Assessment of the Scientific, Educational, Tourism, and Degradation Values of Geological Features as a Basis for Geotourism Development in Bangi Cave, Malang Regency, Indonesia

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Abstract. Bangi Cave is part of a tropical karst landscape in Kedungsalam Village, Malang Regency, developed on the Wonosari Formation limestone and displaying a diversity of exokarst and endokarst features of high scientific and tourism value. To date, no comprehensive study has assessed the geotourism potential of Bangi Cave in an integrated manner, considering scientific, educational, tourism, and degradation risk values, thereby hindering the optimal implementation of conservation-based area development. This study aims to identify the geological characteristics and assess the area's feasibility as a geotourism geosite using quantitative assessment methods in accordance with the guidelines of the Centre for Geological Survey (2017), Indonesia. The research methods include surface geomorphological surveys, lithological characterisation, documentation of endokarst features, and quantitative evaluation of scientific, educational, tourism, and degradation risk values. The results indicate that Bangi Cave features an active karst system, characterised by dolines, uvalas, ponors, horizontal passages, chambers, stalactites, flowstones, and underground rivers. The quantitative assessment yielded the highest education score (77.08), followed by tourism (71.15) and science (64.29), reflecting strong suitability as an education-oriented geosite. However, the degradation risk score (60.00) indicates a relatively high vulnerability to environmental and human activities. Overall, Bangi Cave has excellent potential to become a leading conservation-based geotourism site, if mitigation strategies to address degradation, strengthening of security facilities, and targeted visitor management are implemented to sustain its geological heritage.

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1 Introduction

Two primary geomorphological formations characterise karst landscapes. That is, exokarst and endokarst. Exokarst is a karst landform that develops on the surface as a result of the dissolution process of carbonate rocks, such as polje, ponor, karst hills, and uvala. Meanwhile, endokarst is a karst formation that develops below the surface, resulting from underground dissolution and drainage processes that form a network of caves and underground rivers [1]. The interaction between exokarst and endokarst generates an integrated karst system, in which surface processes influence subsurface dynamics and, conversely, subsurface conditions affect surface features. A comprehensive understanding of both formation types is essential for karst disaster mitigation, water resource management, and geotourism development [2].

Geotourism is a form of sustainable tourism that utilises geological features as tourist attractions for educational, conservation, and economic purposes. Geological elements are one of the determinants of the formation of natural beauty that can be developed into geotourism objects [3]. Karst landscapes are among the natural landscapes with high geotourism value, as they exhibit unique geomorphology, including caves, dolines, and underground rivers. Geotourism development not only serves as a means of geological education but also has the potential to encourage biodiversity conservation, protect geological sites, and improve the welfare of local communities through economic empowerment [4].

One of the main elements of geotourism is a geosite. This site holds significant geological value, often expressed through natural landscapes, rock outcrops, fossils, minerals, and other geological phenomena [3]. A cave is a karst feature, a natural underground space large enough for humans to enter. The internal structure of a cave often displays mineral deposits such as calcite or gypsum, which indicate hydrogeochemical processes [5].

The Bangi Cave area is a karst landscape in Malang Regency, Indonesia, characterised by surface and subsurface geological features that remain hydrologically active [6], [7]. Many studies have focused on the classification, morphology, and hydrology of karst systems in Indonesia. However, studies that integrate geoscientific significance, educational value, tourist appeal, and vulnerability to degradation remain limited and have not been conducted at the research site. This research gap hinders efforts to develop geotourism grounded in scientific principles and conservation.

Based on the description above, a study was conducted to analyse the geotourism potential of Bangi Cave and its surrounding area. The research results can serve as a basis for developing geotourism programs focused on conservation and education.

2 Method

This research was conducted in Kedungsalam Village, Donomulyo District, Malang Regency, Indonesia. Geographically, the research location is located at coordinates around 112.426°–112.427° East Longitude and 8.342°–8.345° South Latitude (**Fig. 1**).

