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Research Article

Integrated flood hazard assessment using multi-criteria analysis and geospatial modeling

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Abstract

Floods are one of the most prevalent disasters worldwide, including in the capital city of Indonesia. Multi-criteria decision analysis is combined with Geographic Information Systems to produce a mapping of flood hazard areas. The weighting for each parameter is based on six criteria: rainfall, slope gradient, topography, soil type, land cover, and distance from rivers. The flood hazard map is validated using inundation data from the Regional Disaster Management Agency for the years 2015 and 2020. From the general analysis, it can be determined that the parameter most influencing floods is rainfall with a weight of 0.270, followed by slope gradient at 0.164, topography at 0.124, soil type at 0.096, land cover at 0.190, and distance from rivers at 0.155. Therefore, through mapping using QGIS, it is revealed that in 2002, highly flood hazard areas comprised 20.99% of the total Ciliwung Watershed area, which increased to 24.31% in 2020. The validation of the flood hazard map was conducted by recording the coordinate points of flood incidents in 2015 and 2020, revealing that the affected areas within the Ciliwung Watershed occurred in high to very high vulnerability zones. This research demonstrates that flood events in the study area occurred in high to very high flood hazard zones. The results of this study are considered valuable and important for providing accurate information to local governments to develop cost-effective and efficient strategies in dealing with potential flood hazards.

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Introduction

The watershed area is one of the highly complex natural resources that play a crucial role in hydrology, consisting of several constituent components such as vegetation (forests), soil, and water, including rivers and tributaries, and the human population residing within the watershed. Humans are heavily reliant on natural resources, and the sustainability of these resources is greatly influenced by human activities. This includes the Ciliwung Watershed, which has become a focal point for economic and social growth. A significant shift in economic activities from agriculture to industry, trade, and services has indeed occurred along the Ciliwung River, particularly in the downstream areas (Kusumastanto and Adrianto, 2018). This is further exacerbated by the continuously increasing population from year to year. The population growth rate in DKI Jakarta is 0.92% annually, resulting in an additional 88 thousand people per year during the 10-year period from 2010 to 2020 (Rahmatulloh, 2017).

The increase in the population of Jakarta has given rise to several issues, including the problem of flooding in the Ciliwung River basin (Arifasihati and Kaswanto, 2016). In the Ciliwung River Basin, flooding incidents occur nearly every year. In 2020, Jakarta, Bogor, Depok, Tangerang, Bekasi, and the surrounding areas experienced severe flooding due to extreme rainfall of 377 mm/day from December 29, 2019, to February 2, 2020 (Pusparisa, 2020). Massive infrastructure development around the Ciliwung River Basin has caused changes in land cover, resulting in a decrease in soil quality and productivity due to various factors, including human activities (Panahi et al., 2010; Tali, 2011; Solín et al., 2013; Siswanto and Francés, 2019; Rahman et al., 2021; Kuntoro et al., 2022), the impact of urban flooding is quite significant in terms of both direct and indirect economic losses. (Tingsanchali, 2012; Moes, 2018).

The topographical conditions and land slope also affect the surface runoff rate in the catchment area (Valeo and Rasmussen, 2013; Lee and Kim, 2021; Rolf et al., 2022). Increasing the green open space area is the most effective way to mitigate floods in the region (Kim et al., 2016; Zimmermann et al., 2016; Brodya et al., 2017). Besides that, land degradation is a factor that triggers flash floods, which refers to the process of decreasing soil quality and productivity due to various factors, including human and natural activities, which include soil erosion, decreased soil fertility, damage to soil structure, decreased organic levels, decreased groundwater availability, and loss of soil biodiversity. Human activities such as intensive agriculture, deforestation, illegal logging, mining, urbanization, and unsustainable use can cause significant land degradation.

Flood mapping is necessary to find solutions for minimizing the impact of flood-related infrastructure losses. Flood mapping is carried out to support decision-makers in policy determination for such events, using an approach based on rainfall patterns and land use and land cover (LULC) management (Mishra et al., 2018; Swain et al., 2020). Furthermore, floods are dynamic and multidimensional phenomena (Smith et al., 2017; Goh, 2019), In addition, floods result from a multitude of factors; not only climate-related but also non-climatic factors play a significant role here. The availability of Geographic Information System (GIS) data can be used to explore areas that are affected by and vulnerable to floods (Sy et al., 2019; Ajim et al., 2020). Weighting is carried out to determine the parameters that significantly influence flood hazard assessment. Weighting is done using the Multi-Criteria Decision Analysis (MCDA) method, which is widely used for various issues, including determining the weights of parameters that have the most impact on flooding.

The Analytical Hierarchy Process (AHP) is the most commonly used MCDA technique for this purpose (Abdullah et al., 2021). After obtaining the weights, it is also important to score each parameter. A scoring system ranging from 1 to 5 is used to determine the level of flood hazard in a specific area, with values corresponding to very low, low, moderate, high, and very high flooding, respectively (Osman and Das, 2023).

There is no information yet on mapping flood hazards in the Ciliwung Watershed by combining multi-criteria analysis and GIS to understand and map flood hazards in the area related to land degradation. In this research, six factors were chosen for spatial analysis to determine flood hazard areas: (1) river distance, where the closer a region is to the river, the higher the likelihood of flooding (Ministry of Forestry Directorate General of Watershed Development Management and Social, 2013), (2) high rainfall intensity and the conversion of forested areas into other land uses are contributing factors to flooding (Christian et al., 2020), (3) topography, regions characterized by high topography or elevation generally experience a lower risk of flood vulnerability in comparison to areas with lower elevation (Xie and Zhao, 2013), (4) slope affects the runoff into rivers, (5) types of land cover that can contribute to land degradation, such as intensive agriculture, and inappropriate land use planning can reduce an area's ability to absorb water (Barus et al., 2019), and (6) the type of soil influences infiltration, which is related to the speed at which water is absorbed into the ground (Basri et al., 2022). The six factors were analyzed using GIS modeling to obtain scores for each flood-causing parameter. The weighting for each parameter will be determined through a multi-criteria analysis based on the six factors mentioned above (Alsamaray, 2017; Widianta et al., 2018; Bataineh et al., 2020).

The aim of this research was to identify flood hazard areas that are influenced by changes in land cover that cause land degradation. In this research, flood hazard mapping was carried out using various parameters, including soil type and land cover. If other land degradation activities occur in the same area, this may influence parameters, such as soil type and land cover, which in turn may influence flood hazard mapping results. Thus, this research provides better insight into how land degradation due to population growth activities can affect flood hazards in the study area. This research looked at changes in land use from 1990, 2002, 2007, 2015, and 2020.

Materials and Methods

The research location was in the Ciliwung River Basin, located between 6º05'00" S - 6º50'00" S and 106º45'00" E - 107º00'00" E, with a total area of 386 km^2; it spans across Bogor Regency, Bogor City, Depok City, South Jakarta, East Jakarta, and extends to Jakarta Bay. For a more comprehensive view, the study location map and rainfall station locations are presented in Figure 1.

