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Research Article

Spatial-Based Landslide Vulnerability Index Assessment in Bogor Area, Indonesia

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ABSTRACT

Within the concept of disaster risk, vulnerability is one of the key determinants. It acknowledges the degree of unsafe conditions in a susceptible zone so that mitigation measures and disaster resilience can be enforced. Bogor area is the most susceptible region to landslides with more than 485 landslide events since 2012. However, there is still inadequate information on its vulnerability to landslides, as the risk reduction challenge per se, is a long-run task. Correspondingly, this study aims to measure the degree of vulnerability to landslides in Bogor area from four focal points (i.e.: social, physical, economic, and environmental dimensions), through the proxy of Vulnerability Index (VI). This study employs a GIS-based spatial analysis on a sub-district level. The result shows that although having high records on landslide events, Bogor area mainly retrieves low VI. In general, Bogor area has low VI [0.347–0.454] on 26 sub-districts. Moreover, 13 sub-districts attain medium VI (0.454–0.562], and 7 sub-districts achieve high VI (0.562–0.670]. Sub-districts that have high VI are: Bogor Tengah, Bogor Barat, Bogor Selatan, Cibinong, Bojonggede, Ciomas, and Bogor Utara; which are mainly promoted by the high indexes on social and physical vulnerabilities. Nevertheless, further study is still needed to extend the knowledge of relationship between landslide susceptibility and this vulnerability result, by using a more extensive and longer data series. That is especially in accord with taking the appropriate mitigation measures in spatial planning and landslide risk management.

Keywords : Landslide; Vulnerability; Vulnerability Index; Bogor Area

INTRODUCTION

Landslide is the second most frequent disaster in Indonesia after floods. Landslide events have been increasing over years, and were peaking in 2016 with a total of 188 fatalities from 612 events (Rahmad et al., 2018). The estimated exposed population to landslide hazard in Indonesia reaches 40.9 million people (Tjandra, 2018). In Indonesia, Bogor area that consists of Bogor City and Bogor Regency records 549 number of landslides in 2022 (BNPB, 2022). Bogor City records the most frequent landslides in 2017, with a total of 179 events (40.5% of the total 442 recorded disaster events) (BPBD Kota Bogor, 2022). Some massive landslides occurred every year, such as the 2021 landslide event in Sukajaya which resulted in 4,146 people being displaced, 6 dead, 3 missing, and 34 people injured (BPBD Kabupaten Bogor, 2022). The landslide occurred due to heavy rains that had happened for the previous few days.

Landslide susceptibility is strongly correlated with the economic development of a region (Pollock & Wartman, 2020). With the high susceptibility of landslides in the Bogor area, there is still a need for further study regarding the impact of devastating landslides. By means of this, analyzing the vulnerability may convey the intrinsic conditions that are susceptible to external perturbation, expressed on a scale from 0 to 1 (Guillard-Gonçalves et al., 2016). Accordingly, the adverse impact of landslides represents a need for in-depth knowledge from a vulnerability viewpoint. Thus, one of the measures that can be taken to mitigate landslides and enforce resilience is by measuring the vulnerability level.

Studies on disaster vulnerability cover a multi-disciplinary science from natural to social perspectives (Pollock & Wartman, 2020), that requires a comprehensive inventory of the subject assets (such as physical, social, economic, and environmental considerations). Moreover, vulnerability also considers the political, cultural, and institutional aspects (Ahmed, 2021). All of these aspects play a role in the possibility of a person or community being affected by hazard (Ahmed, 2021). Furthermore, this makes landslide vulnerability and risk modeling a complex procedure, as it integrates various expertise (Singh et al., 2021).

According to Alkaesi et al (2021), the Regency of Bogor has a potential landslide area of 266,055.24 ha, with 74,100.93 ha of high susceptibility and 191,954.32 ha of moderate susceptibility. Here, several sub-districts with large susceptibility area are Caringin (6,620.57 Ha), Leuwiliang (5,967.68 Ha), Pamijahan (4,719.28 Ha), Sukajaya (6,891.79 Ha) and Nanggung (10,097.47 Ha). Moreover, a study by Harist et al. (2019) explained that in the Regency of Bogor, Sub-district of Babakan Madang Selatan has a generally moderate vulnerability with a fairly low capacity to landslides.

A multidisciplinary study on vulnerability was conducted by Ramli et al. (2023) that combined both spatial and holistic approaches. Besides, Ram & Gupta (2022) conducted vulnerability assessments based on the landslide hazard, physical and environmental aspects. Also, a study by Mosaffaie et al. (2023) analyzed potential resources that were potentially exposed to landslide. Nevertheless, some vulnerability studies were conducted partially, for example (1) physical vulnerability that assessed landslide intensity and building vulnerability (Tiwari et al., 2022); (2) social vulnerability that described disparities in social groups, based on socio-economic indicators (Nor Diana et al., 2021; Sangeeta & Maheshwari, 2022; Wang et al., 2022); and (3) environmental vulnerability that examined land cover aspects (Hani'ah et al., 2017).

