http://journal.uir.ac.id/index.php/JGEET

E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 11 No 3 2026

RESEARCH ARTICLE

Multi-Criteria Geological Assessment for Geosite Prioritization in the Alteration Zone of Bogor Halimun Salak Geopark, West Java, Indonesia

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Received: May 22, 2026; Accepted: Aug 19, 2026.
DOI: 10.24273/jgeet.2016.1.2.001

Abstract

The sustainable development and conservation of geosites require an assessment that distinguishes geoheritage value from the physical capacity of land to support safe use. This study evaluates ten geosites in the hydrothermal alteration zone of the Bogor Halimun Salak Geopark, West Java, Indonesia, using an integrated multi-criteria geological framework. The Geological Agency scheme was modified by exchanging the weights assigned to groundwater availability (14 to 2) and soil-rock bearing capacity (2 to 14), while retaining the total supporting-factor weight. This modification was adopted because the original output was dominated by the hydrogeological pattern, whereas engineering suitability in clay-rich alteration zones is more directly controlled by material strength and stability. GIS overlay, laboratory-derived engineering-geology information, and field verification were used to integrate lithology, slope, bearing capacity, aquifer productivity, landslide susceptibility, and land-use constraints. The modified scheme expanded the high-suitability area from 2,673.88 to 5,898.13 ha, reduced the moderate class from 9,802.93 to 5,552.50 ha, and increased the low class to 2,985.28 ha, thereby improving spatial discrimination. Two geosites were classified as high suitability, two as moderate suitability, and six as low suitability. High-suitability sites are generally associated with competent volcanic rocks, gentle slopes, and relatively high bearing capacity, whereas low-suitability sites commonly occur in clay-rich altered materials with high plasticity, shrink-swell behaviour, and landslide constraints. The framework supports decision-making by separating locations suitable for controlled facilities from sites requiring restricted development and conservation-oriented management.

Keywords: Geosite prioritization, Hydrothermal Alteration, Geological Carrying capacity, Bogor Halimun Salak Geopark

1. Introduction

The preservation of global geological heritage has become an important component of UNESCO's international agenda through the UNESCO Global Geoparks (UGGp) initiative, which is founded on three principal pillars: conservation, education, and sustainable development ((UNESCO, 2021; Pérez-Romero et al., 2023; Ferdowsi and Németh, 2026). Geoparks are recognized not only as areas of significant geological value, but also as instruments for strengthening community participation and promoting regional economic development based on geological, natural, and cultural resources (Zouros, 2010; Joyce, 2010; Duarte *et al.*, 2020; Ruban, Sallam and Wanas, 2019; Canesin, Brilha and Díaz-Martínez, 2020). Effective land-use regulation is therefore essential to balance geoheritage conservation and sustainable utilization (Singh et al., 2022), while land-suitability assessment provides an important basis for geotourism planning and spatial management in protected areas (Peña et al., 2017; Widawski et al., 2018; Verdugo et al., 2025).

Geological characteristics are fundamental to sustainable geopark development because they control both development potential and the identity of geopark landscapes (Wibowo et al., 2024; Guju, Luca and Comănescu, 2025; Martínez-Murillo, Menjíbar-Romero and Remond, 2025). Conventional geosite assessment methods, including GAM, M-GAM, and Brilha-type models, primarily rank scientific, educational, aesthetic, tourism, protection, and degradation-risk values. These approaches are effective for identifying geoheritage significance, but they do not explicitly determine whether altered ground can safely support access routes, viewing facilities, or other visitor infrastructure. Indonesian JGEET studies likewise demonstrate the value of quantitative geosite and geomorphosite inventories for geotourism development (Fadlin et al., 2020; Ansori et al., 2021; Sahara and Setiawan, 2022; Yusuf et al., 2023), while weighted-overlay research shows that slope, lithology, soil, rainfall, and land cover must be integrated when spatial hazards affect site use (Idris, Muksin and Syukri, 2024). Therefore, geological carrying capacity is emphasized here as a complementary planning layer rather than a replacement for scientific, educational, tourism, or conservation-value assessment.

The Bogor Halimun Salak Geopark, formerly known as the Pongkor Geopark, is one of the geoparks in West Java with strong potential for international recognition. A distinctive feature of this geopark is the Pongkor Gold Mining Business Unit, operated by PT Antam, which hosts approximately 6 million tonnes of gold ore with average grades of 17.14 g/t Au and 154.28 g/t Ag (Directorate General of Mineral and Coal (Minerba), 2012). The Pongkor gold-silver deposit is associated with a low-sulfidation epithermal system characterized by quartz-vein mineralization within volcanic and volcaniclastic sequences (Milesi et al., 1994; Milési et al., 1999; Rosana and Matsueda, 2002; Haryanto et al., 2015). This setting reflects a complex hydrothermal alteration system that influences rock-mass properties and the spatial distribution of geosites.

