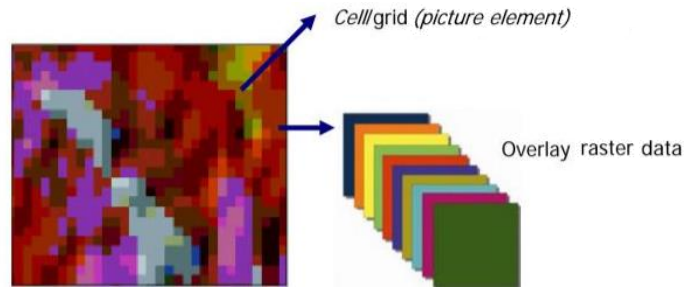


Figure 3. The Illustration of Raster Data [46]

4. Data and Methods

The data used in this study include vulnerability parameters from each factor (social, economic, physical, and environmental), as presented in Table 7, as well as raster-based flood vulnerability data obtained from InaRISK-National Disaster Management Agency (BNPB) (Figure 4). The data used in this study are in 2021, adjusted to match the flood vulnerability raster data.

Table 7. Parameters Used to Assess Vulnerability for Social, Economic, Physical, and Environmental Factors

Vulnerability Factor	Parameter	Data Type	Source
Social	Population Density	Numeric	BPS-Statistics Indonesia
	Gender Ratio		
	Ratio of Vulnerable Age Groups		
	Ratio of Poor Population		
	Ratio of Disabled Population		
Economic	Productive Land	Numeric	BPS-Statistics Indonesia
	Gross Regional Domestic Product (GRDP)		
Physical	Residential Buildings	Raster	Indonesia Geospasial (http://indonesia-geospasial.com); Central Jakarta City Government (https://pusat.jakarta.go.id); North Jakarta City Government (https://utara.jakarta.go.id).
	Public Facilities	Numeric	InaRISK-National Disaster Management Agency (BNPB)
	Critical Facilities		
	Elevation	Raster	Ina-Geoportal (http://tanahair.indonesia.go.id) Indonesia Geospasial (http://indonesia-geospasial.com)
	Land slope		
Environmental	Land Cover	Numeric	Ministry of Environment and Forestry of Indonesia (KLHK) and Jakarta Environmental Agency

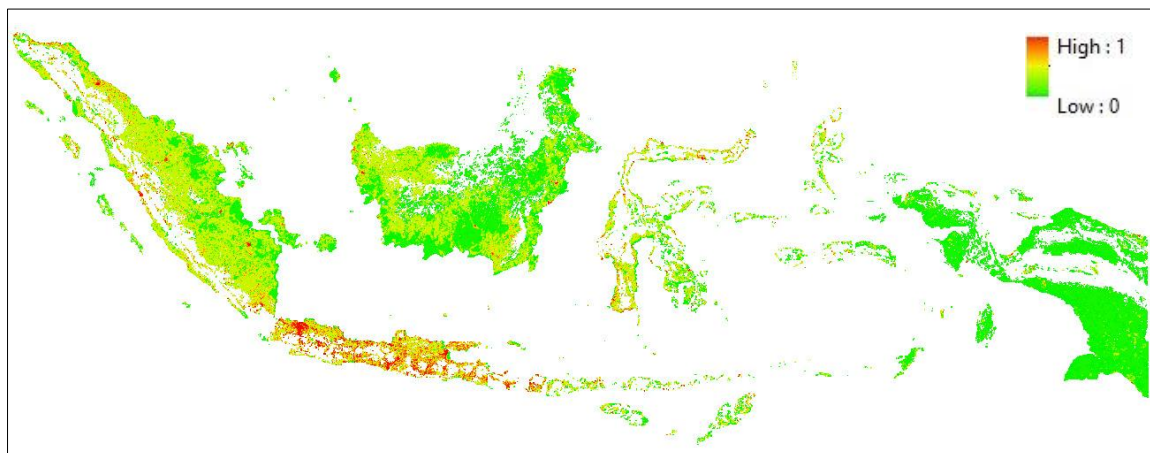


Figure 4. The Flood Vulnerability Raster Data of Indonesia (InaRISK-BNPB)

The theoretical foundation of this study is based on the disaster risk conceptual framework according to IPCC and UNDRR (2022), which defines risk as a function of hazard, exposure, and vulnerability [50, 51]. Accordingly, this study employs a multi-dimensional vulnerability factor to integrate four dimensions of vulnerability (social, economic, physical, and environmental) as recommended by BNPB [12] and described in Section 3.2. These criteria are

operationalized in a GIS-based weighted overlay model, where each variable is weighted to generate a composite spatial vulnerability index. Refined physical parameters, including elevation and slope, are incorporated to enhance the structural sensitivity to flood impacts. The vulnerability model was then combined with raster-based flood hazard and probabilistic spatial modeling to classify flood risk levels and estimate the likelihood of flood occurrence in Central and North Jakarta.

The application of GIS-based weighted overlay modeling in disaster risk assessment has been widely recognized in the literature as an effective method for integrating multiple vulnerability indicators into a single composite index [52]. In this approach, each criterion or variable (social, economic, physical, and environmental indicators) is assigned a weight reflecting its relative contribution to overall vulnerability. Weighted overlay methods allow for spatially explicit assessment, enabling the identification of areas with higher flooding vulnerability [53, 54]. This methodology has been successfully applied in various urban flood risk studies to map multidimensional vulnerability and support disaster management decision-making [55, 56]. The incorporation of refined physical parameters, such as elevation and slope, enhances the ability of the model to capture structural sensitivity to flood impacts. Elevation influences the likelihood of inundation, while slope affects surface runoff and water accumulation, both of which are critical in flood-prone urban environments [57]. The vulnerability model becomes more sensitive to site-specific flood conditions by integrating these physical factors, reflecting the heterogeneity of urban landscapes.

The spatial vulnerability index is combined with raster-based flood hazard maps and probabilistic modeling to estimate flood risk levels. Raster-based hazard mapping provides high-resolution spatial representation of flood-prone areas, whereas probabilistic modeling allows for the estimation of flood likelihood based on historical events and hydrological data [58, 59]. The resulting risk classification reflects not only the potential severity of flooding but also the probability of occurrence, enabling a comprehensive assessment of flood risk in Central and North Jakarta.

The analysis method is illustrated in Figure 5. The analysis begins with the collection of vulnerability parameter data for each factor. Subsequently, flood vulnerability scores are calculated for each respective factor based on assigned weights. Once the scores are obtained, they are overlaid with the flood vulnerability raster data from InaRISK-BNPB. Subsequently, the resulting overlay raster is then converted into polygon format, and the area of each vulnerability class (low, moderate, and high) is calculated. These area calculations are then used as the basis for determining the spatial probability of flood occurrence within the study area.

The area of each flood vulnerability class is used to determine the flood risk category of a region, specifically whether it falls under high risk or low risk. The classification of regional flood risk refers to the disaster risk index, whereby regions with a risk index greater than 0.6 are categorized as high risk (BNPB). Accordingly, in this study, if more than 60% of a region falls within the 'high' flood vulnerability class, it is classified as a high-risk area. Conversely, if 60% or less of the region falls into the 'high' vulnerability class, it is categorized as low risk. The formulas used to calculate the spatial probability of flood occurrence for both high-risk and low-risk areas are presented in Equations 9 and 10, respectively, as follows:

Spatial probability of Flood Occurrence in High-Risk Areas:

$$P_{High Risk} = \frac{\text{Area of 'high' vulnerability class}}{\text{Total area of all vulnerability classes (low, medium, high)}} \tag{9}$$

Spatial probability of Flood Occurrence in Low-Risk Areas:

$$P_{Low Risk} = \frac{\text{Area of 'low' and 'medium' vulnerability classes}}{\text{Total area of all vulnerability classes (low, medium, high)}} \tag{10}$$

