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DEMOGRAPHY AND ANTHROPOGENIC GEOMORPHOLOGY AS THREATS TO GEODIVERSITY IN URBANIZED GEOPARK: GEODIVERSITY HOTSPOT ASSESSMENT IN JOGJA GEOPARK, INDONESIA

Anugrah Aditya INSANI [1], Eko HARYONO [2], Didit Hadi BARIANTO [3*]

[1] Universitas Gadjah Mada, Department of Geological Engineering, Yogyakarta, Indonesia; anugrahaditya@mail.ugm.ac.id (A.A.I.)
[2] Universitas Gadjah Mada, Department of Environmental Geography, Yogyakarta, Indonesia; e.haryono@ugm.ac.id (E.H.)
[3] Universitas Gadjah Mada, Department of Geological Engineering, Yogyakarta, Indonesia; didit_geologi@ugm.ac.id (D.H.B.)

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Abstract: This research assesses geodiversity hotspots to identify areas needing regional geoconservation, focusing on the Jogja Geopark and its geosites-geodiversity sites. Previous studies have modified threat indices by adding, removing, or replacing sub-threat components. Here, population density, representing demographic pressure, and anthropogenic intervention, indicating anthropogenic geomorphology dynamics, are included as sub-threat indices. Geodiversity and threat data were assessed at a 1:50,000 scale with a 0.5 km^2 grid respectively. Involved data includes geopark and geosites outer boundary, lithology, tectonics and structures, landform systems, surface hydrology, hydrogeology, soil order, population density per km^2, and anthropogenic intervention. Feature calculation method was used to calculate geodiversity and threat from those datas. Geodiversity hotspots within the Jogja Geopark, highlighting areas urgently needing regional geoconservation. The Kartamantul (Yogyakarta - Sleman - Bantul) metropolitan area and surrounding three geosites: Kalibawang Eocene-age Nanggulan Formation; Mengger Hills Opak Fault; and Parangtritis Sand Dunes require the most attention. Meanwhile, geodiversity sites in Jogja Geopark generally show low to medium sensitivity. This indicates that the processes and outcomes of socio-economic systems actively threaten geoecosystems, particularly in the relatively passive geodiversity element on Jogja Geopark area and its geosites. Meanwhile, geodiversity sites are threatened by socio-economic systems although in a different intensity from geosites because of the narrow area and the scale of the study that has not been able to accommodate all geodiversity phenomena and threats in it. This study confirms the substantial impact of human activities on geodiversity. By integrating geodiversity and threat indices, critical sites for immediate geoconservation have been identified. The findings stress the urgency of implementing effective conservation policies to protect the geopark from further degradation.

Keywords: geoconservation, population density, anthropogenic geomorphology, Jogja Geopark, geodiversity hotspot

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INTRODUCTION

Geodiversity is a term that came into the spotlight in 1993, following the adoption of the Convention on Biological Diversity at the Rio Earth Summit a year in 1992 (Australian Heritage Commission, 2002; Zwolinski, 2004; Gray, 2018). The concept, as defined by Gray (2013, 2018), encompasses the vast array of geological features such as rocks, minerals and fossils, as well as geomorphological aspects such as landforms, topography and the physical processes that shape our planet.

It also includes soil and hydrological features - all of which combine to form the intricate assemblages, structures and systems that contribute to the diverse landscapes we see around us. Another similar difinition of geodiversity offered by Croft & Gordon (2014, 2015), seeing geodiversity as the variety that includes not only rocks and minerals, but also fossils, landforms, sediments and soils. Thoose two definition emphasise the importance of the natural processes that have shaped these elements throughout Earth's history. As a foundation of our planet's natural heritage, geodiversity faces unprecedented threats due to human activities. For over a century, the delicate balance of geosystems has been disrupted by urbanization, industrialization, and resource extraction (Gray, 2013). With the global population rapidly expanding, the pressure on these systems intensifies, jeopardizing the essential services they provide to both human communities and ecosystems (DeMiguel et al., 2020). Geodiversity plays a pivotal role in supporting these services, from providing clean water and fertile soil to regulating climate and mitigating natural hazards (Gray, 2011; 2013). Yet, it is often overlooked or undervalued, despite its immense significance (Brilha et al., 2018). Beyond its functional value, geodiversity represents a rich cultural and historical legacy, connecting us to Earth's geological past (DeMiguel et al., 2020; Lima et al., 2020).

To safeguard geodiversity, effective conservation strategies that involves a multifaceted approach, including site protection, sustainable land use planning, and regional management initiatives must be implemented (Brilha, 2002; Prosser et

* Corresponding author

al., 2010). GIS has revolutionized geodiversity assessment for its geoconservation, leading to innovative concepts, one of which is a geodiversity hotspot that related with regional management initiatives. The concept of geodiversity hotspots, defined as geographical areas with exceptionally high levels of geodiversity that are under threat (Bétard, 2016; Bétard & Peulvast, 2019). These hotspots are characterized by a combination of high abiotic diversity and significant threats, making them critical areas for geodiversity conservation. In order to identify geodiversity hotspots, a sensitivity index is calculated as the product of a geodiversity index and a threat index (Bétard, 2016; Bétard & Peulvast, 2019; Insani & Haryono, 2025).

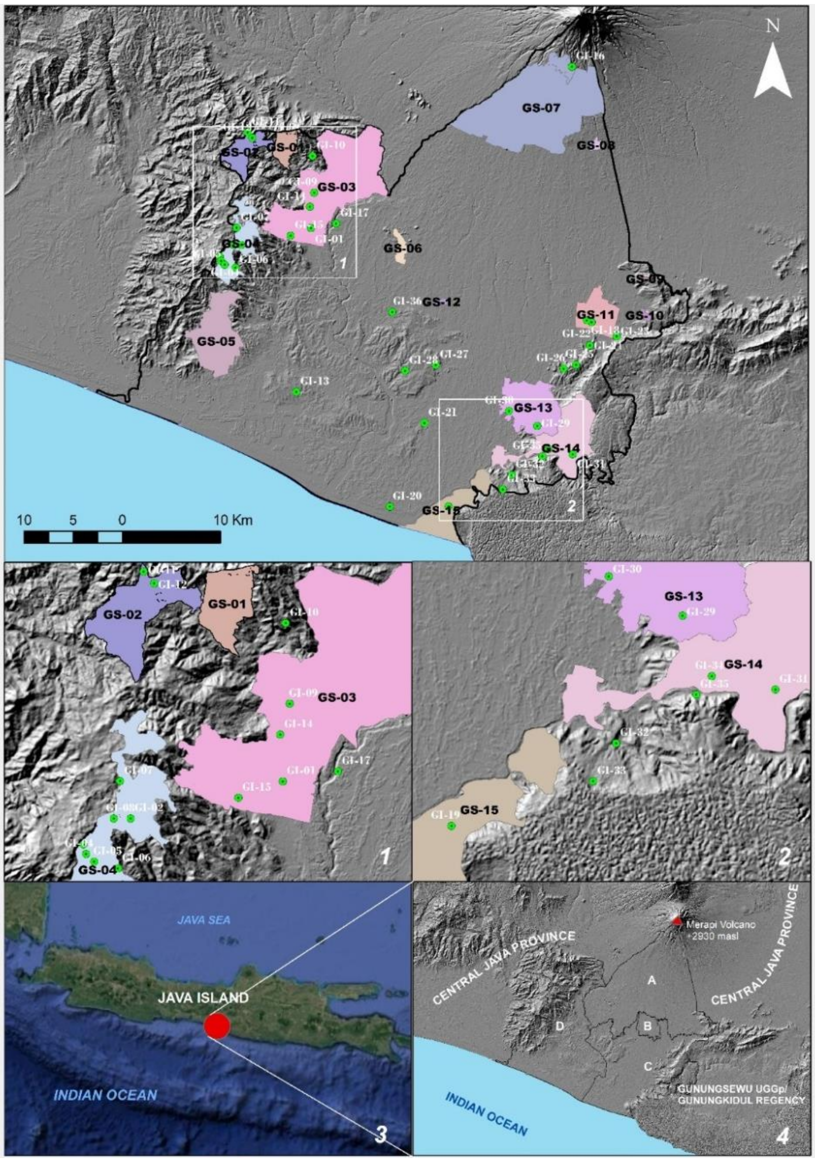

Figure 1. Map of Jogja Geopark including its geosites and geodiversity sites. Inset 1 and 2 shows details on the northwest part and southeast part of Jogja Geopark. The location of Jogja Geopark is shown in inset 3 and 4. The letter in inset 4 is the Regency/City within Jogja Geopark, including (A) Sleman Regency; (B) Yogyakarta City; (C) Bantul Regency; and (D) Kulon Progo Regency

This approach provides a quantitative measure of the sensitivity tendencies of geodiversity features to human pressures and helps to prioritise conservation efforts. The calculation of the threat index represents a crucial methodology for the identification and mapping of geodiversity hotspots. Bétard (2016) indicated that the threat index may be constituted by factors such as urban expansion, land degradation, lack of protection, and others. The term "other" in the Bétard (2016) definition provides a potential avenue for adapting the threat index. Modifications to the threat index may be made by considering demographic factors, such as population, and anthropogenic geomorphology, namely human intervention in landforms, as part of the variables in the geodiversity hotspot calculation (Insani & Barianto, 2024). This argument is based on the concept that human populations can have an impact on abiotic nature, which is characterised by the presence of anthropogenic landforms (Nir, 1983; Piacente, 1996; Szabó, 2010).

This approach offers a more comprehensive representation of the level of threat, encompassing both direct human pressure and alterations to the natural landscape (Insani & Barianto, 2024). It is founded upon geosystem services that continue to be exploited by humans, thereby endangering geodiversity unless geoconservation is not feasible (Gordon et al., 2012; 2018). Our study area is Jogja Geopark, one of Indonesian national geopark located within the Special Region of Yogyakarta, Java (Figure 1 & 2). The demographic processes occurring in the context of Jogja Geopark's location in a metropolitan area represent a significant threat to geopark's continued existence. This is predicated on the premise of an expanding population. The growth of the population has implications for the uptake of geosystem services, which is expressed in anthropogenic interventions on the Earth's surface. Comprising 15 geosites (Table 1), 36 geodiversity sites (Table 2), 7 biosites, and 4 cultural sites, Jogja Geopark offers a unique blend of natural and human-made elements.

Figure 2. The Landscape of Jogja Geopark. Yogyakarta plain seen from the Baturagung range (A). Merapi volcano with very active volcanism (B). Opak River estuary in the south of Jogja Geopark (C). The Menoreh range consists of three paleovolcanoes (D)

Despite its relatively small size, the region is exceptionally rich in abiotic nature, for example in term of landforms, Jogja Geopark showcasing eight of the ten original landform types found on Earth, including volcanic; structural; fluvial; marine; aeolian; solutional; denudational; and anthropogenic processes. The calculation of the threat index represents a crucial methodology for the identification and mapping of geodiversity hotspots.