From the perspective of geosite suitability, hydrothermal alteration is important because it produces rocks and soils with contrasting engineering and hydrogeological properties. In tropical volcanic environments, intense weathering and high rainfall may amplify alteration-related variability, affecting land-use planning, geotourism development, and geoconservation. Clay minerals such as illite, kaolinite, montmorillonite, and smectite may increase water retention, plasticity, swelling potential, and slope instability. Montmorillonite-bearing materials can generate substantial swelling pressure depending on mineral composition and water saturation (Komine and Ogata, 2003), while alteration and weathering processes can contribute to slope instability (Putro, 2019; Silwal, Ota and Yoshida, 2024). In the Pongkor area, argillic alteration zones have also been reported to exhibit very high swelling potential, indicating that clay-rich alteration products may reduce geological carrying capacity and affect geosite safety and suitability (Ginanjar and Sadisun, 2019; Gevor, Indrawan and Warmada, 2024).

Although mining activities in Pongkor provide economic benefits, their management must be aligned with geotourism and conservation-based regional development. This is increasingly urgent because the study area is affected by geohazards, particularly landslides and flooding. Landslide susceptibility in hydrothermal alteration zones is commonly controlled by slope gradient, lithological variability, weathering intensity, clay mineral content, and groundwater conditions, whereas flooding may occur in low-lying areas associated with river valleys and high drainage density. Wetlands, protected rice fields, volcanic hazard zones, and earthquake-related constraints may further influence geosite suitability.

Despite growing research on geopark development, land suitability, and geohazard assessment, these themes are commonly treated as separate analytical domains. Geoheritage models rank the importance and use potential of a site, whereas regional land-suitability maps commonly operate at broader scales and may overlook alteration-related heterogeneity. In low-sulfidation epithermal terrains, a geosite can therefore have high scientific value but low physical suitability because argillic alteration, intense weathering, steep slopes, or groundwater concentration reduce bearing capacity and slope stability. The unresolved methodological problem is not how to replace established geoheritage-value models, but how to add an engineering-geological and hazard-sensitive layer that informs where and how development may safely occur.

To address this gap, this study presents an integrated multi-criteria geological assessment framework that combines geological carrying capacity and geohazard characteristics for geosite prioritization in the alteration zone of the Bogor Halimun Salak Geopark, West Java, Indonesia. The novelty lies in the explicit integration of alteration zonation, geotechnical properties, hydrogeological conditions, and geohazard constraints into a single evaluation framework. This study aims to analyze geosite suitability to support geosite prioritization, risk-informed spatial planning, geoconservation, and sustainable geopark management.

1. Material and Methods

2.1 Study Area

The Bogor Halimun Salak Geopark is located in Bogor Regency, West Java, Indonesia, and comprises 23 geosites and 99 geosite locations distributed across 15 sub-districts (Government of Bogor Regency, 2024a). This study focuses on the Pongkor area and its surrounding regions, which belong to the Pongkor Geological Cluster as defined in the Bogor Regency Geopark Master Plan. Administratively, the study area encompasses parts of the Nanggung, Sukajaya, and Cigudeg sub-districts. Based on statistical data from Bogor Regency Statistics Agency (BPS, 2024), Nanggung covers 15,930 ha and comprises 11 villages, Sukajaya covers 15,618 ha with 11 villages, and Cigudeg covers 17,761 ha with 15 villages.

Geologically, the study area is composed of the Bojongmanik Formation, Old Volcanic Rocks, and Salak Volcanic Rocks (Effendi, Kusnama and Hermanto, 1998), reflecting a complex volcanic and volcaniclastic sequence associated with regional tectono-volcanic activity. The present study examines ten geosites located within the low-sulfidation epithermal alteration zone of the Pongkor area, as illustrated in Fig. 1. The sites were selected purposively to represent contrasting alteration, lithological, geomorphological, hydrogeological, and engineering-geological conditions.

The study area is characterized by significant geohazard conditions, particularly landslides and associated flooding. A major disaster event recorded by the Bogor Regency Disaster Management Agency (Bogor Regency Regional Disaster Management Agency (BPBD), 2020) on 1 January 2020 affected the sub-districts of Sukajaya, Nanggung, and Cigudeg, resulting in substantial casualties and infrastructure damage. Landslides occurred extensively across these areas, affecting all villages in Sukajaya, 10 of the 11 villages in Nanggung, and 5 of the 15 villages in Cigudeg. In addition, flood events were recorded simultaneously at six locations in Cigudeg and one location in Sukajaya (Bogor Regency Statistics Agency (BPS), 2024). These observations are consistent with regional geohazard assessments, which indicate that the study area is predominantly classified as having high to moderate landslide susceptibility. According to the Center for Volcanology and Geological Hazard Mitigation (Center for Volcanology and Geological Hazard Mitigation (PVMBG), no date), approximately 65.3% of the study area falls within the high-susceptibility class, while 31.2% is categorized as moderate susceptibility.

Structural controls also play an important role in governing the spatial distribution of geohazards in the Pongkor region. The area is influenced by four principal structural trends, namely the Sunda, Java, Sumatra, and Meratus patterns. These structural systems control fracture development, permeability pathways, and slope stability, thereby influencing both hydrothermal alteration processes and geohazard distribution (Hilmi and Haryanto, 2008; PT ANTAM Tbk Geomin Unit, 2023). Overall, the combined geological, structural, and geohazard characteristics indicate that landslide susceptibility constitutes the dominant geohazard in the study area.

