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Analysis of Landslide Vulnerability and Its Impact on Population and Infrastructure Exposure in Central Bogor District Using AHP and Open Geospatial Data

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Abstract:

Indonesia's location at the convergence of three active tectonic plates makes it highly susceptible to various natural disasters, with landslides being among the most frequent and destructive, particularly in mountainous and densely populated urban areas. Central Bogor District in West Java represents a vulnerable area where steep topography, high rainfall intensity, and dense population heighten landslide risk. Despite recurrent landslide events, comprehensive vulnerability assessments integrating both physical and socio-environmental factors remain limited. This study aims to produce a spatially explicit landslide vulnerability map for Central Bogor District by utilizing open geospatial data and applying a GIS-based multi-criteria decision-making approach. The Analytical Hierarchy Process (AHP) was employed to assign weights to four primary physical parameters—rainfall, slope, lithology, and land cover—based on their relative contribution to landslide susceptibility. Supporting data were derived from Sentinel-1A imagery (InSAR), Landsat-8 classification, CHIRPS precipitation records, and official geological maps. These physical layers were then integrated with exposure indicators, including population density, infrastructure distribution, and accessibility data from OpenStreetMap. The results delineated three landslide vulnerability zones: high (49.87 ha), moderate (481.82 ha), and low (236.45 ha). High-risk zones, such as Gudang and Paledang Sub-districts, feature steep slopes, weak geological formations, and dense settlements. Overlay analysis also revealed a significant concentration of critical infrastructure within moderate-to-high vulnerability zones, highlighting exposure and potential service disruption during hazard events. The study underscores the critical value of combining open geospatial data with AHP-based weighting to inform targeted disaster mitigation, infrastructure planning, and resilient urban development. The resulting maps can guide policy and preparedness strategies to reduce landslide impacts in high-risk urban areas.

Keywords: AHP; Central Bogor district; GIS; landslide vulnerability; urban disaster vulnerability

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1. Introduction

Indonesia is located at the intersection of three major tectonic plates: the Indo-Australian Plate, which moves northward; the relatively stable Eurasian Plate; and the Pacific Plate, which shifts westward [1]. This unique geological configuration positions Indonesia as one of the most disaster-prone countries in the world. As a result, the country frequently experiences a wide range of natural hazards, including earthquakes, volcanic eruptions, floods, droughts, and landslides [2]. According to the National Disaster Management Authority (BNPB), a total of 1,556 disaster events occurred in 2024, resulting in 1,379 fatalities. These events—whether caused by natural factors, human activity, or a combination of both—pose significant threats to human life, economic stability, and infrastructure [3].

Among these hazards, hydrometeorological disasters—such as floods, extreme weather events, droughts, and landslides—are the most frequent, accounting for 76.1% (1,184 events) of the total disasters reported in 2024 [4]. Landslides are among the most destructive hazards affecting mountainous and hilly terrains, which is defined as the downslope movement of soil, rock, or debris due to a loss of slope stability [5]. As noted by Hidayat et al. [6], this instability can result from various factors, including geological conditions, soil permeability, shear strength, and anthropogenic modifications to slopes, such as excavation and construction. Bagal et al. [7] further emphasize that poor slope management and increased human settlements in high-risk areas significantly heighten the likelihood of landslide events.

The city of Bogor in West Java is one such region that is highly susceptible to landslides, due to its steep topography, unstable soil types, and high annual rainfall. Within this city, the Central Bogor District stands out as an area particularly vulnerable to landslides. According to data from the Bogor City Disaster Management Agency (BPBD), landslides occur regularly and remain one of the most prevalent local hazards. In 2023, 271 landslide incidents were recorded out of a total of 1,011 disasters in the city. The Geological Agency (PVMBG) has identified several areas within Bogor as falling into medium to high landslide hazard zones [8]. The intensity of these hazards is influenced by a combination of natural and anthropogenic factors, including steep slopes, poor soil cohesion, intense rainfall, and the conversion of land for residential and infrastructure development—all of which increase pressure on already unstable slopes [9].