Table 1. Characteristics of geosites on Jogja Geopark (Source: Jogja Geopark Masterplan (Jogja Geopark Managing Agency, 2022)

Geosite Code	Geosite Name	Geosite Description
GS-01	Kendil Suroloyo Ancient Caldera	Remnants of the caldera of Menoreh ancient volcano
GS-02	Widosari Structural Hills	Remnants of Menoreh Ancient Volcano that have been affected by structural processes
GS-03	Kalibawang Eocene-age Nanggulan Formation	Geological record of marine - terrestrial transition environment that marks the period before the ancient volcanic period in Jogja
GS-04	Kiskendo Cave	The highest karst cave in Java Island and marks the end of the paleogene - neoegene volcanism
GS-05	Kliripan-Karangsari Manganese Mine	Manganese deposits that were mined during Dutch Colonial era and the early Republic of Indonesia
GS-06	Godean Intrusion Hills Complex	The result of magmatism process in the form of diorite intrusion that forms a complex of hills
GS-07	Turgo - Plawangan Old Merapi Complex	Remnant of Proto Merapi Volcano of early Quaternary age
GS-08	Bakalan Pyroclastic Flow	The pyroclastic flow deposits in 2010 Merapi eruption with VEI 4
GS-09	Sambirejo Pyroclastic Cliff	Relatively preserve Semilir Formation outcrops that represent the product of explosive eruption of Ancient Volcano
GS-10	Ngelepen Creeping Mass Wasting	Creeping-type mass wasting process triggered by the Yogyakarta Earthquake in May 2006
GS-11	Berbah Pillow Lava	Pillow lava from old submarine volcanism process in the Paleogene - Neogene
GS-12	Gamping Eocene-age Limestone	Eocene-aged shallow marine geological record before the Paleogene - Neogene volcanism
GS-13	Mengger Hills Opak Fault	Relatively preserve Semilir Formation outcrops that represent the traces of the active Opak Fault that triggered Yogyakarta Earthquake in May 2006
GS-14	Mangunan Old Lava	Remains of Mangunan Ancient Volcano that active in the Paleogene - Neogene
GS-15	Parangtritis Sand Dunes	Sand Dunes with Barchan type formed in tropical environment

Table 2. Geodiversty sites on Jogja Geopark (Source: Jogja Geopark Masterplan (Jogja Geopark Managing Agency, 2022)

Site Code	Geodiversity Site Name
GI-01	Watu Puru Eocene Aged Nanggulan Formation
GI-02	Grojogan Sewu Hill
GI-03	Kembang Soka Waterfall
GI-04	Mudal River
GI-05	Kedung Pedut Waterfall
GI-06	Kedung Banteng River
GI-07	Kidang Kencono Cave
GI-08	Watu Blencong Hill
GI-09	Sriti Cave
GI-10	Sidoharjo Waterfall
GI-11	Gunung Jaran Summit
GI-12	Proman Hill
GI-13	Kebon Cave
GI-14	Ngepoh Banjararum Hill
GI-15	Khayangan Dam
GI-16	Watu Grojogan-Kalikuning Columnar Joint
GI-17	Minggir Ancient Lake
GI-18	Watu Kapal Riverside
GI-19	Surocolo Springs
GI-20	Srigading - Samas Beach Ridge
GI-21	Gilangharjo Wetland
GI-22	Gunung Wangi Hills
GI-23	Plumpatan River
GI-24	Tompak Hill
GI-25	Bucu Summit
GI-26	Tuwondo Waterfall
GI-27	Selarong Cave
GI-28	Banyunibo Waterfall
GI-29	Sewu Watu Ancient Volcano
GI-30	Watu Ngelak Riverside
GI-31	Gajah Cave
GI-32	Kedung Tolok Waterfall
GI-33	Cerme Cave
GI-34	Watu Lawang-Srikeminut Valley Wall
GI-35	Lemah Rubuh Mass Wasting
GI-36	Tubing Karst

The study of geodiversity hotspot based on demography and anthropogenic geomorphology is required in Jogja Geopark. This is based on its characteristics, which are rich in geodiversity but threatened by expansive urbanization. Our study aims to (1) analyse the geodiversity index in Jogja Geopark; (2) offer an alternative threat index in geodiversity hotspots with a demographic process approach in the form of population and anthropogenic intervention in the form of anthropogenic landforms; (3) analyse geodiversity hotspots based on the modified threat index; and (4) provide recommendations for areas that require geoconservation based on geodiversity hotspot. This study is expected to provide an overview of geodiversity hotspots by utilising population and land use data for geoconservation.

MATERIALS AND METHODS

1. Data Collection and Preparation

The data set comprised the boundaries of the Jogja Geopark, as delineated by the Jogja Geopark Managing Agency (2022); the outer boundary of geosite zoning in the Jogja Geopark, as defined by the Jogja Geopark Managing Agency (2022); geodiversity site points in the Jogja Geopark, as identified by the Jogja Geopark Managing Agency (2022); lithological data sourced from the Ministry of Energy and Mineral Resources Republic of Indonesia (2022); tectonic data obtained from the Ministry of Energy and Mineral Resources Republic of Indonesia (2022); land systems from the Geospatial Information Agency Republic of Indonesia (2024); aquifer productivity from the Ministry of Energy and Mineral Resources (2022); springs from the Research, Development, and Planning Agency of the Special Region of Yogyakarta; rivers from the Geospatial Information Agency Republic of Indonesia (2024); soil order from the Ministry of Agriculture Republic of Indonesia (2022); land use from the Geospatial Information Agency (2020); and population density from the World Population (2020). All data were aligned with a same coordinate system in preparation for subsequent processing.

2. Data Analysis

2.1. Geodiversity Index Analysis

The analysis of the geodiversity index (GI) is initiated with the preparation of data on lithology, tectonic and structural characteristics, landforms, aquifer productivity, springs, rivers, and soil order. The GI calculations and mapping were conducted in accordance with the methodologies previously established in the literature, namely the feature calculation method based on the grid, each index, or sub-index (Figure 3) (Santos et al., 2017; Araujo & Pereira, 2018). Subsequently, the results of the GI are subjected to a linear fuzzy membership analysis. In order to generate values for geosite and geodiversity site, zonal statistics of the maximum value for geosite and the extraction of multivalues to points on geodiversity site are performed. To ascertain the geodiversity at geodiversity sites, a value extraction to multipoint analysis was conducted at geodiversity site locations on the assumption that geodiversity sites within the Jogja Geopark occupy a relatively limited area (local scale) and that the measurement of geodiversity value is inspired by the observation method proposed by Hjort et al. (2022). The observation method by Hjort et al. (2022) employs a maximum radius of 25 meters to assess geodiversity. In this study, observations were conducted at a radius of 30 meter, in alignment with the geospatial data generated on 30 meter per pixel. Thus, value extraction to multipoint analysis still complies with the rules proposed by Hjort et al. (2022). This process of extracting value to multipoint was also applied to the threat index and sensitivity index/geodiversity hotspot.

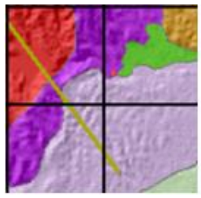

Figure 3. Assessing GI involves examining various aspects of geodiversity indices, such as lithology and geological structure. In the given example, there are three polygons representing lithology and one line representing geological structure, resulting in a total count of four (Source: Insani & Haryono, 2025

2.2. Threat Index Analysis

The threat index analysis (TI) commences with the preparation of data pertaining to land use and population density. The land use data was transformed into anthropogenic geomorphology data in accordance with the classification of anthropogenic interventions proposed by Szàbo (2010). Moreover, a calculation analogous to GI was conducted, namely the feature calculation method based on the grid at each index. Concurrently, to obtain the population density index, a linear fuzzy membership analysis was performed. Both were then summed up to obtain TI. To generate values at the geosite and geodiversity site, zonal statistics of the maximum type were performed at the geosite and multivalue was extracted to point at the geodiversity site.

2.3. Geodiversity Hotspot Analysis

Geodiversity hotspot is the result of multiplying GI and TI using raster calculator. GI and TI data that have been carried out linear fuzzy membership analysis are multiplied. Thus, sensitivity index that represent geodiversity hotspot visualisation is obtained. To produce values on geosite and geodiversity site, zonal statistics of type maximum on geosite and extract multivalue to point on geodiversity site are performed.

RESULTS AND DISCUSSION

1. Geodiversity Index of Jogja Geopark

The Geodiversity Index in Jogja Geopark is calculated using the following indices: geological diversity index, geomorphological diversity index, hydrological diversity index, and pedological diversity index. The methodology employed in the modelling of the geodiversity index is based on the use of indices. Consequently, the areas that exhibit a high level of geodiversity are those that have the greatest number of indices. In this case, this refers to the intersection of mapping units present in the maps that comprise the geodiversity index, which is made up of four indices. A similar phenomenon was observed in the analysis of the geodiversity index in the Jogja Geopark. The spatial pattern of the geodiversity index in the Jogja Geopark follows the river flow and transition between mapping units. This is due to an increase in the number of indices in the region. From a physiographic perspective, there are at least three areas that exhibit high geodiversity, namely area 1: the transition between the Baturagung Mountain Range and the Yogyakarta – Bantul Volcanic Alluvial Plain including along the Opak - Oyo River, the second area is along the Progo River including its transition with the Kulon Progo Mountain Range and Sentolo Hills, and the third area is situated in the upper to middle reaches of the Serang River including its transition with the Kulon Progo Mountain Range and Sentolo Hills (Figure 4). Additionally, there are other locations with moderate levels of geodiversity that merit attention due to the relatively low levels of surrounding geodiversity. These include area 4: Godean Intrusive Hills; area 5: Bedog River Valley; and area 6: Merapi Upper Slope (Figure 4).

Area 1 has significant physiographic changes from rocky mountains of paleogene - neogene age with thin soils to volcanic alluvial plains of Quaternary age with deep and fertile soils. Area 1 is also an area of significant topographic change, from mountainous in the Baturagung Mountain Range to almost flat in the Yogyakarta - Bantul Volcanic Alluvial Plain. The presence of the Opak – Oyo rivers and its tributary also enriches the geodiversity of the region. The Opak River plays an important role in the process of land formation and distribution of volcanic deposits, which creates fertile soil around the alluvial plain and provides geosystem services for the surrounding communities. While the Oyo River in its landscape evolution eroded the Baturagung Mountain Range, creating a wide and deep river valley with fertile river terraces. In other words, the presence of rivers in area 1 and its landscape arrangement has high geodiversity value and can support the civilization to grow on it through geosystem services. The complexity of geological, geomorphological, hydrological and pedological processes in the Oyo River is detected by the indices method, resulting in a high geodiversity index. The confluence of the Opak and Oyo Rivers has a high level of geodiversity.