The research method employed includes a geological survey that involves geomorphological analysis, lithological characteristics, and an examination of the interior conditions of Bangi Cave. Geomorphological data are used to characterize the landscape and its formation processes. Lithological data are used to characterise the rocks that form Bangi Cave and its surroundings. The interior of the cave is used to characterize Bangi Cave. In addition to the geological survey, this study uses a quantitative assessment method to assess the potential of the Bangi Cave geosite based on the Technical Guidelines for Geological Heritage Resource Assessment published by the Indonesian Geological Survey Centre (2017), which includes an assessment of the potential of geological sites measured through several criteria, parameters, and indicators quantitatively. Jose Brilha previously introduced this method in 2016 [8]. The criteria used in this assessment are scientific, educational, tourism, and degradation risk value, each with predetermined weights.

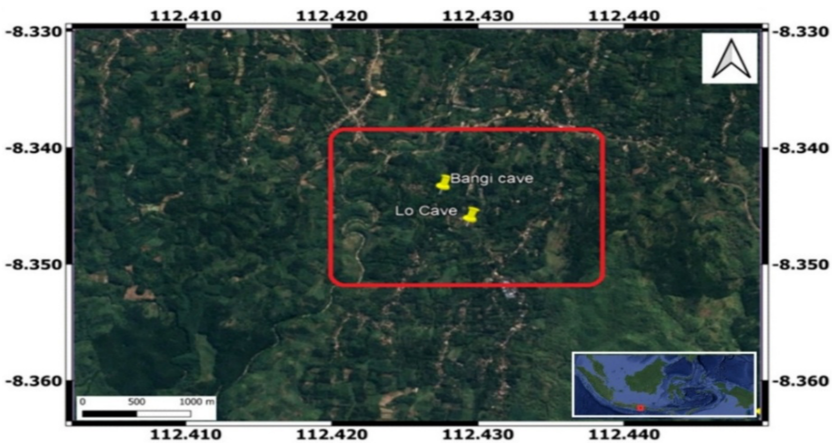

Fig. 1. Research Location Map

3 3. Results and discussion

3.1 Geological and geomorphological conditions

The geological map (**Fig. 2**) shows that Bangi Cave is a karst feature that is geologically part of the Wonosari Formation (Tmwl). The Wonosari Formation is a geological unit composed primarily of limestone, formed in a shallow-marine environment during the Middle to Late Miocene epoch. The presence of reef limestone, layered limestone, and marl characterises this formation. This lithology is massive, highly fractured, and has undergone intensive karstification, resulting in a well-developed cave system, dolines, and exokarst morphology.

To the north of the study area lies the Campurdarat Formation (Tmcl), comprising more impermeable carbonate marl and mudstone. Its presence serves as an essential hydrogeological boundary and potentially controls the direction of surface flow toward the carbonate zone to the south.

Fig. 3 is a karst morphology map of Bangi Cave, illustrating the complex development of its karst landscape with diverse exokarst forms. Residual karst hills are densely packed and irregularly distributed, forming high-elevation zones flanking various closed depressions. In the basins, small to medium-sized dolines predominate and form clusters, indicating intensive dissolution of the carbonate rocks.

A broader depression, the uvala, has been identified as the result of the merging of several dolines, particularly in the area around Bangi Cave. The polje, located in the northwest, appears as a relatively flat, enclosed plain with surface flow leading to an active pond. The surface river network follows the depression's contours and disappears as it enters the underground drainage zone.