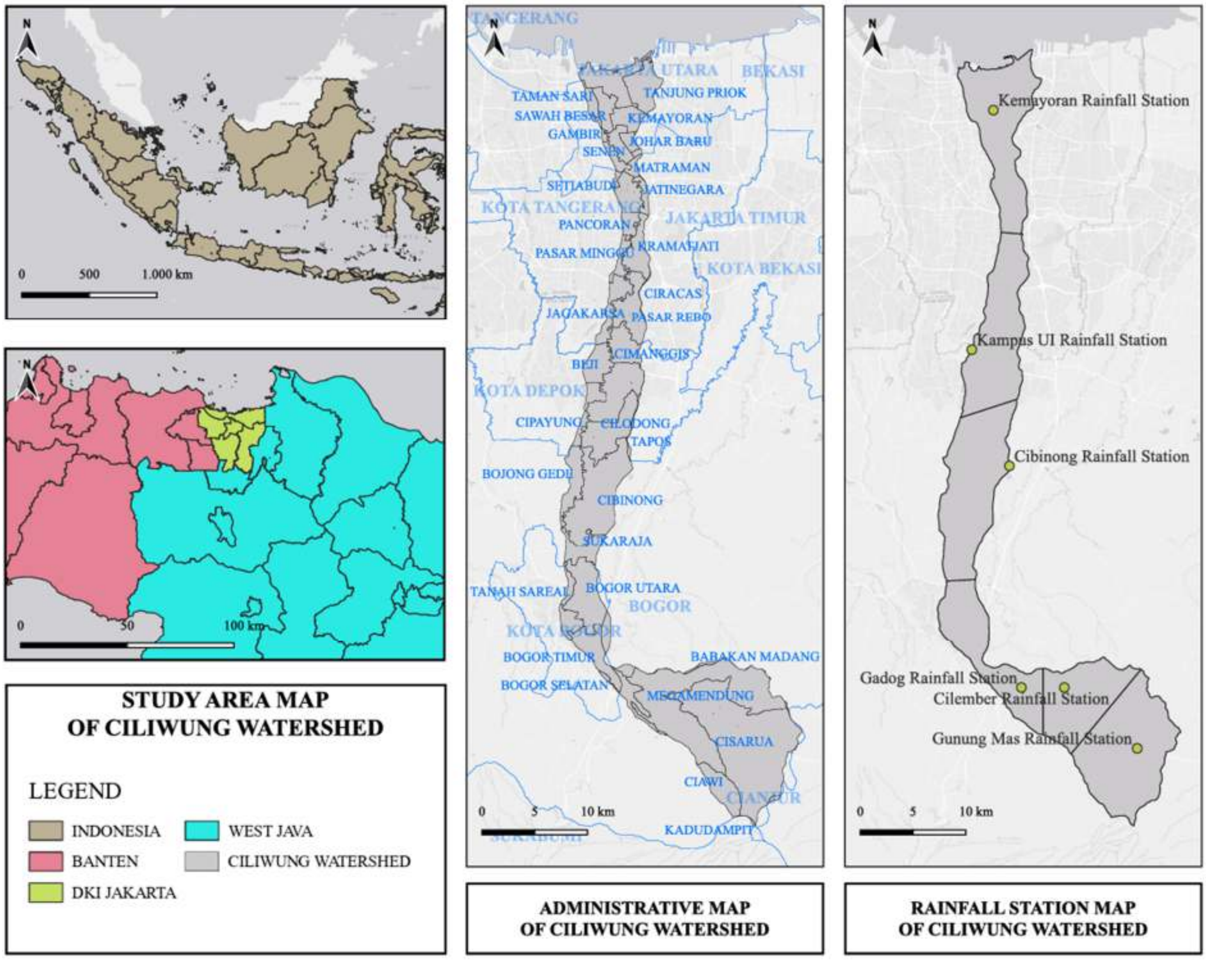


Figure 1. (a) Location of the study area and (b) Rainfall station map of Ciliwung Watershed.

Effective parameters are highly essential in generating flood hazard maps for the river basin. Several key variables have distinct roles in flood hazard mapping (Zain et al., 2021). Data collection involved six key parameters influencing flood hazard: rainfall, slope, topography, soil type, land cover, and distance from the river. Rainfall data were collected from Chirps satellite data and local meteorological stations (Table 1). Digital elevation models were utilized for slope and topography analysis, soil type and land cover data were acquired from remote sensing sources.

The distance from the river was determined using geospatial techniques. Rainfall is categorized into five flood risk hazard classes as follows: rainfall exceeding 3,000 mm/year falls under the "very wet" category with a score of 5, rainfall between 2,500 to 3,000 mm/year is classified as "wet" with a score of 4, rainfall ranging from 2,000 to 2,500 mm/year is considered "moist/moderate" with a score of 3, rainfall between 1,500 to 2,000 mm/year is in the "dry" class with a score of 2, and rainfall less than 1,500 mm/year is categorized as "very dry" with a score of 1. The slope inclination data is grouped into five classes. The steeper the slope in an area, the higher the water runoff, whereas areas with low (gentle) slopes tend to accumulate water, increasing the potential for flooding in those areas. The slope parameter score is also divided into five classes, namely slopes between 0-8% fall under the "Flat" category with a score of 5, slopes between 8-15% are classified as "Gentle" with a score of 4, slopes between 15-30% are categorized as "Moderate" with a score of 3, slopes between 30-45% are labeled as "Steep" with a score of 2, and slopes greater than 45% are considered "Very Steep" with a score of 1.

The topography of an area influences the occurrence of flood hazards because water naturally flows downhill due to gravity. Consequently, areas at higher elevations have a lower potential for flooding compared to lower-lying areas (Zain et al., 2021), The topography parameter scores are also divided into five classes. Elevation between 0-12.5 m is assigned a score of 5, elevation between 12.5-25 m is given a score of 4, elevation between 25-50 m is scored 3, elevation between 50-75 m is scored 2, and elevation between 75-100 m is scored 1. Elevation greater than

100 m is scored as 0. The type of soil has a significant impact on the infiltration process. Soils with fine textures have low infiltration rates, leading to increased surface runoff (Booij, 2017). Conversely, coarse-textured soils have high infiltration capacity. The higher the infiltration capacity, the lower the surface runoff (Umar et al., 2018). For the soil type parameter scores, they are divided into five classes based on their infiltration rates. Alluvial soil type falls into the "Slow" category with a score of 5. Regosol soil type is categorized as "Moderate" with a score of 4, Latosol soil type is classified as "Average" with a score of 3, Brown Andosol soil type is labeled as "Somewhat Fast" with a score of 2, Black Andosol soil type is categorized as "Fast" with a score of 1.

Regions dominated by vegetation, especially forests or trees, which have a high capacity to absorb water into the soil, ultimately have a low risk of flooding. This means there is a negative correlation between flood events and the density of vegetation in an area (Alsamaray, 2017; Widianta et al., 2018; Bataineh et al., 2020). In urban areas and developed regions, surface water runoff becomes very high because the surface is unable to absorb water (Toosi et al., 2019). Therefore, the way land is utilized and the type of land cover play a crucial role in determining the extent to which an area is vulnerable to flood risk.