Geodiversity in area 2 is controlled by fluvial and hillslope processes. Region 2 has significant topographic changes, from the steep slope of Kulon Progo Mountain Range and Sentolo hills to the relatively deep Progo river valley.

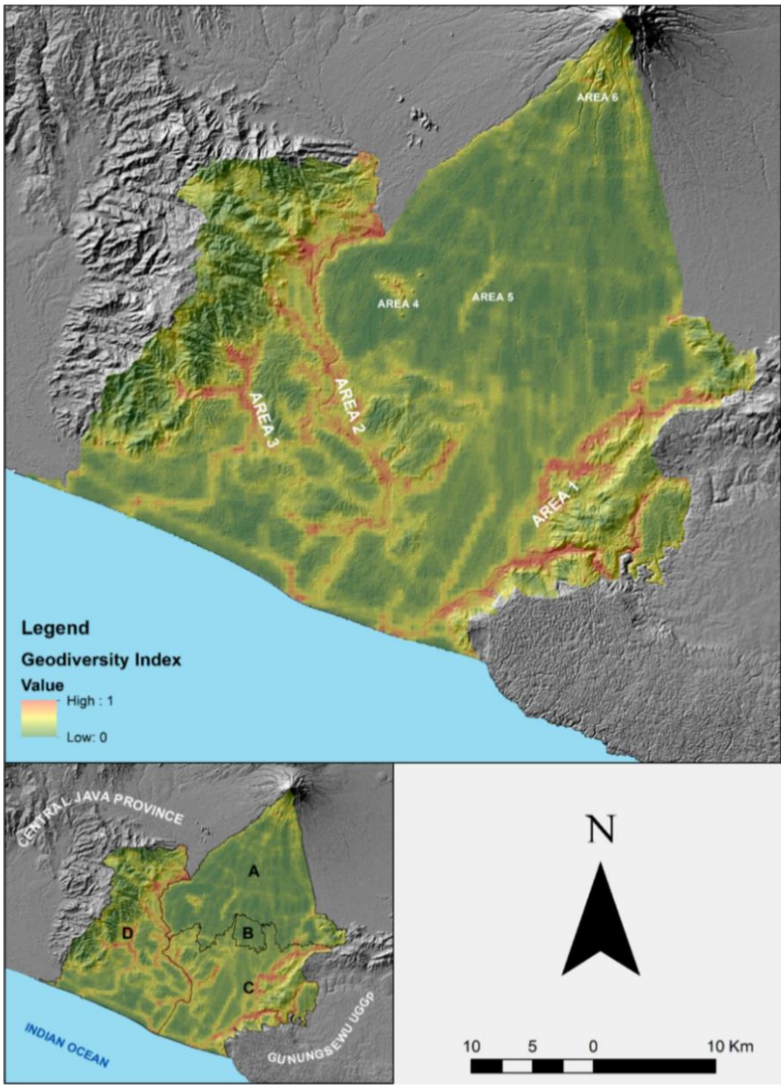

Figure 4. Geodiversity index of Jogja Geopark. Administrative area in the Jogja Geopark:
A = Sleman Regency; B = Yogyakarta City; C = Bantul Regency; and D = Kulon Progo Regency

In addition, the high river order - as a reflection of the amount of material transported through the river - in this region determines the high value on geodiversity index. The Progo River that cuts through the Sentolo Hills creating erosional formations also has implications for the high value on geodiversity index. A similar pattern also occurs in area 3: the hillslope process in the Menoreh montain range and the high order of the river are determinants of the high geodiversity index. According to its morphoarrangement, this region is not only a centre of water accumulation, but also a transition area between geodiversity units that has an influence on the geological and hydrological dynamics around it. As part of a wider hydrological and geological - geomorphological system, the interaction between the Serang River and the Menoreh Mountains forms an important geosystem service for the community. Area 4, which is composed of intrusions complex that formed isolated hills landscapes, has a moderate level of geodiversity and stands out when compared to the surrounding areas. This is an implication of the differences in rock formations and landforms. The rock formations in the Godean Intrusion Hills (area 4) are composed of diorite intrusion rocks, volcanic product Kebobutak Formation, and Nanggulan Formation composed of carbonate rock which is a xenolith within the diorite intrusion. Area 5, Bedog River Valley, is an area with a moderate geodiversity index due to fluvial processes of valley deepening and river terrace formation. The fluvial process forms an elongated open depression landform, causing the value of indices to increase. Area 6, the Merapi Upper Slope, has a moderate geodiversity value due to its landforms, rivers, and rock formations. The landscape setting of Merapi Upper Slope is not only the young cone, but also the remnant of proto-Merapi namely the Turgo - Plawangan hills.

Statistical zonal analysis with statistic type ‘maximum’ was applied in this study to determine the highest level of geodiversity at ceratain geosite (Table 3, Figure 5). Geosites that have the highest maximum value of geodiversity index are GS-03 (Kalibawang Eocene-age Nanggulan Formation), GS-05 (Kliripan-Karangsari Manganese Mine), GS-11 (Berbah Pillow Lava), GS-13 (Mengger Hills Opak Fault), GS-14 (Mangunan Old Lava), and GS-15 (Parangtritis Sand Dunes). These areas have the maximum value of geodiversity index due to the variation of lithology, structure, landform, and river order at the same time and are relatively more diverse than other geosites (Table 3). Meanwhile, geosites with medium geodiversity index values include GS-01 (Kendil Suroloyo Ancient Caldera), GS-02 (Widosari Structural Hills), GS-04 (Kiskendo Cave), GS-06 (Godean Intrusion Hills Complex), and GS-07 (Turgo-Plawangan Old Merapi Complex).

Table 3. Geodiversity value of geosites in Jogja Geopark (higher is better)

Site Code	Geosite	Geodiversity index Classes
GS-01	Kendil Suroloyo Ancient Caldera	Medium Geodiversity
GS-02	Widosari Structural Hills	Medium Geodiversity
GS-03	Kalibawang Eocene-age Nanggulan Formation	High Geodiversity
GS-04	Kiskendo Cave	Medium Geodiversity
GS-05	Kliripan-Karangsari Manganese	High Geodiversity
GS-06	Godean Intrusion Hills Complex	Medium Geodiversity
GS-07	Turgo - Plawangan Old Merapi Complex	Medium Geodiversity
GS-08	Bakalan Pyroclastic Flow	Low Geodiversity
GS-09	Sambirejo Pyroclastic Cliff	Low Geodiversity
GS-10	Ngelepen Creeping Mass Wasting	Low Geodiversity
GS-11	Berbah Pillow Lava	High Geodiversity
GS-12	Gamping Eocene-age Limestone	Low Geodiversity
GS-13	Mengger Hills Opak Fault	High Geodiversity
GS-14	Mangunan Old Lava	High Geodiversity
GS-15	Parangtritis Sand Dunes	High Geodiversity

Similar to the geosites with high maximum geodiversity index values, GS-01, GS-02, GS-04, GS-06, and GS-07 have moderate geodiversity index values due to variations in lithology, structure, landform, and river order as well, but are not more diverse than GS-03, GS-05, GS-11, GS-13, GS-14, and GS-15. It is because they are relatively located in one large lithological and landform unit, which is recorded as an area with a not-so-high geodiversity index by the indices method. On the other hand, GS-08 (Bakalan Pyroclastic, GS-09, GS-10 and GS-12 have relatively low geodiversity index values due to their small size and location in one lithological and landform unit at a scale of 1:50,000 - 1:100,000 (indices were measured at a scale of 1:50,000). Therefore, large-scale features and their variations are not captured by the indices method.

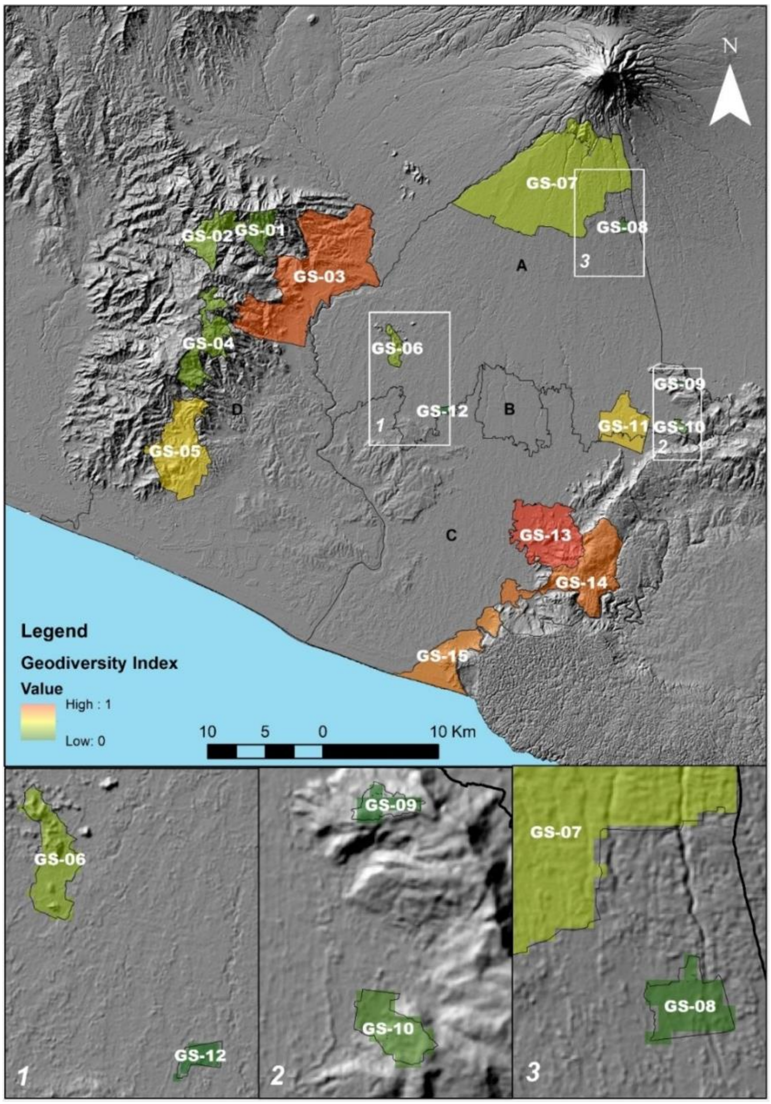

Figure 5. Maximum geodiversity index values on geosites of Jogja Geopark. Administrative area in the Jogja Geopark: = Sleman Regency; B = Yogyakarta City; C = Bantul Regency; and D = Kulon Progo Regency

