LIMNOTEK Perairan Darat Tropis di Indonesia
transforming into Journal Limnology and Water Resources
p-ISSN: 0854-8390 e-ISSN: 2549-8029
https://ejournal.brin.go.id/limnotek

Assessment of Flash Flood Vulnerability Index in a tropical watershed region: a case study in Ciliwung Hulu watershed, Indonesia

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Received: 30 August 2023; Accepted: 12 November 2023; Published: 20 December 2023

Abstract: Flash floods, an unpredicted swift climatological disaster, frequently occur in Indonesia. However, there are limited vulnerability assessments, especially in urban and vital regions such as Bogor District. The study aims to assess the vulnerability index of Ciliwung Hulu Watersheds as one of the most susceptible areas in the district. Flash flood vulnerability index (FFVI) is selected to be calculated as the indicator. Data were obtained from the official government offices and processed using the FFVI formula referring to the work of Nasiri *et al.,* (2019) and Perka BNPB No. 2/ 2012 and then mapped using ArcGIS 10.3. The results and the maps show that the study area is categorized as highly to very highly vulnerable to flash flood disasters. The attained results help facilitate the governance interplay processes in building a more disaster-ready management plan and to construct a more resilient society.

Keywords: flash flood, Ciliwung Hulu, vulnerability index, watershed

1. Introduction

A flash flood is one of the most frequent disasters in Indonesia (Badan Nasional Penanggulangan Bencana/BNPB, 2018). The leading causes of the disaster in the country are high precipitation rates, steep topography, and the vast occurrence of barren land (Mahmood *et al.*, 2016). The flood is categorized as a climatological disaster that is unpredicted, swift, and severe; thus, the causalities level is usually significant (Hastanti and Miardini 2020; Rahman *et al.* 2016). Considering its massive impacts, an assessment of the vulnerability level of a location to the flood is imperative to be conducted. Vulnerability assessment is defined as the inability of a specific individual or community, and it can be used to mitigate the severity of flood causalities (Rijanta *et al.*, 2014).

Bogor, a district in West Java, Indonesia, is selected as the study site of our vulnerability assessment study. The district is an important supporting and satellite area for Jakarta, the capital of Indonesia, and is frequently accused as the flood sender to the capital city (Harsoyo, 2013). The district is known as one of the hot spots where flash flood frequently occurs due to its topography. The district typically has small upstream systems and is prone to experiencing landslides – the principal prerequisite to flash floods (BNPB, 2018).

Considering the importance of the district, the development of a flash flood disaster-ready is a necessity; thus, an assessment of flash floods in Bogor district is imperative. However, until recently, there have been only limited studies focusing on this sector in such cities in Indonesia as most vulnerability studies were conducted in major cities (cf. Azmiyati and Poernomo, 2019). To fill this gap, it is necessary to assess the flash flood vulnerability index as an input of disaster-ready management planning, where this study can generate a vital contribution (cf. Larsen *et al.*, 2001).

DOI: 10.55981/limnotek.2023.1105

In the district, we mainly focus on the area of Ciliwung Hulu Watershed, where a relatively recent colossal flash flood in the watershed area, especially in Gunung Mas, Tugu Selatan Village just happened. The flood had caused an emergency evacuation of 474 people and 134 households and destroyed their houses, bridges, and roads (Maulana, 2021). The repeated and the scale of the resulted damage make the area is suitable to be used as our case study (cf. Dewi and Abdi 2017).

2. Materials and Methods

2.1. Study site

Administratively, Ciliwung Hulu Watershed is an approximately 14-thousand-hectare areas, which comprises four sub-districts in Bogor District and Bogor Municipality (Ciawi, Cisarua, Sukaraja, Megamendung, and Bogor Timur) (Figure 1a). The watershed is dominated by dryland agricultural, dryland forest, and settlement areas covering about 47, 26, and 23 km^2 area, respectively, as presented by the land use and land cover map (LULC) provided by The Ministry of Environment and Forestry/MoEF (2020) (Figure 1b).