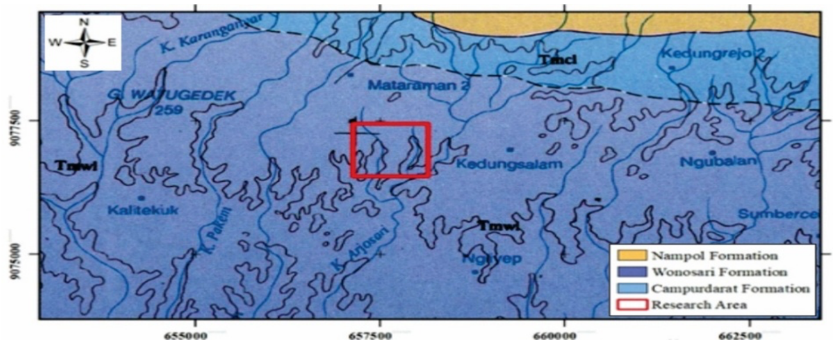

Fig. 2. Geological map of the research area

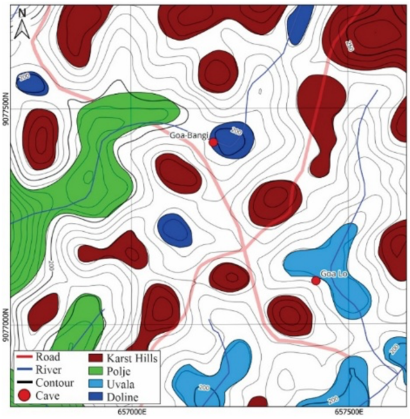

Fig. 3. Karst Morphology Around Bangi Cave

Bangi Cave and Lo Cave are located in the karst foothill zone and exhibit a cave development pattern consistent with a tropical karst system. This position confirms that speleogenesis in the study area is strongly influenced by the dynamics of surface water entering the karst hill section underground. This finding aligns with the results of Jiang et al. [9], who found that the foothill zone has the highest inflow concentration (recharge zone), particularly during periods of maximum rainfall. Under these conditions, surface water flowing by gravity towards the base of the slope will undergo intensive infiltration through fractures, bedding planes, and zones of weakness in carbonate rocks. This process accelerates rock dissolution and encourages the enlargement of underground cavities in Bangi Cave and other caves.

3.2 Distribution of exokarst features around Bangi Cave

Fig. 4a shows the typical karst hills in the Bangi Cave area, with rivers flowing through inter-hill valleys. This pattern of narrow canyons and isolated hills not only reflects long-term dissolution processes but also offers a visually appealing landscape with potential for development as a geomorphological interpretation trail. **Fig. 4b** shows the morphology of a 4-meter-high waterfall formed by differences in lithology or rock hardness. The presence of the waterfall and natural pools adds aesthetic value and enhances the water-based tourism experience.

Fig. 4. Ekxokarst features in the Bangi Cave area

Fig. 4c shows the vertical mouth of Lo Cave, the result of dissolution following weak zones in the rock, such as fractures or bedding planes. This vertical morphology is a common feature of active tropical karst, serving as the primary route for surface water infiltration [10]. Such structures can be developed as educational points for visitors, providing insight into speleogenesis and karst hydrological dynamics. **Fig. 4d and 4e** show the ponor, or sinkhole, that serves as an infiltration zone in the karst system. The ponor plays a vital role in channelling rainwater and surface runoff into the underground network [11], making it a strategic location to introduce the concepts of aquifer recharge, water conservation, and the vulnerability of karst systems to land-use changes.

Fig. 4f shows an ephemeral river disappearing through a rock fracture, a phenomenon known as a sinking stream. This feature indicates high connectivity between the surface and subsurface, as well as the presence of complex underground drainage [12]. This phenomenon has great potential to be developed into an educational geotourism package that explains the relationship between fluviokarst processes, flow dynamics, and cave network formation.

The diversity of exokarst features (**Fig. 4**) not only reflects the activity level of the Bangi Cave karst system but also offers significant opportunities for the development of education- and conservation-based geotourism.

3.3 Internal conditions of Bangi Cave

Fig. 5a shows the mouth of Bangi Cave, located at the foot of a hill or doline depression. The relatively broad, horizontally oriented cave mouth suggests that the entrance formed naturally through lateral dissolution. The dense vegetation around the cave mouth reflects a humid tropical environment, which significantly enhances the biological and chemical weathering processes of carbonate rocks. The combination of organism activity, organic matter accumulation, and infiltration of low-pH rainwater accelerates dissolution and the expansion of the subsurface cavity, as described in various studies of karst speleogenesis [13]. These conditions provide crucial educational value, especially regarding the processes of speleogenesis and the dynamics of the tropical environment that forms caves.