2.2 Data Collection

This study applies a geological land suitability framework to evaluate geosite suitability in the Bogor Halimun Salak Geopark (BHSG), focusing on the alteration zone of the Pongkor area and its surroundings. The assessment considers geological resource and supporting factors, including favourable lithological, hydrogeological, and geomorphological conditions, as well as limiting factors such as geological hazards and terrain constraints. Groundwater availability was assessed using hydrogeological maps, while soil and rock bearing capacity was evaluated from geotechnical maps of the alteration zones. These datasets were obtained from the Geological Agency (no date),, Ministry of Energy and Mineral Resources Bandung, and (PT ANTAM Tb Geomin Unit, Unpublished). Morphological conditions and slope classes were derived from the Cihiris Sheet of the RBI map at a scale of 1:25,000 (Bakosurtanal, 2000). Spatial analysis, statistical analysis, and field verification were integrated using thematic datasets on hydrogeology, slope, lithology, geotechnical conditions, hazards, wetlands, river density, flood zones, and protected rice fields, as summarized in Table 1.

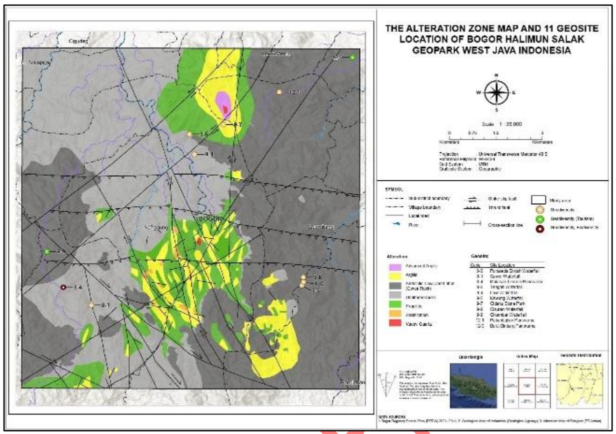

Fig. 1. Distribution of geosite locations in alteration zone. Source: Modified from PT ANTAM Tbk Geomin Unit (unpublished report)

Table 1. Matrix showing the relationship between research objectives, data types, data sources, analytical methods, and outputs.

Research objectives	Data Type	Data Collection and Sources	Analysis Techniques	Results
analyze geosite suitability within the alteration zone of the Bogor Halimun Salak Geopark in order to support geosite prioritization, risk-informed spatial planning, and sustainable geopark management.	1. Resources Factors availability of groundwater (hydrogeological map), landform and slope class (slope class map) rock type and geotechnical (geotechnical map) combine drilling geotech) a. availability of groundwater (hydrogeological map), b. landform and slope class (slope class map) c. rock type and geothecnical (geothechnical map) combine driling geotech)	Secondary Data from: a. (Murtianto, no date) publish by Environmental Geology Agency, Bandung Geological Agency, Ministry of Energy and Mineral Resources b. (Bakosurtanal, 2000) c. Environmental Geological Agency Bandung (Geological Agency, no date), Ministry of Energy and Mineral Resources (T. Tobing and Lutfhi, 1996), and PT ANTAM Tbk Geomin Unit (unpublished report)	1. Spatial analysis and overlay using GIS software 2. Laboratory analysis	Geological Characteristics Suitability Map
	2. Constraints factors: geological hazards of earthquakes (earthquake map) Volcanic eruptions of Mount Salak (Mount Salak KRB map) Landslide (Landslide susceptibility map) wetlands (wetland map) River density a. geological hazards of earthquakes (earthquake map) b. Volcanic eruptions of Mount Salak (Mount Salak KRB map) c. Landslide (Lanslide susceptibility map) d. wetlands (wetland map) e. River density	1. Secondary Data from: a. (Center for Volcanology and Geological Hazard Mitigation (PVMBG), no date) b. (Haerani *et al.*, 2003) c. (Sumaryono, 2022) d. (Government of Bogor Regency, 2024b) e. Analysis of the RBI map using Daryono's classification (Daryono, 2006)		
	3. Reducing Factor a. Flood Hazard zone b. Protected Rice Fields	2. Secondary Data from: a. (Geospatial Information Agency (BIG), Meteorological and Directorate General of Water Resources, 2017) b. Directorate of Land Rights Control, Land Use Change, Islands and Specific Regions (Ministry of Agrarian Affairs and Spatial Planning/National Land Agency (ATR/BPN), 2025)		

Table 2. Geological resource components

No	Component	Weight	Range	Class	Value	Score
1	Availability of groundwater to meet clean water needs	14	High	Good	3	42
			Moderate	Good	2	28
			Low	Moderate	1	14
2	Morphology (for ease of construction and accessibility)	8	Flat (0-5%)	Good	3	24
			Gentle slope (5-15%)	Moderate	2	16
			Steep (>15%)	Poor	1	8
3	Bearing capacity of rock soil (for foundations)	2	High	Good	3	6
			Moderate	Moderate	2	4
			Low	Poor	1	1