Table 4. Geodiversity value classes of geodiversity sites in Jogja Geoparks (higher is better)

Site Code	Geodiversity Site	Geodiversity index Classes
GI-01	Watu Puru Eocene Aged Nanggulan Formation	Low Geodiversity
GI-02	Grojogan Sewu Hill	Low Geodiversity
GI-03	Kembang Soka Waterfall	Low Geodiversity
GI-04	Mudal River	Low Geodiversity
GI-05	Kedung Pedut Waterfall	Low Geodiversity
GI-06	Kedung Banteng River	Low Geodiversity
GI-07	Kidang Kencono Cave	Low Geodiversity
GI-08	Watu Blencong Hill	Low Geodiversity
GI-09	Sriti Cave	Medium Geodiversity
GI-10	Sidoharjo Waterfall	Low Geodiversity
GI-11	Gunung Jaran Summit	Low Geodiversity
GI-12	Proman Hill	Low Geodiversity
GI-13	Kebon Cave	Low Geodiversity
GI-14	Ngepoh Banjararum Hill	Medium Geodiversity
GI-15	Khayangan Dam	Medium Geodiversity
GI-16	Watu Grojogan-Kalikuning Columnar Joint	Low Geodiversity
GI-17	Minggir Ancient Lake	Medium Geodiversity
GI-18	Watu Kapal Riverside	Medium Geodiversity
GI-19	Surocolo Springs	Medium Geodiversity
GI-20	Srigading - Samas Beach Ridge	Medium Geodiversity
GI-21	Gilangharjo Wetland	Low Geodiversity
GI-22	Gunung Wangi Hills	Medium Geodiversity
GI-23	Plumpatan River	Medium Geodiversity
GI-24	Tompak Hill	Medium Geodiversity
GI-25	Bucu Summit	Low Geodiversity
GI-26	Tuwondo Waterfall	Medium Geodiversity
GI-27	Selarong Cave	Low Geodiversity
GI-28	Banyunibo Waterfall	Medium Geodiversity
GI-29	Sewu Watu Ancient Volcano	Low Geodiversity
GI-30	Watu Ngelak Riverside	Medium Geodiversity
GI-31	Gajah Cave	Low Geodiversity
GI-32	Kedung Tolok Waterfall	Low Geodiversity
GI-33	Cerme Cave	Low Geodiversity
GI-34	Watu Lawang-Srikeminut Valley Wall	Medium Geodiversity
GI-35	Lemah Rubuh Mass Wasting	Medium Geodiversity
GI-36	Tubing Karst	Low Geodiversity

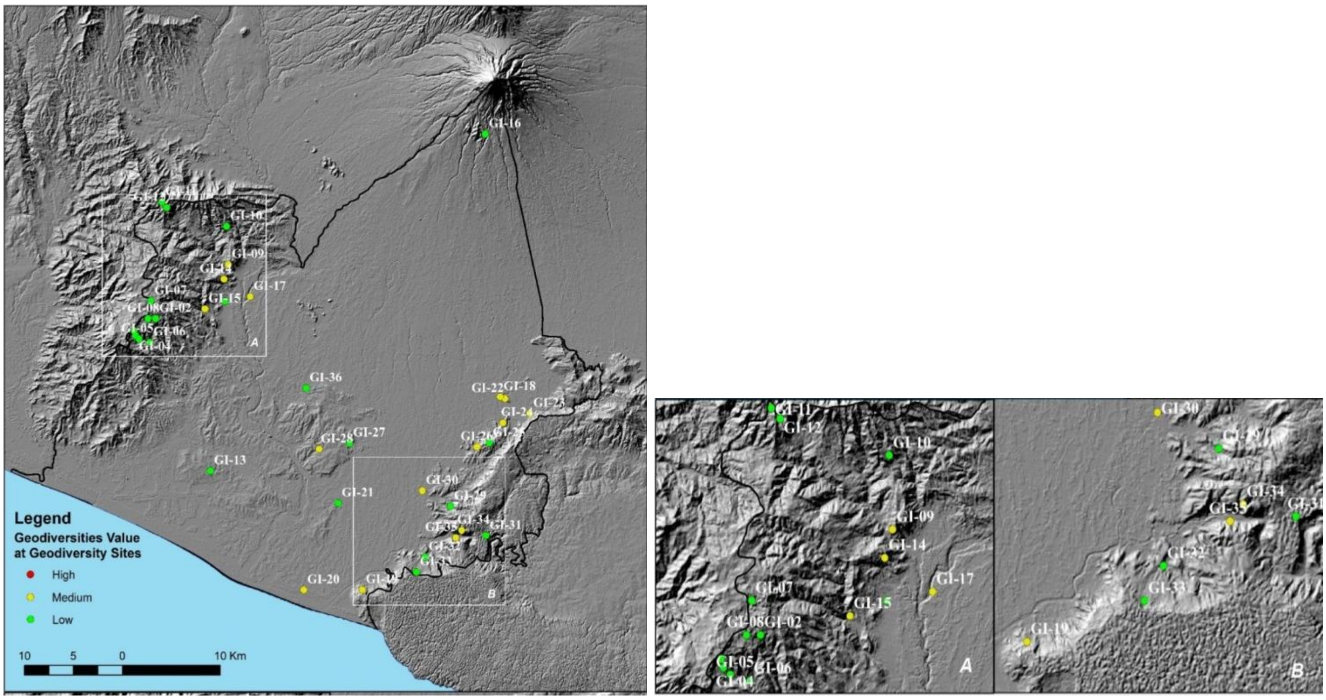

Figure 6. Geodiversity index values on geodiversity sites of Jogja Geopark

Among the identified geodiversity sites, 15 are classified as having medium geodiversity values, while 21 fall into the category of low geodiversity (Table 4, Figure 6). The classification reflects variations in the intrinsic characteristics and complexity of each site, as determined by the geodiversity index. Sites with medium geodiversity values typically exhibit a moderate level of geological, geomorphological, hydrological, and pedological diversity. In contrast, sites with low geodiversity values possess fewer distinctive features or less pronounced diversity across these attributes, indicating a relatively simplified abiotic natural system. These classifications highlight the heterogeneous nature of geodiversity across the landscape and underscore the need for differentiated management approaches to conserv it's integrity. Sites with medium geodiversity values may warrant closer monitoring and targeted conservation efforts to maintain their functional integrity, while those with low values might require strategies to mitigate potential degradation and enhance their resilience.

2. Threat Index of Jogja Geopark

Demography is one of the key factors influencing anthropogenic geomorphology, as highlighted by Nir (1983). Human activities, when considered at the individual level, lack the capacity to induce large-scale changes to the landscape (Nir, 1983). However, because humans inherently act within social structures and groups, the impact of anthropogenic geomorphology becomes significant when examined through the lens of demographic factors (Nir, 1983). Demographic data, such as population density, provides insights into the distribution and intensity of human activities, making it a critical factor in identifying areas at greater risk of degradation. Thus, demographic factors, such as population density, can serve as key layers in the development of threat indices. In other hand, anthropogenic landforms, as manifestations of human interventions in nature (Nir, 1983; Panizza, 1996; Szàbo, 2010), can also be used as factor maps in threat indices because they represent the tangible influence of humans on the environment. This approach to threat indices offers the advantage of a comprehensive evaluation by integrating socio-economic and physical landscape factors, particularly in the context of human utilization of geosystem services, which often leads to threats to geodiversity. However, its limitations include potential data inaccuracies, especially in rapidly evolving urban areas, and the difficulty of distinguishing natural landform changes from anthropogenic intervention. Despite these challenges, this method remains a valuable tool for prioritizing conservation efforts, emphasizing the importance of robust, up-to-date data and interdisciplinary approaches.

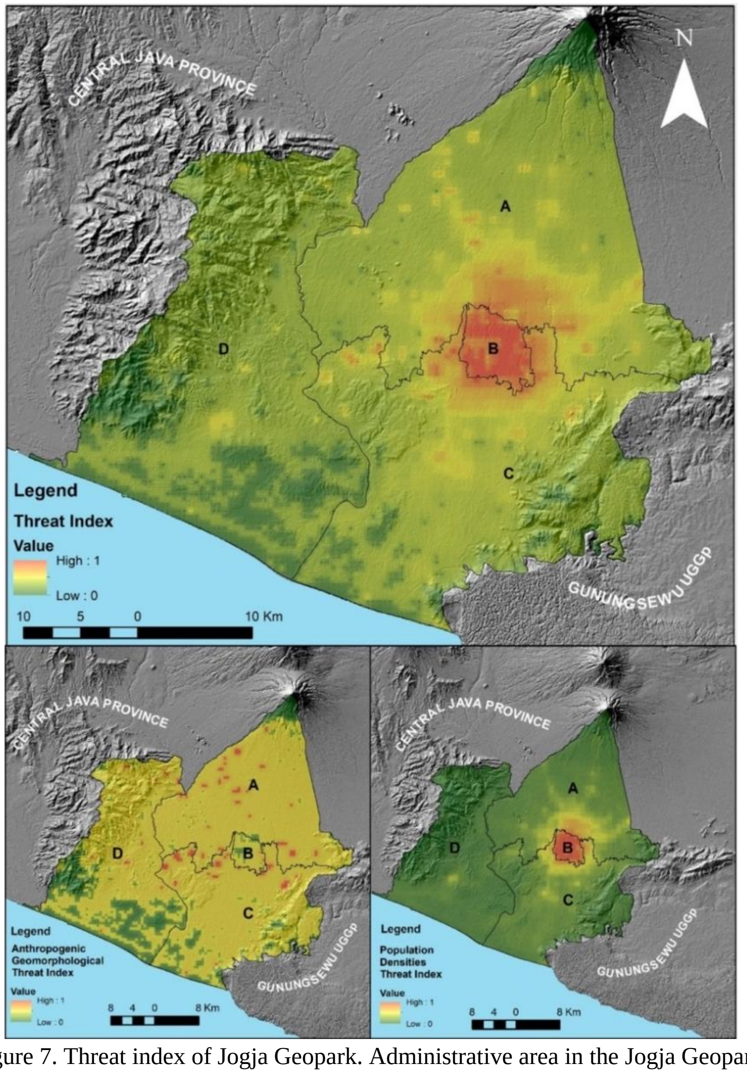

Figure 7. Threat index of Jogja Geopark. Administrative area in the Jogja Geopark:
A = Sleman Regency; B = Yogyakarta City; C = Bantul Regency; and D = Kulon Progo Regency

The Population Density Index within the Jogja Geopark region reveals a distinct pattern, with the highest concentrations found in the Kartamantul metropolitan area, encompassing Yogyakarta, Sleman, and Bantu (Figure 7). This urban core serves as the region's primary population center and is characterized by intensive land use and urban development. Beyond this core, the corridor that connects the metropolitan area to adjacent regions, including Yogyakarta – Magelang corridor, Yogyakarta – Solo corridor, Yogyakarta – Kulon Progo corridor, and Yogyakarta – Bantul corridor demonstrates moderate population density values. This corridor's population distribution reflects ongoing urban expansion and rural-urban transition zones, where anthropogenic activities and its development pressures steadily increase. The anthropogenic geomorphology index within the Jogja Geopark further underscores the medium level of human intervention observed across most areas within the region. This index, derived through grid-based feature calculations, quantifies the extent to which human activities, such as agricultural expansion, infrastructure development, and urbanization, indicates the alteration of natural geomorphological landscape. While these interventions have led to notable modifications, the natural geomorphology of the region has not been entirely transformed, highlighting a balance between natural landforms and anthropogenic influences. This medium index value reflects the cumulative impact of human activities, emphasizing the transitional state of the landscape as it adapts to growing development pressures. The threat index, a composite measure that integrates the population density index and the anthropogenic geomorphology index, serves as a critical indicator of the sensitivity tendencies of the Jogja Geopark's key features, including geosites and geodiversity sites.