Land use changes are divided into water bodies, settlements, grassland or shrubland, and forests. In ArcGIS, proximity analysis is used to create a dataset representing distances from rivers. The closer a region is to a river, the higher the potential for flooding caused by river overflow as it becomes unable to contain higher water discharge. For the parameter score of distance from the river is divided into five classes: the distance from the river between 0-50 m falls into the "Very Vulnerable" category with a score of 5, the distance from the river between 50-100 m is categorized as "Vulnerable" with a score of 4, the distance from the river 100-250 m falls into the "Somewhat Vulnerable" category with a score of 3, the distance from the river 250-500 m is classified as "Safe" with a score of 2, and the distance from the river greater than 500 m is considered "Very Safe" with a score of 1. Vertical movement downward or water infiltration significantly impacts flood occurrences (Kowalik and Walega, 2015; Anni et al., 2020).

To determine the relative weights of the six flood hazard criteria, such as rainfall, slope, and soil type, the Analytic Hierarchy Process (AHP) method can be utilized using software such as Expert Choice or SuperDecision. The steps involved include creating a hierarchy of criteria, making relative comparisons between criteria, calculating weights based on these comparisons, and evaluating the consistency of comparisons. Understanding AHP and selecting the appropriate software is key to obtaining accurate and relevant decisions regarding flood hazards, including the impact of land degradation or soil degradation. Flood events in 2015 and 2020 can be used to validate flood hazard maps by comparing flood-affected locations with high-risk areas identified in assessments, which may also be related to soil degradation issues.

The significance of each parameter's contribution to flood hazards was measured through weighting, which may consider factors related to land degradation. The integrated analysis impact in identifying high-risk areas can be explored in the context of flood risk management and mitigation, including strategies to address land degradation contributing to flood risk. Flood hazard calculations involve integrating data from several parameters, including soil type and land cover, to generate values representing the vulnerability of areas to potential floods, which may also be influenced by soil degradation conditions. Flood hazard was calculated using the following Equation (1).

$$FH = (Wr \times Sr) + (Wtp \times Stp) + (Ws \times Ss) + (Wst \times Sst) + (Wlc \times Slc) + (Wdfr \times Sdfr) \quad (1)$$

where:

FH = Flood hazard
Wr = Weight of rainfall
Wtp = Weight of topography
Ws = Weight of slope
Wst = Weight of soil type
Wlc = Weight of the land cover
Wdfr = Weight of distance from the river
Sr = Score of rainfall
Stp = Score from topography
Ss = Score of slope
Sst = Score of soil type
Slc = Score of land cover
Sdfr = Score of distance from the river

The weight of rainfall, topography, and other parameters represent the relative importance of each in the context of evaluating flood risk related to land degradation. In this study, the weights for each parameter are determined through expert assessment. Meanwhile, the rainfall score, topography score, and so forth are values assigned to each evaluated area for each parameter. These scores depict the characteristics or conditions related to each parameter and their calculation results in flood vulnerability values for each evaluated area. Regions with higher vulnerability values generally are more susceptible to potential floods, which may be associated with the level of land degradation in those areas.

Results and Discussion

Weighting with AHP was conducted to obtain a flood hazard map (Figure 2a) based on the hazard-forming parameters (Figure 2b). AHP analysis was carried out based on questionnaires provided to 5 experts from BBWS, the Provincial Government of DKI Jakarta, BNPB, BNPB experts, and academia. The result is a weighted analysis of each flood hazard-causing parameter (Figure 3 and Table 1), with an inconsistency value of 4%. Based on an inconsistency value below 10%, the results of this analysis are acceptable.

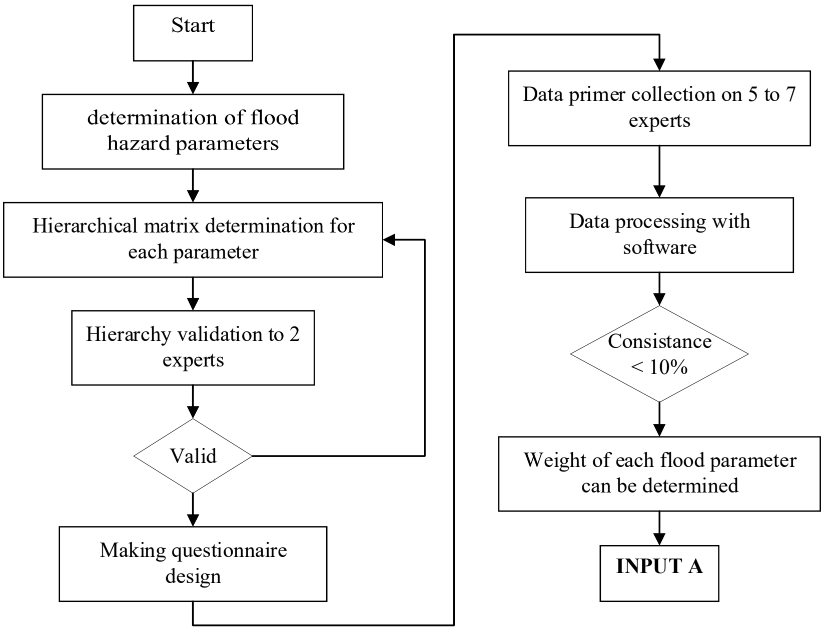


Figure 2a. Flow chart input A for weight parameter.

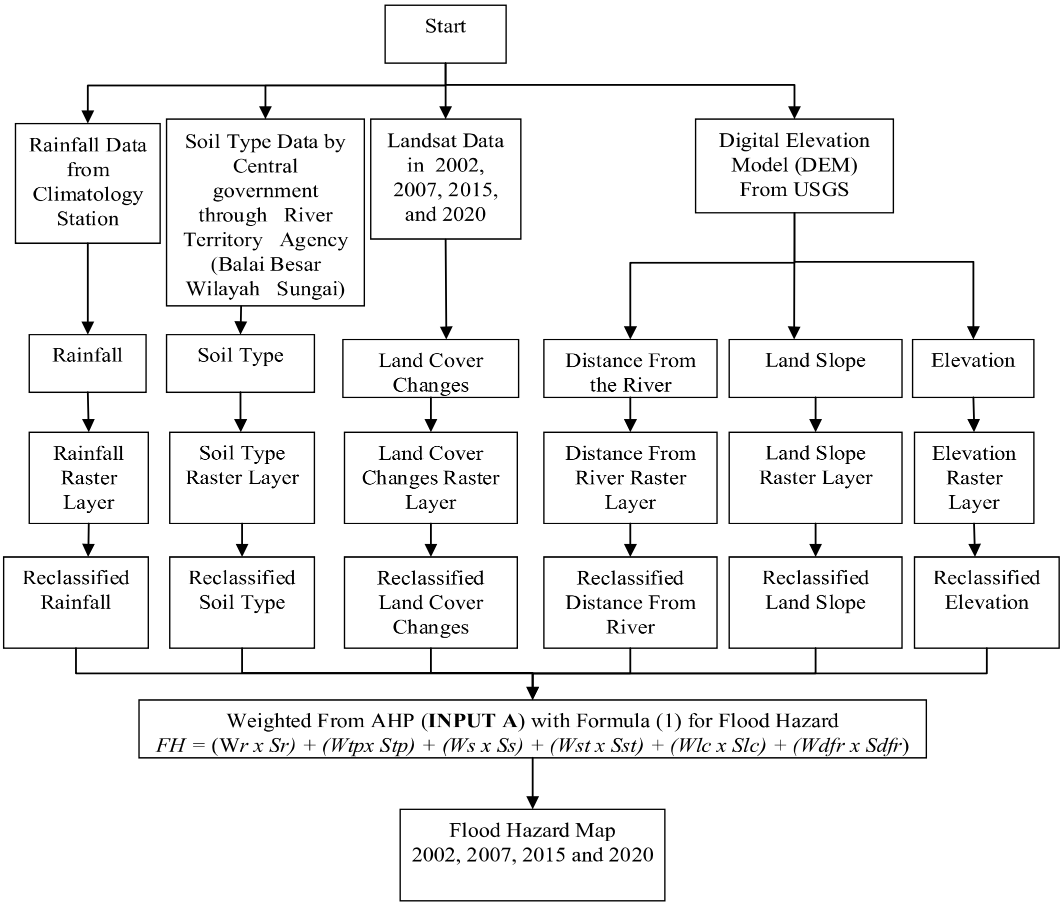


Figure 2b. Flow chart of flood hazard map.