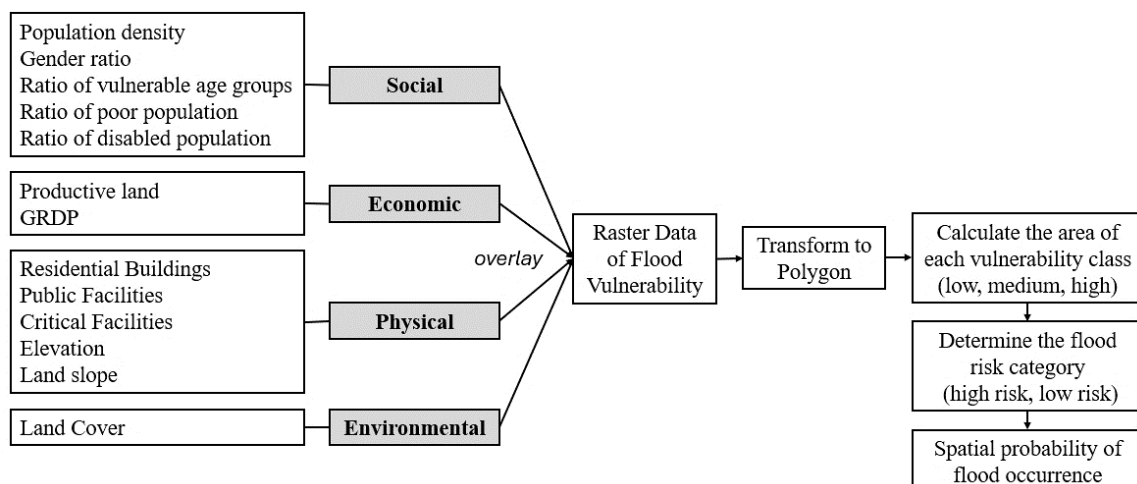


Figure 5. Diagram of Data Analysis

5. Results and Discussion

5.1. Social Vulnerability Analysis

The scoring of social vulnerability to flooding, derived from the analysis conducted in Central Jakarta and North Jakarta, is presented in the following Table 8:

Table 8. The Scoring of Social Vulnerability to flooding in Central and North Jakarta

City	Subdistrict	Population density (people/ha) (60%)	Class score	Vulnerable Group (40%)								Social Vulnerability Score	Social Vulnerability Class
				Gender ratio (%)	Class score	Ratio of vulnerable age group (%)	Class score	Ratio of poor population (%)	Class score	Ratio of disabled population (%)	Class score		
Central Jakarta	Senen	281.69	3	106	1	29.91	2					2.3	Moderate
	Tanah Abang	188.16	3	115	1	16.96	1					2.2	
	Sawah Besar	198.99	3	100	1	19.53	1					2.2	
	Menteng	122.91	3	101	1	18.83	1					2.2	
	Kemayoran	331.74	3	101	1	9.95	1	4.68	1	0.05	1	2.2	
	Johar Baru	562.53	3	103	1	16.42	1					2.2	
	Gambir	120.80	3	102	1	19.67	1					2.2	
	Cempaka Putih	200.40	3	99	1	17.20	1					2.2	
North Jakarta	Penjaringan	89.49	3	102.78	1	17.35	1					2.2	Moderate
	Pademangan	170.29	3	104.19	1	16.11	1					2.2	
	Tanjung Priok	166.29	3	101.91	1	17.70	1					2.2	
	Koja	261.37	3	103.12	1	15.36	1	6.78	1	0.03	1	2.2	
	Kelapa Gading	352.37	3	96.40	1	19.83	1					2.2	
	Cilincing	114.90	3	102.33	1	14.69	1					2.2	

Source: BPS-Statistics Indonesia.

The data were collected from BPS-Statistics Indonesia for both Central Jakarta and North Jakarta. While most data were available at the subdistrict level, some datasets were only available at the city-wide level. Some of the collected data did not directly yield final values but required additional calculations according to the specific formulas of each ratio. For example, to calculate the ratio of vulnerable age groups, data were first gathered on the population aged 0–4, 60–64, 65–69, 70–75, and 75+ (as defined by BPS), along with the total population of each subdistrict. The ratio of vulnerable age groups was then calculated using these values. The gender ratio is the comparison between the number of male and female residents. The data were then classified into vulnerability classes (low, moderate, high) using the criteria presented in Table 2. The vulnerability class scores are categorized as: 1 = low, 2 = moderate, 3 = high, as mentioned before. The classification of social vulnerability scores into vulnerability classes was based on the three-level vulnerability criteria described in Equation 8.

The scoring results presented in Table 8 indicate that all subdistricts in Central Jakarta and North Jakarta fall into the ‘moderate’ social vulnerability class. This pattern suggests that although socio-demographic characteristics vary across subdistricts, the overall capacity of communities to anticipate, respond to, and recover from flood events remains limited. Population density emerges as the most influential factor, with the highest-class score in nearly all subdistricts. Highly concentrated areas such as Johar Baru, Sawah Besar, Kemayoran, and Kelapa Gading exhibit dense built environments that elevate people’s exposure to inundation and intensify pressure on drainage, emergency response systems, and evacuation infrastructure. These findings are consistent with previous research conducted in other parts of Jakarta and Southeast Asia, which also identified population density as a dominant driver of social vulnerability. For example, previous research studies found that dense urban settlements significantly reduce adaptive capacity due to limited evacuation space and constrained social support networks [60, 61]. Similarly, the other study reported that densely populated coastal zones in Jakarta demonstrate heightened sensitivity to repeated flood events, even when indicators such as poverty levels or age-based vulnerability are moderate [62]. In contrast, other parameters in the present study, such as the ratio of vulnerable age groups, the proportion of poor residents, and the proportion of disabled populations, show lower class scores. This aligns with the findings of previous study which noted that not all

socio-economic fragility indicators strongly influence community vulnerability when urban density is the primary determinant of exposure [60]. However, moderate levels of socio-demographic fragility can still interact with physical exposure to amplify risk, echoing tendencies observed in prior studies on Jakarta's flood-prone districts [63].

Figure 6 presents the social vulnerability map of Central and North Jakarta. The map was generated based on the scoring results outlined in Table 8, which show that all subdistricts in both Central and North Jakarta fall within the 'moderate' social vulnerability class in relation to flood hazards. Consequently, these areas are represented in yellow on the map, indicating a moderate level of vulnerability.



Figure 6. The Social Vulnerability Map to Flooding in Central and North Jakarta

The overall classification of 'moderate' vulnerability across all subdistricts further reflects the broader trend identified in earlier assessments indicating that Jakarta's urban communities possess partial resilience capacities. Therefore, the present findings reinforce previous evidence that Jakarta's social vulnerability to flooding is shaped not by a single critical variable but by the interaction between demographic characteristics, spatial exposure, and the limitations of community coping mechanisms.

5.2. Economic Vulnerability Analysis

Economic vulnerability is measured using two parameters: the value of productive land and the GRDP by sector. Productive land, in the context of economic vulnerability, includes various types of land use that contribute to community income and livelihoods. This includes land used for forestry, plantations, livestock, food crops (agriculture), mining, and other sectors. GRDP measures the total value of goods and services produced by several sectors within a region over a specific period, typically one year. It serves as a key indicator for assessing the economic condition and development of a region. In contrast to social vulnerability, for which data were collected at the subdistrict level, a different approach was applied to assess economic vulnerability. The data for each economic vulnerability parameter were available only at the city level for Central and North Jakarta. Productive land was measured through several land use productivity sectors, including agriculture, plantations, livestock, forestry, as well as mining and energy. Adjustments were made based on the availability of data obtained from BPS-Statistics Indonesia.

For GRDP, the data were calculated by economic sector, so the resulting economic vulnerability assessment applies to the entirety of Central and North Jakarta. A key limitation of this approach is that the economic vulnerability assessment relied on city-level GRDP and productive land valuation because subdistrict-level economic indicators are not publicly available in Jakarta's statistical databases. As a result, the economic values were applied uniformly across all subdistricts, which may mask intra-city variation and reduce the sensitivity of the economic vulnerability differentiation. This limitation may lead to a flattening of the economic score distribution across subdistricts.

The classification criteria for economic vulnerability levels refer to Table 3. The vulnerability class scores are categorized as: 1 = low, 2 = moderate, 3 = high. The classification of economic vulnerability scores into vulnerability classes was based on the three-level vulnerability criteria described in Equation (8). For example, Central Jakarta has a total productive land value of IDR 7,833,189.50 million. This value falls into the 'high' class category (> IDR 200 million), thus the class score for the productive land parameter is 3 (corresponding to the high vulnerability score).