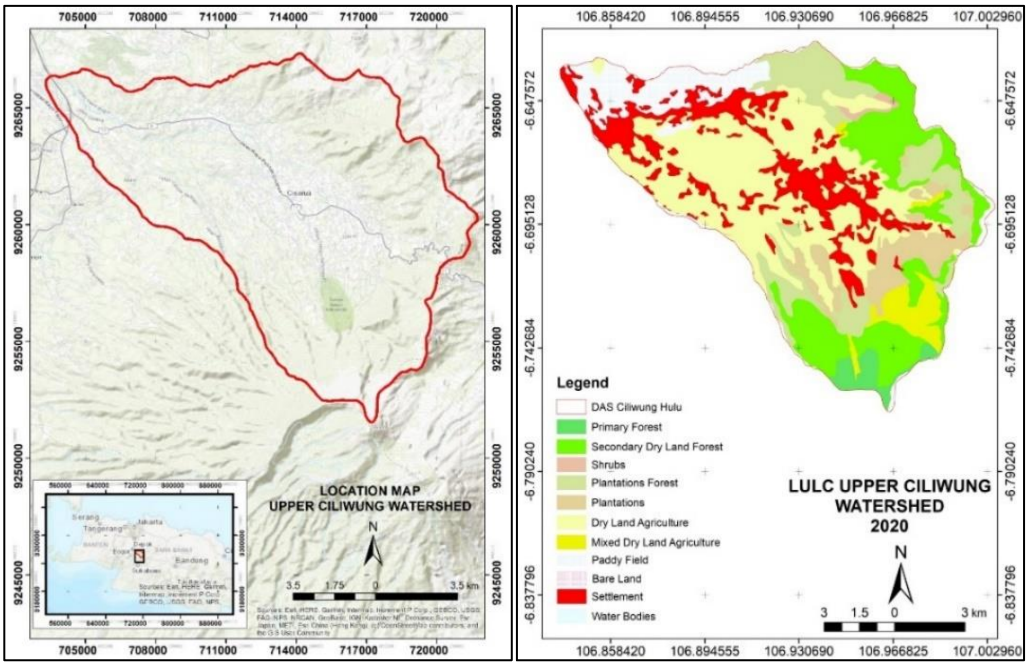

Figure 1. (a) Ciliwung Hulu Watershed; (b) Land use and land cover map of Ciliwung Hulu Watershed (MoEF, 2021)

The last flash flood that took place in 2021 impacted about 11 km^2 of agricultural area (BNPB, 2021). We could not obtain the economic impact of the 2021 flash flood, but as a proxy, a total of 11.2 billion IDR was estimated to be lost during the year due to repeated floods (ibid).

2.2. Data collection

We relied on the data published by the official websites of the sub-districts in Ciliwung Hulu Watershed, Bogor District, and West Java Provincial Government. We declare that there was no primary data collection was conducted to verify the obtained secondary data. Further, we also included the data which was extracted from the websites of the National Statistic Agency (Balai Pusat Statistik/BPS), the Provincial and District Disaster Prevention Agencies (Badan Penanggulangan Bencana/ BNPB), and MoEF. In addition, in case the data could not be obtained in the websites, a series of surveys to the sub-district and the district level government offices were conducted in June 2023.

To categorize the data, we refer to the methodology used by Hastanti and Miardini (2021) and Handoko *et al.* (2017). The data included: 1. The extent of the rice planting area and the average productivity; 2. The density of housing, public and emergency facilities; and 3. Housing market price.

2.3. Data analysis

The components of the index consist of social, economic, environmental, and physical vulnerability dimensions following the work of Nasiri *et al.* (2019), which was also used in the official document of BNPB, such as Perka BNPB No. 2/ 2012. *Social vulnerability* is defined as the level of openness of an individual or society to the social and environmental stressors that cause unpredicted disturbances in people's livelihoods (Adger, 1999).