Table 3.Geological hazard components

No	Component	Weight	Range	Class	Value	Score
1	Earthquake (disrupting structural stability)	-4	very low	Good	0	0
			Low	Good	0	0
			Moderate	Moderate	1	-4
			High	Poor	2	-8
2	Susceptibility to landslide (related to construction stability)	-	Very low	Good	0	0
			Low	Moderate	1	-2
			Moderate	Poor	2	-4
3	Volcano (related to land and building damage)	-	Safe	Good	0	0
			High-risk Zone I	Moderate	1	-1
			High-risk area II	Poor	2	-2
4	Wetlands/swamps	-2	Dry	Good	0	0
			wet	Poor	1	-2
5	River density (related to infrastructure development)	-2	Low	Good	0	0
			Moderate	Moderate	1	-2
			High	Poor	2	-4

2.3 Weighting and Scoring Method

The weighting scheme was divided into three groups: supporting factors, limiting factors, and reducing factors. Supporting factors include groundwater availability, morphology or slope, and soil/rock bearing capacity (Table 2), while limiting factors consist of earthquake hazard, landslide susceptibility, volcanic eruption hazard, wetlands, and river density (Table 3). In addition, two parameters were treated as reducing factors, namely flood hazard zones and protected rice fields. These reducing factors were applied because an area may have favorable geological characteristics but still be unsuitable for development due to flood exposure or land-use protection status. Each of these components was overlaid using GIS to produce the final suitability classification.

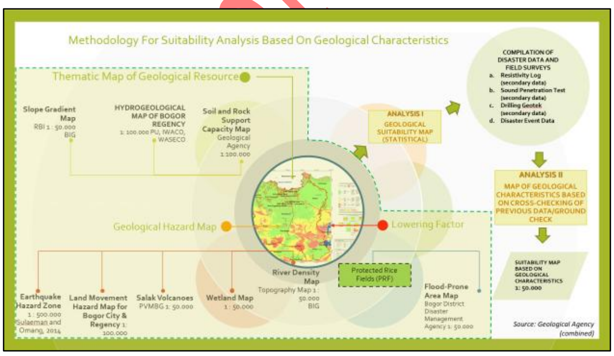

Fig. 2. Workflow for analysing geological characteristics in GBHS development

2.4 Spatial Analysis

All parameters were overlaid to produce a geological characteristics map showing high, medium, nd low suitability classes. The analysis follows the geological land-suitability framework of the Geological Agency (no date), in which the final suitability score reflects the balance between supporting and limiting factors. Land classified as affected by flood hazard or protected rice field status was downgraded in the final suitability assessment. The workflow of the analysis is shown in Fig. 2.

2.5 Modification of Weighting

The initial analysis using the original weighting scheme of the Geological Agency showed that the spatial distribution of geological characteristics was disproportionately controlled by groundwater availability, which had the highest weight of 14. As a result, the suitability pattern closely resembled the hydrogeological map representing clean water availability, thereby reducing its ability to distinguish geosite suitability.

The weighting scheme was modified by reducing the groundwater-availability weight from 14 to 2 and increasing the soil-rock bearing-capacity weight from 2 to 14, while morphology remained weighted at 8. This reciprocal exchange preserves the total positive weight (24) and therefore isolates the effect of changing the relative importance of the two parameters. The decision was based on: (i) comparison of the original overlay with its input layers, which showed that the output closely reproduced the hydrogeological pattern; (ii) field and laboratory evidence that alteration-related clay content, plasticity, weathering, and material competence directly control foundation and slope behaviour; and (iii) the study objective, which concerns physical suitability for geosite access and supporting facilities rather than domestic water-supply potential alone. Flood-hazard zones and Protected Rice Fields were retained as reducing constraints and were assigned to low suitability irrespective of the positive score. The modified theoretical score range was divided into three ordered classes using the distribution of attainable scores and continuity with the Geological Agency's three-class interpretation: low (0-23), moderate (24-47), and high (48-65) as shown in **Table 4.** These intervals represent, respectively, dominance of constraints, a balance between resources and constraints, and dominance of supporting geological conditions.

Table 4. Classification of geological characteristic suitability in the alteration zone

Land Suitability	Class Interval (Geological Agency, n.d.)	Class Interval (modified)	Description
High	47-72	48-65	High geological resources factors, low constraints, making it easy to implement and low cost
Moderate	21-46	24-47	geological resources factors are balanced with constraints, so implementation requires moderate costs.
Low	(-2)-20	0-23	Low geological resources factors, high constraints, making implementation difficult and costly

2.6 Sensitivity Analysis

A scenario-based sensitivity test compared the original Geological Agency weighting (groundwater 14; morphology 8; bearing capacity 2) with the modified scheme (groundwater 2; morphology 8; bearing capacity 14). Because the total supporting-factor weight was held constant, differences in mapped area can be attributed to the exchange between groundwater and bearing capacity rather than to a change in the overall score magnitude. Under the original scheme, the high, moderate, and low classes covered 2,673.88 ha (18.52%), 9,802.93 ha (67.91%), and 1,959.10 ha (13.57%), respectively. Under the modified scheme, these classes covered 5,898.13 ha (40.86%), 5,552.50 ha (38.46%), and 2,985.28 ha (20.68%). Thus, the high class increased by 3,224.25 ha (+120.58%), the moderate class decreased by 4,250.43 ha (-43.36%), and the low class increased by 1,026.18 ha (+52.38%). The pronounced redistribution confirms that classification is sensitive to the groundwater bearing capacity trade-off. It also shows why the modified result should be interpreted as a purpose specific engineering suitability scenario, not as a universally optimal weighting solution.