Table 9. The Scoring of Economic Vulnerability to flooding in Central and North Jakarta

Parameter	Sector	Central Jakarta	North Jakarta
Productive land (IDR million) (60%)	Agriculture:		
	Food Crop Production (Rice)	-	12,538.44
	Plantation:		
	Vegetable Crop Production	26.60	6,010.00
	Bio-pharmaceutical Plant Production	1.53	-
	Fruit Production	44.70	19,416.80
	Forestry:		
	Economic Value of Forestry Products	4,226.12	15,762.28
	Livestock:		
	Egg Production	-	3,346.26
	Dairy Milk Production (Dairy Cows)	225.12	-
	Poultry Meat Production	16,284.83	27,005.38
	Lamb Meat Production	1,287.11	5,013.01
	Goat Meat Production	16,065.11	59,505.35
	Aquaculture Production	35.41	31,179.14
	Mining and Energy:		
	Value of Distributed Water	439,992.97	829,455.60
	Value of Electricity Sold	7,090,000.00	7,088,000.00
	Sum of all sectors	7,833,189.50	8,096,232.26
	Class Score		3
GRDP (IDR million) (40%)	Agriculture, Forestry, and Fisheries	50,000	732,690
	Mining and Quarrying	-	-
	Manufacturing Industry	6,430,000	173,539,270
	Electricity and Gas Supply	1,910,000	1,517,960
	Water Supply, Waste Management, Wastewater, and Recycling	90,000	272,800
	Construction	61,140,000	76,290,830
	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles	117,680,000	94,163,160
	Transportation and Warehousing	16,570,000	26,528,960
	Accommodation and Food Service Activities	35,740,000	21,967,950
	Information and Communication	60,420,000	11,491,190
	Financial and Insurance Activities	175,430,000	9,122,490
	Real Estate	42,600,000	29,357,060
	Business Services	70,080,000	36,438,870
	Public Administration, Defense, and Compulsory Social Security	60,710,000	9,056,630
	Education Services	39,020,000	19,127,300
	Health Services and Social Activities	15,530,000	9,106,040
	Other Services	24,650,000	17,259,480
Sum of all sectors	728,050,000	535,972,680	
Class Score		3	3
Economic Vulnerability Score		3	3
Economic Vulnerability Class		High	High

Source: BPS-Statistics Indonesia.

According to the scoring results in Table 9, both Central Jakarta and North Jakarta are classified as having high economic vulnerability to flood hazards. This implies that these areas are at considerable risk of experiencing significant economic losses in the event of a flood. The productive land values presented in Table 9 reveal that sectors such as forestry products, livestock production, fruit production, and aquaculture, particularly in North Jakarta, carry significant economic weight. The higher the contribution of productive land and sector output, the greater the potential damages when these assets are exposed to flooding. Additionally, the GRDP data reinforce this classification. Both Central Jakarta and North Jakarta contribute substantially to the provincial GRDP, with particularly large outputs in wholesale and retail trade, construction, manufacturing, public administration, and information and communication sectors. In flood-prone urban areas, strong GRDP sectors can become a double-edged sword: while they indicate economic strength, they also represent a high concentration of assets and investments that are vulnerable to disruption. When a flood occurs, disruptions to commercial centers, transport logistics, port operations, and administrative services can generate cascading economic impacts not only locally but across the wider metropolitan region.

These findings are consistent with earlier studies on Jakarta's urban flood risk dynamics. The previous study demonstrated that the economic exposure of Jakarta's coastal and central urban zones is among the highest in Southeast Asia, with potential losses strongly influenced by the concentration of capital-intensive sectors rather than by the extent of physical inundation alone [64]. Marfai & King [65] also emphasized that in coastal urban regions of Indonesia, economic vulnerability is amplified by the dependency on high-value assets, port logistics, and industrial activities, making economic exposure one of the key determinants of total flood losses. Therefore, the present findings reinforce the broader evidence that Jakarta's economic vulnerability to flooding is not merely a function of inundation depth or hazard frequency but is deeply shaped by the spatial concentration of high-value productive activities and essential economic sectors. The classification of both Central and North Jakarta as 'high' economic vulnerability zones reflects the reality that any significant flood event is likely to generate extensive financial losses, long recovery periods, and systemic disruptions to the wider provincial and national economy.

The economic vulnerability map of Central and North Jakarta is shown in Figure 7. The map is not disaggregated by subdistrict due to alignment with the analysis results presented in Table 9. The findings indicate that both Central and North Jakarta fall into the 'high' economic vulnerability class with respect to flood hazards. Accordingly, these areas are represented in red (high vulnerability) on the map.

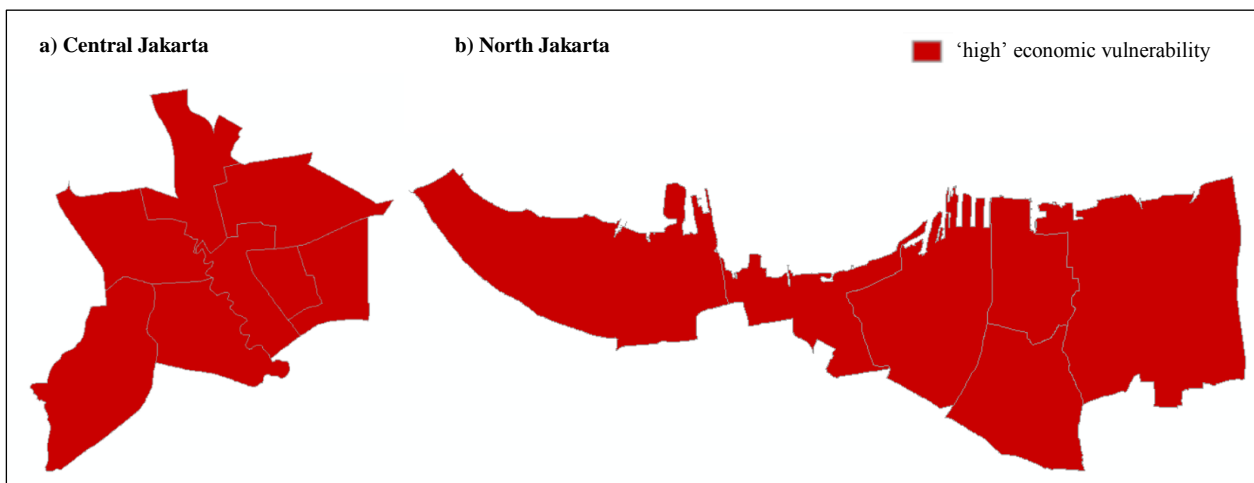


Figure 7. The Economic Vulnerability Map to Flooding in Central and North Jakarta

5.3. Physical Vulnerability Analysis

For the analysis of physical vulnerability, three primary parameters were considered: residential buildings, public facilities, and critical facilities. In addition, two supplementary variables, elevation and land slope, were incorporated to enhance the spatial accuracy of the physical vulnerability assessment to flooding. The integration of elevation and slope is essential in urban flood assessments, as these variables influence water accumulation, drainage efficiency, and flow pathways across built environments. Incorporating these parameters therefore strengthens the spatial accuracy of the physical vulnerability classification, particularly in highly urbanized and low-lying regions such as Central and North Jakarta.