However, measuring the social, economic, and environmental vulnerability is still a challenge in landslide studies (Fu et al., 2020). Accordingly, there is still a gap in how to formulate the exposure components in estimating the degree of vulnerability, on account of landslide hazard. Here, the challenge to configuring the vulnerability equation requires the understanding of specific characteristics or certain sensitivity of the elements or assets to landslide exposure. For practical examples; parameters that have more extensive losses in terms of economic cost or also subjects that invoke greater assistance from the communities or societies.

In spite of the gap in the complete knowledge regarding the vulnerability to landslide risk in Bogor area, this study aims to measure the degree of vulnerability to landslides within 46 sub-districts. It integrates the four focal points (i.e.: physical, social, economic, and environmental dimensions), through the proxy of the Vulnerability Index (VI), where a higher VI implies higher vulnerability to landslides. The estimated VI is modified from the Perka BNPB 2/2012 on Guideline for Disaster Risk Assessment, particularly in regard to data availability and weight scoring. The objective of this study is to conduct a vulnerability analysis to landslides in Bogor Area, including Bogor city and regency (Figure 1), from the multiple aspects of social, physical, economic, and environmental dimensions. The vulnerability is measured through a proxy of the Vulnerability Index (VI) that indicates the degree of vulnerability to landslide hazard at a sub-district level.

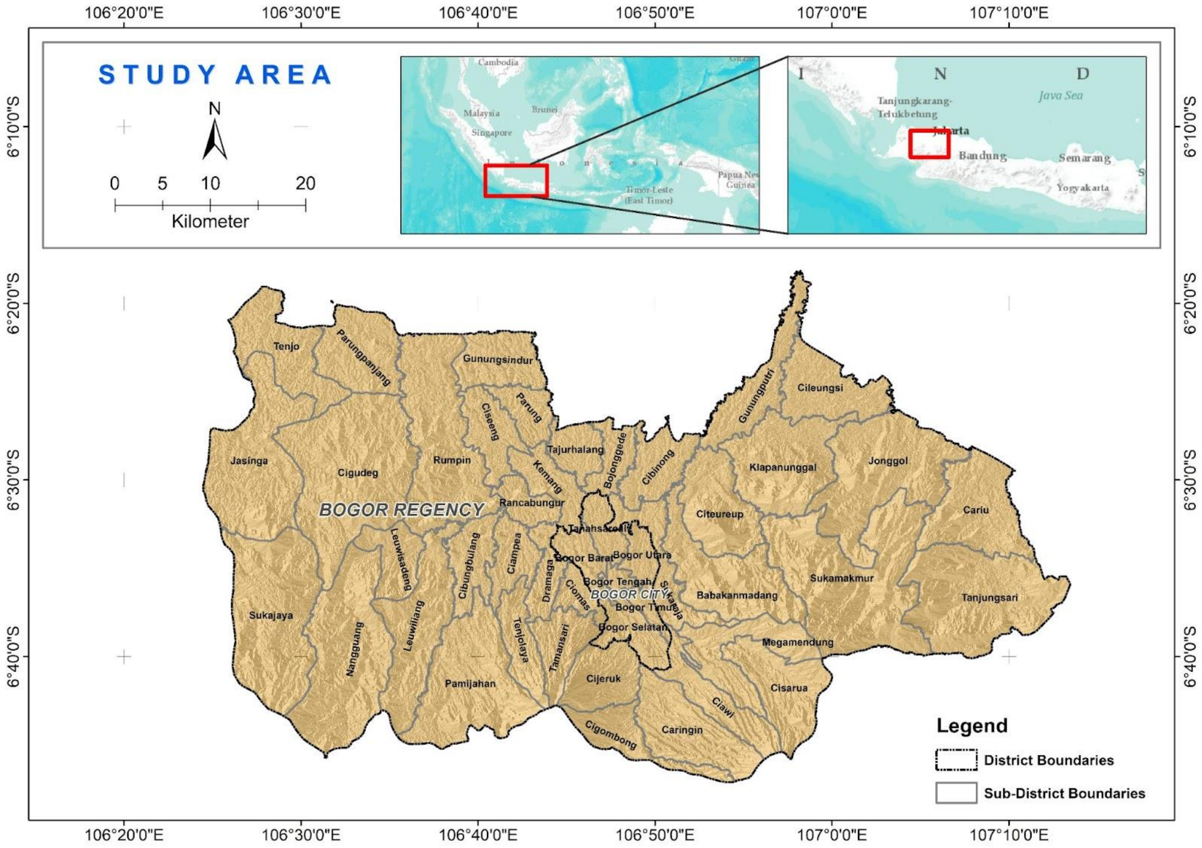

Figure 1. Study Area

METHODS

Data

Figure 2 below shows the framework of parameters used for vulnerability analysis, integrated with the data source and their weighing values. All of the data used are from the latest acquisition from the respective institutions.