2.7 Field Validation

Field validation was undertaken across the ten assessed geosites using purposive observations designed to cover altered and comparatively less-altered materials, contrasting slope classes, and the three predicted suitability classes. At each accessible site, the mapped class was checked against exposed lithology and weathering, alteration products, slope condition, evidence of instability, surface or spring-water conditions, flood indicators, wetlands, and protected-rice-field status. Engineering-geology samples representing the alteration zones were evaluated using compressive-strength, XRD, and soil-property information. Validation was performed as a criterion-by-criterion agreement check: the GIS class was considered supported when the observed material competence, terrain condition, and mapped constraints were consistent with the dominant score components. The observations generally supported the spatial interpretation, particularly the association of low suitability with clay-rich altered ground and landslide-prone slopes, and of higher suitability with more competent volcanic materials. Remaining discrepancies were associated mainly with the scale and publication date of secondary maps and with local conditions that cannot be represented in regional static datasets.

3. Result and Discussion

3.1 Result

a. Water Availability

The hydrogeological map shows four main hydrogeological units, namely a moderately productive aquifer with wide distribution (dark turquoise colour): an aquifer through fractures and intergranular spaces in old volcanic rocks and lava and unweathered volcanoes. However, according to (Murtianto, no date), this aquifer consists of sandy tuff, tuffaceous breccia lahar and basaltic andesite lava. The discharge is generally 0.8 and 36.4 m/day. Areas with scarce or insignificant groundwater (marked in brown on the map) have fissure or nest aquifers in basalt-andesite lava flows from old volcanoes and unweathered volcanoes consisting of andesite-basalt lava flows with a yield ranging from 10-4 to 10-1 m/day, as well as sandstone, clay, and napal silt with a discharge of 10-3-1 m/day. Locally, productive aquifers (light green on the map) are aquifers through fractures and intergranular spaces that are products of young volcanoes and unweathered volcanoes. That consist of andesite-basalt breccia, andesite lava, tuff and agglomerate. Water yield ranges from 10-2-10 m/day with total 9,652.09 ha. Locally, the moderately productive aquifer (light blue) is an aquifer with flow through intergranular spaces of undisturbed young volcanoes. The rocks in this aquifer consist of sandy pumice tuff, tuffaceous breccia lahar and andesite-basalt lava. The discharge is generally 0.8 and 36.4 m/day.

b. Morphology

The steep slope class (>15%) covers 4,553.78 hectares or about 30% of the area, and is mainly distributed in the southern and southwestern parts of the map, which is associated with altered volcanic rock units and andesite breccia. Flat slopes (0–5%) cover only 837.65 hectares (approximately 5%), mainly in the main river valley and local alluvial plains around the villages of Leuwisadeng and Nanggung.

c. Engineering Geology

The alteration map included in this weighting provides an overview of the geological conditions in the Bogor Halimun Salak Geopark area, which forms the basis for the creation of the engineering geology map. Samples were taken from each alteration zone for compressive strength, XRD, and soil properties testing. The results of the laboratory tests were used to create a classification that was then used to create a technical geological map.

d. Landslide Hazard

There are two types of landslide identified in the field shown in Fig. 3.:

1) Translational sliding, where the bedrock becomes a sliding plane for soil material. As in Curug Love, the Cikasungka Formation rock

Fall type with debris material consisting of soil, gravel-sized rocks up to boulders.

Fig. 3. a. Aerial photograph of a translational slip type with a slip plane on brecciated sandstone of the Cikasungka Formation with soil material, b. Exposure of rocks of the Cikasungka Formation with rock position N 100°E/4°,

The results of the calculation of the area of each landslide susceptibility class. Each zone has the following characteristics:

1) High Landslide Suceptibilty Zone. This zone covers an area of ±65% and is associated with weathered volcanic units and plastic-expansive clayey soil on steep slopes with andesite breccia code R(sc-sg) and andesite lava/lahar code AN-LV, thick weathering, fine to coarse-grained material, low to moderate permeability with constraints of landslides and erosion.
2) Medium Landslide Suceptibilty Zone. This zone covers an area of ±31%, generally located on the shoulders to the foot of slopes and undulating hills with materials that tend to be problematic with a mixture of clayey sand/sandy loam (R(cm-cs), R(cs-sc)) and some andesite lava/lahar (AN-LV).
3) Low Landslide Suceptibilty Zone. This zone covers approximately 3.48% of the study area. This zone has more stable units or foothill plains with a composition of propylitic altered clayey sand code R(sc-pa) and silicification code R(sc-sa) that is non-expansive, low to medium plasticity, moderate to good bearing capacity, and slopes that tend to be stable, especially when there is carbonate/silica cementation.
4) Very Low Landslide Suceptibilty Zone This zone covers approximately 0.08% of the study area. It is limited to valley/alluvial plains at the bottom of rivers. The material is relatively stable on very gentle slopes but has a small potential for landslides. However, caution is still needed regarding cliff erosion or river scouring.

e. Volcanic Eruption

Several points closer to Mount Salak and its surroundings may indicate areas that are more vulnerable to volcanic eruption hazards, but overall, this map shows that most of the studied area is not in a high-risk zone related to active volcanic eruptions at this time. The distance from the study area to Mount Salak is approximately 27 km in a straight line and is not directly affected by the hazards of the Salak Volcano eruption.

f. River Density

Based on the analysis of the river density map and spatial assessment of the study area, encompassing Nanggung, Leuwiliang, Leuwisadeng, and adjacent areas in Bogor Regency, two principal river density classes were identified, namely moderate and high density. Areas with moderate river density covered approximately 1,604.46 ha, while high river density was the dominant class, extending over approximately 12,831.45.