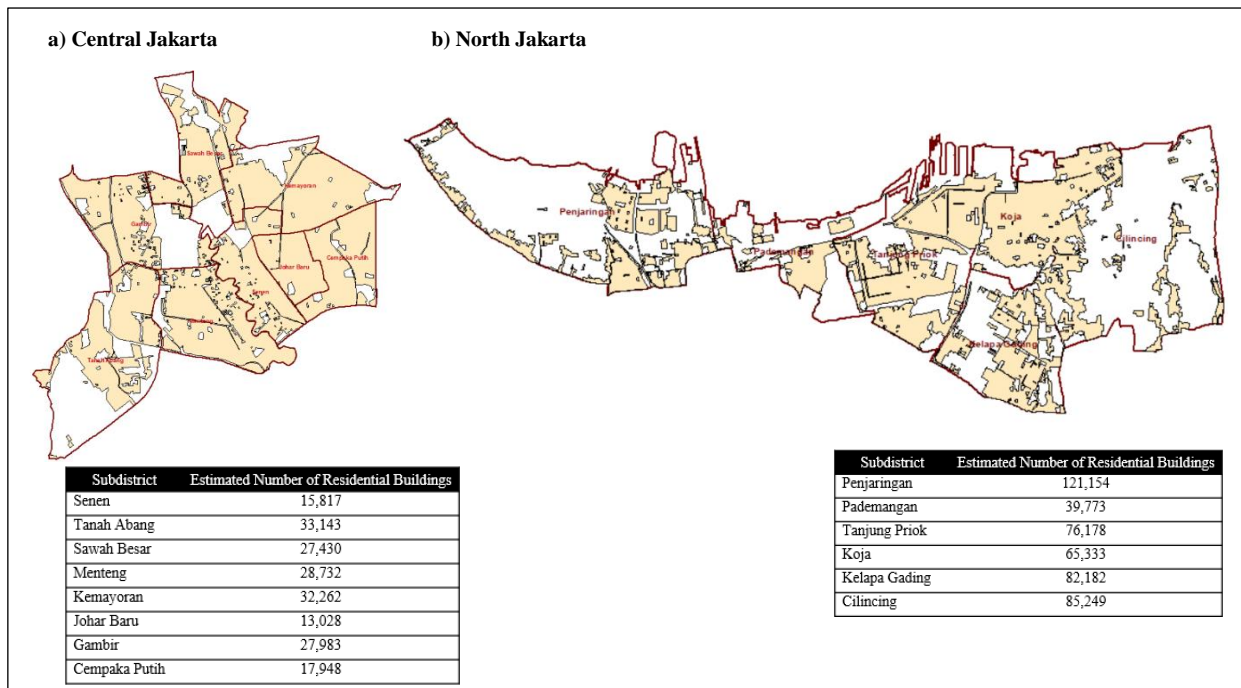


Figure 8. The Map of Estimated Number of Residential Buildings in Each Subdistricts of Central and North Jakarta

The estimated number of residential buildings was based on an analysis of the total residential land area divided by a standard residential building size of 150 m², in accordance with the Disaster Risk Guidelines published by BNPB (2016), as referenced in Fitria et al. [66]. This approach is consistent with widely applied methodologies in Indonesian flood risk assessments, where building counts cannot be extracted from cadastral data and must instead be approximated using raster-based land-use proxies. A limitation of this method is that estimating the number of buildings by dividing total residential land area by the BNPB standard unit of 150 m² may lead to overestimation or underestimation in certain urban contexts. Areas characterized by multi-story housing, high-rise apartments, Kampung settlements, or mixed-use structures do not conform to uniform building footprints, and therefore the estimated number of residential units may not fully represent the actual structural density. This constraint should be considered when interpreting the physical vulnerability scores, and future studies may benefit from integrating more detailed building footprint datasets. Furthermore, the justification for flood-induced losses was derived from residential parameters across different hazard classes: for low hazard zones, the number of residential buildings was multiplied by IDR 5 million; for moderate hazard zones, by IDR 10 million; and for high hazard zones, by IDR 15 million [67]. The residential land area was obtained through spatial analysis using ArcGIS software, based on settlement raster data. The settlement raster data were then used to calculate the area of residential land within each subdistrict. This area was divided by the standard residential unit size (150 m²) to estimate the number of residential buildings in each subdistrict of Central Jakarta and North Jakarta.

Figure 8 illustrates the spatial distribution of estimated residential buildings across subdistricts in Central and North Jakarta. The results show significant variation between the two cities. North Jakarta contains a markedly larger number of residential buildings, with areas such as Penjaringan, Cilincing, and Kelapa Gading, demonstrating the highest concentrations. In contrast, Central Jakarta presents a more clustered urban density pattern, with Tanah Abang, Menteng, and Kemayoran, hosting substantial but comparatively smaller building counts. These findings highlight two important implications. First, North Jakarta’s extremely high residential density, combined with its low elevation and proximity to the coastline, substantially elevates the physical vulnerability of assets to flood hazards. Second, even though Central Jakarta has fewer residential buildings overall, its built environment remains densely consolidated, creating high exposure within smaller spatial units. This means that flood events in these areas are likely to result in concentrated asset losses due to the tightly packed urban fabric.

The public facilities data used in the physical vulnerability analysis refer to educational facilities, while the critical facilities data consist of health facilities located within the study area, in accordance with the flood hazard classes provided by InaRISK BNPB. Spatial analysis was conducted using elevation data from DEMNAS (National Digital Elevation Model) in Tagged Image File (.tif) format and slope data in shapefile (.shp) format. The elevation and slope maps of Central and North Jakarta are presented in Figure 9 and 10, respectively. Based on Figure 9, it is evident that Central Jakarta generally has low elevation, as indicated by the predominance of green shades on the map. The presence of dark and light green colours signifies that most areas in Central Jakarta lie within an elevation range of - 4.03 to 9.15 meters above sea level (masl). Similarly, the slope map is also dominated by green areas, indicating that Central Jakarta is generally flat, with slope gradients of less than 8%.

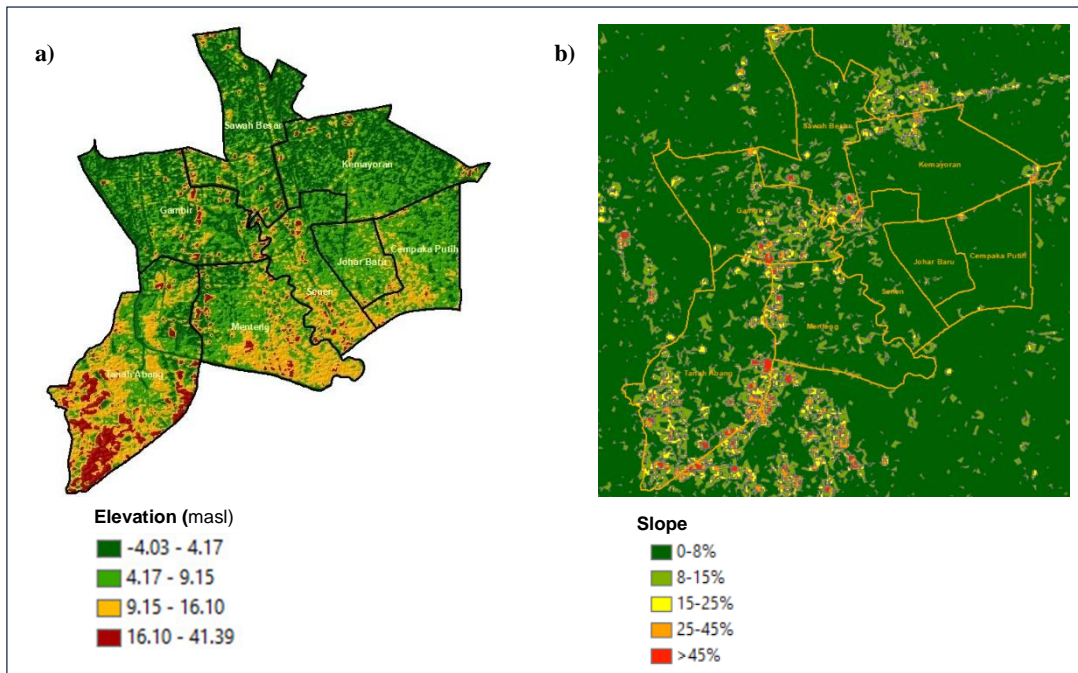


Figure 9. The Elevation and Land Slope Map of Central Jakarta

Figure 10 presents the elevation and slope maps of North Jakarta. The elevation in most areas of North Jakarta is relatively low, as indicated by the predominance of green on the map. Overall, the map shows that the elevation in North Jakarta is lower compared to Central Jakarta. The slope map, similarly, dominated by green tones, indicates that North Jakarta being a coastal region is generally flat. Lower elevation increases the risk of flooding, and similarly, flatter slopes contribute to a higher potential for flood occurrence.

The summary of physical vulnerability scoring is presented in Table 10. The results of the physical vulnerability analysis indicate that all areas in Central and North Jakarta exhibit a high level of physical vulnerability to flooding. The calculation of the residential buildings parameter value (IDR million) for each subdistrict in Central and North Jakarta was based on the estimated flood-induced damage, using the flood hazard index provided by BNPB. Subdistricts in Central Jakarta fall under the low hazard category; thus, the estimated residential buildings losses were calculated by multiplying the total number of residential buildings by IDR 5 million (assuming all residential buildings are affected). In contrast, subdistricts in North Jakarta fall under varying hazard categories: low (Tanjung Priok, Pademangan), moderate (Koja, Cilincing, Kelapa Gading), and high (Penjaringan). Penjaringan was classified as high hazard due to the presence of many slum settlements, which increases its vulnerability to flood-related damage.