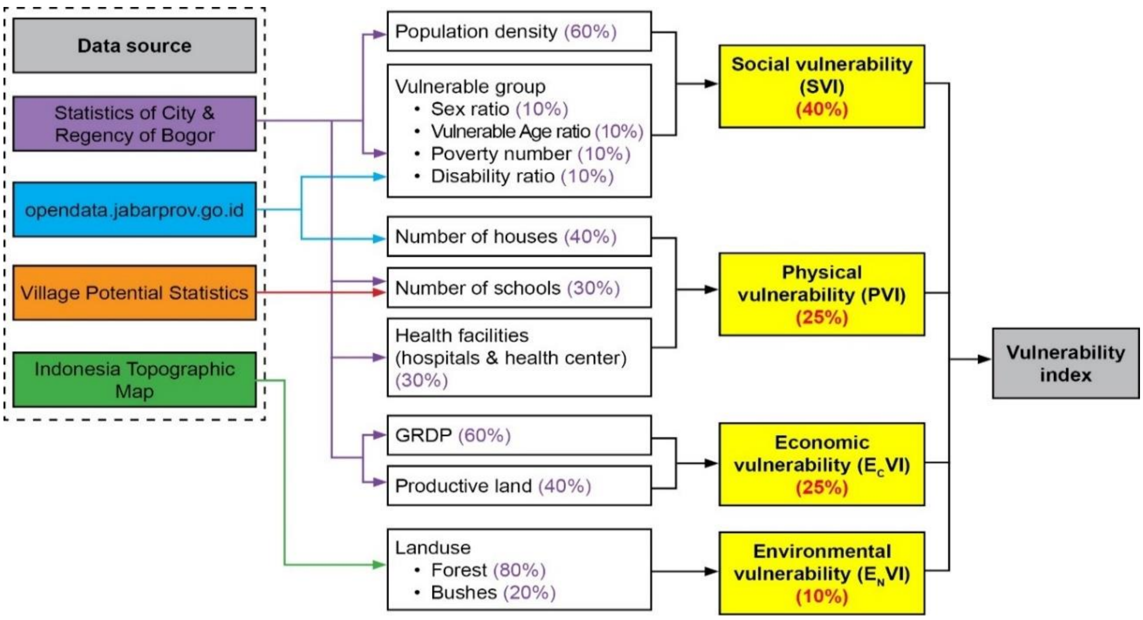

Figure 2. Framework for vulnerability analysis: variables, parameters, weighing and data source

Vulnerability Index (VI)

Vulnerability is defined as the potential degree of loss on the elements at risk exposure (Ram & Gupta, 2022). It refers to the characteristics and circumstances of assets that are susceptible or affected by the damaging hazard. Figure 2 conceptualizes the vulnerability structure that is composed of four dimensions on the physical, social, economic, and environmental dimensions. The exposed assets within each of vulnerability facets possess certain sensitivity to a disaster exposure. This sensitivity can be compliant through the weighing and scoring processes, based on an adept assessment. Equation 1 expresses the Vulnerability Index from the four variables. Whereas eq. (2) – eq. (5) convey the four dimensions of vulnerability variables (social, physical, economic, and environmental facets) (BNPB, 2012).

$$VI=(SVI \times 0,4) + (PVI \times 0,25) + (E\_C\ VI \times 0,25) + (E\_N\ VI \times 0,1) \quad (1)$$

where VI is the vulnerability index, SVI is the social vulnerability index, PVI is the physical vulnerability index, E_C VI is the Economic Vulnerability Index, and E_N VI is the environmental vulnerability index.

Social Vulnerability Index (SVI)

Referring to BNPB (2012), social vulnerability parameters consist of population density and vulnerable groups. Vulnerable groups include sex ratio, vulnerable age ratio, poverty number, and disability ratio. These data were collected from Statistics of the city and regency of Bogor. For each sub-district, the collected data were then classified into three classes low, medium, and high. Basically, for the population density and poverty population, the collected data were classified equally into three classes based on the maximum and minimum of the value. Overall, the weighing score and classification of each parameter can be seen in Table 1. Lastly, SVI is calculated by using equation below:

$$SVI = \left(0.6 \times P_{op}D_{en}\right) + (0.1 \times P_{ov}N) + (0.1 \times SexR) + \ (0.1 \times \ V_{uln}AgeR) + (0.1 \times \ D_{isb}R) \quad (2)$$

where SVI is the social vulnerability index, $P_{op}D_{en}$ population density, $P_{ov}N$ poverty number, $SexR$ sex ratio, $V_{uln}AgeR$ vulnerable age ratio, and $D_{isb}R$ disability ratio.

Table 1. Social Vulnerability Parameters and the Weighing Score (modified from BNPB, 2012)

Parameter	Weight (%)	Class		
		Low	Medium	High
Population Density (pop density/km^2)	60	< 3837,11	3837,12–7671,07	> 7671,07
Poverty Number	10	< 158,797	158,798–264,863	> 264,863
Sex Ratio	10	> 40	20–40	< 20
Vulnerable Age Ratio	10	< 20	20–40	> 40
Disability Ratio	10	< 20	20–40	> 40

Physical Vulnerability Index (PVI)

Physical vulnerability can be defined as the susceptibility of physical elements that can be damaged in case of natural disaster. The parameters of the physical vulnerability include house amount, public facilities, and critical facilities. House amount was collected from opendata of West Java Province, while public facilities were collected from Village Potential Statistics as well as Statistics of the city and regency of Bogor. Furthermore, critical facilities were collected from Statistics of the city and regency of Bogor. After collecting these data for each sub-district, they are then divided into three classes i.e., low, medium, and high. From the collected data, the three classes from the maximum and minimum values can be classified as seen in Table 2. Finally, PVI is calculated by using the Equation 3:

$$PVI = (0.4 \times HA) + (0.3 \times PF) + (0.3 \times CF) \quad (3)$$

where PVI is the physical vulnerability index, HA housing amount, PF public facilities, and CF critical facilities.