The parameters used to estimate the social vulnerability index comprise population density, sex ratio, poverty, disability, and age group ratio (BNPB, 2012). The method to calculate each parameter and their definition of the ratios are elucidated in Table 1. Meanwhile, the formula to calculate the Social Vulnerability Index (SVI) (Equation 1) is defined as:

$$SVI = (0.6\ x\ population\ density) + (0.1\ x\ sex\ ratio) + (0.1\ x\ poverty\ ratio) + (0.1\ x\ disability\ ratio) + (0.1\ x\ vulnerability\ age\ group\ ratio) \text{ ....(Eq. 1)}$$

Whereas the Economic Vulnerability Index (EVI) is parameterized using the extent of the fertile land area (monetarized as 2021 Indonesian Rupiah/IDR) and the percentage of susceptible workers (Aisha *et al.*, 2019; BNPB, 2012). To identify the susceptible workers, we referred to the definition of susceptible work fields by Aisha (2019), which are farming, fishing, informal trade and service sectors, and daily workers.

The formulas to calculate the EVI (Equation 2) and the calculation of each parameter (Table 2) are:

$$\text{EVI}=(0.6 \times the\ monetary\ value\ of\ fertile\ land\ area\ ) + (0.4 \times the\ percentage\ of\ susceptible\ workers) \text{ ....(Eq. 2)}$$

Table 1. Parametrization of the Social Vulnerability Index (SVI)

Parameter	Definition	Weight (%)	Class range			Score
			Low	Medium	High	1: low, 2: medium; 3: high class range
Population density	The number of people who live in one square km area	60	<500 people/km^2	500 – 1000 people/km^2	>1000 people/km^2	Class/maximum score class
Sex ratio	The number of men per 100 women	10	<20%	20 – 40%	>40%	
Poverty ratio	The percentage of people who live below the marginal poverty line in Bogor District	10				
Disability ratio	The number of disable people divided by the numbers of population in each sub-district	10				
Vulnerable age group ratio	The number of people categorized in 0–14-year-old age group and more than 65-year-old divided by the number of populations in each sub district	10				

Source: (BNPB, 2012)

Table 2. Parametrization of the Economic Vulnerability Index (EVI)

Parameter	Weight (%)	Class range			Score (1: low, 2: medium; 3: high class range
		Low	Medium	High	
Fertile land	60	<50 million IDR	50 – 200 million IDR	>200 million IDR	Class/maximum score class
Susceptible workers	40	<20%	20 – 40%	>40%	

Source: (Aisha *et al.*, 2019; BNPB, 2012; Widyantoro & Usman, 2021)

The Physical Vulnerability Index (PVI) is a composite index consisting of housing density (permanent, semi-permanent, and non-permanent houses), the availability of public facilities, and the occurrence of emergency facilities (BNPB, 2012). Housing density is the result of the division of the number of houses and the extent of the area (e.g., villages). The result is then converted to the housing market price (Table 3). The formula to estimate the PVI (Equation 3) is written as:

$$\boldsymbol{PVI} = (0.4 \times \textit{the monetary vvalue of housing density}) + (0.3 \times \textit{the monetary value of public facilities}) + (0.3 \times \textit{the monetary value of emergency facilities})$$ ....(Eq. 3)

Table 3. Parametrization of the Physical Vulnerability Index (PVI)

Parameter	Weight (%)	Class range			Score (1: low, 2: medium; 3: high class range
		Low (million IDR)	Medium (million IDR)	High (million IDR)	
Housing density	40	<400	400 – 800	>800	Class/maximum score class
Public facilities	30	<500	500 – 1,000	>1,000	
Emergency facilities	30	<500	500 – 1,000	>1,000	

Source: (BNPB, 2012; Hastani & Miardini, 2021)