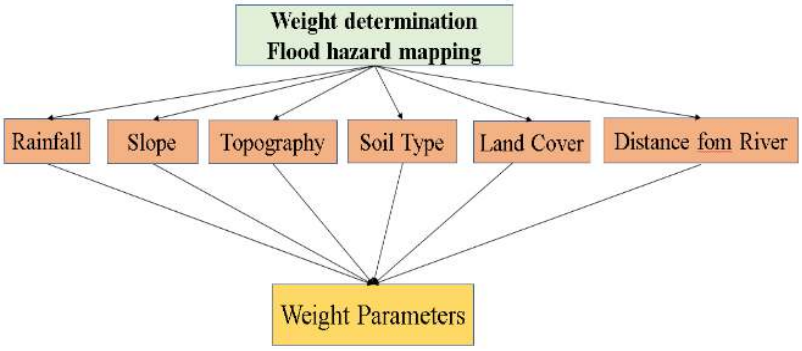


Figure 3. Matrix for determining weight parameters of flood hazards.

Table 1. Pairwise comparison from questionnaire result.

	Rainfall	Slope	Topography	Soil Type	Land Cover	Distance from River
Rainfall	1.00	1.28	1.25	2.41	1.99	2.93
Slope	0.78	1.00	1.36	1.84	1.20	1.04
Topography	0.80	0.74	1.00	1.28	2.38	1.04
Soil Type	0.41	0.54	0.78	1.00	1.96	2.94
Land Cover	0.50	0.83	0.42	0.51	1.00	1.18
Distance from River	0.34	0.96	0.96	0.34	0.85	1.00

Based on the multi-criteria analysis results, the weights of each flood hazard-causing factor could be observed. It is known that rainfall has the highest weight, which is 0.270. This finding is supported by a study conducted in 2022. Eleven flood-causing factors were analyzed based on Direct Influence Matrix (MDI) and Indirect Influence Matrix (MII). It has been identified that rainfall and distance from the river are the most influential variables in causing flood hazards (Ariyani et al., 2022b). Following rainfall, land cover is the next most influential factor, with a weight of 0.190. The complete weights of each parameter can be found in Table 2. These weights were then used to determine the flood vulnerability index based on Equation (1).

Table 2. Parameter weight results.

No	Parameters	Weight
1	Rainfall	0.270
2	Slope	0.164
3	Topography	0.124
4	Soil type	0.096
5	Land cover	0.190
6	Distance from river	0.155
	Total Weight	1.000

Rainfall analysis in the context of flood hazards is a crucial process that involves monitoring, data collection, and the use of hydrological models to identify potential flood hazards. The steps involve weather monitoring, assessment of historical rainfall data, and determining the levels of flood hazards, ranging from minor floods to extreme ones (Cheng et al., 2021). During heavy rainfall events, early warning systems are used to inform the public about potential flood hazards. Additionally, the results of rainfall analysis are used for flood control infrastructure planning and safer flood-resistant spatial planning. Post-flood evaluations help improve mitigation and warning systems to reduce the adverse impacts of floods on communities and the environment. From Figure 4, it is evident that the increase in maximum daily rainfall from 1980 to 2022 is 15 mm, using time series analysis with the Mann-Kendall method (Karmeshu, 2012; Ariyani et al., 2020) and considered not too significant (Setiawan and Ma'mun, 2021).

The parameters analyzed to determine the level of flood hazard include slope, topography, soil type, and distance from the river (Figure 5). The Ciliwung River Watershed has gentle slopes, with 54% of the Ciliwung River Watershed having slopes ranging from 0% to 8% and only 7% having slopes greater than 45%. In the Ciliwung Watershed, 64% of the area has elevations above 100 meters above sea level (masl), while about 12% of the area has elevations less than 12 masl, which are located in the downstream areas of the Ciliwung River leading to the sea. The Ciliwung Watershed consists of three soil types, with Latosol soil being prevalent in various locations, especially in hilly areas that are part of the Ciliwung River Basin. Latosol soil is generally suitable for agriculture but needs proper management to address issues related to clay texture and low nutrient content. The majority of the Ciliwung Watershed's soil type is Latosol, accounting for 76.7%.

The distance from the river affects the spread of flood hazards. The closer residential areas are to the river, the higher the risk. Distance from the river is analyzed using the Euclidean method in QGIS. It is important to understand the relationship between river proximity and flood risk when planning development, selecting housing locations, and making property-related decisions. Monitoring flood warnings and following guidelines from local authorities during flood threats is always crucial. According to the regulations of the Republic of Indonesia regarding riverbanks, the safe distance from the river in urban areas with a river depth of 3 to 20 m is a minimum of 15 m from the left and right banks along the river's course (Government of Indonesia 2011; Sunarhadi et al., 2015). For land cover data, satellite data from USGS, specifically Landsat 5, 7, and 8, were used. The data description can be found in Table 3.

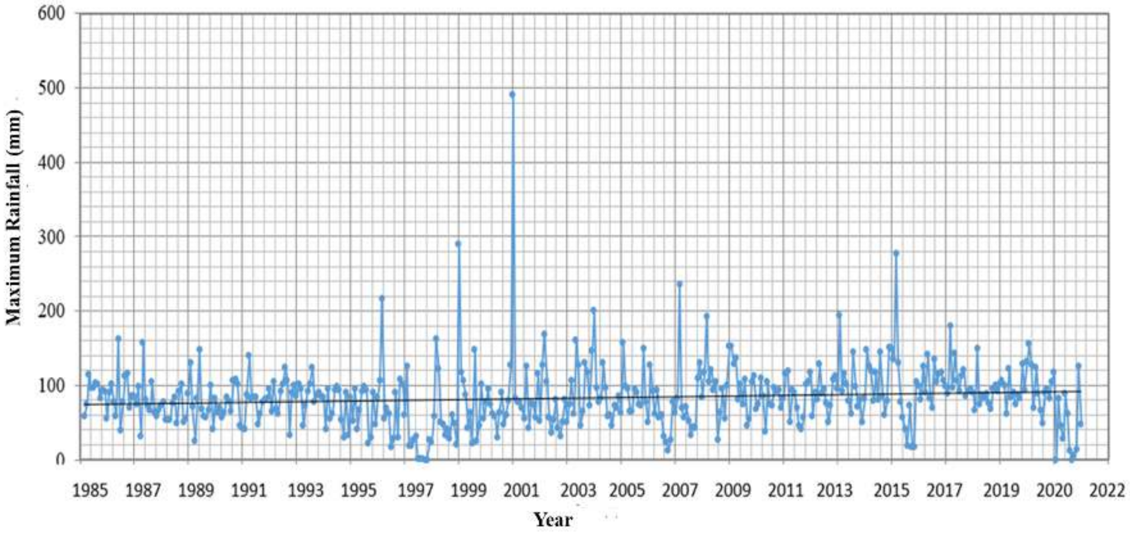


Figure 4. Maximum monthly rainfall.