Table 2. Physical Vulnerability Parameters and the Weighing Score (modified from BNPB, 2012)

Parameter	**Weight (%)**	**Class**		
		Low	**Medium**	**High**
Housing Amount	40	<38,933	38,934–64,134	> 64,134
Public Facilities	30	< 170	171–289	> 289
Critical Facilities	30	< 6	7–12	> 12

Economic Vulnerability Index (E_CVI)

The economic vulnerability parameters consist of the area of productive fields (specifically cropland and plantation) along with regional gross domestic product (Regional GDP). The productive fields is the total field used to grow and harvest certain commodities such as paddy, corn, potatoes, etc. These parameters are obtained from data provided by Statistics of the city and regency of Bogor. These parameters are analyzed using the maximum and minimum values of each parameter then distributed into three classes. The classes of each parameter can be seen on Table 3. Lastly, the economic vulnerability is calculated by using the Equation 4 (Suprapto et al., 2022):

$$E_cVI = (0.6 \times P_{rod}F) + (0.4 \times RGDP) \quad (4)$$

where E_cVI is the economic vulnerability index, $P_{rod}F$ productive field, and $RGDP$ is the regional gross domestic product.

Table 3. Economic Vulnerability Parameters and the Weighing Score (modified from BNPB, 2012)

Parameter	**Weight (%)**	**Class**		
		Low	**Medium**	**High**
Productive field (ha)	60	< 64.781	64.782–121.196	> 121.196
Regional GDP (million rupiah)	40	< Rp. 606,421.373	Rp. 606,421.374–Rp. 1,209,845.158	> Rp. 1,209,845.158

Environmental Vulnerability Index (E_NVI)

Environmental vulnerability parameters consist of forest and shrub. These data were collected from the Indonesia Topographic Map. The area of those parameters for each sub-district was classified into three classes (i.e., low, medium, and high) based on the maximum and minimum values. The classification and the weighing scores are shown in Table 4. Finally, the E_NVI can be calculated using the Equation 5.

$$E_nVI = (0.8 \times F_r) + (0.2 \times S_h) \quad (5)$$

where E_nVI is the environmental vulnerability index, F_r is forest, and S_h is shrub.

Table 4. Environmental Vulnerability Parameters and the Weighing Score

Parameter	Weight (%)	Class		
		Low	Medium	High
Forest (ha)	80	< 3,050.416	3,050.417–6,100.833	> 6,100.833
Shrub (ha)	20	< 1,704.728	1,704.729–3,409.324	> 3,409.324

RESULTS AND DISCUSSION

Vulnerability Index (VI) is conducted based on the BNPB (2012) which explain Guideline for Disaster Risk Assessment, where higher VI implies higher vulnerability to landslides. Figure 3 addresses the resulting VI that integrates the vulnerabilities of social (SVI), physical (PVI), economic (ECVI), and environmental (ENVI) indexes.

Social Vulnerability Index (SVI)

Social Vulnerability Index (SVI) is identified through two main determinants, i.e., population density and vulnerable groups (poverty number, age ratio, sex ratio, and disability ratio), that may suffer worse impact in the face of landslides. Although having the heaviest weight (60%), population density does not directly affect the sub-district's overall SVI. The vulnerable group proportions however, also define the sub-district's final SVI.

The resulting SVI (Figure 4a) in Bogor area mostly has low index [0.367–0.512], that is recorded in 31 sub-districts. While the medium and high SVI are fit on 7 and 8 sub-districts, respectively. The high SVI (0.658–0.800] is mainly promoted by high population density and medium age ratio. On the other hand, although having highly vulnerable group on poverty number or age ratio, 7 sub-districts still fall low on their SVI, i.e.: Cariu, Cigudeg, Citeureup, Gunungsindur, Cisarua, Jasinga, and Parungpanjang. This condition is mainly supported by having low indexes on population density, sex ratio, and disability ratio. High population density was found as a major cause of medium and high SVI in our study, which is in line with the former study of Arrogante-Funes et al. (2021) as well as Liu & Miao (2018).

Physical Vulnerability Index (PVI)

Physical Vulnerability Index (PVI) brings overview fragility on the public and vital facilities that may aggravate the adversity upon the shock event. The PVI is measured through the number of settlements, school, and hospitals or public health centre on sub-district level. The PVI of Bogor area (Figure 4b) predominantly fits low [0.333–0.478] in 32 sub-districts. Moreover, there are 9 sub-districts on medium PVI (0.478–0.622], and 5 sub-districts with high PVI (>0.622).