High threat index values are predominantly observed within the Kartamantul metropolitan area and the connecting corridors to Solo and Magelang. These areas, due to their high population density and significant human-induced geomorphological changes, face heightened sensitivity tendencies to anthropogenic pressures. In contrast, as distance increases from the metropolitan core and these major corridors, the threat index values gradually decrease, indicating reduced sensitivity tendencies in peripheral regions. Among the geosites assessed, those with the highest threat index values include GS-03, GS-07, and GS-11 (Table 5, Figure 8), reflecting their exposure to significant anthropogenic pressures.

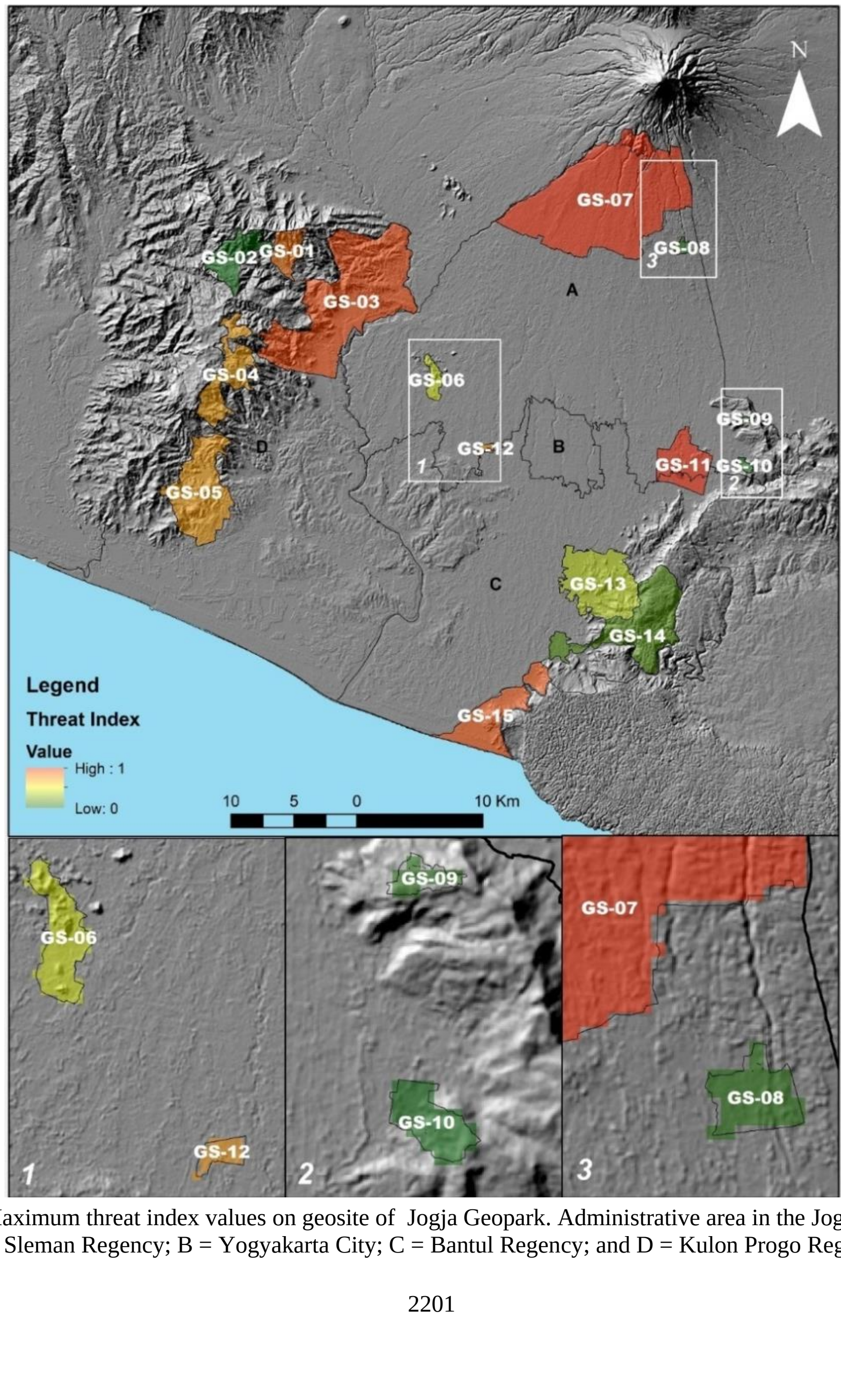

Figure 8. Maximum threat index values on geosite of Jogja Geopark. Administrative area in the Jogja Geopark: A = Sleman Regency; B = Yogyakarta City; C = Bantul Regency; and D = Kulon Progo Regency

Table 5. Threat value of geosites in Jogja Geopark

Site Code	Geosite	Threat index Classes
GS-01	Kendil Suroloyo Ancient Caldera	Medium Threat
GS-02	Widosari Structural Hills	Medium Threat
GS-03	Kalibawang Eocene-age Nanggulan Formation	High Threat
GS-04	Kiskendo Cave	Medium Threat
GS-05	Kliripan-Karangsari Manganese	Medium Threat
GS-06	Godean Intrusion Hills Complex	Medium Threat
GS-07	Turgo - Plawangan Old Merapi Complex	High Threat
GS-08	Bakalan Pyroclastic Flow	Medium Threat
GS-09	Sambirejo Pyroclastic Cliff	Medium Threat
GS-10	Ngelepen Creeping Mass Wasting	Medium Threat
GS-11	Berbah Pillow Lava	High Threat
GS-12	Gamping Eocene-age Limestone	Medium Threat
GS-13	Mengger Hills Opak Fault	Medium Threat
GS-14	Mangunan Old Lava	Medium Threat
GS-15	Parangtritis Sand Dunes	Medium Threat

Conversely, other geosites demonstrate medium and low threat index values, suggesting varying levels of sensitivity across the Jogja Geopark. Similarly, an assessment of geodiversity sites reveals that nine sites exhibit low threat index values, while the remainder are classified as having medium values (Table 6, Figure 9).