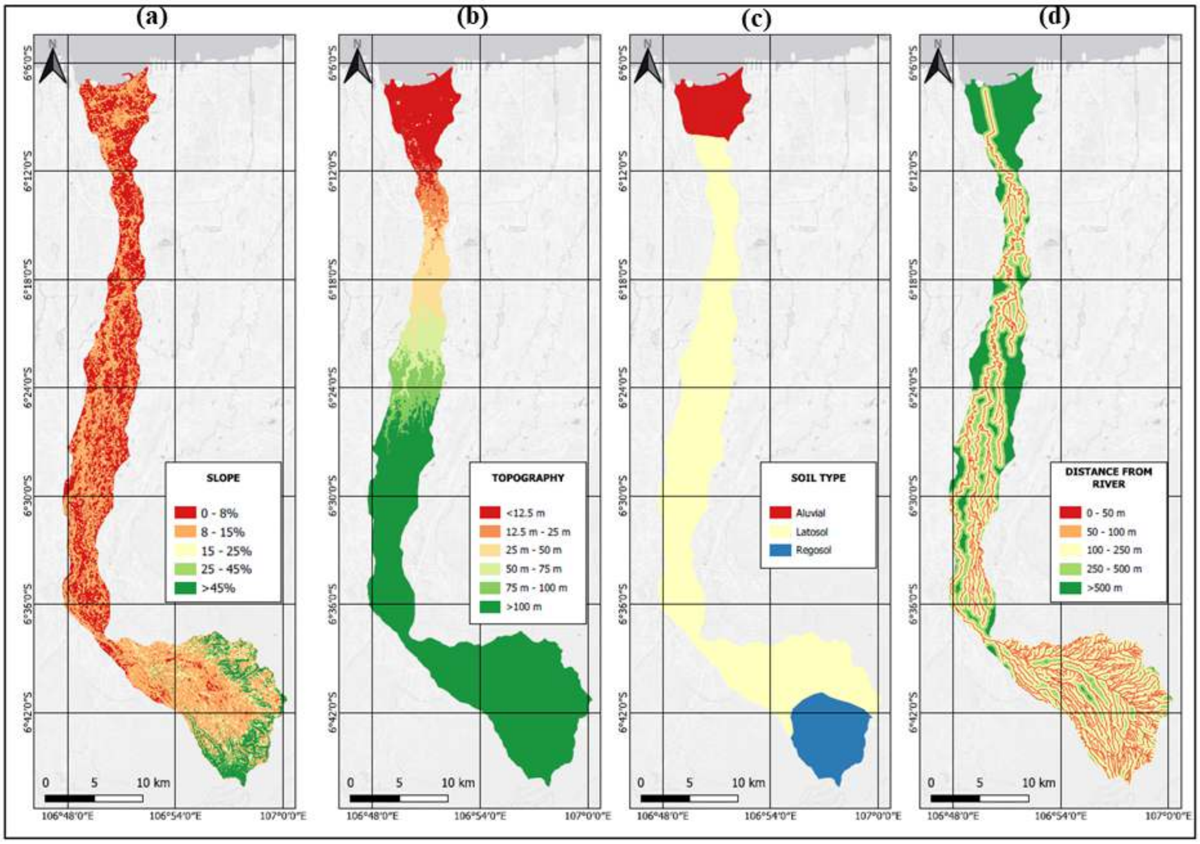


Figure 5. Raster layer of (a) slope, (b) topography, (c) soil type, (d) distance from river.

Table 3. Suitability of land cover data.

Years	Satellite Data / Satellite Sensor Type	Date Data required	Download Date
1990	Landsat 5 Thematic Mapper (TM) C2 L1 Path 122 Row 064 & 065 Tier 1	7/9/1990	2/10/2022
2002	Landsat 7 Enhanced Thematic Mapper Plus (ETM+) C2 L1 Path 122 Row 064 & 065 Tier 1	8/3/2002	9/3/2021
2007	Landsat 5 Thematic Mapper (TM) C2 L1 Path 122 Row 064 & 065 Tier 1	9/26/2007	9/3/2021
2015	Landsat 8 Operational Land Imager (OLI) C2 L1 Path 122 Row 064 & 065 Tier 1	8/31/2015	7/4/2021
2020	Landsat 8 Operational Land Imager (OLI) C2 L1 Path 122 Row 064 & 065 Tier 1	5/24/2020	6/26/2021

Land cover analysis was carried out using QGIS, and the results can be seen in Figure 6. Following that, the accuracy of the land cover map in the Ciliwung Watershed was tested using the ACATAMA plugin in QGIS (Manandhar et al., 2009; Rwanga and Ndambuki, 2017; Ismai et al., 2020; Castillo-Santiago et al., 2022), The results obtained in 1990 showed an accuracy of 91%, in 2002 the accuracy test yielded 98%, in 2007 the accuracy test resulted in 87%, in 2015 the accuracy test yielded 94%, and in 2020, the accuracy test showed 98%. From the accuracy test results, it can be concluded that the land cover mapping using Landsat data is accurate, as it exceeds 80%, and can thus be used for further analysis.