The high PVI on those 5 sub-districts is mainly sustained by the medium to high number of houses and schools within each sub-district. The Sub-district of Bogor Barat however, acquires the highest index (0.767) for having high number of health facilities, although it has medium index on the number of houses and schools. Moreover, the constant low numbers on schools and health facilities are the main incitement for commonly low PVI in Bogor area. A high number of settlements in the study of Ram & Gupta (2022) has also caused high vulnerability and subsequently to high-risk zone to landslide.

Economic Vulnerability Index (ECVI)

Economic Vulnerability Index (ECVI) may overarchingly indicate monetary loss at the disastrous event. The falling impact on labor-absorbing sectors may bring layoff or unemployment, cautioning the poverty line and economic growth. Here, ECVI (Figure 4c) is measured through the proxies of GRDP and productive land as one of the major economic sectors.

In Bogor area, 24 sub-districts primarily fall on the low ECVI [0.333–0.467], followed by 20 sub-districts on the medium ECVI (0.467–0.600]. And there are only two sub-districts that have high ECVI (0.733), i.e.: Bogor Selatan and Bogor Tengah.

Both sub-districts with high ECVI are majorly promoted by their first and second highest GRDP among other sub-districts, and not by their relatively low area of productive land. Moreover, there are 9 subdistricts that record medium ECVI due to their fairly high productive land but low in GRDP value, i.e.: Cigudeg, Cariu, Nangguang, Jonggol, Sukajaya, Jasinga, Rumpin, Cileungsi, and Pamijahan. On the other hand, all of the low ECVI falls presentably low on both GRDP and productive land area.

Concerning the economic vulnerability, a related study by Arrisaldi et al. (2023) measured the economic vulnerability through the proxies of productive land, economic activity, and non-economic area. Here, the study concluded that the medium and high economic vulnerabilities were reliant on the productive land (agricultural land) as well as economic activity on the settlement area (market and infrastructure). Likewise, study by Arrisaldi et al. (2023) is accordant with our study, where the medium and high vulnerability indexes are sustained by high GRDP and productive land. Moreover, Liu & Miao (2018) found that high vulnerability to landslides is in the area with high economic density.

Environmental Vulnerability Index (ENVI)

Forestry area performs a fundamental role in landslide susceptibility zone. Challenge in deforestation or forest conversion may imperil the landslide hazard zone. Environmental Vulnerability Index (ENVI) can bridge two-ways recognition on the forest vulnerability as well as its protection function. Moreover, shrubs may increase vulnerability to landslides as it doesn’t provide strong rooting.

The ENVI (Figure 4d) shows that the majority of sub-districts have low ENVI [0.333–0.511], 5 sub-districts have medium index (0.511–0.689], and 2 sub-districts have high ENVI (0.867). Both sub-districts with high ENVI (Nangguang and Sukajaya) preserve the two highest forestry areas with reasonably low shrub coverage. With this condition, the environmental concern occurs even as the forestry area is at the highest. Meanwhile on the medium ENVI, 5 sub-districts generally have medium forest area with low shrub coverage. And on the low ENVI, 39 sub-districts considerably have low forest area, whereas 22 of them has no forest at any rate.

Pertaining to this environmental vulnerability, a study by Hani’ah (2017) measured it through the areas of forest, mangrove, and shrubs. This study is also in general agreement to our study, where high environmental vulnerability is on the largest forest area, and low environmental vulnerability has lower greenness density.