Moderate river density commonly develops in areas with gently undulating to moderately steep hilly morphology, where relatively higher rock permeability allows a portion of rainfall to infiltrate into the subsurface. These areas display a moderately developed drainage system that is not yet densely organized, indicating relatively permeable lithological conditions and an intermediate degree of weathering. In hydrogeological terms, such areas are likely to possess greater groundwater recharge potential than zones with high river density, and may therefore serve as potential aquifer recharge areas.

g. Wetlands

The distribution of wetlands in the study area has been determined by Bogor Regency Regulation No. 1 of 2024 concerning the 2024-2044 Spatial Plan for Bogor Regency (Government of Bogor Regency, 2024c). Wetlands are defined as swamps, brackish areas, peatlands and water bodies: natural or artificial; permanent or temporary; with stagnant or flowing water, fresh, brackish or salty, including sea areas with a depth of no more than 6 metres at low tide. Wetlands in the study area include not only swamps, but also water catchment areas (Article 12 of Presidential Decree No. 32 of 1990 concerning the Management of Protected Areas (Government of Indonesia, 1990) as an effort to preserve wetlands so that their functions are maintained and preserved, including several types of areas such as riverbanks, water catchment areas, and areas around lakes/reservoirs. The rock typology in the water catchment area is shown in Fig 4.

h. Flood

The identified flood zones have significant values in areas with a slope class of 0-5%, indicating that areas with gentle slopes are more prone to flooding. Flood zones are more often associated with high river density. The higher the river density, the greater the tendency for flooding to occur. The results of calculations of the flood area covering 9.5 ha in the Cikaniki River in Pangkaljaya Village and Nanggung Village in the northern part of the study.

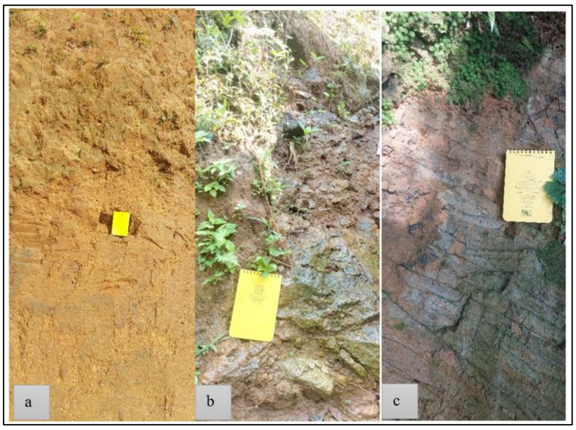

Fig. 4. Rock profile in the water catchment area of Pabangbon Village a. volcanic soil layer consisting of tuff to lapilli, b. beneath the soil layer is breccia with fragments of tuff and andesite, c. beneath the breccia with fragments of tuff and andesite is layered and fractured tuffaceous sandstone.

Pangkaljaya Village has a high river density, and the phenomenon of river meanders is clearly visible on satellite imagery maps and river density maps. Rivers with meanders tend to slow down the flow of water, so that when rainfall is high, water can become trapped in the bends of the river and create flooding.

i. Protected Rice Fields

Protected rice fields within forest areas cover approximately 228.7 hectares (1.58% of the total study area), while those outside forest areas cover 1,418.3 hectares (9.82%). The distribution indicates that protected rice fields are predominantly located outside forest areas. These areas are mainly associated with river valleys and sub-volcanic plains characterized by relatively gentle slopes. Such landforms are identified in the Cikaniki and Cidurian river valleys, where sedimentation and weathering of volcanic materials have resulted in fertile soils. Conversely, non-LSD areas cover approximately 89% of the total study area and include settlements, dryland, mining zones, and hydrothermal alteration areas that are unsuitable for rice cultivation. A portion of these areas spatially coincides with argillic and propylitic alteration zones in the Pongkor region. These zones are characterized by high soil acidity and the presence of expansive clay minerals, particularly montmorillonite and kaolinite. Such conditions are associated with reduced soil stability and low water retention capacity, limiting their suitability for paddy field development.

j. Geological Characteristics

The two weighting scenarios produced markedly different suitability patterns. Using the Geological Agency weights, the moderate class dominated 9,802.93 ha (67.91%), while the high and low classes occupied 2,673.88 ha (18.52%) and 1,959.10 ha (13.57%), respectively. After the weights of groundwater and bearing capacity were exchanged, the high class expanded to 5,898.13 ha (40.86%), the moderate class contracted to 5,552.50 ha (38.46%), and the low class increased to 2,985.28 ha (20.68%). The simultaneous growth of the high and low classes indicates stronger spatial differentiation: competent volcanic ground is separated more clearly from weak, clay-rich alteration zones, whereas the original scheme compressed much of this contrast into the moderate class.