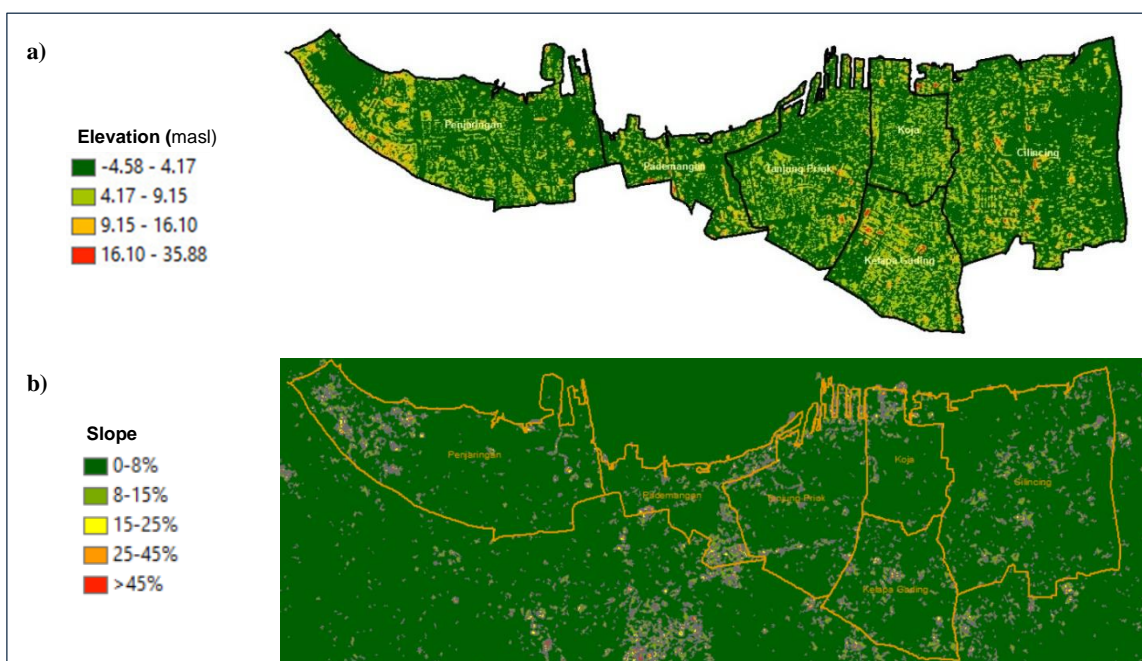


Figure 10. The Elevation and Land Slope Map of North Jakarta

Table 10. The Scoring of Physical Vulnerability to flooding in Central and North Jakarta

City	Subdistrict	Physical Vulnerability Parameter (BNPB)				Physical Vulnerability Parameter (Additional)		Physical Vulnerability Score	Physical Vulnerability Class		
		Residential Buildings (IDR million)	Class Score	Public Facilities (IDR million)	Class Score	Critical Facilities (IDR million)	Class Score			Elevation (Class Score)	Land Slope (Class Score)
Central Jakarta	Senen	79,085	3					3	3	3	High
	Tanah Abang	165,715	3					3	3	3	
	Sawah Besar	137,150	3					3	3	3	
	Menteng	143,660	3	913 × 9,000 = 8,217,000	3	66 × 19,000 = 1,254,000	3	3	3	3	
	Kemayoran	161,315	3					3	3	3	
	Johar Baru	65,140	3					3	3	3	
	Gambir	139,915	3					3	3	3	
	Cempaka Putih	89,740	3					3	3	3	
North Jakarta	Penjaringan	1,817,310	3					3	3	3	High
	Pademangan	198,865	3					3	3	3	
	Tanjung Priok	380,890	3	1,084 × 9,000 = 9,756,000	3	61 × 19,000 = 1,159,000	3	3	3	3	
	Koja	653,330	3					3	3	3	
	Kelapa Gading	821,820	3					3	3	3	
	Cilincing	852,490	3					3	3	3	

Note: 1. The vulnerability class scores: 1 = low, 2 = moderate, 3 = high
 2. Detailed data on public facilities and critical facilities at the sub-district level are not available.
 3. The estimated economic losses for public and critical facilities are used to represent their physical vulnerability: public facilities = IDR 9,000 million & critical facilities = IDR 19,000 million [68].

The results of the physical vulnerability analysis indicate that all areas in Central and North Jakarta exhibit a high level of physical vulnerability to flooding and are illustrated in Figure 11 as follows:

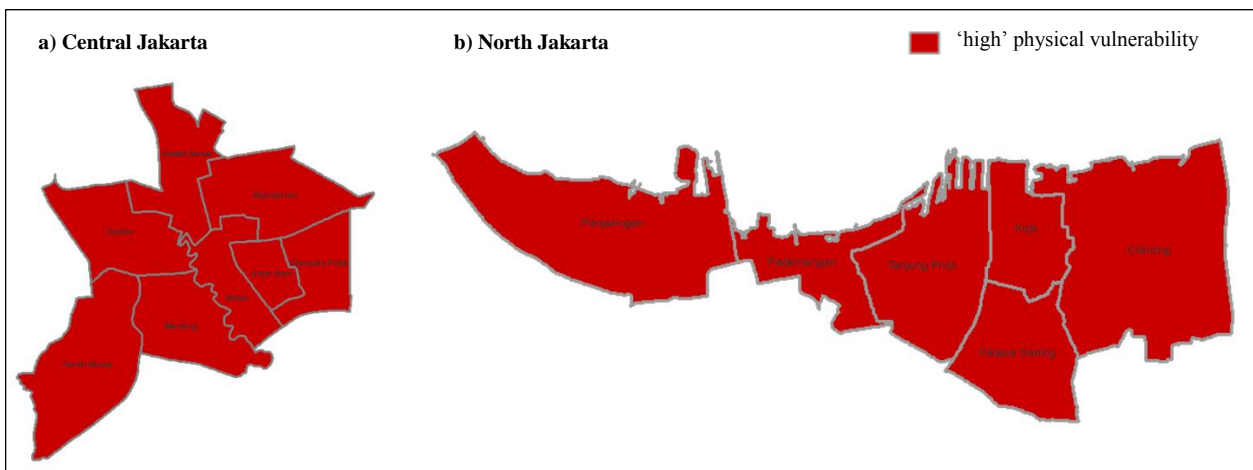


Figure 11. The Physical Vulnerability Map to Flooding in Central and North Jakarta

The results of this study are consistent with earlier research. Ward et al. [63] and Pauline [67] found that physical flood vulnerability in Jakarta is strongly driven by the spatial distribution of built-up areas and the concentration of buildings in zones with poor drainage and low elevation. Similarly, Marfai & King [65] emphasized that low-lying coastal subdistricts, especially in North Jakarta, face substantially higher physical vulnerability due to a combination of land subsidence, high-density settlements, and insufficient flood protection structures. The present findings therefore reinforce the established conclusion that physical exposure, manifested through residential building concentration and unfavorable topographic characteristics, is a primary determinant of flood-related physical vulnerability in Jakarta’s urban environment.

5.4. Environmental Vulnerability Analysis

In this study, the scoring of environmental vulnerability classes was conducted using the Land Cover Quality Index (LCQI), as defined by the Ministry of Environment and Forestry of Indonesia (KLHK) and Jakarta Environmental

Agency [45]. The LCQI is derived from the proportional area of forest vegetation (protected forest, natural forest, and mangroves) and non-forest vegetation (such as shrubland and wetlands). Table 11 presents the results of the LCQI calculation for Central and North Jakarta.