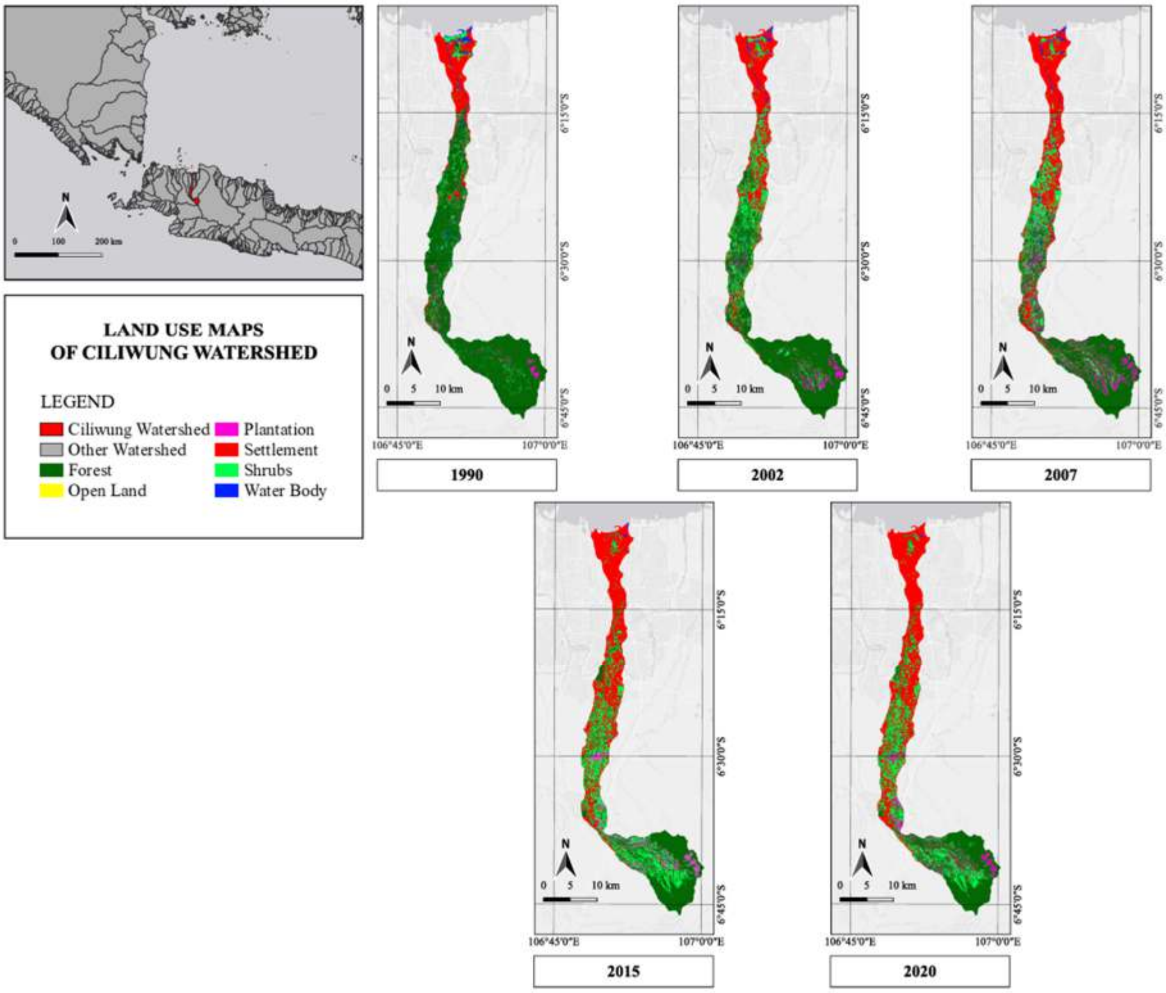
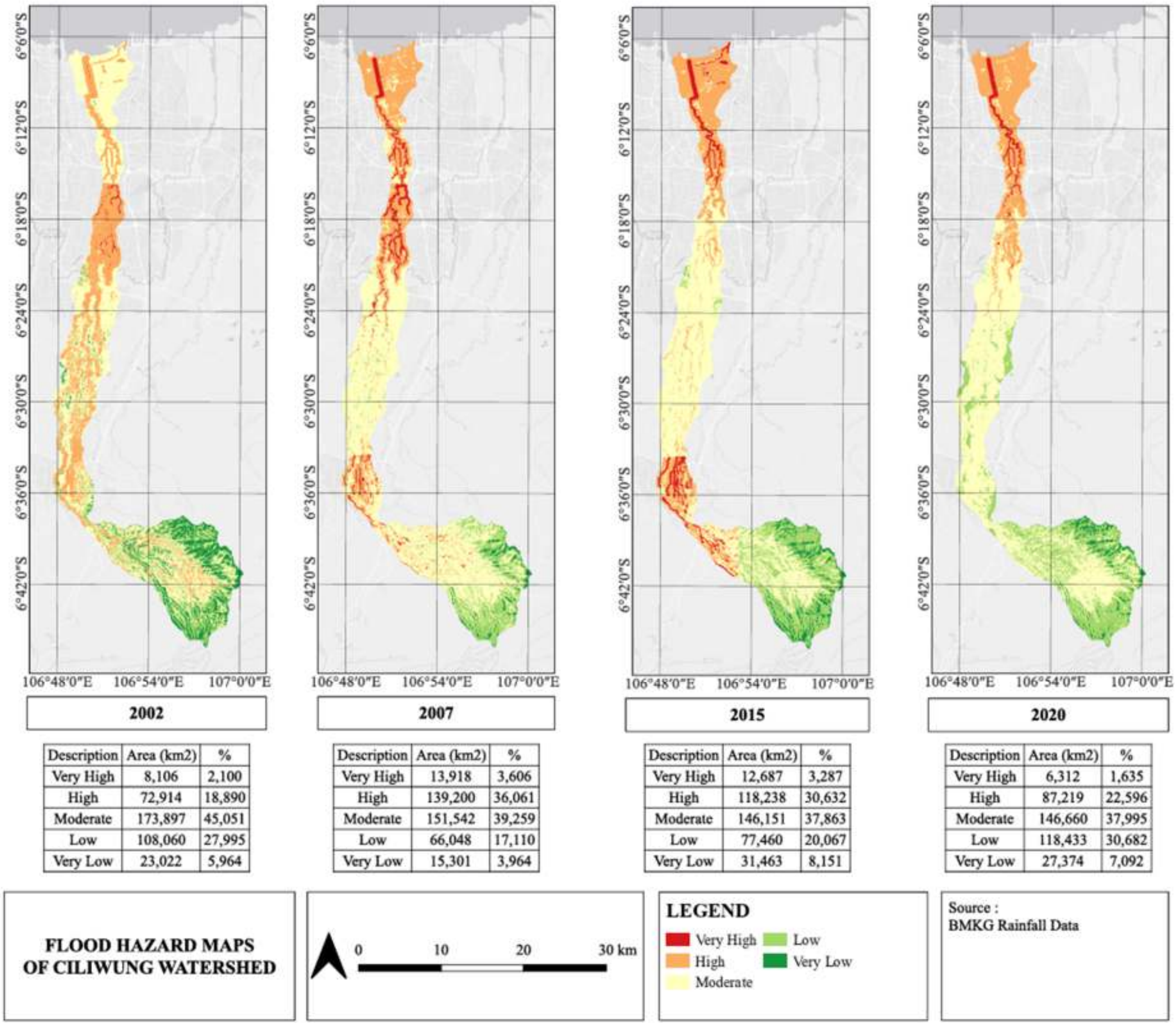


Figure 6. Land cover analysis (a) 1990, (b) 2002, (c) 2007, (d) 2015, and (e) 2020.

From the land cover map results, significant changes in land cover from 1990, 2002, 2007, 2015, and 2020 can be observed (Figure 6), especially in the transformation of forested areas into settlements. In 1990, the urban area covered 91,527 km^2 or 23.71% of the total area, and by 2020, the urban area had increased by 100% to 204,335 km^2 or 52.94% of the total watershed area. The extent of urbanization will affect the rate of water infiltration into the ground, as rainwater finds it difficult to penetrate when it falls on developed land (Brodya et al., 2017; Goodarzi et al., 2019).