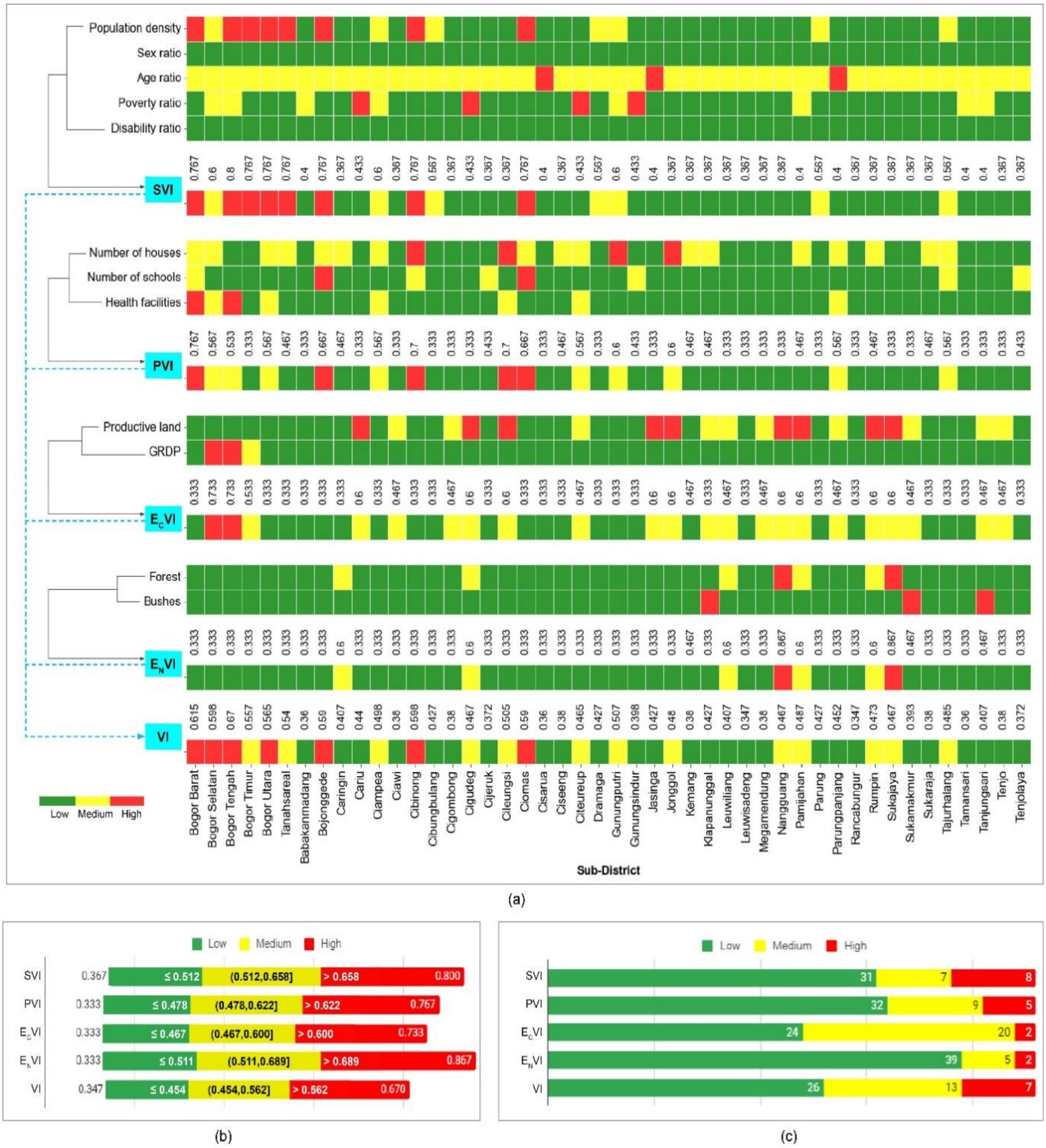

Figure 3. (a) Class of each parameter in SVI, PVI, E_CVI, E_NVI, and VI; (b) Interval ranges on SVI, PVI, E_CVI, E_NVI, and VI classes (low, medium, and high); (c) Number of sub-districts by SVI, PVI, E_CVI, E_NVI, and VI classes