A devastating event in 2022 underscores the severity of the threat. Triggered by prolonged rainfall, a landslide in the Gang Barjo area of Kebon Kalapa Sub-district, Central Bogor District, resulted in five deaths and six injuries. The incident caused significant damage to infrastructure and disrupted socio-economic activities in the surrounding community. The translational movement of soil occurred in two locations—Gang Barjo and Gang Kapithan—highlighting the acute vulnerability of densely populated areas located near steep and unstable slopes.

These recurring disasters highlight the critical need for timely and accurate spatial information to identify landslide-prone zones and inform effective mitigation strategies. Geographic Information Systems (GIS) and remote sensing technologies have proven essential for this task, as they facilitate the management, analysis, and visualization of complex spatial data across large areas. Despite the potential of these tools, there is a notable lack of comprehensive studies addressing landslide vulnerability in dense urban district like Central Bogor, especially studies that consider the combined effects of physical susceptibility, population exposure, infrastructure distribution, and accessibility—elements that are crucial for disaster preparedness and planning, particularly in the context of near-future urban risk projections for 2025.

To fill this gap, the present study adopts the Analytical Hierarchy Process (AHP), a widely used multi-criteria decision-making method, to develop a landslide vulnerability map for the Central Bogor district. The analysis integrates both physical indicators (such as slope, soil type, and rainfall intensity) and socio-environmental factors (including population density, road network proximity, and infrastructure distribution), offering a more holistic and multidimensional understanding of landslide risk.

This study offers a distinct contribution by integrating openly available geospatial data with key exposure variables—such as population concentration and infrastructure accessibility—tailored to the context of a densely populated urban environment. The use of open-source datasets not only ensures transparency and replicability but also supports broader applicability across similar urban landscapes. Beyond its methodological contributions, the findings are intended to inform practical policy interventions. The generated vulnerability maps can serve as a strategic tool for local governments in developing adaptive land-use plans, strengthening disaster-resilient infrastructure, and enhancing public awareness and preparedness in high-risk areas such as Central Bogor District.

2. Methods

2.1. Research Location

This study was conducted in Central Bogor District, which is located at 106.776752, -6.612908, and 106.814975, -6.568912. Central Bogor District is situated in the central part of Bogor City, West Java, and comprises 11 sub-districts. The research was carried out over a five-month period, from December 2024 to April 2025. The spatial extent of the study area is illustrated in **Figure 1**.

Figure 1. Research location

2.2. Tools and Data

This study utilized a laptop equipped with ArcMap 10.8.2 for spatial analysis, SNAP for processing Sentinel-1A imagery, and Microsoft Excel for AHP calculations. Several datasets were integrated to assess landslide vulnerability. Rainfall data (January–December 2024) were sourced from CHIRPS, while slope gradient was derived from Sentinel-1A SLC imagery processed using Interferometric Synthetic Aperture Radar (InSAR) techniques (August 12 and December 30, 2024) from Copernicus. Lithological data were obtained from the West Java geological shapefile (scale 1:25,000) published by the Ministry of Energy and Mineral Resources in 2020 (ESDM). Land cover classification was conducted using Landsat-8 imagery (October 26–29, 2024) from USGS. Socio-environmental data, including 2024 population density, were provided by the Bogor City Statistics Bureau (BPS), and infrastructure and accessibility data were obtained from OpenStreetMap. These datasets were processed and analyzed in a GIS environment to support a multi-criteria landslide vulnerability assessment.

2.3. Research Procedures

2.3.1. Remote Sensing and GIS Data Processing

Rainfall data were obtained from the CHIRPS dataset for the year 2024, which integrates satellite imagery with ground station observations to provide high-resolution precipitation estimates, even in areas with limited monitoring stations. The annual average rainfall was calculated to represent one of the primary landslide-triggering factors, especially on steep and unstable slopes where intense or prolonged precipitation can significantly increase soil saturation and slope instability.