In this research, an innovative approach was used to determine flood hazard mapping in the context of disaster risk reduction, utilizing satellite data based on several flood parameters. GIS analysis was conducted on four other parameters, namely rainfall, soil type, topography, and distance from the river. Subsequently, scoring was performed on six parameters with a scale of values ranging from 1 to 5. After obtaining the scores for each parameter, a weighting analysis was conducted based on the weights from Table 2. The flood vulnerability map, which contains flood hazard areas, was obtained by overlaying the six flood parameters, namely land cover, distance from the river, slope, elevation, rainfall, and soil type. Flood hazard zones were analyzed for the years of the most severe flood events, namely 2002, 2007, 2015, and 2020. From the mapping results using GIS and the weights from AHP, flood hazard areas can be determined (Figure 7). From the analysis results in 2002, using rainfall data from BMKG, it is observed that the vulnerable to a highly vulnerable area covered 90.02 km^2 or 20.99% of the total river basin area. In 2007, the vulnerable to highly vulnerable areas increased to 153.12 km^2 (39.67%). In 2015, the total area that was vulnerable to highly vulnerable was 130.93 km^2 (33.92%), while in 2020, the area vulnerable to highly vulnerable reached 93.53 km^2 (24.23%). Changes in flood hazard area zoning are influenced by rainfall, with the highest weight based on AHP. The weighting of each parameter (Table 2) significantly influences the determination of flood hazard areas. Validation of the flood hazard map was carried out by examining information about flood events in 2015 and 2020 (Figure 7). Information about flood events was obtained from the Regional Disaster Management Agency (BPBD) and the government of the DKI Jakarta Province.

The locations of flood events were then overlaid with the flood hazard map for 2015 (Figure 8a) and 2020 (Figure 8b), revealing that most of the flood events in those years occurred in high-vulnerability zones.



2002

Description	Area (km2)	%
Very High	8,106	2,100
High	72,914	18,890
Moderate	173,897	45,051
Low	108,060	27,995
Very Low	23,022	5,964

2007

Description	Area (km2)	%
Very High	13,918	3,606
High	139,200	36,061
Moderate	151,542	39,259
Low	66,048	17,110
Very Low	15,301	3,964

2015

Description	Area (km2)	%
Very High	12,687	3,287
High	118,238	30,632
Moderate	146,151	37,863
Low	77,460	20,067
Very Low	31,463	8,151

2020

Description	Area (km2)	%
Very High	6,312	1,635
High	87,219	22,596
Moderate	146,660	37,995
Low	118,433	30,682
Very Low	27,374	7,092

Figure 7. Flood hazard analysis 2002, 2007, 2015, and 2020.

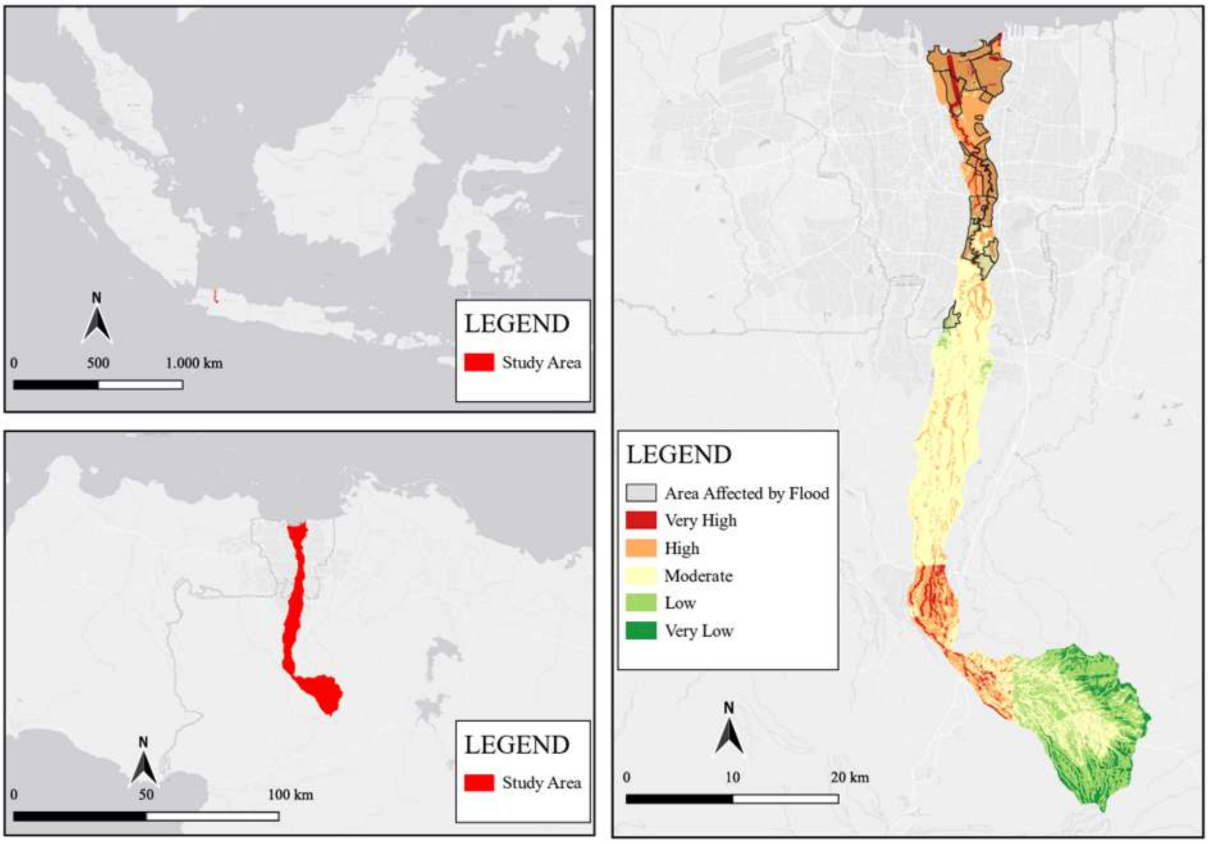


Figure 8a. Validation of flood hazard maps for flood-affected areas in 2015.