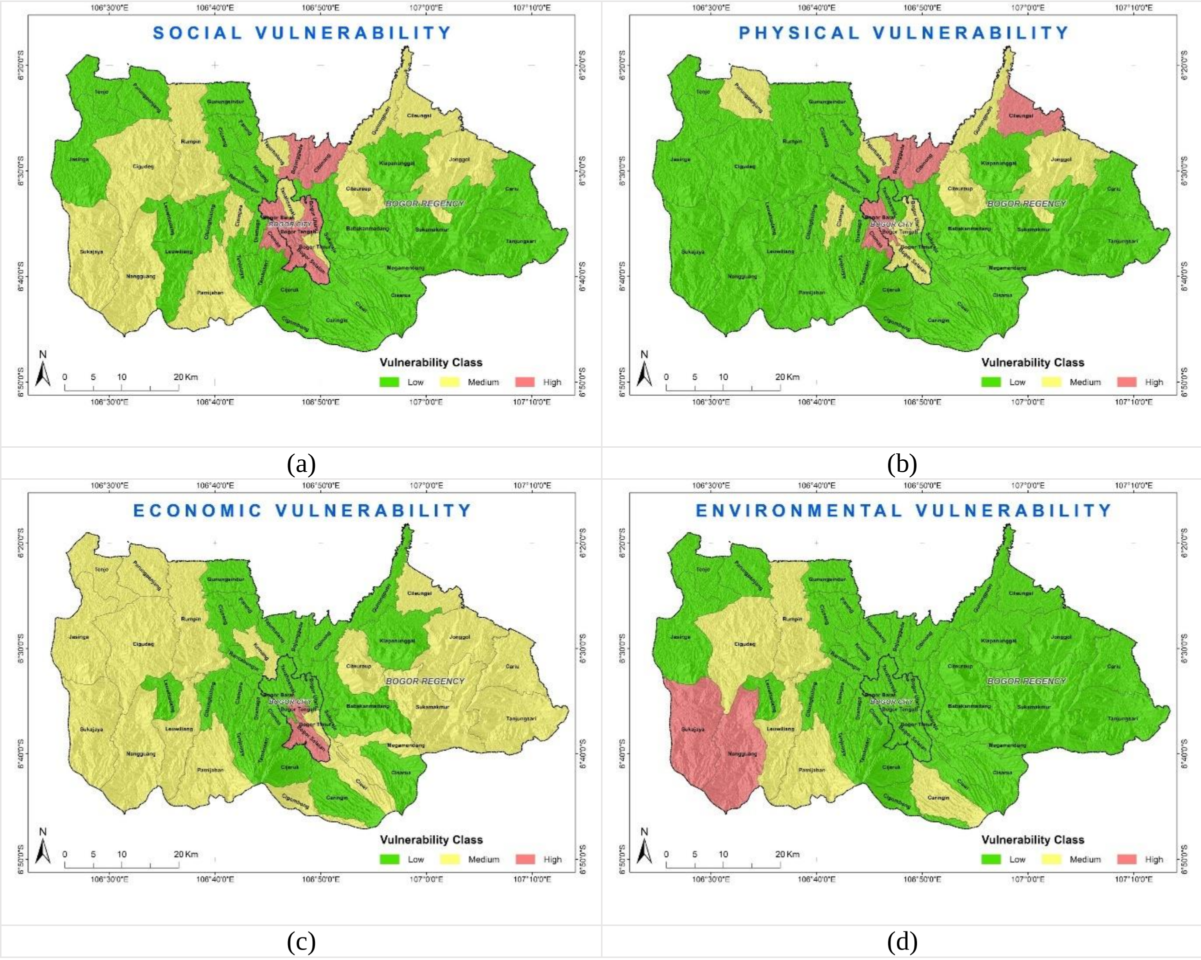

Figure 4. Maps of four vulnerability index: (a) SVI, (b) PVI, (c) ECVI, and (d) ENVI

Vulnerability Index (VI)

Figure 5 illustrates the resulting VI on sub-district level. Vulnerability Index (VI) integrates the social, physical, economic and environmental vulnerabilities. The essential parameters in vulnerability variables play a major role in indicating the imperil states of: fatality and injury, structural destruction, service collapse, economic loss, and environmental disruption.

The resulting VI ranges from 0.347 to 0.670 and is divided into low [0.347–0.454], medium (0.454–0.562], and high (0.562–0.670] classes. In general, Bogor area has low VI on 26 sub-districts. Two sub-districts with the lowest VI (0.347) are Leuwisadeng and Rancabungur, which evenly record the lowest indexes on all of four vulnerabilities. Moreover, there are 7 sub-districts that attain high VI, i.e.: Bogor Tengah (0.670), Bogor Barat (0.615), Bogor Selatan (0.598), Cibinong (0.598), Bojonggede (0.590), Ciomas (0.590) and Bogor Utara (0.565). These high VIs are mainly promoted by having high indexes on social and physical vulnerability. Furthermore, the rest of the 13 sub-districts achieve medium VI.