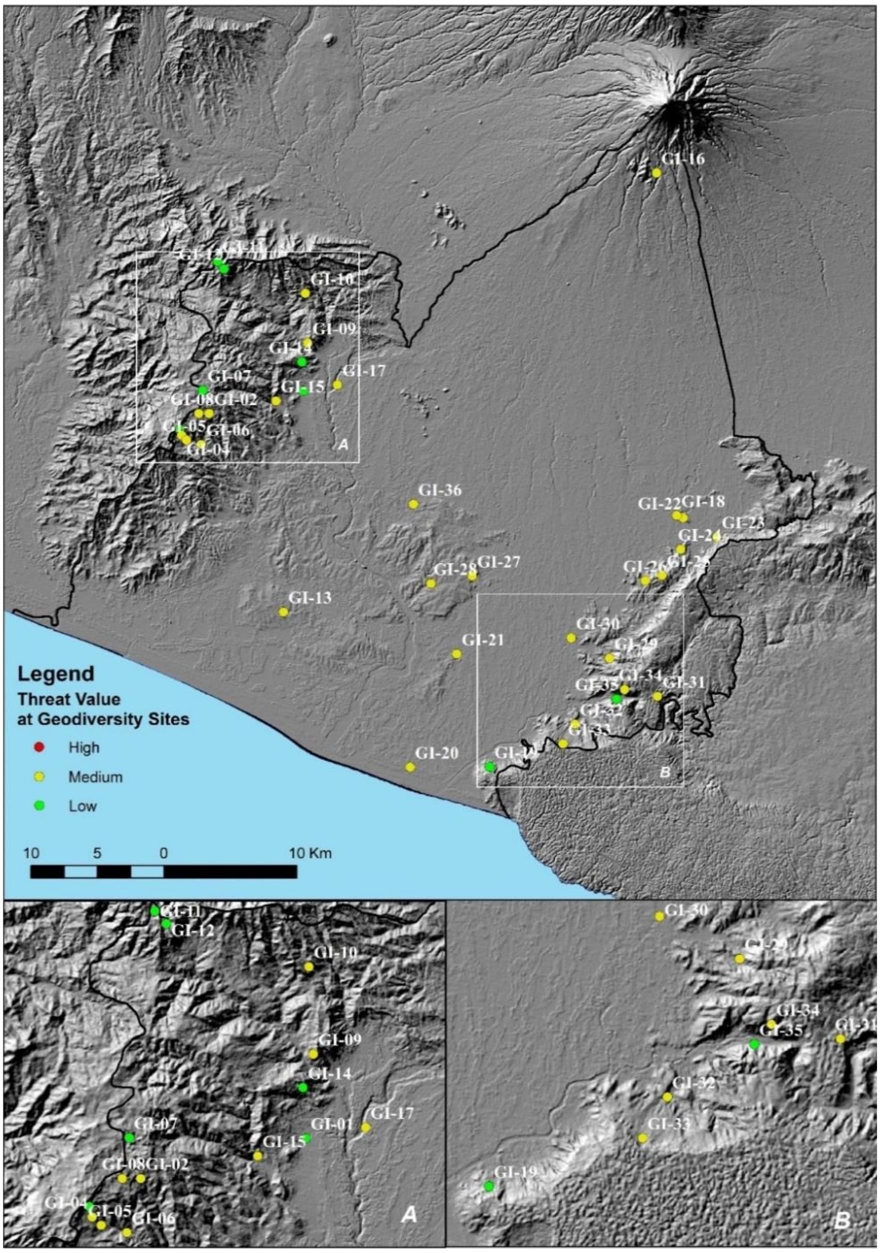

Figure 9. Threat index values on geodiversity sites of Jogja Geopark

Table 6. Threat index value classes of Jogja Geoparks geodiversity sites

Site Code	Geodiversity Site	Threat index on Geodiversity
GI-01	Watu Puru Eocene Aged Nanggulan Formation	Low Threat
GI-02	Grojogan Sewu Hill	Medium Threat
GI-03	Kembang Soka Waterfall	Low Threat
GI-04	Mudal River	Medium Threat
GI-05	Kedung Pedut Waterfall	Medium Threat
GI-06	Kedung Banteng River	Medium Threat
GI-07	Kidang Kencono Cave	Low Threat
GI-08	Watu Blencong Hill	Medium Threat
GI-09	Sriti Cave	Medium Threat
GI-10	Sidoharjo Waterfall	Medium Threat
GI-11	Gunung Jaran Summit	Low Threat
GI-12	Proman Hill	Low Threat
GI-13	Kebon Cave	Low Threat
GI-14	Ngepoh Banjararum Hill	Low Threat
GI-15	Khayangan Dam	Medium Threat
GI-16	Watu Grojogan-Kalikuning Columnar Joint	Medium Threat
GI-17	Minggir Ancient Lake	Medium Threat
GI-18	Watu Kapal Riverside	Medium Threat
GI-19	Surocolo Springs	Low Threat
GI-20	Srigading - Samas Beach Ridge	Medium Threat
GI-21	Gilangharjo Wetland	Medium Threat
GI-22	Gunung Wangi Hills	Medium Threat
GI-23	Plumpatan River	Medium Threat
GI-24	Tompak Hill	Medium Threat
GI-25	Bucu Summit	Medium Threat
GI-26	Tuwondo Waterfall	Medium Threat
GI-27	Selarong Cave	Medium Threat
GI-28	Banyunibo Waterfall	Medium Threat
GI-29	Sewu Watu Ancient Volcano	Medium Threat
GI-30	Watu Ngelak Riverside	Medium Threat
GI-31	Gajah Cave	Medium Threat
GI-32	Kedung Tolok Waterfall	Medium Threat
GI-33	Cerme Cave	Medium Threat
GI-34	Watu Lawang-Srikeminut Valley Wall	Medium Threat
GI-35	Lemah Rubuh Mass Wasting	Low Threat
GI-36	Tubing Karst	Medium Threat

These findings underscore the spatial variability in the sensitivity tendencies of geosites and geodiversity sites within the Jogja Geopark and highlight the need for targeted conservation strategies to mitigate the impacts of anthropogenic activities and ensure the sustainability of the region's geosites and geodiversity sites.

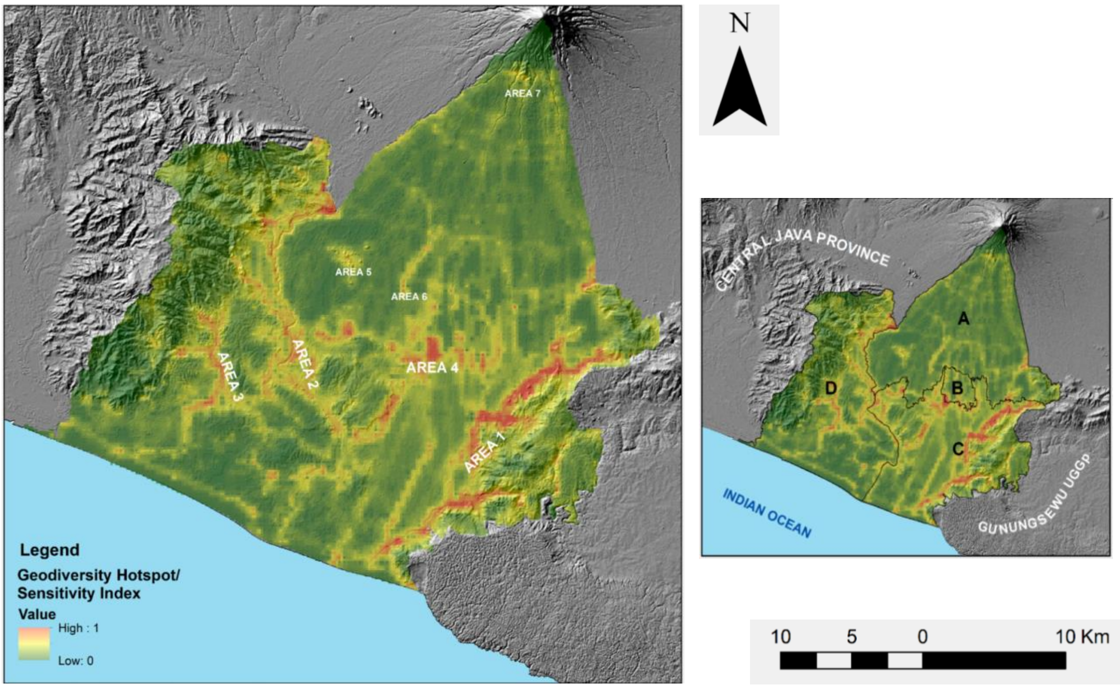

Figure 10. Geodiversity hotspot of Jogja Geopark

3. Geodiversity Hotspot of Jogja Geopark

The identification of geodiversity hotspots is crucial for evaluating the sensitivity of geopark area, geosites, and geodiversity sites to potential threats posed by human activities. These hotspots serve as indicators of regions where geoconservation efforts should be prioritized to mitigate the impacts of anthropogenic pressures. Typically, the spatial distribution of geodiversity hotspots corresponds closely with patterns in the geodiversity index.

These patterns follow the natural courses of rivers (Serang River, Progo River, and Opak River); alongside Opak Fault; and the transitional boundaries between different mapping features, reflecting areas of dynamic geological and geomorphological processes with potential threats posed by various human activities (Figure 10). However, a notable deviation from this general trend is observed in the southern part of the Kartamantul Metropolitan Area, where a significantly elevated threat index has been recorded due to increased urbanization and associated land-use pressures. The geodiversity hotspots, indicating areas of high sensitivity within the Jogja Geopark, are primarily concentrated in the western and eastern regions of the park. The areas requiring effective geoconservation management include the Serang River, the Progo River, the Godean Intrusion Hills complex, the northern side of the Sentolo Hills, the southern part of Yogyakarta City, and the Opak-Oyo River/Opak Fault corridor. The geodiversity hotspots along the Serang River, the Progo River, and the Opak-Oyo River/Opak Fault are attributed to the high diversity of geodiversity features. This is due to these areas representing transitional zones between different geodiversity map units, particularly in geological diversity, geomorphological diversity, and pedological diversity. A specific condition is observed in hydrological diversity, as the Serang River, the Progo River, and the Opak-Oyo River/Opak Fault, located within the boundaries of the Jogja Geopark, represent the highest-order streams according to Strahler's stream order classification.

The northern side of the Sentolo Hills and the southern part of Yogyakarta City exhibit high geodiversity hotspot values due to their high threat index, despite their moderate geodiversity index values. These areas are characterised by significant anthropogenic intervention and high population density. Spatially, these regions serve as urban buffer zones with moderate abiotic diversity. The Godean Intrusion Hills complex exhibits a high geodiversity hotspot value within a limited area. This is because the Godean Intrusion Hills form an isolated hill amid the extensive Merapi volcanic landscape. This isolated hill contains a diverse range of geodiversity features within a confined area, resulting in a relatively high geodiversity index despite the limited spatial extent. Furthermore, this region is also threatened by anthropogenic intervention, making its geodiversity hotspot value significantly distinct from the surrounding Merapi Volcano landscape.

Among the geosites analyzed, GS-03, GS-13, and GS-15 are identified as the most sensitive (Table 7, Figure 11), demonstrating the highest sensitivity values. These sites are characterized by a combination of unique geological, geomorphological, hydrological, and pedological features that render them highly sensitive to anthropogenic pressures.

Table 7. Sensitivity value of Jogja Geoparks geosites

Site Code	Geosite	Sensitivity index Classes
GS-01	Kendil Suroloyo Ancient Caldera	Medium Concern for Geoconservation
GS-02	Widosari Structural Hills	Low Concern for Geoconservation
GS-03	Kalibawang Eocene-age Nanggulan Formation	Urgent Need for Geoconservation
GS-04	Kiskendo Cave	Low Concern for Geoconservation
GS-05	Kliripan-Karangsari Manganese	Medium Concern for Geoconservation
GS-06	Godean Intrusion Hills Complex	Low Concern for Geoconservation
GS-07	Turgo - Plawangan Old Merapi Complex	Low Concern for Geoconservation
GS-08	Bakalan Pyroclastic Flow	Low Concern for Geoconservation
GS-09	Sambirejo Pyroclastic Cliff	Low Concern for Geoconservation
GS-10	Ngelepen Creeping Mass Wasting	Low Concern for Geoconservation
GS-11	Berbah Pillow Lava	Medium Concern for Geoconservation
GS-12	Gamping Eocene-age Limestone	Low Concern for Geoconservation
GS-13	Mengger Hills Opak Fault	Urgent Need for Geoconservation
GS-14	Mangunan Old Lava	Medium Concern for Geoconservation
GS-15	Parangtritis Sand Dunes	Urgent Need for Geoconservation

Their elevated sensitivity underscores the critical need for immediate conservation interventions to prevent degradation and preserve their intrinsic and functional values. Effective conservation strategies for these sites should prioritize minimizing anthropogenic disturbances, enhancing protective measures, and promoting sustainable management practices. Conversely, geosites such as GS-01, GS-05, GS-11, and GS-14 are classified within the medium sensitivity category (Table 7).

These sites exhibit a moderate level of vulnerability, often attributable to a balance between their intrinsic attributes and the external pressures they face. While the urgency for intervention is less critical compared to highly sensitive sites, these geosites still require targeted conservation measures to mitigate potential risks and maintain their ecological and cultural significance. The remaining geosites are categorized as having low sensitivity, indicating a relatively stable condition under existing circumstances. These sites typically possess attributes that confer greater resilience to environmental and anthropogenic stressors. However, despite their lower vulnerability, ongoing monitoring and preventative management remain essential to ensure their continued stability and to address any emerging threats.