Topographic characteristics, particularly slope, were derived using InSAR processing of Sentinel-1A SLC imagery acquired on August 12 and December 30, 2024. The data were processed in SNAP software, where Goldstein Phase Filtering was applied to effectively reduce phase noise. An external SRTM 1 Arc-Second DEM was incorporated for topographic phase removal and Range-Doppler terrain correction, ensuring accurate geometric alignment of the slope surface. The resulting slope information is essential for identifying areas where steep terrain may amplify the effects of heavy rainfall, increasing landslide susceptibility.

In addition to slope, the geological composition of the terrain plays a crucial role in determining slope stability. Lithological data were sourced from a 1:25,000-scale shapefile of West Java obtained from the Ministry of Energy and Mineral Resources (ESDM). Using ArcMap, geological units were reclassified based on their physical characteristics and rock hardness. Formations such as old volcanic deposits, alluvial fans, and sandy pumice tuff were categorized according to their relative susceptibility to landslides, providing insights into how different lithologies respond to triggering factors like rainfall and slope steepness.

Land cover conditions further influence the stability of slopes. Classification was carried out using Landsat-8 OLI/TIRS imagery acquired between October 26–29, 2024. The ISODATA unsupervised classification algorithm was applied in ArcMap 10.8.2 to group image pixels into spectral clusters automatically. The classification results were then manually verified to ensure accuracy. Land cover information helps identify areas where vegetation loss, urbanization, or agricultural expansion may exacerbate erosion processes and reduce slope resistance to landslides.

To assess social vulnerability, population data from the 2024 Bogor City Statistics Bureau (BPS) were integrated with village-level administrative boundaries. By linking population density with landslide-prone zones, the analysis provides an indication of the number of people potentially exposed to landslide hazards, which is critical for prioritizing mitigation and evacuation planning.

Finally, infrastructure and accessibility were evaluated to understand the exposure and connectivity of critical facilities in hazard-prone areas. Data from OpenStreetMap included two main components: infrastructure facilities categorized into government centers, economic hubs, healthcare, education, and tourism; and road networks classified into trunk, primary, secondary, and tertiary roads. Network analysis techniques were employed to assess proximity and connectivity to key infrastructure, highlighting areas where landslide events could disrupt essential services and hinder emergency response efforts.

2.3.2. Analytical Hierarchy Process (AHP)

To generate the landslide vulnerability map, this study utilized the Analytical Hierarchy Process (AHP), a widely recognized method for multi-criteria decision-making [12]. AHP involves structuring complex decisions based on pairwise comparisons of factors and calculating their relative weights based on expert judgment. Four parameters were considered crucial in determining landslide vulnerability: rainfall, slope, lithology, and land cover. These parameters were compared using a pairwise comparison matrix (**Table 1**), reflecting the perceived importance of one parameter over another on a scale of 1 to 9. Rainfall was considered the most influential factor in landslide occurrence due to its direct triggering role in slope failures.

Table 1. Pairwise comparison matrix of landslide parameters [12]

Parameters	Rainfall	Slope	Lithology	Land Cover
Rainfall	1.000	1.667	5.000	7.000
Slope	0.600	1.000	4.000	6.000
Lithology	0.200	0.250	1.000	4.000
Land Cover	0.143	0.167	0.250	1.000
Total	1.943	3.084	10.250	18.000

After constructing the pairwise matrix, normalization was performed by dividing each element by the total of its column. The average of each row in the normalized matrix gave the weight (or priority vector) for each parameter, as shown in **Table 2**.