The Environmental Vulnerability Index (ENVI) includes the extent of land coverage by protected forests, natural forests, mangroves, bushes, and swamp areas (Table 4). The ENVI is calculated based on Equation 4 below:

$$ENVI = (0.3 \times protected\ forest) + (0.3 \times natural\ forest) + (0.3 \times Mangrove) + (0.1 \times bushes) + (0.2 \times swamps)$$ ....Eq. 4)

The Flash Flood Vulnerability Index value (FFVI), a composite index of SVI, EVI, PVI, and ENVI, is generated using the Analytic Hierarchy Process (AHP) by combining the indices mentioned above with their weight (BNPB, 2012) (Equation 5). The calculated FFVI is then used to categorize the level of vulnerability as revealed in Table 5.

$$FFVI = (0.4 \times SVI) + (0.25 \times PVI) + (0.25 \times EVI) + (0.1 \times ENVI)$$ ....(Eq. 5)

Table 4. Parametrization of environmental vulnerability index (ENVI)

Parameter	Weight (%)	Class range			Score 1: low, 2: medium; 3: high class range
		Low (ha)	Medium (ha)	High (Ha)	
Mangrove	30	<20	20 – 50	>50	Class/maximum score class
Natural forest	30	<25	25 – 75	>75	
Mangrove	10	<10	10 – 30	>30	
Bushes	10	<10	10 – 30	>30	
Swamps	20	<5	5 – 20	>20	

Source: (BNPB, 2012; Widyantoro & Usman, 2021)

Table 5. The categorization of the Flash Flood Vulnerability Index (FFVI)

Flash flood vulnerability index	Vulnerability level
0 – 0.6	Very low
0.61 – 1.20	Low
1.21 – 1.80	Medium
1.81 – 2.40	High
2.41 – 3.00	Very high

Source: Authors' creation based on the level of vulnerability categorization in Widyantoro & Usman (2021), Aisha *et al.*, (2019); Wahyuni (2015); Hastanti & Miardini (2021); and BNPB (2012)

3. Results and Discussion

The calculated SVI (Table 6) shows that the five sub-districts are included in the very high vulnerability level. The extremely high population density generates a 60% contribution to the SVI. The result indicates that the sub-districts are highly susceptible to environmental hazards (Das *et al.*, 2020; Armaş & Gavriş, 2016).

The second most influencing parameter to SVI is the sex ratio. The calculated ratio reveals that there are more men than women in the study area; thus, the vulnerability becomes lower since women generally require more time to resonate from the disaster impacts. This situation happens because, in general, women have higher pressures in child caring and bearing, and they receive lower income than men do (Viet Nguyen, 2015; Armaş & Gavriş, 2013).

Table 6. The calculated SVI

No	Sub-district	Population density		Sex ratio		Poverty ratio		Disability ratio		Vulnerable age group ratio		SVI class	
		Value	Score	Value	Score	Value	Score	Value	Score	Value	Score	Value	Class
1	Ciawi	1,481.06	3	106.7	1	7.69	1	0.03	1	36.92	2	2.30	High
2	Cisarua	2,700.11	3	108.2	1	7.69	1	0.02	1	33.40	2	2.30	High
3	Mega-mendung	1,448.36	3	110.0	1	7.69	1	0.02	1	37.09	2	2.30	High
4	Sukaraja	33,04.94	3	104.5	1	7.69	1	0.01	1	34.07	2	2.30	High
5	Bogor Timur	10,278.52	3	102.9	1	6.68	1	0.19	1	31.49	2	2.30	High

Meanwhile, the assessed EVI (Table 7) also elucidates that most of the study area is grouped into the high-vulnerability category except for Cisarua sub-district. The sub-district is categorized as a very high vulnerability condition.

The monetary value of the extent of fertile land area, the most influencing parameter, supports 60% of the EVI, which indicates that the decline or disappearance of fertile land will severely affect people's livelihoods. In all sub-districts, fertile land is categorized in the high-class range (score 3), which shows critical vulnerable conditions. On the contrary, the vulnerable worker ratio is categorized as low for all sub-districts except for Cisarua. The score of the ratio in the sub-district is included in the high level (Table 7).