Fig. 5 shows the spatial differences in geological characteristic classes produced by weighting schemes A and B. Under weighting A, the medium-suitability class is spatially dominant, whereas weighting B results in a broader distribution of high- and low-suitability classes. This indicates that changes in the weighting of supporting factors substantially affect the spatial pattern of geological suitability in the study area.

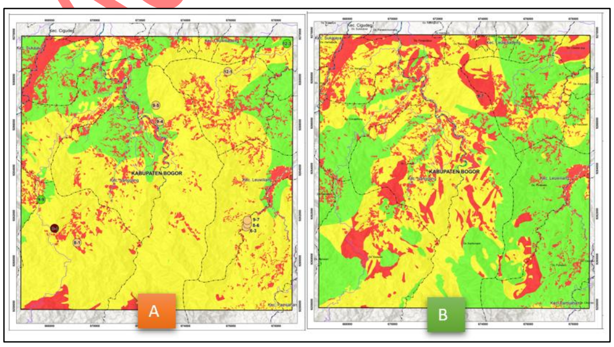

Fig. 5. Changes in the area of geological characteristic classes with different weightings of supporting factors.

Table 5 shows that the distribution of geosites across the geological characteristic classes is dominated by the low class. Of the ten geosites evaluated, six were classified as low, two as moderate, and only two as high. The high class includes Pabangbon Panorama and Cikembar Waterfall, whereas the moderate class consists of Cikawung Waterfall and Bukit Bintang Panorama. Meanwhile, the low class comprises Malasari Terrace Panorama, Love Waterfall, Sawer Waterfall, Curug Cisuren, Curug Tengah, and Puraseda Endah Waterfall. These results indicate that most of the geosites identified in the study area fall within the low geological characteristic class, while only a smaller proportion are included in the moderate and high classes.

The geological characteristics map shows the spatial distribution of land suitability classes for geosite-related activities in the Bogor Halimun Salak Geopark, particularly in the western and southern parts of Bogor Regency, including Nanggung, Cigudeg, and Leuwiliang sub-districts. Based on the modified weighting scheme, the study area is classified into high, moderate, and low geological suitability classes.

1) The high-suitability class is distributed mainly in the central to southeastern part of the study area, especially around Leuwiliang and parts of Nanggung Subdistrict. This class is generally associated with gentle to undulating topography, relatively stable young volcanic lithologies, and favorable drainage conditions.

Table 5. Geosites in the geological characteristic class Geological Characteristic Class

Geological Characteristic Class	Geosite
High	1) Geosite 12-1 (Pabangbon Panorama) 2) Geosite 9-9 (Cikembar Waterfall)
Moderate	1) Geosite 9-5 (Cikawung Waterfall) 2) Geosite 12-3 (Bukit Bintang Panorama)
Low	1) Geosite 8-4 (Malasari Terrace Panorama) 2) Geosite 9-4 (Love Waterfall) 3) Geosite 8-1 (Sawer Waterfall) 4) Geosite 9-8 (Curug Cisuren) 5) Geosite 8-6 (Curug Tengah) 6) Geosite 6-3 (Puraseda Endah Waterfall)

2) The moderate-suitability class is widely distributed in the central and southwestern parts of the study area, extending from Nanggung Subdistrict toward the Sukajaya border. It is generally associated with old volcanic rocks and pyroclastic breccia occurring on moderately steep slopes.
3) The low-suitability class is identified mainly in the northern part of the study area, especially in Cigudeg, the southwestern margin near the Sukajaya border, and several areas around the volcanic hills of the Halimun Salak region. These areas are characterized by steep slopes, altered volcanic breccia, and the presence of active structural features.

Overall, the three suitability classes show contrasting geological and geomorphological characteristics across the study area. The distribution of geosites within these classes is presented in Table 6, while further spatial detail is shown in Appendix 2.

3.2 Discussion

The sensitivity comparison demonstrates that weighting is not a neutral technical step: it determines which physical attribute dominates the suitability result. The original scheme favoured groundwater availability and produced a relatively homogeneous moderate-suitability pattern. The modified scheme emphasizes the capacity of soil and rock to support facilities and therefore separates competent volcanic units from weak altered materials more distinctly. This emphasis is appropriate for planning access, viewing platforms, trails, and supporting infrastructure, but it does not imply that bearing capacity is intrinsically more important for every geopark objective.

The proposed framework differs from GAM, M-GAM, Brilha's model, and related geosite-assessment approaches in both purpose and output. Those models evaluate scientific significance, educational and tourism use, protection needs, and degradation risk; the present framework evaluates the physical suitability of the land on which geosite use would occur. Its principal advantage is the explicit integration of bearing capacity, hydrogeology, slope, landslide susceptibility, flooding, wetlands, and protected-land constraints. Its limitation is that a low suitability score may occur at a geosite of exceptional scientific or educational value. Accordingly, the two assessment families should be used sequentially or in parallel: geoheritage-value models establish why a site merits conservation and interpretation, while the geological carrying-capacity layer determines the intensity, location, and engineering requirements of permissible development.