Table 2. Normalized pairwise matrix and parameter weights

Parameters	Rainfall	Slope	Lithology	Land Cover	Row Total	Weight
Rainfall	0.515	0.541	0.488	0.389	1.933	0.515
Slope	0.309	0.324	0.390	0.333	1.356	0.339
Lithology	0.103	0.081	0.098	0.222	0.503	0.126
Land Cover	0.073	0.054	0.024	0.056	0.207	0.051
Total	1.000	1.000	1.000	1.000	-	1.000

To ensure the reliability of the expert judgments, a consistency check was performed. The result confirmed that the consistency ratio (CR) was within the acceptable threshold (<0.1), validating that the weight values are consistent and suitable for further analysis. The final weights—rainfall (0.515), slope (0.339), lithology (0.126), and land cover (0.051)—were then applied in a GIS-based weighted overlay analysis to produce a landslide vulnerability map of the study area. These results highlight rainfall and slope as dominant contributing factors to landslide occurrences in Central Bogor District.

3. Result and Discussion

3.1 Physical Parameters of Landslide Vulnerability

This section presents the spatial analysis results of key parameters influencing landslide vulnerability in Central Bogor District, namely rainfall, slope, lithology, and land cover (**Figure 2**). Figure 2a shows the spatial distribution of annual rainfall in Central Bogor District, ranging from 4,165.26 mm to 4,773.32 mm. The highest rainfall (>4,600 mm/year) occurs in the southern and central areas, including Gudang, Paledang, and Panaragan Sub-districts, while lower values are found in the northeast, particularly in Tegalega and parts of Babakan Sub-districts. This spatial pattern indicates a concentration of hydrometeorological risk in the southern zone, where intense rainfall acts as a major landslide trigger by increasing soil saturation and reducing cohesion.

Topographic conditions also influence landslide susceptibility. As shown in Figure 2b, slopes are predominantly flat (0–8%) in Cibogor, Pabaton, Gudang, and Babakan Pasar Sub-districts, with moderate slopes (8–25%) in Ciwaringin, Kebon Kelapa, Panaragan, and Tegalega Sub-districts. Steeper slopes (>45%) are concentrated in Paledang, Babakan, and parts of Sempur Sub-districts. According to Ministry of Public Works Regulation No. 41/PRT/M/2007, steeper gradients significantly increase susceptibility due to gravitational instability, while flatter terrain generally poses lower risk unless affected by poor drainage or weak soils.

Lithological characteristics further affect slope stability (Figure 2c). Three main units are identified: Old Volcanic Rock Deposits, Alluvium, and Sandy Pumice Tuff. Old volcanic deposits dominate the western and central zones, alluvial fans occupy the east, and sandy pumice tuff occurs in limited areas in the southwest. Unconsolidated alluvium and pumice exhibit weak cohesion, making them more vulnerable to failure under prolonged rainfall [5].

Land cover patterns (Figure 2d) comprise settlements, water bodies, dense vegetation, and vacant land. Settlements dominate Tegalega, Babakan, and Babakan Pasar Sub-districts, where impervious surfaces increase runoff. Water bodies align with the Ciliwung River through Paledang and Sempur Sub-districts, affecting drainage. Dense vegetation in Paledang and Gudang Sub-districts provides stabilizing effects, while vacant land in scattered locations may become susceptible if unmanaged.