Fig. 5b shows the central cave passageway with walls and ceilings dominated by stalactite development. These features are formed through the precipitation of calcium carbonate from mineral-rich meteoritic water droplets. Surface water dissolving limestone produces a calcium bicarbonate solution; when this solution enters the cave, and CO_2 is released, mineral precipitation gradually forms stalactites [14]. The presence of active stalactites makes Bangi Cave an ideal location for interpreting the formation of cave ornaments and the water cycle in a karst environment.

Fig. 5c shows a larger cave chamber or space formed by the widening of the cavity through prolonged dissolution. Such open spaces are beautiful to visitors because they create a monumental impression and facilitate safer, more comfortable geological interpretation. **Fig. 5d** shows details of stalactites with a fine and shiny microcrystalline texture, indicating the presence of stable carbonate precipitation and the possible presence of secondary minerals. These deposits are composed predominantly of calcite ($CaCO_3$), which forms through the precipitation of calcium bicarbonate solutions when air droplets infiltrate and release CO_2 inside the cave cavity [15].

Fig. 5e shows flowstone that develops with a morphology resembling a stone curtain on the wall of Bangi Cave. Flowstone is formed from deposits of calcium carbonate ($CaCO_3$), gypsum ($CaSO_4 \cdot 2H_2O$), and other minerals that accumulate on the surface of the cave wall due to consistent flowing or dripping water [4]. Flowstone is an essential record of long-term hydrogeochemical conditions and a highly sought-after aesthetic element in cave geotourism. Meanwhile, **Fig. 5f** shows an active underground river flowing in the cave's deepest part. This flow is formed by rainwater infiltrating the karst system through fractures, fissures, and ponors, confirming that Bangi Cave is an active epigenic karst system. The dynamics of this underground flow offer significant opportunities for interpreting karst hydrology, surface-subsurface connectivity, and the importance of conserving catchment areas.

Fig. 5. Endokarst features in the Bangi Cave area

3.4 Results of the tourism values assessment in Bangi Cave

The geotourism potential assessment used a quantitative descriptive approach based on the guidelines of the Geological Survey Center (2017), detailed in **Tables 1-4**.

Table 1 shows the results of the scientific value assessment for Bangi Cave. The criteria for scientific understanding and geological site conditions obtained a high score (14.29). This score indicates that the site provides clear, readily observed, and relevant geological data for scientific study, particularly regarding speleogenesis, karst hydrogeology, and endokarst development, as shown in **Fig. 4 and 5**. Conversely, Bangi Cave obtained a low score of 3.57 for the criterion of the presence of other geological heritage within the region. This limitation can reduce the regional scientific context, especially in comparative analyses between geosites. Furthermore, the criteria for locations representing the geological framework and key research locations each received a score of 7.14, indicating that Bangi Cave's role as a primary reference for the region's geological framework still needs to be strengthened through further research. The criteria for obstacles to site utilisation yielded a medium value (10.71), indicating that accessibility and physical factors in the cave are relatively straightforward; however, several obstacles remain, such as limited entry routes and cave microclimate conditions, which require caution in both scientific and tourism activities.

Overall, the scientific value of 64.29 indicates that Bangi Cave has strong potential as a geosite for research and education. Efforts to identify the area's geodiversity, improve scientific documentation, and optimise scientific access could enhance the site's value and strengthen its position as an essential part of the karst geological heritage of Kedungsalam Village.

Table 1. Weighting criteria used for the assessment of a type of geological heritage based on scientific values

No.	Criteria	Weight (%)	Evaluation value of geosite Bangi Cave	Bangi Cave geosite score
1	Locations that represent the geological framework	30	2	7.14
2	Key research locations	20	2	7.14
3	Scientific understandingn	5	4	14.29
4	Geological site conditions	15	4	14.29
5	Geological diversity	5	2	7.14
6	Presence of geological heritage sites in one region	15	1	3.57
7	Barriers to site use	10	3	10.71
Science value assessment score			18	64.29

Table 2 presents the results of the educational value assessment, indicating that Bangi Cave has strong academic potential, with a total score of 77.08. This score means that Bangi Cave is suitable for development as a location for geological education and research. The highest scores are for the criteria Educational Potential (research) and Geological Diversity, each receiving 8.33. These results indicate that Bangi Cave offers a range of readily observable geological features relevant to learning activities, including endokarst morphology, dissolution processes, and cave ornamentation. The Location Achievement and Supporting Facilities criteria also received a high score of 8.33. This indicates that access to Bangi Cave is relatively easy and that basic facilities are sufficient to support educational visits.