Table 11. The Scoring of Environmental Vulnerability to flooding in Central and North Jakarta

City	Total area (Ha)	Forest Vegetation Area (Ha)	Non-forest Vegetation Area (Ha)	Land Cover (LC)	Land Cover Quality Index (LCGI)	Land Cover Condition	Class Score	Environment Vulnerability Class
Central Jakarta	4,848.60	-	325.51	0.040	26.085	Moderate	2	Moderate
North Jakarta	14,120.18	86.97	638.88	0.033	25.443	Poor	3	High

The analysis results presented in Table 11 indicate notable differences between the two administrative areas. Central Jakarta falls into the ‘moderate’ environmental vulnerability class, while North Jakarta is classified as having a ‘high’ level of environmental vulnerability to flood hazards. This outcome reflects the fact that the existing vegetation in North Jakarta is insufficient to compensate for the area’s extensive built-up surfaces, coastal exposure, and rapid land-use conversion. The classification outcomes in this research are consistent with previous studies emphasizing the role of land cover degradation in increasing flood susceptibility. The previous study found that coastal urban areas with diminished mangrove cover exhibit significantly reduced natural buffering capacity, leading to greater exposure to tidal flooding [65]. Similarly, Ward et al. [64] demonstrated that decreased vegetation and widespread impervious surfaces in Jakarta intensify surface runoff and reduce infiltration capability, thereby elevating flood risk even under moderate rainfall conditions. These findings align with the results of the present study, particularly the ‘high’ environmental vulnerability score assigned to North Jakarta. The limited vegetation cover and degraded land conditions support earlier conclusions that ecological resilience in the northern coastal zone has significantly weakened over time.

Meanwhile, the ‘moderate’ environmental vulnerability score observed in Central Jakarta aligns with prior assessments, reflecting a complex balance of risk and resilience factors. In Central Jakarta, the green open space (Ruang Terbuka Hijau, RTH) was reported around 12.59% in 2024 [69]. Consequently, while Central Jakarta may not face the highest levels of environmental vulnerability compared to coastal or heavily waterlogged areas, the combination of urban densification, reduced green cover, and impaired hydrological functions places it in the ‘moderate’ category. In other words, the city is not yet at a critical stage, but the limited capacity to absorb and mitigate environmental stressors suggests that without intervention, its vulnerability could escalate over time. This moderate classification underscores the importance of strategic urban greening and improved water management initiatives to strengthen resilience.

Overall, the classifications of ‘moderate’ environmental vulnerability in Central Jakarta and ‘high’ environmental vulnerability in North Jakarta highlight the inadequacy of natural land cover in both regions. In ecological terms, insufficient vegetation reduces the landscape’s capacity for infiltration and natural buffering against extreme rainfall events. Areas with low LCQI values also tend to exhibit higher surface runoff, diminished soil stability, and lower ecological resilience, making them more susceptible to flood hazards even under moderate rainfall conditions.

The environmental vulnerability map is presented in Figure 12 as follows:

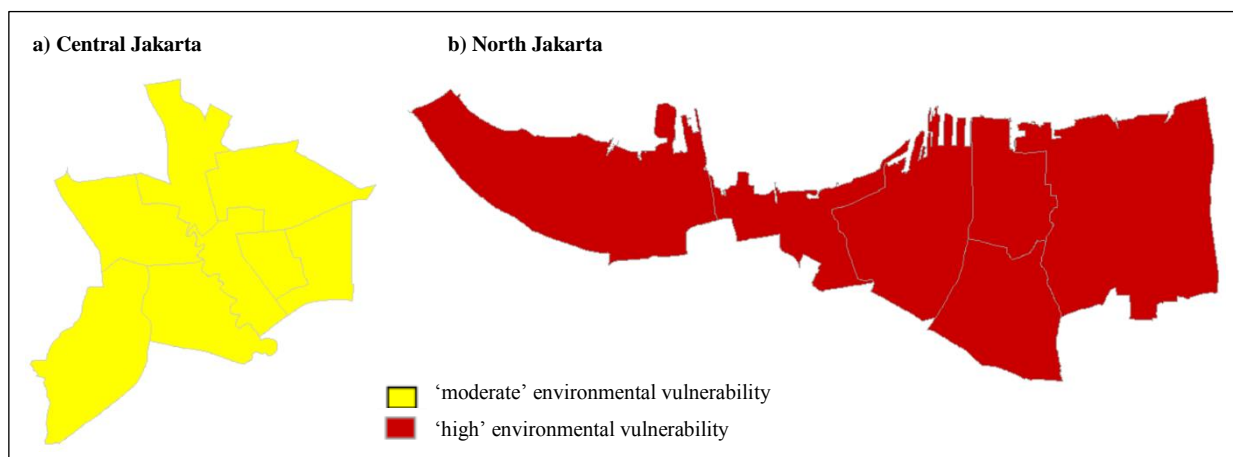


Figure 12. The Environmental Vulnerability Map to Flooding in Central and North Jakarta

5.5. Spatial Analysis of Flood Vulnerability in Central Jakarta

In this study, all spatial area calculations and map-processing steps were conducted using the Universal Transverse Mercator (UTM) Zone 48S (WGS 84) projected coordinate system. This projection was selected because it provides metric units and minimizes spatial distortion within the Jakarta region, thereby improving the accuracy of area, distance, and polygon-based analyses. The use of UTM projections, particularly within zones that match the geographic extent of the study area, offers superior local accuracy because scale distortion is smallest near the central meridian, making UTM highly appropriate for engineering, environmental, and hazard-mapping applications [70, 71].

The spatial analysis began with the extraction process, which involved vector data analysis to extract spatial information from specific features. Since the flood vulnerability data from InaRISK-BNPB is available for the entire territory of Indonesia, the flood vulnerability layer was clipped using the layer of administrative boundary of Central Jakarta. The extraction tool used was Clip, with the flood vulnerability raster data for Indonesia as the input layer (Figure 4), and the administrative boundary of Central Jakarta as the clipping feature. This process generated an output layer that is the flood vulnerability raster for Central Jakarta (Figure 13), which was then used to calculate the spatial probability in this study. The results of the flood vulnerability mapping will determine the flood risk categories for a whole Central Jakarta, as well as for each sub-district within the area.

The resulting output was further used to map the flood risk in Central Jakarta through the Reclassify function. The reclassification was performed to categorize the areas based on flood vulnerability levels, defined as follows: areas with a ‘low’ flood vulnerability class have an index of $0.0 < \text{index} \leq 0.3$; ‘moderate’ vulnerability class: $0.3 < \text{index} \leq 0.6$; ‘high’ vulnerability class: $0.6 < \text{index} \leq 1.0$ [11, 12, 22]. This process was carried out to visualize the distribution of flood vulnerability index values across Central Jakarta. Prior to this reclassification step, all vulnerability parameters were normalized into a 0–1 scale by using min-max normalization, to ensure that variables with different units and value ranges could be combined appropriately during the weighted overlay process, thereby preventing any single variable from disproportionately influencing the final index [11, 12]. The results of the extraction and reclassification processes are presented in Figure 13, illustrating the spatial distribution of flood vulnerability index values across Central Jakarta.

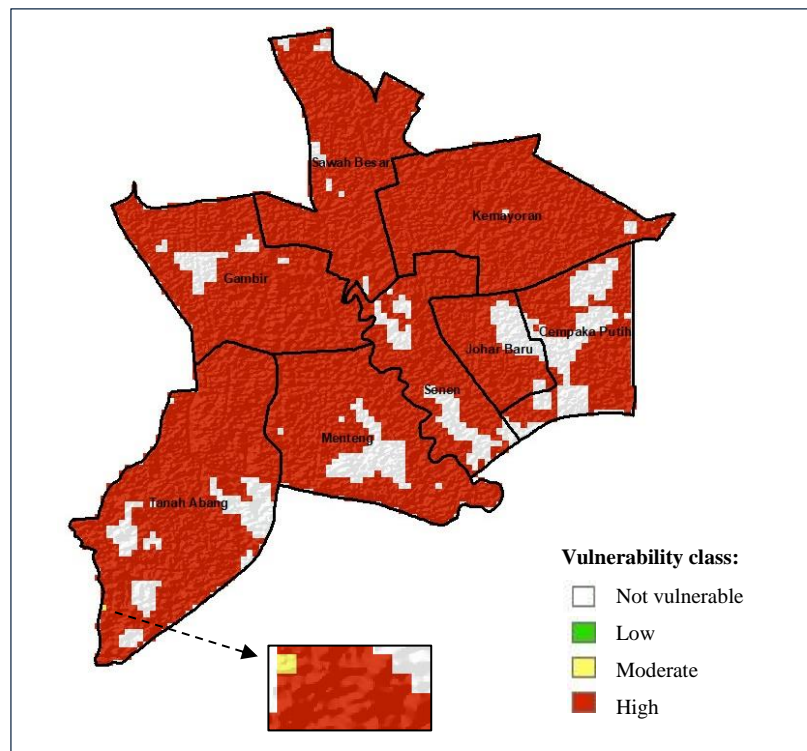


Figure 13. The Flood Vulnerability Raster Map of Central Jakarta

The flood vulnerability raster map was then overlaid with the results of the vulnerability factor analyses presented in Subsections 5.1 to 5.4 (a summary of the results is provided in Table 12). The overlaid raster was subsequently converted into a polygon layer. The purpose of this conversion was to transform raster data into vector format, as polygons represent one of the fundamental geometries in the vector data model. The overlay polygons, containing the flood vulnerability scores for Central Jakarta, are shown in Figure 14.