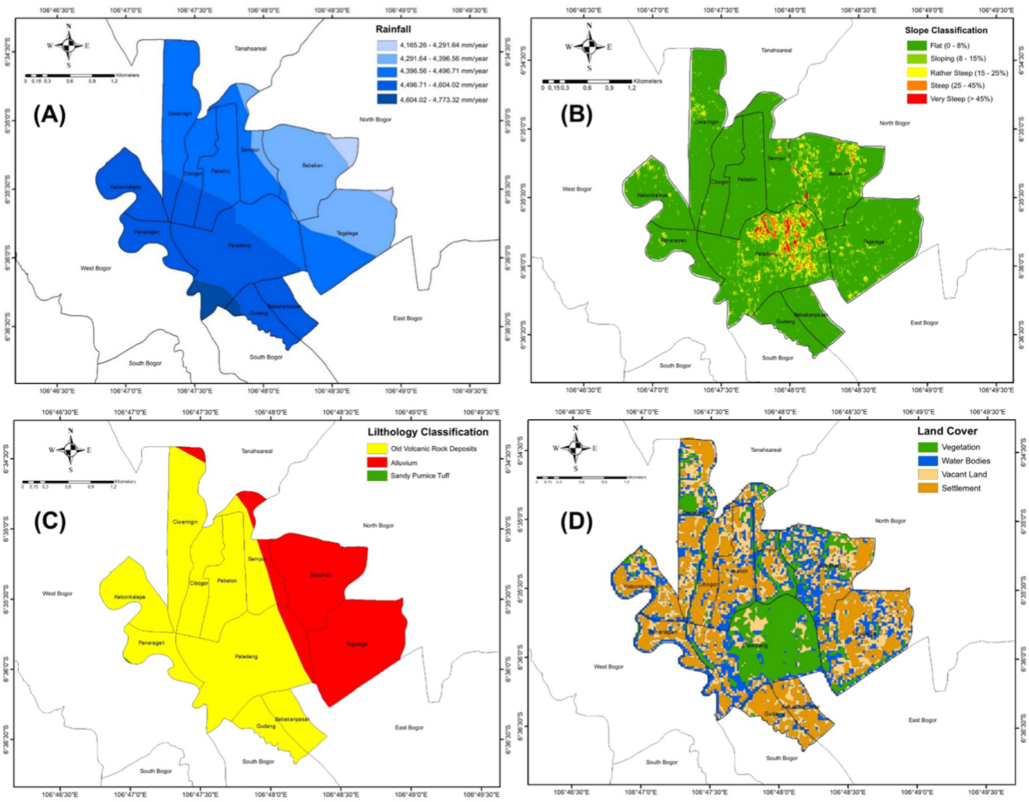

Figure 2. Result of thematic maps. (a) rainfall distribution, (b) slope classification, (c) lithology classification and (d) land cover types.

3.2 Population Density, Infrastructures and Accessibility

Figure 3 presents the distribution of population density across each sub-district (left) and the spatial distribution of public infrastructure along with its accessibility based on road proximity (right). It also illustrates how infrastructure accessibility relates to population distribution.

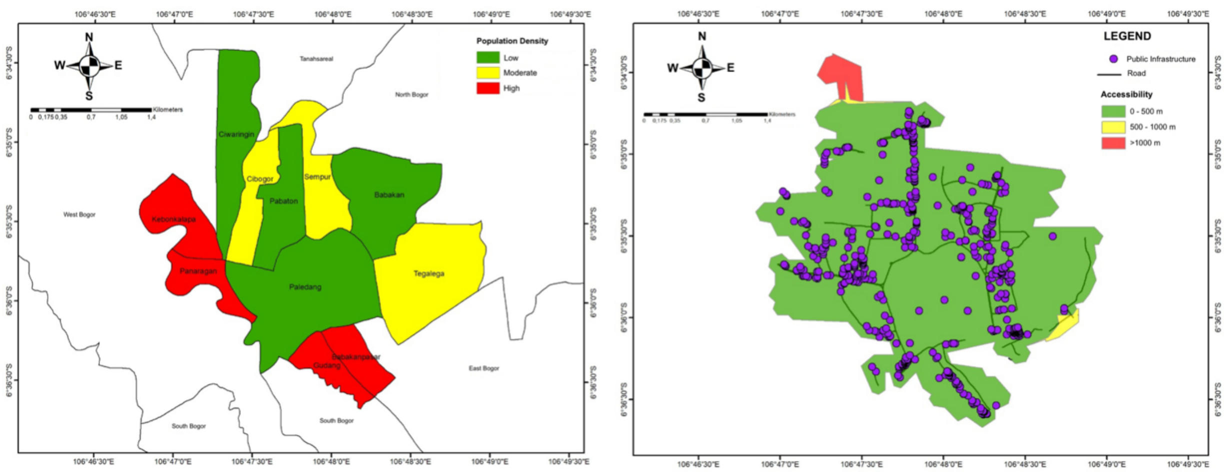

Figure 3. Spatial distribution of population density and infrastructure accessibility