The final geological characteristics map in Appendix 1 serves not only as a spatial representation, but also as a decision-support tool for geosite prioritization. The classification into high, moderate, and low suitability reflects variations in geological carrying capacity, hazard exposure, and geotechnical stability. This interpretation is in line with Rohaendi *et al.* (2021), who showed that land-suitability classification can guide land use and geotourism management. Similarly, Ansori *et al.* (2024) emphasized that lithology, geomorphology, and groundwater are key physical resources controlling development potential and geopark identity.

From a management perspective, high-suitability areas are more appropriate for controlled geotourism development and supporting infrastructure, provided that conservation objectives are maintained. Moderate-suitability areas require cautious management because geological resources and limiting factors are relatively balanced. Low-suitability areas, although commonly associated with higher physical risk, may still possess significant geoheritage value and therefore require conservation-oriented management rather than intensive development. This distinction highlights that areas with lower physical suitability are not necessarily of lower scientific or conservation importance. In hydrothermal alteration environments, argillic zones may contain clay-rich materials with high plasticity, swelling potential, low shear strength, and reduced bearing capacity. These conditions may limit infrastructure development but provide educational value related to alteration, mineralization, weathering, and geohazard processes.

The spatial patterns derived from the final suitability map also support a zoning-based management approach. The tripartite zoning concept of core, buffer, and transition zones was originally developed within the UNESCO Man and the Biosphere Programme and has been widely used in protected-area management (UNESCO, 1996; Ishwaran, Persic and Tri, 2008). In this study, high-suitability areas may correspond to transition zones for controlled geotourism and supporting facilities, moderate-suitability areas may function as buffer zones with stricter management controls, and low-suitability areas may be designated as core conservation zones where high geoheritage value coincides with geotechnical vulnerability or geohazard exposure.

Hydrothermal alteration provides the process-based explanation for this distinction. Argillic alteration converts primary volcanic minerals into clay assemblages that may increase plasticity, water sensitivity, swelling potential, and strength loss. Fracturing and weathering further enhance infiltration and create contrasts in permeability; during intense rainfall, these contrasts can promote perched saturation and reduce effective stress on slopes. Conversely, silicification may locally increase intact-rock competence, although discontinuities can still control block instability. The suitability class therefore reflects the combined effects of alteration mineralogy, weathering, structure, slope, and groundwater rather than lithology alone.

Uncertainty arises because the overlay combines secondary datasets produced by different institutions, at different scales, and in different years. Positional mismatch, generalized class boundaries, and differences in mapping objectives may propagate into the final classification. In addition, landslides and floods are dynamic processes controlled by rainfall, land-cover change, drainage modification, and antecedent moisture, whereas the input maps represent static snapshots. The resulting map should therefore be used for screening and zoning, followed by site-specific investigation before construction, rather than as a substitute for detailed geotechnical design or real-time hazard assessment.

Overall, integrating geotechnical parameters into the weighting scheme provides a more robust basis for geosite prioritization. By linking Figure 5 with Appendix 1, this study demonstrates that land-suitability assessment can support risk-informed spatial planning and sustainable geopark management in tropical hydrothermal alteration environments. The proposed framework bridges economic geology, engineering geology, geohazard assessment, and geoheritage-based spatial planning by showing that geosite prioritization should consider geological value, land stability, hazard exposure, and conservation requirements.

4. Conclusion

This study shows that integrating hydrothermal alteration, engineering-geological properties, hydrogeology, terrain, and geohazards adds a distinct physical-suitability dimension to geosite prioritization. The principal scientific contribution is the demonstration that exchanging the relative weights of groundwater availability and soil-rock bearing capacity, without changing the total positive weight, transforms a groundwater-dominated output into a more differentiated representation of competent and weak altered ground. The modified scenario increased the high-suitability area from 18.52% to 40.86%, reduced the moderate class from 67.91% to 38.46%, and increased the low class from 13.57% to 20.68%. At geosite level, two sites were classified as high suitability, two as moderate, and six as low.

For geopark managers and spatial planners, the classification provides a screening basis for locating controlled visitor facilities in higher-suitability areas, applying additional investigation and engineering controls in moderate areas, and prioritizing conservation-oriented, low-intensity use in physically vulnerable areas. A low physical-suitability class must not be interpreted as low geoheritage value; several clay-rich altered sites remain scientifically important because they expose alteration, mineralization, weathering, and geohazard processes.

The principal limitations are the purpose-specific weighting, dependence on multi-source static maps, and the absence of a fully probabilistic uncertainty model. Generalization should therefore be limited to tropical hydrothermal-alteration settings with comparable geological controls and should be recalibrated elsewhere. Future studies should optimize weights through structured expert elicitation and AHP or Fuzzy-AHP, test uncertainty using Monte Carlo or probabilistic sensitivity analysis, incorporate time-dependent rainfall and land-cover information, and validate predictions using independent geotechnical and hazard-event datasets.

Acknowledgements

The authors express their gratitude to the Head of the Geological Resources Research Center, National Research and Innovation Agency; Rahmi Karmellia and Popi Rismayanti of the Regional Development Planning, Research and Development Agency (Bappeda) of Bogor Regency; and Singgih Irianto Trisilo Hadi, Henny Purwanti, and Lilis Sri Mulyawati of Universitas Pakuan for their assistance and cooperation.

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