At the same time, we found a more interesting finding about the calculated PVI (Table 8). The results show that all sub-districts are highly physically vulnerable. The very dense housing likely becomes the main factor behind the condition, as hinted by Aisha *et al.* (2019), who found that the level of causalities increases with the increment of housing density.

Meanwhile, the assessed ENVI reveals the different results (Table 9). Based on the ENVI, the environmental susceptibility of the study area is categorized as low level for Sukaraja and Bogor Timur and medium level for Ciawi, Cisarua, and Megamendung. The occurrence of protected forest areas in these last three districts (which is categorized in the medium class) becomes the principal factor explaining their relatively higher vulnerability compared to the first two sub-districts.

The results imply that the existence of protected forest areas in Ciawi, Cisarua, and Megamendung does not reduce the environmental susceptibility of the area, as hinted by Hastanti and Miardini (2021). The reason for this circumstance is that the calculation of the index is based on the conversion of the extent of the area, including forested area, into monetary value; therefore, the areas with a more considerable extent of forest area may suffer more significant economic loss. Nevertheless, reducing forest area is not a solution to reduce environmental susceptibility (ibid).

Table 7. The calculated EVI

No.	Sub-district	The extent of paddy field area (Ha)	The valuation of extent of fertile land area (Million IDR)	Score	The percentage of vulnerable workers (%)	Score	EVI class	
							Total score	
1	Ciawi	704	3,949.44	3	12.52	1	2.2	High
2	Cisarua	198	2,107.82	3	28.39	3	3.0	Very high
3	Megamendung	274	1,461.35	3	18.25	1	2.2	High
4	Sukaraja	80	108.65	3	7.53	1	2.2	High
5	Bogor Timur	57	765.99	3	6.94	1	2.2	High

Table 8. The calculated PVI

No.	Sub-district	Housing density		Public facilities			Emergency facilities			PVI class	
		House price (million IDR)	Score	Numbers	Price (million IDR)	Score	Numbers	price (million IDR)	Score	Total Skor	Kelas
1	Ciawi	1,035.53	3	232	46,400	3	13	3,250	3	3	Very high
2	Cisarua	1,939.96	3	228	45,600	3	15	3,750	3	3	Very high
3	Mega-mendung	1,153.81	3	234	46,800	3	11	2,750	3	3	Very high
4	Sukaraja	2,658.15	3	266	53,200	3	12	3,000	3	3	Very high
5	Bogor Timur	4,678.62	3	137	27,400	3	14	3,500	3	3	Very high

Table 9. The calculated ENVI

No.	Sub-district	Protected forest		Natural forest		Mangrove		Bushes		Swamps		ENVI	
		Area (Ha)	Score	Area (Ha)	Score	Area (Ha)	Score	Area (Ha)	Score	Area (Ha)	Score	Total score	Class
1	Ciawi	864.05	3	0	1	0	1	0	1	0	1	1.60	Medium
2	Cisarua	1,268.66	3	5.93	1	0	1	0	1	0	1	1.60	Medium
3	Mega-mendung	184.55	3	1.26	1	0	1	2.66	1	0	1	1.60	Medium
4	Sukaraja	0	1	0	1	0	1	0	1	0	1	1.00	Low
5	Bogor-Timur	0	1	0	1	0	1	0	1	0	1	1.00	Low

Overall, the mapping of the results of the calculation of the SVI, EVI, PVI, and ENVI shows that in almost all the sub-districts have low (the green area in Figure 2d) to very high vulnerability (the red area in Figure 2a-2d) to flash flood disasters depending on the calculated index. However, the calculation of the FFVI (Table 10 and Figure 3) indicates that all sub-districts are highly vulnerable to flash floods (the yellow area in Figure 3) except for the Cisarua Sub-district that has very high vulnerability (the red area in Figure 3).