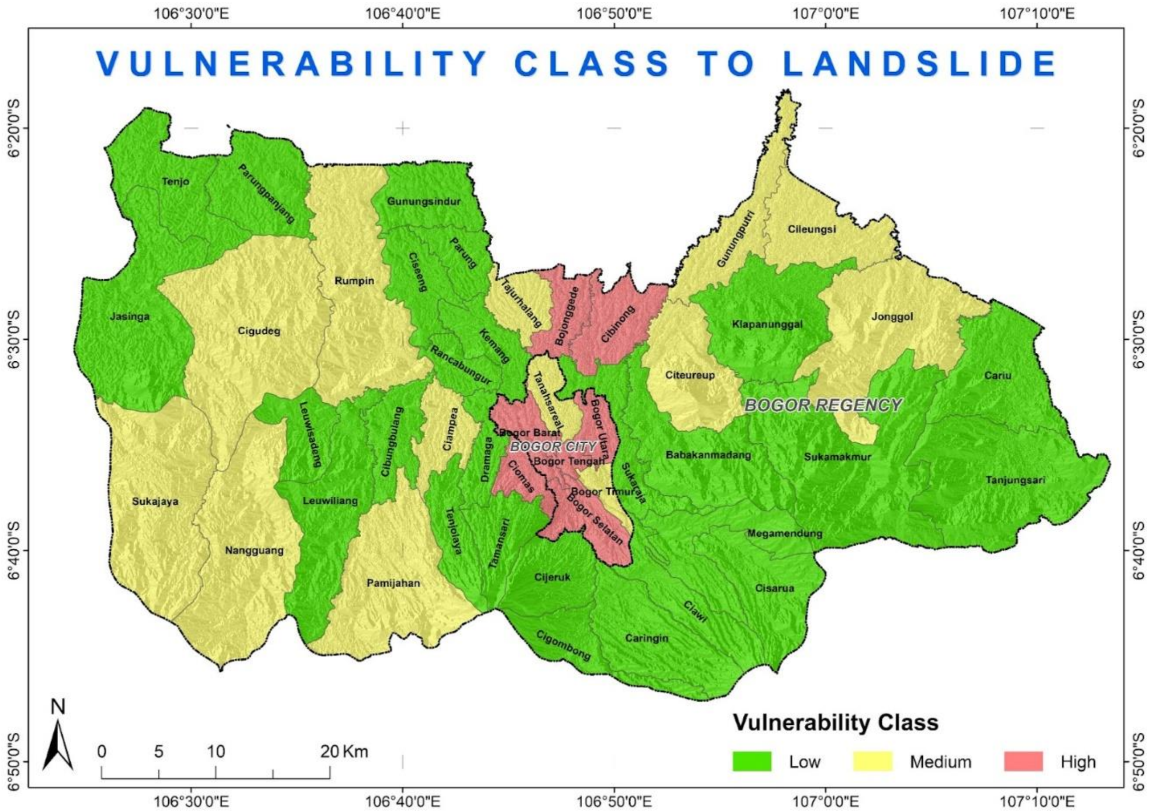

Figure 5. Map of landslide vulnerability index

Resultantly, the high VI is mainly promoted by high social and physical vulnerabilities, where high vulnerability to landslide risk was mostly correlated with high population density. Here on the resulting high VI, 6 out of the 7 sub-districts (i.e. Bogor Tengah, Bogor Barat, Cibinong, Bojonggede, Ciomas, and Bogor Utara) exhibit high population density. Additionally, the high vulnerability could also be imposed by the lack of infrastructures such as hospitals and police station, as the physical assets (Regmi & Agrawal, 2022). Concerning this, 4 sub-districts (Bogor Barat, Cibinong, Bojonggede, and Ciomas) perform high on the PVI, and 3 sub-districts (Bogor Tengah, Bogor Selatan, and Bogor Utara) have medium PVI.

Attributed to this result, there were at least two former studies that measured the village-level vulnerability to landslides in Bogor area, based on the modified Perka BNPB 02/2012. In 2019, a relevant study at the Sub-district of Babakan Madang, Regency of Bogor (Harist et al., 2019) used 4 parameters, i.e.: population density, sex ratio, house density and public facilities. And in 2023, a related study at the Sub-district of Pamijahan, Regency of Bogor used 4 variables of social, physical, economic, and environmental vulnerabilities (Ramadhan & Dahlia, 2023) . Correspondingly, it implies that the study on the vulnerability to landslides in Bogor area is considerably modest and partial. In this regard, it is unfeasible to perform a comparison between our results with the former studies.

CONCLUSION

Within the course of disaster risk, vulnerability is one of the key determinants. It acknowledges the degree of unsafe conditions in a susceptible zone so that mitigation measures and disaster resilience can be enforced. This study aims to measure the degree of vulnerability to landslides in Bogor Area on the sub-district level, through a proxy of the Vulnerability Index (VI). VI is conducted based on the Perka BNPB 2/2012 on Guideline for Disaster Risk Assessment, where higher VI implies higher vulnerability to landslides. This VI integrates the social, physical, economic, and environmental vulnerabilities.

There is an underlining concern where although more than a half of sub-districts commonly record low VI [0.347–0.454] in 26 sub-districts, there are 13 sub-districts that attain medium VI (0.454–0.562], and 7 sub-districts that achieve high VI (0.562–0.670]. The high VI occurs in Bogor Tengah (0.670), Bogor Barat (0.615), Bogor Selatan (0.598), Cibinong (0.598), Bojonggede (0.590), Ciomas (0.590) and Bogor Utara (0.565). These high VI are mainly promoted by high SVI and PVI.

The SVI assists the underlying societal imperilment of fatality and injury in the face of landslide. The SVI in Bogor area mostly has low index [0.367–0.512] in 31 sub-districts. Moreover, the PVI implies structural devastation and service collapse (in school, health facilities, and settlements) while facing landslides. The PVI in Bogor area generally fits low [0.333–0.478] in 32 sub-districts. Likewise, the ECVI portrays an overarching view of monetary loss at the disastrous event, through the proxies of GRDP and productive land. In the Bogor area, 24 sub-districts fall on the low ECVI [0.333–0.467]. Furthermore, the ENVI attempts to bring dual concerns on forest areas, as protection function and perilous impact. Moreover, shrubs may increase the landslide hazard as it does not provide strong rooting. The ENVI shows that the majority in 39 sub-districts have low index [0.333–0.511].

In conclusion, the result shows that although it has high records on landslide events, Bogor area generally retrieves low on its VI. This significant result prominently shows the vulnerability level to landslides among the 46 sub-districts in Bogor area, where rigorous concern shall be taken into account on the 7 highly vulnerable sub-districts. This resulting VI also plays a key role in pivotal risk assessment, by combining hazard and capacity. Thus, appropriate measures for landslide mitigation can be taken.

Moreover, further study is also needed to extend the knowledge on the relationship between landslide susceptibility and this vulnerability result, by using a more extensive and longer data series. Where the challenge of holistic study requires a frequent evaluation, related to its dynamic environment and database availability. In spite of the gap in the complete knowledge, this VI result conveys an endeavouring effort to improve the insight on the degree of vulnerability to landslides in Bogor area.

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DECLARATIONS

Conflict of Interest

The authors declared that they had no known competing interests.

Ethical Approval

On behalf of all authors, the corresponding author states that the paper satisfies Ethical Standards conditions, no human participants, or animals are involved in the research.

Informed Consent

On behalf of all authors, the corresponding author states that no human participants are involved in the research and, therefore, informed consent is not required by them.

DATA AVAILABILITY

Data used to support the findings of this study are available from the corresponding author upon request.

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