Population density in Central Bogor Districts ranges from 5,047 to 32,444 people/km², with considerable spatial variation. High-density sub-districts such as Gudang, Babakan Pasar, Panaragan, and Kebon Kalapa Sub-districts coincide with zones of elevated landslide vulnerability, whereas sparsely populated areas like Ciwaringin, Babakan, and Paledang Sub-districts generally correspond to lower vulnerability levels. This relationship indicates that higher population density intensifies anthropogenic pressures on land and modifies the urban microclimate, thereby increasing slope instability [13]. These patterns emphasize the importance of integrating population distribution into spatial planning and risk mitigation strategies.

Infrastructure distribution further illustrates the potential consequences of landslide events. Spatial analysis identified 522 infrastructure units, including government buildings, educational facilities, healthcare centers, and economic institutions. A significant proportion of these facilities is located in moderate to high landslide vulnerability zones, particularly in Paledang and Gudang Sub-districts. The concentration of critical infrastructure in at-risk areas poses substantial threats not only to physical assets but also to the continuity of essential public services during disaster events. This highlights the need for prioritized protection and disaster preparedness planning for key infrastructure.

Accessibility plays a vital role in shaping both exposure and response capacity. Road network proximity was classified into high (0–500 m), moderate (500–1,000 m), and low (>1,000 m) accessibility levels. While most of Central Bogor District exhibits high accessibility, which supports effective evacuation and emergency response, certain northern and southeastern peripheries display moderate to poor accessibility, potentially hindering response operations during landslides. Strengthening accessibility networks in these areas is therefore crucial for enhancing disaster response efficiency and overall community resilience [14].

Collectively, the spatial patterns of population density, infrastructure distribution, and accessibility reveal that landslide risk in Central Bogor is not solely determined by physical factors but is significantly shaped by human settlement patterns and spatial development. Integrating these social and infrastructural dimensions into landslide risk management is essential for developing comprehensive and effective mitigation strategies.

3.3 Landslide Vulnerability Zonation

The landslide vulnerability map, derived from the weighted overlay of key physical parameters, classifies Central Bogor District into three zones: high, moderate, and low vulnerability (**Figure 4**). Each parameter was categorized, scored according to its contribution to susceptibility, and weighted using the Analytical Hierarchy Process (AHP). The final vulnerability index was obtained by summing the weighted scores for each sub-area (**Table 3**), ensuring a consistent and comparable assessment across the district.

The high vulnerability zone (index 3.00–4.02) covers 49.87 ha, predominantly in Gudang and parts of Paledang Sub-districts. These areas experience high annual rainfall (>4,605 mm), steep to very steep slopes, and weak lithologies such as sandy pumice tuff and old volcanic deposits. Dense settlements further increase land pressure, intensifying slope instability.

The moderate vulnerability zone (index 2.23–3.00) occupies the largest area, spanning 481.82 ha across Kebon Kalapa, Panaragan, and Babakan Pasar Sub-districts. This zone combines moderate to steep slopes, intermediate rainfall, and varied land cover, creating transitional conditions that result in medium susceptibility levels. Although less critical than high-risk zones, these areas require continuous monitoring and appropriate land-use management to prevent risk escalation.

The low vulnerability zone (index 1.25–2.23) covers 236.45 ha, mainly in northern and eastern sub-districts such as Ciwaringin, Cibogor, Sempur, Babakan, and Tegalega Sub-districts. Flat terrain, lower rainfall, stable lithologies, and dense vegetation collectively reduce landslide potential, though localized risks may persist in unmanaged or newly developed areas.

Overall, the spatial distribution of vulnerability reflects the interaction between topography, rainfall intensity, lithology, and land use. High-risk zones coincide with steep, geologically weak, and densely populated areas, whereas stable terrain and vegetative cover correspond to lower susceptibility.