Table 12. The Summary of Flood Vulnerability Factor Analysis in Central Jakarta

Vulnerability Analysis	Weight	Vulnerability Score	Vulnerability Class
Social	40%	2	Moderate
Economic	25%	3	High
Physical	25%	3	High
Environmental	10%	2	Moderate
Flood Vulnerability in Central Jakarta		2.5	High

The resulting polygon features were then used to calculate the area of each flood vulnerability class. A similar procedure was applied to determine the area of other zones through geometric calculations, utilizing ArcGIS software based on the coordinates of vertices that define the polygons within a projected coordinate system. The calculated area for each flood vulnerability class in Central Jakarta is presented in Table 13.

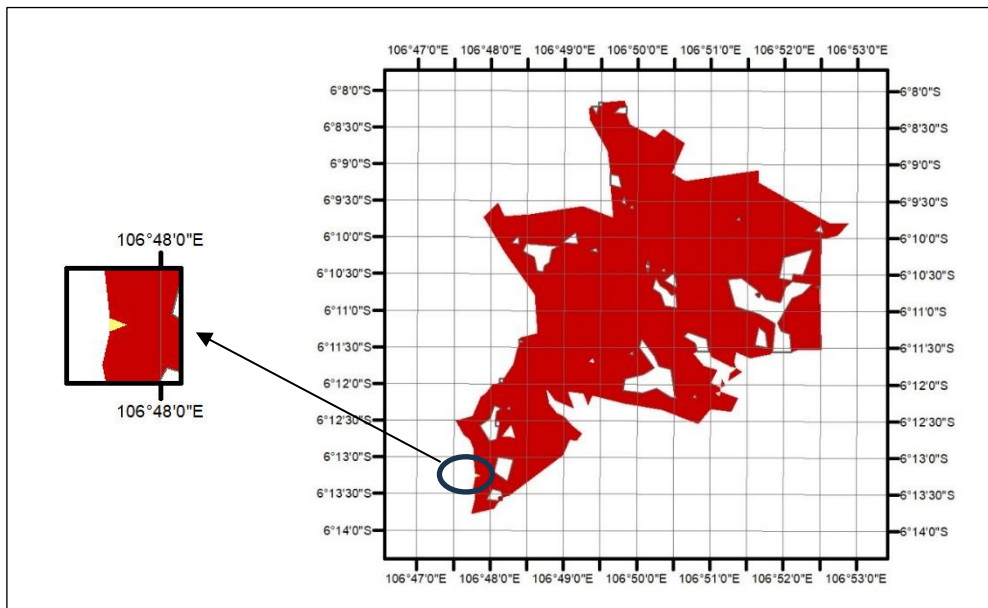


Figure 14. The Overlay Polygons with Flood Vulnerability Score in Central Jakarta

Table 13. The Area of Flood Vulnerability Class in Central Jakarta

Vulnerability Class	Vulnerability Index	Area (ha)	Percentage Area (%)
Not vulnerable	Index = 0.0	436.23	9.30
Low	0.0 < Index ≤ 0.3	0.00	0.00
Moderate	0.3 < Index ≤ 0.6	0.64	0.01
High	0.6 < Index ≤ 1.0	4,254.39	90.69
Total		4,691.26	100.00

Table 13 shows that in Central Jakarta, an area of 436.23 hectares (ha) is classified as not vulnerable to flooding, 0.64 ha fall into the moderate vulnerability category, and 4,254.39 ha are categorized as high vulnerability. There are no areas classified under the low vulnerability category. This indicates that nearly the entire area of Central Jakarta falls within the high flood vulnerability class. In total, 90.69% of Central Jakarta’s area is classified as having high flood vulnerability. According to the Disaster Risk Index classification by BNPB, areas where more than 60% (or 0.6 proportionally) of the territory falls under a high vulnerability class are at high risk. Therefore, Central Jakarta can be categorized as a high-risk area for flood disasters. Subsequently, a spatial probability analysis of flood occurrence was conducted using Equation (9), focusing on areas classified under the high vulnerability class, given that Central Jakarta is categorized as a high-risk area. In this spatial probability calculation, areas categorized as not vulnerable were excluded, as their flood vulnerability probability is zero (i.e., not susceptible to flooding). The spatial probability value was determined by comparing the area of high vulnerability zones to the total area of all vulnerable zones (i.e., moderate and high vulnerability) in Central Jakarta. This spatial probability reflects the likelihood of flood occurrence in Central Jakarta based on the spatial distribution of flood vulnerability. The following Equation (11) presents the calculation of the spatial probability of flood occurrence in Central Jakarta:

$$P_{Central\ Jakarta} = \frac{4,254.39}{(0+0.64+4,254.39)} = 99.9\% = 0.999 \tag{11}$$

The spatial probability value of flood vulnerability in Central Jakarta, which is 0.999, can be interpreted as follows: if rainfall with an intensity of at least 100–150 mm/day occurs in Central Jakarta, then based on its spatial flood vulnerability conditions, the probability of flooding in the area on that day is 0.999. This implies that flooding is almost certain to occur under such rainfall conditions. The probability represents the likelihood of flood impact under assumed triggering conditions, such as heavy rainfall ($\geq 100\text{--}150$ mm/day), following the high-intensity rainfall classification issued by the Indonesian Meteorology, Climatology, and Geophysical Agency (BMKG), and is therefore driven by spatial exposure and vulnerability patterns rather than hydrometeorological processes.

5.6. Spatial Analysis of Flood Vulnerability in North Jakarta

The same projection system (UTM Zone 48S, WGS 84) was also applied to all spatial calculations and mapping processes in North Jakarta to ensure consistency and maintain area-calculation accuracy across both study regions. The spatial analysis steps for North Jakarta follow the same procedure as previously conducted for Central Jakarta. However, in the case of North Jakarta, the analysis also incorporates vulnerability due to tidal flooding (coastal flooding), which was not included in the analysis for Central Jakarta. This addition is necessary because North Jakarta is a coastal area that is particularly susceptible to tidal floods. The flood vulnerability analysis in North Jakarta utilizes a combination of two raster vulnerability datasets: the flood vulnerability raster and the tidal flood vulnerability raster (derived from extreme wave and coastal abrasion data), as shown in Figure 15.

As in the Central Jakarta assessment, all vulnerability parameters were normalized to a uniform 0–1 scale prior to the weighted overlay operation. This normalization step is critical for methodological consistency and analytical accuracy. The parameters incorporated into the North Jakarta vulnerability framework come from multiple domains, including social, economic, physical, environmental, and coastal hazard variables, which naturally differ in units, ranges, and value distributions. Through min–max normalization, each parameter was rescaled based on its minimum and maximum observed values, enabling comparability across dimensions. This ensures that the subsequent weighted overlay reflects the intended analytical design, where parameter contributions are governed by their assigned weights rather than their original numeric scales.