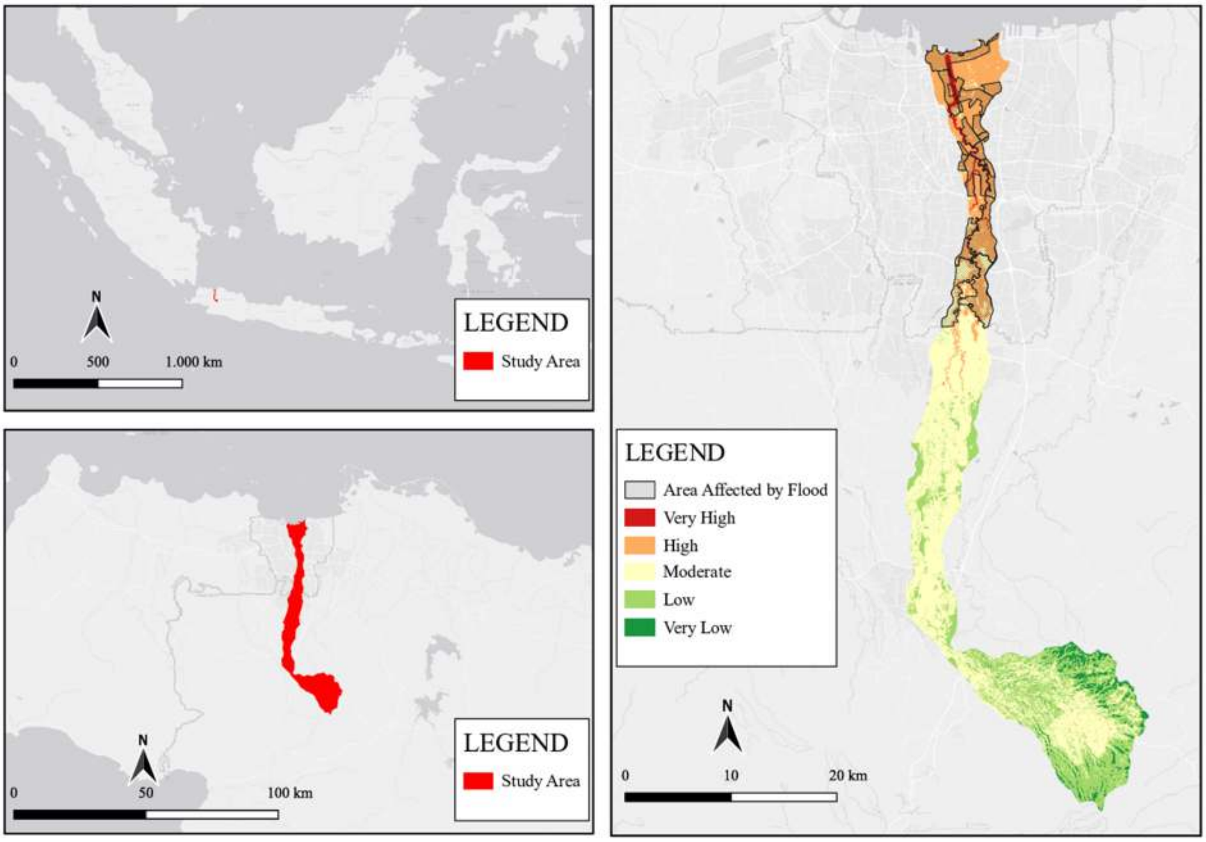


Figure 8b. Validation of flood hazard maps for flood-affected areas in 2020.

This research was conducted with the aim of evaluating flood hazards in the Ciliwung Watershed in Indonesia, using the MCDA method with AHP through the SuperDecision software integrated with Geographic Information Systems (GIS). The goal was to identify areas with a high level of flood hazard by analyzing six key parameters that influence flooding. In this analysis, weighted coefficients were used to determine the priority level of each parameter in assessing flood hazards through pairwise comparisons using the AHP method.

The results of the research included a flood hazard map that integrates the six factors influencing floods, categorizing the hazard levels into five main groups: very low, low, moderate, high, and very high. Slope, topography, soil type, and land cover were found to have a more significant impact on flood hazard assessment, while the distance from the river had a lower impact. The use of the AHP method combined with GIS allows for a comprehensive analysis of flood hazard risks in the Ciliwung Watershed. This approach has proven to be effective in identifying and mapping areas with high vulnerability to flood hazards (Omena et al., 2020; Osman and Das, 2023) because it can consider many contributing factors and their respective importance. From the data analysis results, it is known that the highest flood hazard zone is in South Jakarta, specifically in the districts of Pasar Minggu, Pancoran Mas, Jagakarsa, and surrounding areas. This is primarily due to the overflow of the Ciliwung River and poor drainage of excess water. In contrast, floods in North Jakarta, such as in the districts of Tanjung Priok and Pademangan, have also been observed.

Model validation is also necessary to compare the model outputs with observational data at the study site and assess the level of conformity both quantitatively and qualitatively with the actual conditions. Many researchers use various types of models to evaluate flood hazard vulnerability worldwide. However, it is essential to test the model outputs and ensure that the model used accurately represents the field conditions or well-documented observations (Puno et al., 2021). By comparing the model outputs with observed data, model calibration and validation can be performed (Castillo-Santiago et al., 2022). In the Ciliwung River Basin, historical flood events were identified through field observations, and flood event data were collected from the Regional Disaster Management Agency (BPBD). These locations were then compared with the model's output. Figure 3 displays the flood-affected areas from the collected data in accordance with the model's predictions. The historical flood areas are located in high and very high flood hazard zones, indicating the reliability of the flood vulnerability model used in this study.

Flood hazard zoning is paramount in the comprehensive spatial planning of municipalities situated in the South Jakarta, Depok, Cibinong, Bogor City, and Bogor District areas, especially considering the issue of land degradation along the Ciliwung River. It serves as a crucial guideline for infrastructure development within flood hazard zones. Given the heightened vulnerability of these areas, they necessitate special attention and top priority in terms of flood prevention measures. Hence, strategies for flood prevention, encompassing both structural and non-structural elements, must be promptly implemented, particularly in densely populated regions experiencing significant development. These measures not only lay the groundwork for emergency planning but also contribute to disaster risk reduction and prevention efforts. Integration of flood hazard zones into spatial planning, establishment of operational communication protocols, dissemination of disaster information and response, and implementation of effective early warning systems are imperative actions to be taken in this regard (Birkmann, 2006; Rimba et al., 2017), This method can maximize the determination of safe evacuation routes during flood conditions, reduce disaster risks, and minimize resulting losses.

Through accurate flood hazard mapping integrated with land degradation assessment along the Ciliwung River, an information system can be developed to provide precise and detailed guidance on safe evacuation routes during floods. Thus, communities can be better prepared to face flood risks and mitigate the resulting losses from the disaster.

Conclusion

The approach adopted in this study aimed not only to optimize the identification of evacuation routes during floods but also to reduce disaster risks and minimize associated losses, including the impacts of land degradation occurring along the Ciliwung River due to land use changes. Changes in land use, such as deforestation and conversion of land cover from forests to urban areas or intensive agriculture, are significant factors in increasing vulnerability to floods in areas surrounding the river. Therefore, the mapping of flood hazard zones and flood risk management strategies applied in this research also consider the condition of land degradation as a result of land use changes.

By understanding how changes in land use contribute to land degradation and flood risks, this research provides a better understanding of the complexity of factors involved in land availability and flood management in the Ciliwung River Basin. In this study, an integrated approach was used, combining Multi-Criteria Decision Analysis (MCDA), geospatial modeling, hydrological analysis, and hydraulics, thus enhancing our understanding of flood vulnerability and supporting effective flood risk management planning. The use of remote monitoring technology and parametric multi-criteria methods helps identify factors influencing floods. The analysis considers six key parameters: rainfall, topography, soil type, slope, elevation, and land cover, along with the distance from the river. These parameters are weighted using the Analytic Hierarchy Process (AHP) by Saaty, determining criteria with the greatest impact on flood hazards.

The weights assigned to each parameter, as seen in Table 2, show that rainfall criteria have the highest weight, significantly contributing to flood hazards (0.270), followed by slope (0.164), topography (0.124), soil type (0.096), land cover (0.190), and distance from the river (0.155). These weights influence the raster layers of each parameter, allowing for the determination of flood hazard zones using Equation (1) (Figure 5). Validation results of the flood hazard map indicate that the model used in this study, which incorporates six flood parameters (Figure 6), closely mirrors real-world conditions in the field. Locations of flood incidents in 2015 and 2020, as depicted in Figure 5, fall within high vulnerability zones.

The modeling approach based on these six parameters can be applied to predict flood hazard zones in other river basins. The weightings assigned to each parameter closely approximate real-world conditions, making the findings of this study valuable for decision-makers in formulating disaster risk reduction policies based on flood hazard zones.

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