Table 3. Scores and Weights of physical parameters for landslide vulnerability

Parameter	Class	Score	Weight	Weighted Score
Rainfall	4605–4773 mm/year	5	0.501	2.505
	4496–4604 mm/year	4		2.004
	4396–4496 mm/year	3		1.503
	4291–4396 mm/year	2		1.002
	4165–4291 mm/year	1		0.501
Slope	Very Steep (>45%)	5	0.322	1.610
	Steep (25–45%)	4		1.288
	Moderate (15–25%)	3		0.966
	Gentle (8–15%)	2		0.644
	Flat (0–8%)	1		0.322
Lithology	Old Volcanic Deposits	3	0.125	0.375
	Alluvial Fan	2		0.250
	Sandy Pumice Tuff	1		0.125
Land Cover	Settlement	4	0.052	0.208
	Open Land	3		0.156
	Water Body	2		0.104
	Dense Vegetation	1		0.052

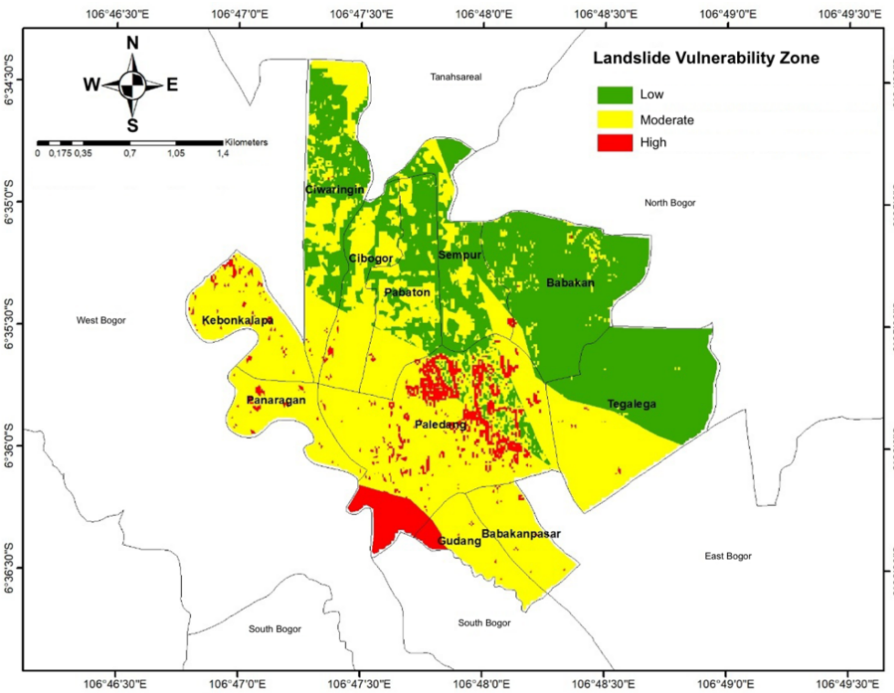

Figure 4. Landslide vulnerability zones

3.4 Spatial Integration of Landslide Vulnerability with Population Density and Infrastructure Accessibility

Figure 5 illustrates the distribution of various public infrastructure types, including government offices, economic centers, healthcare facilities, educational institutions, and tourism sites. The highest concentration of these facilities is observed in the central and southern sub-districts, such as Pabaton, Paledang, Babakan Pasar, and Gudang Sub-districts.

The spatial relationship between landslide vulnerability, population density, and infrastructure accessibility (**Figure 5**) demonstrates important insights for risk mitigation planning. Areas such as Gudang and Paledang Sub-districts, which are densely populated and exhibit moderate to high landslide vulnerability, pose significant disaster risks. Although no infrastructure is directly in the high-risk zone, these sub-districts' demographic pressure and proximity to vulnerable slopes elevate their exposure to landslide impacts.

On the other hand, Babakan and Tegalega Sub-districts, with low vulnerability and moderate to low population density, represent relatively safer zones. These areas also benefit from adequate road accessibility, further strengthening their resilience. Importantly, sub-districts with both good accessibility and moderate population density—such as Sempur and Cibogor Sub-districts —tend to coincide with low landslide vulnerability zones. This supports the theory that well-connected regions are better equipped for mitigation and emergency response.