Table 2. The factors used to assess geological heritage are based on their educational value

No	Criteria	Weight (%)	Evaluation value of geosite Bangi Cave	Bangi Cave geosite score
1	Vulnerability	10	3	6.25
2	Location achievement	10	4	8.33
3	Barriers to site utilization	5	3	6.25
4	Security facilities	10	2	4.17
5	Supporting facilities	5	4	8.33
6	Population density	5	3	6.25
7	Relationship with other values	5	3	6.25
8	Location status	5	2	4.17
9	Distinctiveness	5	2	4.17
10	Conditions on observation of geological elements	10	3	6.25
11	Potential Education/ research Information	20	4	8.33
12	Geological diversity	10	4	8.33
Educational value assessment score			37	77.08

Several criteria scored low, particularly security facilities, site status, and uniqueness, each scoring only 4.17. This score indicates that security management is suboptimal, that the area's protection status remains limited, and that the geological uniqueness requires further interpretation to enhance its educational value. The criteria for vulnerability, site utilisation barriers, population density, and geological element observation conditions scored moderately at 6.25. These results indicate that although the site is relatively stable and usable, there are limitations to direct observation and sustainable use. Overall, Bangi Cave has good educational value, but improving security facilities, strengthening geological interpretation, and establishing the area's protected status are priorities to maximise the geosite's potential as an academic and research facility.

Table 3 presents the results of the tourism value assessment at the Bangi Cave Geosite, indicating that accessibility and proximity to recreational areas contributed the most to the overall value. These two aspects scored 7.69, suggesting that Bangi Cave is relatively easy to reach and has potential for integration with other nearby tourist destinations. Tourism support systems, such as supporting facilities, also scored well (7.69), thus increasing the geosite's attractiveness to visitors. Conversely, aspects such as security, the social status of the surrounding community, and the uniqueness of the site received low scores, each at 3.85. These scores indicate that Bangi Cave still requires improvements in security facilities and community empowerment, and the strengthening of interpretive narratives to highlight its geological characte. The lowest economic value (1.92) suggests that current tourism activities have not significantly contributed to the local economy. The vulnerability component, geological element observation conditions, and interpretation potential each scored moderately at 5.77. This score indicates that the geological features in Bangi Cave are relatively easy to observe and have educational potential. However, they still require improved conservation management to mitigate the risk of damage. Overall, the tourism score of 71.15 indicates that Bangi Cave has strong geotourism development potential.

Table 4 presents the results of the degradation risk assessment for the Bangi Cave Geosite, indicating that the geological element damage criterion has the most significant weight (35) and a score of 2, resulting in a total score of 10. Criteria related to potential activities around the geosite also contributed significantly to the degradation risk, resulting in a score of 15. These findings suggest that community activities in the area, such as land use and agricultural practices, may disrupt the karst system by inducing vibrations, altering surface drainage, or increasing sedimentation. The legal protection aspect received a score of 10, indicating that the existing protection status is insufficient to mitigate the threat of long-term degradation. This condition underscores the need for clearer regulations and more intensive field monitoring to maintain the integrity of the geosite. Furthermore, relatively easy accessibility (score 10) can increase anthropogenic pressure if not accompanied by effective visitor management. Meanwhile, the surrounding population density, which received a score of 15, indicates that human interaction with the cave area is relatively high, thus increasing the risk of disruption to the physical condition and cave environment.