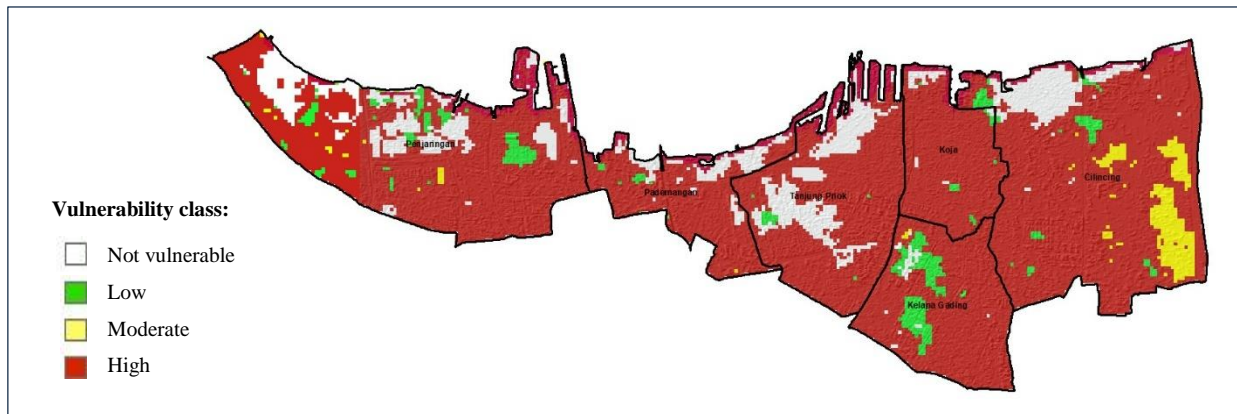


Figure 15. The Flood Vulnerability Raster Map of North Jakarta

Table 14. The Summary of Flood Vulnerability Factor Analysis in North Jakarta

Vulnerability Analysis	Weight	Vulnerability Score	Vulnerability Class
Social	40%	2	Moderate
Economic	25%	3	High
Physical	25%	3	High
Environmental	10%	3	High
Flood Vulnerability in North Jakarta		2.6	High

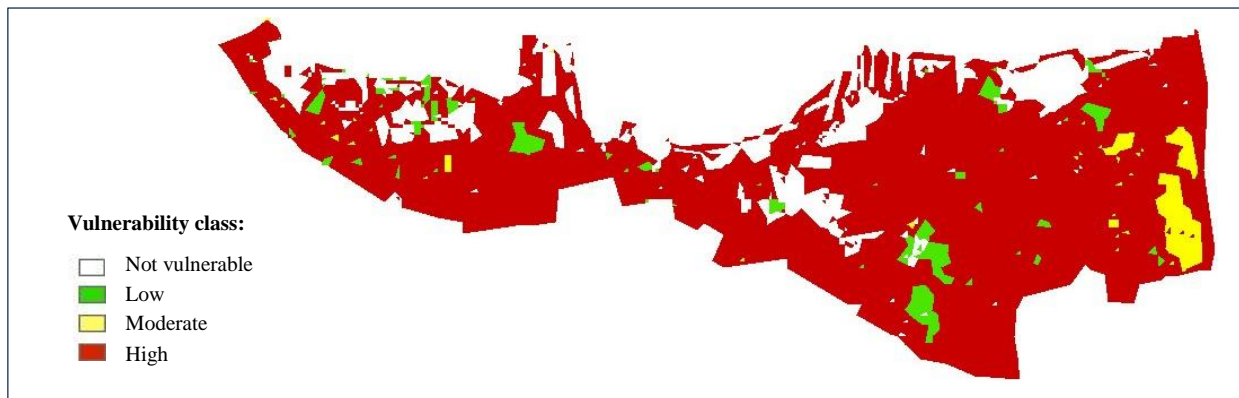


Figure 16. The Overlay Polygons with Flood Vulnerability Score in North Jakarta

The flood vulnerability raster map was overlaid with the results of the vulnerability factor analyses, as presented in Subsections 5.1 to 5.4, and summarized in Table 14. The resulting overlaid raster was then converted into a polygon layer. The overlay polygons, containing the flood vulnerability scores for North Jakarta, are shown in Figure 16. The calculated area for each flood vulnerability class in Central Jakarta is presented in Table 15:

Table 15. The Area of Flood Vulnerability Class in North Jakarta

Vulnerability Class	Vulnerability Index	Area (ha)	Percentage Area (%)
Not vulnerable	Index = 0.0	1,060.23	7.76
Low	0.0 < Index ≤ 0.3	499.16	3.65
Moderate	0.3 < Index ≤ 0.6	365.79	2.68
High	0.6 < Index ≤ 1.0	11,743.64	85.82
Total		13,668.82	100.00

Table 15 indicates that in North Jakarta, approximately 1,060.23 hectares are categorized as not vulnerable to flooding, 499.16 hectares fall into the low vulnerability category, 365.79 hectares into the moderate vulnerability category, and 11,743.64 hectares are classified as high vulnerability. In total, 85.82% of the area in North Jakarta falls within the high flood vulnerability class. According to the Disaster Risk Index developed by BNPB, regions in which more than 60% (or a proportion of 0.6) of the area is classified as highly vulnerable are at high risk. Therefore, North Jakarta is classified as a high-risk area for flood disasters. The following Equation (12) presents the calculation of the spatial probability of flood occurrence in North Jakarta:

$$P_{North\ Jakarta} = \frac{11,743.64}{(499.16+365.79+11,743.64)} = 93.14\% = 0.9314 \tag{12}$$

The spatial probability value of flood vulnerability in North Jakarta, which is 0.9314, can be interpreted as follows: if rainfall with an intensity of at least 100–150 mm/day occurs in North Jakarta, then based on its spatial vulnerability conditions, the probability of flooding on that day is 0.9314. This indicates that flooding is very likely to occur in North Jakarta under such conditions. Furthermore, this flood event may include tidal flooding (coastal inundation), as heavy rainfall can lead to elevated water levels, contributing to tidal overflow in the coastal zones of the city. The probability represents the likelihood of flood impact under assumed triggering conditions, such as heavy rainfall (≥100–150 mm/day), following the high-intensity rainfall classification issued by BMKG, and is therefore driven by spatial exposure and vulnerability patterns rather than hydrometeorological processes.

6. Conclusion

This study assessed flood vulnerability in Central and North Jakarta by integrating four key components, social, economic, physical, and environmental, together with raster-based flood vulnerability data from BNPB. The results show that Central Jakarta obtained a spatial flood vulnerability score of 2.5, while North Jakarta recorded a score of 2.6; both fall within the ‘high’ vulnerability category. Component-level analyses indicate that social vulnerability in both areas is ‘moderate’, driven primarily by very high population density that elevates exposure despite the presence of some coping capacities. In contrast, economic and physical vulnerability levels are ‘high’ in both regions, reflecting the substantial value of productive land, the concentration of economic activities, and the susceptibility of buildings, public facilities, and critical infrastructure to flood-related damage. Environmental vulnerability differs between the two areas, with Central Jakarta classified as ‘moderate’ and North Jakarta as ‘high’, indicating inadequate land cover and limited ecological buffering capacities, particularly in coastal zones.

Spatial analysis showed that 90.69% of Central Jakarta and 85.82% of North Jakarta are highly vulnerable, exceeding the BNPB 60% high-risk threshold. The spatial probabilities of flood occurrence were estimated at 0.999 for Central Jakarta and 0.9314 for North Jakarta, representing the likelihood of impact under assumed triggers, such as heavy rainfall (≥ 100 –150 mm/day, per BMKG), driven by spatial exposure and vulnerability rather than hydrometeorological processes. In North Jakarta, tidal flooding may also contribute. Overall, the findings highlight that the high flood vulnerability of both districts is shaped by the interplay between dense urban populations, concentrated economic assets, infrastructure exposure, and insufficient environmental protection. These results emphasize the need for integrated flood risk reduction strategies that strengthen community capacity, protect critical infrastructure, and enhance environmental resilience to support long-term disaster mitigation in Jakarta.

7. Declarations

7.1. Author Contributions

Conceptualization, J.H. and P.P.O.; methodology, P.P.O., A.D.S., and H.K.; software, P.P.O.; validation, J.H., A.D.S., and H.K.; formal analysis, P.P.O.; investigation, A.D.S. and H.K.; resources, J.H.; data curation, P.P.O. and J.H.; writing—original draft preparation, P.P.O. and J.H.; writing—review and editing, A.D.S. and H.K.; visualization, P.P.O.; supervision, J.H., A.D.S., and H.K.; project administration, P.P.O.; funding acquisition, P.P.O. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are openly available in ‘Source’ column in Table 7.

7.3. Funding and Acknowledgments

The authors are grateful to the Indonesian Education Scholarship (Beasiswa Pendidikan Indonesia, BPI), the Center for Higher Education Funding and Assessment (Pusat Pembiayaan dan Asesmen Pendidikan Tinggi, PPAPT) and the Indonesia Endowment Fund for Education (Lembaga Pengelola Dana Pendidikan, LPDP), for supporting this research.

7.4. Institutional Review Board Statement

Not applicable.

7.5. Informed Consent Statement

Not applicable.

7.6. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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