This integrated spatial analysis confirms findings from [15], who emphasized that improved accessibility can significantly reduce disaster risks by enabling timely evacuation and resource mobilization. Conversely, the combination of limited access, high population density, and moderate landslide risk, as seen in Babakan Pasar and Panaragan Sub-districts, should be flagged as priority areas for risk reduction strategies.

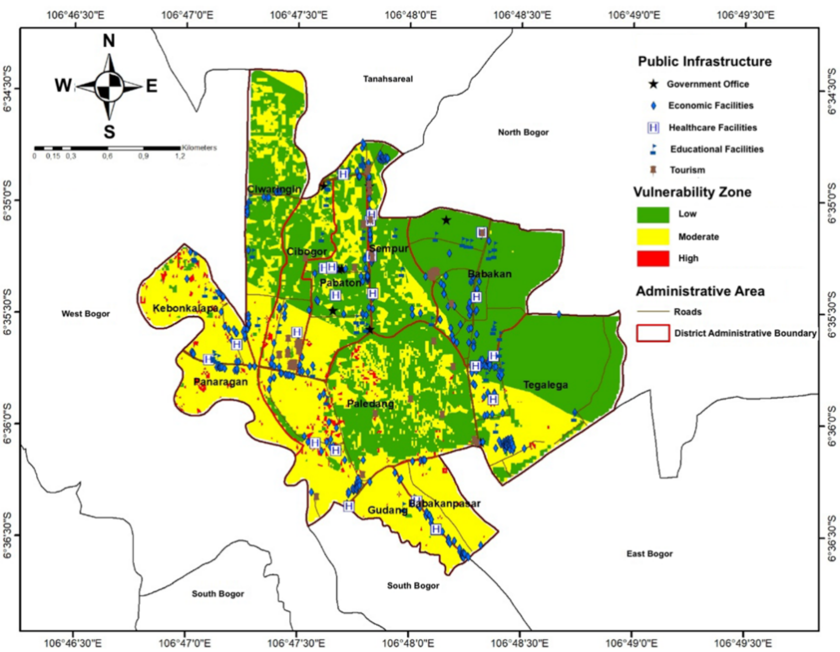

Figure 5. Integration of landslide vulnerability, population density and public infrastructure accessibility

4. Conclusion

This study applied a spatial multi-criteria approach using the Analytical Hierarchy Process (AHP) within a Geographic Information System (GIS) framework to develop a detailed landslide vulnerability map for Central Bogor District. Four key physical parameters—rainfall, slope, lithology, and land cover—were integrated with socio-environmental factors such as population density, infrastructure distribution, and road accessibility. The final vulnerability map categorized the district into three zones: high, moderate, and low vulnerability.

Results reveal that areas like Gudang and Paledang Sub-districts fall within the high vulnerability zone due to a combination of high rainfall, steep slopes, weak geological formations, and dense settlements. Meanwhile, sub-districts such as Ciwaringin and Sempur Sub-districts are less vulnerable, benefiting from flatter terrain, lower rainfall, and better vegetation cover. Importantly, the spatial overlay with demographic and infrastructure data highlights the compounded risks in densely populated areas with limited accessibility, reinforcing the need for integrated planning.

This research contributes both methodologically and practically. By leveraging open-access geospatial datasets and AHP-based weighting, it provides a replicable and data-driven framework for urban landslide risk assessment. The findings serve as a valuable tool for local authorities and urban planners, offering evidence-based insights to support disaster mitigation strategies, zoning policies, infrastructure planning, and community preparedness programs.

Given the increasing frequency of hydrometeorological hazards and the growing urban pressure in Central Bogor District, proactive measures must be taken to safeguard vulnerable communities and critical infrastructure. Future efforts should include field validation, incorporation of temporal rainfall variability, and participatory planning to ensure that spatial risk assessments translate into tangible resilience-building interventions.

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