The map in the figure illustrates the zonation of the flash flood vulnerability index within a 150-meter distance from the river. This distance, a result of an overlay between the flood hazard index map (BNPB, 2016) and the most recent flash flood events in the research area, is a particular area that should be cautioned during the flash flood. However, there is a possibility that other areas which are not mapped can be at a greater risk. Hence, a comprehensive assessment that considers potential high-risk zones beyond the mapped areas is a necessity for future assessment.

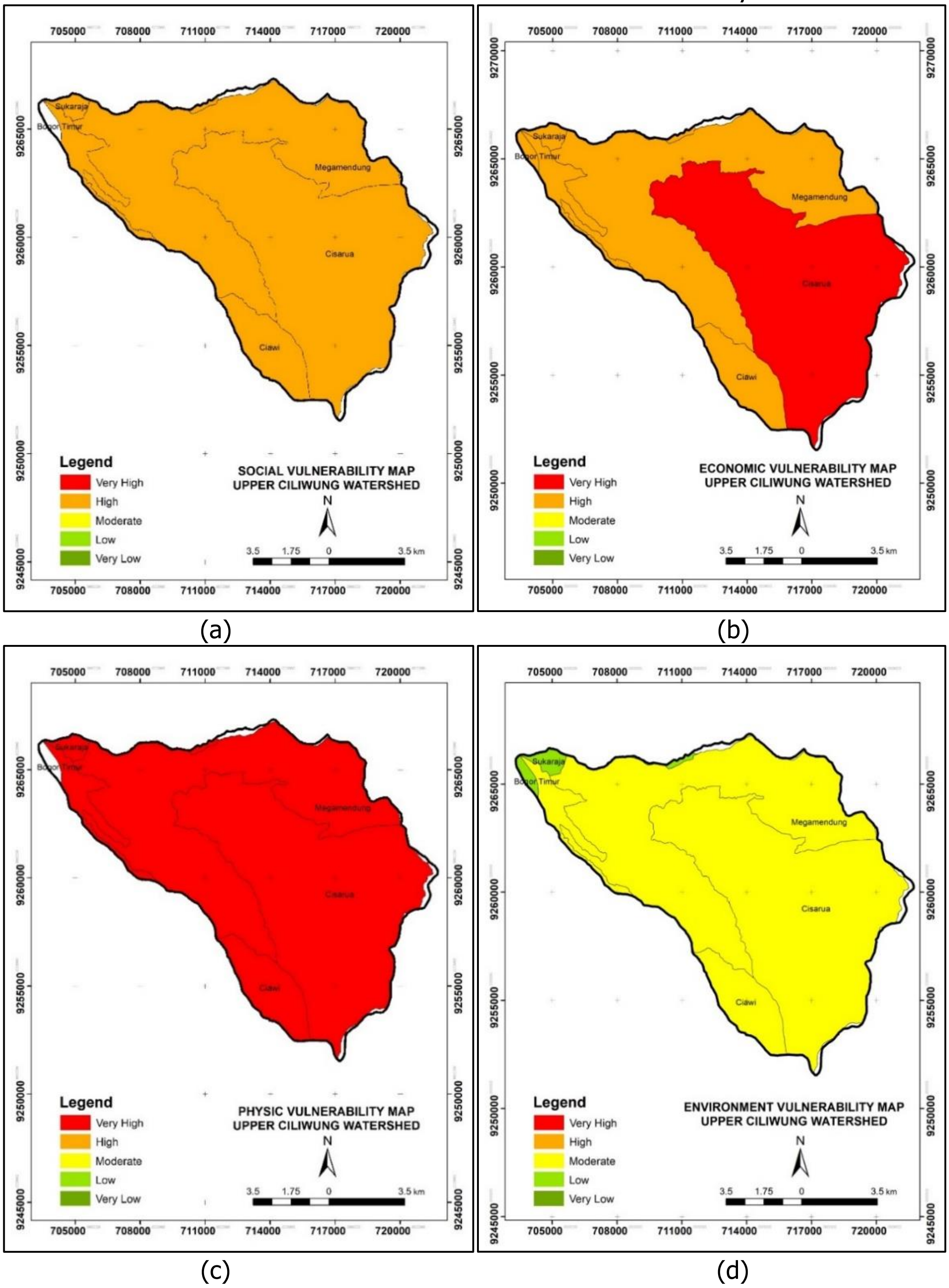

Figure 2. The mapping of (a) SVI; (b) EVI; (c) PVI; (d) ENVI

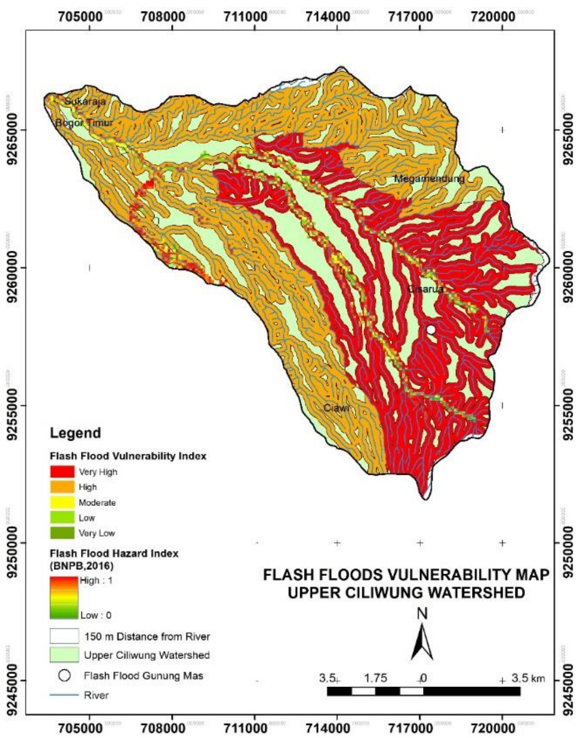

Figure 3. The map of the FFVI

Table 10. The calculated FFVI

No.	Sub-district	The flash flood vulnerability index Score	Class
1	Ciawi	2.38	High
2	Cisarua	2.58	Very high
3	Megamendung	2.38	High
4	Sukaraja	2.32	High
5	Bogor Timur	2.32	High

The assessed FFVI and the map are crucial for prioritizing intervention management to effectively reduce and manage the risks of flash floods in the study area. The map can be used to establish a robust early warning system and to aid the development of evacuation routes, shelters, and community awareness programs. Furthermore, it is also helpful for the establishment of a post-flash-flood recovery plan towards a more resilient community.

4. Conclusion

The Ciliwung Hulu Watershed area is highly susceptible to the occurrence of flash flood disasters. Our results provide essential data for the government to plan disaster-ready management planning as well as raise the resident's awareness of the hazards. However, this is only the early step in the development of a flash flood resilience society. To aid further effort, we suggest that future research include the assessment of the mapping of vulnerability index in the larger areas. Further, to fully develop the disaster-ready management plan, the establishment of more coordinated cooperation between local, regional, and national authorities is essential. This is a process that requires interplaying governance processes aided by this study.

Data availability statement

We state that the source of all required data has been written in the manuscript. The secondary data can be found in the mentioned sources.

Funding statement

All fund for data collection, data analysis, and other aspects of the publication of this manuscript is provided by Rumah Program Kebencanaan 2023, Research Organization for Earth Sciences and Maritime, National Research and Innovation Agency (BRIN).

Conflict of interest

All authors have declared that there is no conflict of interest in the writing and the submission of the manuscript.

Contributor statement

RN and **FAW** (the principal contributors): data collection, analysis, illustration, writing the original draft, and revision. **EP** and **EGAS** (the supporting contributors): data collection

Acknowledgements

We convey our gratitude to the distinguished reviewer (s), and the editor (s) for significant supports in the publication process.

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