This hierarchical sensitivity classification provides a valuable framework for prioritizing conservation actions, enabling resource allocation to be focused where it is most needed. Furthermore, among the 36 identified geodiversity sites, eight have been categorized as exhibiting medium sensitivity, while the remaining sites are classified as having low sensitivity

(Table 8, Figure 12). This classification reflects the varying degrees of vulnerability of these sites to anthropogenic pressures and natural disturbances. Sites with medium sensitivity are characterized by a moderate level of sensitivity to external impacts, often due to their unique geological, geomorphological, hydrological, or pedological features that are relatively less resilient to change or low in threat. These sites may also be located in areas subject to higher levels of human activity or environmental stressors, increasing the urgency for protective measures. In contrast, sites with low sensitivity exhibit a greater degree of resilience, attributed to either their less distinctive attributes or their reduced exposure to potential threats.

However, it is important to note that even low-sensitivity sites require appropriate management strategies to ensure their long-term conservation, particularly in the face of escalating environmental and developmental pressures.

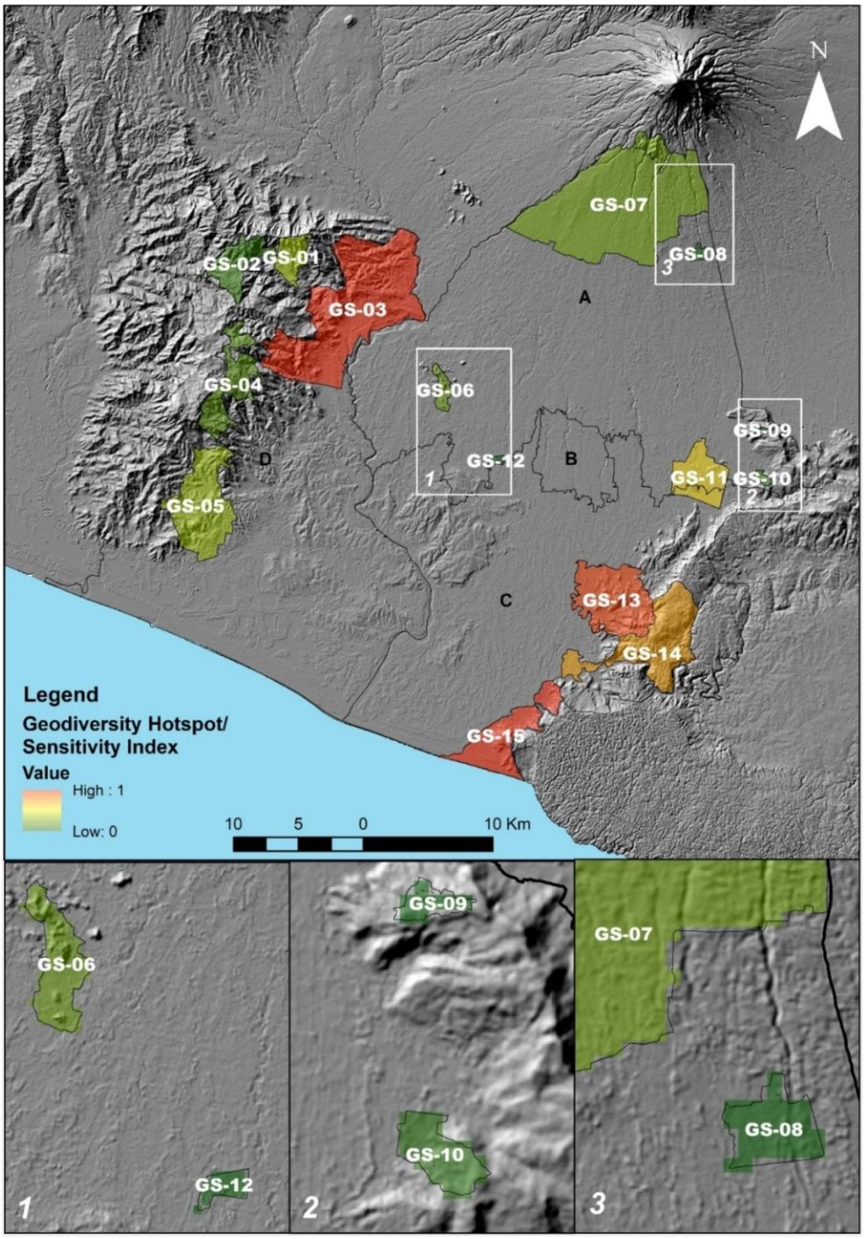

Figure 11. Maximum geodiversity hotspot or sensitivity index values on geosites of Jogja Geopark

The sensitivity classification provides critical insights into the geosystem's capacity to withstand and recover from disturbances, thereby guiding the prioritization of geoconservation efforts. A geodiversity hotspot represents a strategic approach to identifying priority areas for conservation efforts (Insani & Haryono, 2025). This concept is rooted in the understanding that geodiversity underpins biodiversity, as established by several studies (Gray, 2013; Hjort et al., 2015). Also, geodiversity encompasses the variety of geological, geomorphological, and soil features within a region, providing essential ecological functions and resources that support diverse ecosystems. Beyond its foundational role in sustaining biodiversity, geodiversity also contributes significantly to cultural diversity. Many cultural practices, traditions, and heritage sites are intimately tied to specific geological and geomorphological contexts, further highlighting the multifaceted value of geodiversity. Consequently, conservation strategies should extend beyond geoconservation alone. While the protection of abiotic features—such as rocks, landforms, and soils—is crucial, it is equally important to consider the conservation of biological and cultural elements, particularly in regions of high geodiversity and sensitivity.

Table 8. Sensitivity index value of Jogja Geoparks geodiversity sites

Site Code	Geodiversity Site	Sensitivity Index Classes
GI-01	Watu Puru Eocene Aged Nanggulan Formation	Least Concern for Geoconservation
GI-02	Grojogan Sewu Hill	Least Concern for Geoconservation
GI-03	Kembang Soka Waterfall	Least Concern for Geoconservation
GI-04	Mudal River	Least Concern for Geoconservation
GI-05	Kedung Pedut Waterfall	Least Concern for Geoconservation
GI-06	Kedung Banteng River	Least Concern for Geoconservation
GI-07	Kidang Kencono Cave	Least Concern for Geoconservation
GI-08	Watu Blencong Hill	Least Concern for Geoconservation
GI-09	Sriti Cave	Least Concern for Geoconservation
GI-10	Sidoharjo Waterfall	Least Concern for Geoconservation
GI-11	Gunung Jaran Summit	Least Concern for Geoconservation
GI-12	Proman Hill	Least Concern for Geoconservation
GI-13	Kebon Cave	Least Concern for Geoconservation
GI-14	Ngepoh Banjararum Hill	Least Concern for Geoconservation
GI-15	Khayangan Dam	Least Concern for Geoconservation
GI-16	Watu Grojogan-Kalikuning Columnar Joint	Least Concern for Geoconservation
GI-17	Minggir Ancient Lake	Medium Concern for Geoconservation
GI-18	Watu Kapal Riverside	Medium Concern for Geoconservation
GI-19	Surocolo Springs	Least Concern for Geoconservation
GI-20	Srigading - Samas Beach Ridge	Least Concern for Geoconservation
GI-21	Gilangharjo Wetland	Least Concern for Geoconservation
GI-22	Gunung Wangi Hills	Medium Concern for Geoconservation
GI-23	Plumpatan River	Medium Concern for Geoconservation
GI-24	Tompak Hill	Medium Concern for Geoconservation
GI-25	Bucu Summit	Least Concern for Geoconservation
GI-26	Tuwondo Waterfall	Medium Concern for Geoconservation
GI-27	Selarong Cave	Least Concern for Geoconservation
GI-28	Banyunibo Waterfall	Medium Concern for Geoconservation
GI-29	Sewu Watu Ancient Volcano	Least Concern for Geoconservation
GI-30	Watu Ngelak Riverside	Medium Concern for Geoconservation
GI-31	Gajah Cave	Least Concern for Geoconservation
GI-32	Kedung Tolok Waterfall	Least Concern for Geoconservation
GI-33	Cerme Cave	Least Concern for Geoconservation
GI-34	Watu Lawang-Srikeminut Valley Wall	Least Concern for Geoconservation
GI-35	Lemah Rubuh Mass Wasting	Least Concern for Geoconservation
GI-36	Tubing Karst	Least Concern for Geoconservation

Such areas often exhibit complex interactions between geological features, ecosystems, and human activities, necessitating integrated conservation approaches. Moreover, regions characterized by high geodiversity are often vulnerable to anthropogenic pressures, including human population and human intervention that created anthropogenic landforms. Addressing these challenges requires a holistic framework that prioritizes the conservation of abiotic, biotic, and cultural resources. This integrated perspective ensures that geodiversity hotspots serve as focal points for sustainable development, fostering resilience and promoting the long-term preservation of both natural and cultural heritage.

CONCLUSION

This study highlights the geodiversity index, threat index, and sensitivity index or geodiversity hotspot that represent the significant impact of human activities on geodiversity within the Jogja Geopark. Geodiversity indices in the Jogja Geopark with significant values are spread across six spots, namely (1) the transition between the Baturagung Mountain Range and the Yogyakarta-Bantul Alluvial Plain; (2) the Progo River and surrounding area; (3) the Serang River and surrounding area; (4) the Godean intrusive Hills; (5) the Bedog River Valley; and (6) the upper slope of Mount Merapi.

This area shows that geodiversity is quite high spatially, where all elements of geodiversity, namely geology, geomorphology, pedology, and hydrology, influence the geodiversity value. This has implications for geosites and geodiversity sites that have a high geodiversity index value. The geosites with high values include GS-03, GS-05, GS-11, GS-13, GS-14, and GS-15. Meanwhile, in geodiversity sites, although the values are not as significant as geosites, 15 of the 36 geodiversity sites have moderate values, while the rest have low values.

The Threat Index, which is based on population density and anthropogenic intervention data, is used to assess the threats faced by geoparks in urbanized areas. High threat index values are predominantly observed within the Kartamantul metropolitan area and the connecting corridors to Solo and Magelang. These areas, due to their high population density and significant human-induced geomorphological changes, face heightened sensitivity tendencies to anthropogenic pressures. In contrast, as distance increases from the metropolitan core and these major corridors, the threat index values gradually decrease, indicating reduced sensitivity tendencies in peripheral regions. This also has an impact on threats to geosites and geodiversity sites. No geosites have low threat values, with 3 out of 15 having high threat levels. Meanwhile, for geodiversity sites, 27 out of 36 show moderate threat values, with the rest showing low values.