Table 3. The factors used to assess geological heritage are based on their tourism values

No	Kriteria	Weight (%)	Evaluation value of geosite Bangi Cave	Bangi Cave geosite score
1	Vulnerability	10	3	5.77
2	Location achievement	10	4	7.69
3	Barriers to site utilization	5	3	5.77
4	Security facilities	10	2	3.85
5	Supporting facilities	5	4	7.69
6	Population density	5	3	5.77
7	Relationship with other values	5	3	5.77
8	Social status	5	2	3.85
9	Distinctiveness	5	2	3.85
10	Conditions on observation of geological elements	10	3	5.77
11	Interpretive potential	10	3	5.77
12	Economic level	5	1	1.92
13	Close to recreational areas	5	4	7.69
Tourism value assessment score			37	71.15

Table 4. Criteria Used in Geological Heritage Assessment Based on Degradation Risk Value Parameters

No.	Criteria	Weight (%)	Evaluation value of geosite Bangi Cave	Bangi Cave geosite score
1	Damage to geological elements	35	2	10.00
2	Adjacent to areas/activities that could potentially cause degradation	20	3	15.00
3	Legal protection	20	2	10.00
4	Accessibility	15	2	10.00
5	Population density	10	3	15.00
Degridation risk assessment score			12	60.00

Overall, the final degradation risk score of 60.00 indicates that Bangi Cave is in the moderate-to-high risk category. This situation underscores the need for a more targeted conservation strategy, including certain access restrictions, increased public education, and strengthened regulations. These mitigation efforts are crucial to preserving Bangi Cave's geological features as a geotourism asset and a geological heritage of scientific value

The assessment results indicate that Bangi Cave has strong potential to be developed as a geotourism geosite due to its prominent geological, geomorphological, hydrological, and educational characteristics. The Wonosari Formation, which dominates the study area, provides a massive, fracture-rich carbonate lithology, thereby creating a well-developed exokarst and endokarst system. The presence of residual karst hills, dolines, uvalas, and poljes indicates that the surface landscape has evolved through intensive dissolution processes. This morphology offers both visual appeal and high interpretive value for visitors.

Below the surface, Bangi Cave exhibits horizontal passages, expansive chambers, active stalactites, flowstones, and underground rivers. These features demonstrate ongoing epigenetic speleogenesis and can be used as educational tools to illustrate the dynamics of tropical karst systems. The clarity and easy-to-observe endokarst features make this cave an ideal natural laboratory for geology, speleology, and hydrogeology education.

The results of the geological heritage assessment (**Table 5**) indicate that Bangi Cave fulfils the three main pillars of geotourism: scientific, educational, and tourist value. The variety of geological features easily understood by lay visitors also enhances its interpretive potential. However, the degradation risk indicates that Bangi Cave is vulnerable to anthropogenic pressures and environmental changes; therefore, the development of Bangi Cave as a geotourism destination must be accompanied by a strict conservation strategy to sustain its geological features. Restricting access to sensitive areas, strengthening local regulations, and educating visitors are essential steps to minimise damage to speleothems and hydrological disturbances.

Table 5. Final Results of the Geological Heritage Assessment at the Bangi Cave Geological Site

No	Criteria	Assessment Score
1	Science Value	64.29
2	Educational Value	77.08
3	Tourism Value	71.15
4	Degradation Risk Value	60.00
Total		272.52
Category		Currently

4 Conclusion

Geomorphological, geological, and internal character analyses of the cave indicate that the karst landscape of Bangi Cave and its surrounding areas constitutes a tropical karst system developed on limestone of the Wonosari Formation. The presence of dolines, ponors, significant passages and chambers, and underground rivers confirms that speleogenesis is controlled by massive carbonate lithology and intense fracture structures. These diverse exokarst and endokarst features not only demonstrate the ongoing dynamics of karst evolution but also provide a strong basis for the development of education-based geotourism. The results of the geological heritage assessment reinforce this potential, with a value of 77.08 for education, 71.15 for tourism, and 64.29 for science. These values confirm that Bangi Cave has visual appeal and holds essential geological information. However, the degradation risk level of 60.00 requires implementing strict conservation strategies, including access restrictions in sensitive areas and the management of tourist routes. With a conservation-based approach, Bangi Cave is well-suited for development as a leading geosite, offering both educational and economic benefits.

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