The assessment of geodiversity hotspots, using both geodiversity and threat indices, has identified critical areas that require immediate geoconservation efforts. The Kartamantul metropolitan area -represent with area 1, 4, 5, 6; Kulon Progo area represent with area 2 and 3; and surrounding geosites, namely Kalibawang Eocene-age Nanggulan Formation, Mengger Hills Opak Fault, and Parangtritis Sand Dunes, has been found to be under substantial threat due to high population density and anthropogenic interventions. The study underscores the importance of implementing effective conservation strategies to safeguard these geopark area, geosites, and geodiversity sites from its anthr opogenic pressure. By prioritizing areas with high sensitivity, such as the Kalibawang Eocene-age Nanggulan Formation, Mangunan Old Lava, and Parangtritis Sand Dunes, we can mitigate the adverse effects of human impacts. This research provides a comprehensive framework for regional geoconservation, emphasizing the need for sustainable land use planning and regional management initiatives to preserve the unique geological and geomorphological features of the Jogja Geopark.

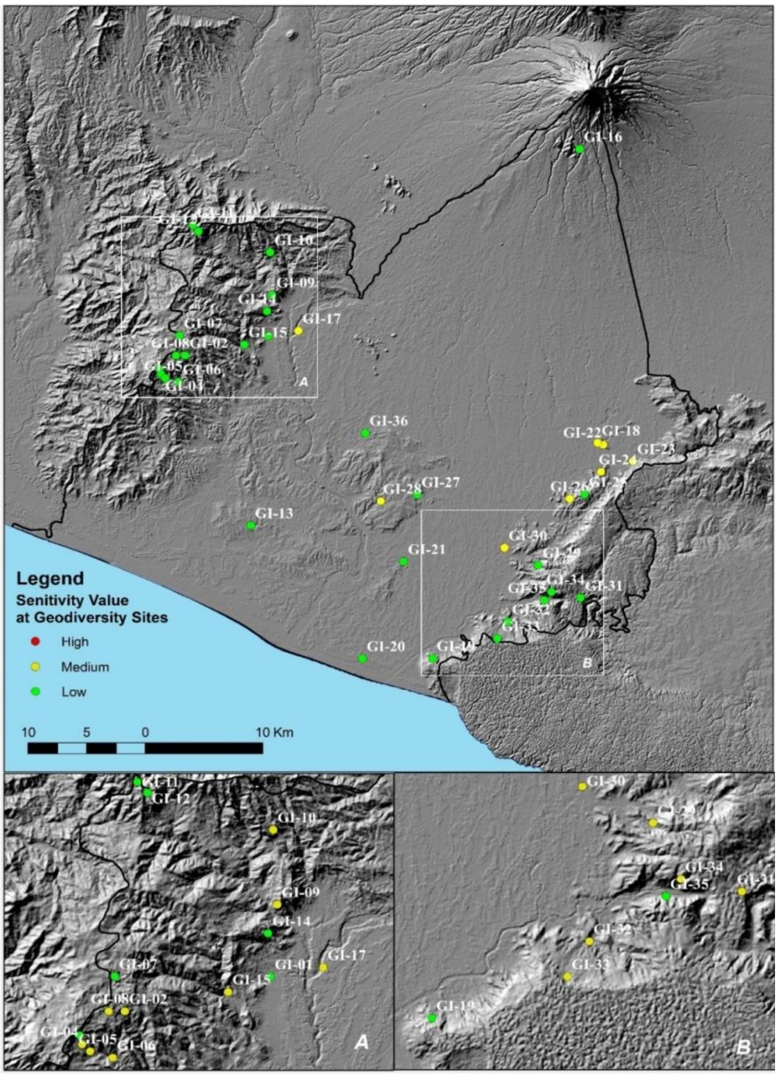

Figure 12. Sensitivity index values/geodiversity hotspot on geodiversity sites of Jogja Geopark

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REFERENCES

Araujo, A. M., & Pereira, D. Í. (2018). A new methodological contribution for the geodiversity assessment: Applicability to Ceará State (Brazil). *Geoheritage, 10*(4), 591–605. https://doi.org/10.1007/s12371-017-0250-3

Australian Heritage Commission. (2002). *Australian natural heritage charter* (2nd ed.). Australian Heritage Commission.

Bétard, F. (2016). *Geodiversity hotspots: A proposed conceptual and methodological framework for defining geoconservation priorities*. ResearchGate. https://www.researchgate.net/publication/301566896

Bétard, F., & Peulvast, J. P. (2019). Geodiversity hotspots: Concept, method and cartographic application for geoconservation purposes at a regional scale. *Environmental Management, 63*(6), 822–834. https://doi.org/10.1007/s00267-019-01168-5

Brilha, J. (2002). Geoconservation and protected areas. *Environmental Conservation, 29*(3), 273–276. https://doi.org/10.1017/S0376892902000188

Brilha, J., Gray, M., Pereira, D. I., & Pereira, P. (2018). Geodiversity: An integrative review as a contribution to the sustainable management of the whole of nature. *Environmental Science and Policy, 86*, 19–28. https://doi.org/10.1016/j.envsci.2018.05.001

Crofts, R., & Gordon, J. E. (2014). Geoconservation in protected areas. *PARKS, 20*(2), 61–76. https://doi.org/10.2305/IUCN. CH.2014.PARKS-20-2.RC.en

Crofts, R., & Gordon, J. E. (2015). Geoconservation in protected areas. In G. L. Worboys, M. Lockwood, A. Kothari, S. Feary, & I. Pulsford (Eds.), *Protected area governance and management* (pp. 531–568). Australian National University Press. http://press-files.anu.edu.au/downloads/press/p312491/pdf/CHAPTER18.pdf

DeMiguel, D., Brilha, J., Melendez, G., & Azanza, B. (2020). Geoethics and geoheritage. In C. Vasconcelos, S. Scheineider-Voß, & S. Peppoloni (Eds.), *Teaching geoethic: Resource for higher education*. University of Porto.

Geospatial Information Agency Republic of Indonesia. (2020). *Topographical map of Indonesia*.

Geospatial Information Agency Republic of Indonesia. (2024). *Land system of Indonesia*.

Gordon, J. E., Barron, H. F., Hansom, J. D., & Thomas, M. F. (2012). Engaging with geodiversity-why it matters. *Proceedings of the Geologists Association, 123*(1), 1–6. https://doi.org/10.1016/j.pgeola.2011.08.002

Gordon, J. E., Crofts, R., Díaz-Martínez, E., & Woo, K. S. (2018). Enhancing the role of geoconservation in protected area management and nature conservation. *Geoheritage, 10*(2), 191–203. https://doi.org/10.1007/s12371-017-0240-5

Goudie, A., & Viles, H. A. (2016). *Geomorphology in the Anthropocene*. Cambridge University Press.

Gray, M. (2011). Other nature: Geodiversity and geosystem services. *Environmental Conservation, 38*(3), 271–274. https://doi.org/10. 1017/S0376892911000117

Gray, M. (2013). *Geodiversity: Valuing and conserving abiotic nature*. John Wiley and Sons.

Gray, M. (2018). Geodiversity: The backbone of geoheritage and geoconservation. In E. Reynard & J. Brilha (Eds.), *Geoheritage: Assessment, protection, and management*. Elsevier.

Gregorič Bon, N., Josipovič, D., & Kanjir, U. (2018). Linking geomorphological and demographic movements: The case of Southern Albania. *Applied Geography, 100*, 55–67. https://doi.org/10.1016/j.apgeog.2018.09.002

Hjort, J., Tukiainen, H., Salminen, H., Kemppinen, J., Kiilunen, P., Snåre, H., Alahuhta, J., & Maliniemi, T. (2022). A methodological guide to observe local-scale geodiversity for biodiversity research and management. *Journal of Applied Ecology, 59*(7), 1756–1768. https://doi.org/10.1111/1365-2664.14183

Insani, A. A., & Barianto, D. H. (2024). *Demographic and anthropogenic geomorphology based geodiversity hotspot for geoconservation area selection: Study on Jogja Aspiring Geopark and its geosites – Geodiversity sites, Indonesia* [Paper presentation]. The 5th Regional Geoheritage Conference: How The Rocks Connect Us & Geoheritage for Sustainable Development.

Insani, A. A., & Haryono, E. (2025). Geodiversity hotspot and SWOT-TOWS-AHP assessment for regional geoconservation strategies in Kulon Progo Regency, Jogja Geopark, Indonesia. *International Journal of Geoheritage and Parks, 13*(1), 144–165. https://doi.org/10.1016/j.ijgeop.2025.02.002

Jogja Geopark Managing Agency. (2022). *Geodiversity sites of Jogja Geopark*.

Jogja Geopark Managing Agency. (2022). *Geosites zonation of Jogja Geopark*.

Jogja Geopark Managing Agency. (2022). *Jogja Geopark boundaries*.

Lima, N. P., & Pereira, D. I. (2023). Living and dying on Planet Earth: An approach to the values of geodiversity. *Geoheritage, 15*(1), Article 18. https://doi.org/10.1007/s12371-022-00776-8

Ministry of Agriculture Republic of Indonesia. (2022). *Soil order map*.

Ministry of Energy and Mineral Resources Republic of Indonesia. (2022). *Geological map of Indonesia*.

Ministry of Energy and Mineral Resources Republic of Indonesia. (2022). *Groundwater map of Indonesia*.

Nir, D. (1983). *Man, a geomorphological agent: An introduction to anthropic geomorphology*. Keter Publishing House.

Piacente, S. (1996). Man as geomorphological agent. In M. Panizza (Ed.), *Environmental geomorphology*. Elsevier Science B.V.

Prosser, C. D., Burek, C. V., Evans, D. H., Gordon, J. E., Kirkbride, V. B., Rennie, A. F., & Walmsley, C. A. (2010). Conserving geodiversity sites in a changing climate: Management challenges and responses. *Geoheritage, 2*(3), 123–136. https://doi.org/10.1007/s12371-010-0016-7

Santos, D. S., Mansur, K. L., Gonçalves, J. B., Arruda, E. R., & Manosso, F. C. (2017). Quantitative assessment of geodiversity and urban growth impacts in Armação dos Búzios, Rio de Janeiro, Brazil. *Applied Geography, 85*, 184–195. https://doi.org/10.1016/j.apgeog.2017.03.009

Szabó, J. (2010). Anthropogenic geomorphology: Subject and system. In J. Szabó, L. Dávid, & D. Lóczy (Eds.), *Anthropogenic geomorphology: A guide to man-made landforms*, 3–10, Springer Netherlands. https://doi.org/10.1007/978-90-481-3058-0_1

World Population. (2020). *Global population density*.

Zwolinski, Z. (2004). Geodiversity. In A. S. Goudie (Ed.), *Encyclopedia of geomorphology*, 417–418, Routledge.

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