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

GIS-Based Zoning for Integrating Geosite Inventory with Spatial Planning: Evidence from Meratus Geopark, Indonesia

Rusdasopia Fahriani[1], Usman Firdaus[1], Muhammad Yusuf Ridhani[1], Defin Helda Leliana[1], Resita Rahmitiasari[2], Kiky Permana Setiawan[1*]

[1] *Department of Urban and Regional Planning, Faculty of Engineering, Muhammadiyah University of Banjarmasin, Indonesia*
[2] *Meratus Geopark Management Agency, Banjarbaru, South Kalimantan, Indonesia*

* Corresponding author: kikypermana@umbjm.ac.id
Tel.: +62 81351168011
Received: Jun 16, 2026; Accepted: Aug 5, 2026.
DOI: 10.24273/jgeet.2016.1.2.001

Abstract

Geopark planning often begins with geosite inventories, yet translating these inventories into spatial planning interpretations remains limited. This study develops a GIS-based zoning interpretation of Meratus Geopark, South Kalimantan, Indonesia, by examining how official geosite distribution, development-potential density, accessibility, formal spatial planning categories, and field-survey evidence jointly shape geopark management implications. Its principal contribution is the development of a reproducible GIS framework that transforms official geosite inventories into analytical zoning to support spatial planning decisions. The analysis used 54 official geosites and combined weighted kernel density estimation, accessibility analysis, spatial plan overlay, and sensitivity–suitability assessment within a GIS framework, with field observations used to validate representative zoning conditions. The results show that Meratus Geopark is spatially differentiated across four routes. The weighted KDE, based on 54 official geosites and 3,647 selected toponymy points, produced a statistically clustered pattern, with a nearest-neighbor index of 0.184, z-score of -11.478, and p-value < 0.001. Accessibility also varies strongly, from the highly accessible Western Route at 8.2 km from Tugu Nol Banjarmasin to the peripheral Northern Route at 121.1 km. The integrated analysis produced five proposed zoning categories: core zone, buffer zone, geopark corridor, limited development zone, and special management zone. The proposed workflow provides planning-relevant evidence for geopark managers and spatial planners to differentiate conservation priorities, visitor-service provision, mobility corridors, and site-specific management needs, while maintaining that the resulting zoning interpretation is analytical rather than legally binding.

Keywords: geoheritage governance; kernel density estimation; network accessibility; spatial zoning; planning overlay; South Kalimantan

1. Introduction

Geoparks are increasingly positioned as territorial platforms that connect geoheritage conservation with education, community participation, tourism, and sustainable regional development. Rather than being limited to a catalog of geological attractions, a geopark represents a managed landscape where geological, ecological, cultural, economic, and institutional elements interact within a defined territory (Dias et al., 2023; Naydenov, 2022). This view is consistent with the broader evolution of geopark thinking, which treats geoheritage not only as an object of protection but also as a basis for local welfare, territorial identity, and place-based development (De Castro et al., 2022; Varriale et al., 2022). In this perspective, geoparks function as spatially differentiated management systems that integrate geoheritage, biodiversity, cultural identity, accessibility, and local development within a common territorial framework (Frey, 2021; Popa et al., 2017).

This territorial character has important implications for spatial planning. Geoparks span landforms, settlements, ecological systems, mobility networks, cultural meanings, and governance arrangements that do not always align with simple administrative or tourism boundaries (Ferdowsi and Németh, 2025; Shiri et al., 2025; Zhuang et al., 2024). From a geographical perspective, geological value is inseparable from the social, ecological, economic, and political relations that shape how space is used and regulated (Mo et al., 2023; Sulistyadi et al., 2024). Geoparks may also function as regional branding instruments that support tourism, investment, and local economic growth, but these opportunities require governance mechanisms capable of addressing spatial complexity, land-use conflicts, and cross-sectoral coordination (El Hamidy and Errami, 2025; Lee and Jayakumar, 2021; Ristiawan et al., 2023). Consequently, geopark planning requires more than simply recognizing geosites. It requires an area-based approach that integrates conservation, education, visitor management, local livelihoods, settlement functions, infrastructure, and spatial control (Briggs et al., 2022; Ferdowsi and Németh, 2025; Martínez-Martín et al., 2023). The successful integration of geoparks into spatial planning heavily relies on the richness of their geological and tectonic history. This is evidenced by geochemical, petrographic, and microfossil analyses in areas such as Ciletuh and Karangsambung, which serve as the primary basis for geoheritage conservation (Hafidhah Nurul Haq et al., 2024). Therefore, a systematic geodiversity inventory is a crucial first step for an aspiring geopark. Qualitative evaluations of the educational, scientific, and tourism aspects of geological manifestations, such as active fault zones, provide legitimacy for determining spatial functions for sustainable tourism (Utama et al., 2025). Although GIS-based techniques have increasingly been adopted in geoheritage and geopark studies, most applications remain descriptive and inventory-oriented. Existing studies commonly employ GIS to map geosite distribution, evaluate tourism potential, or assess individual environmental characteristics, yet only limited attention has been given to translating these spatial datasets into operational zoning frameworks that directly support statutory spatial planning and land-use regulation (Brilha, 2016; Ferreira and Valdati, 2022; Zhuang et al., 2024). Consequently, previous GIS-based zoning studies often indicate where valuable geoheritage resources occur but provide insufficient guidance on how different parts of a geopark should be managed across diverse conservation, development, and regulatory contexts.

These methodological limitations are particularly relevant in Indonesia, where geoparks have increasingly been promoted as instruments for tourism development, environmental conservation, destination branding, and regional economic transformation (Cahyadi and Newsome, 2021; Lestari and Indrayati, 2022; Ristiawan et al., 2023). However, integrating geoparks into formal spatial planning remains challenging. Geopark governance cannot rely only on the recognition of geoheritage and cultural value; it must also engage with zoning rules, land-use categories, institutional mandates, and legal instruments that regulate space (Dias et al., 2023; Nikolova and Sinnyovsky, 2018; Zhuang et al., 2024). In South Kalimantan, Regional Regulation No. 6 of 2023 on the Provincial Spatial Plan (RTRW) 2023–2042 provides the formal framework for spatial structure, spatial patterns, and the utilization and control of space use (Indonesia, 2023). The regulation distinguishes between protected and cultivation areas. It operationalizes them through categories such as water bodies, conservation areas, production forests, agriculture, tourism, settlements, and other designated land-use functions (Indonesia, 2023). Therefore, integrating a geopark into spatial planning requires an understanding of how geosites intersect with these formal spatial categories.

Meratus Geopark offers a strategic case for examining this relationship. The geopark comprises 54 official sites organized into four travel routes, distributed across several regencies and cities in South Kalimantan (Meratus, 2023). Its territorial context is complex, combining riverine cultural landscapes, upland settlements, reservoir and lake systems, conservation areas, customary cultural assets, religious-historical sites, caves, hot springs, mining heritage, and tourism destinations. At the same time, parts of South Kalimantan have experienced land-cover change, extractive pressure, and spatial-use mismatch associated with coal mining and infrastructure expansion (Adhi et al., 2022; Afkarina et al., 2019; Wibisono et al., 2023). Broader land conversion from natural vegetation and agricultural areas into built-up and infrastructure land also creates long-term ecological risks for ecosystems and local livelihoods (Khan and Chen, 2025; Shen et al., 2022; Syaban and Appiah-Opoku, 2024). These pressures coexist with the high geo-biodiversity, biodiversity, cultural resources, and ecotourism potential of the Meratus Mountains (Cahyadi and Aufa, 2022; Magriaty, 2025; Naydenov, 2022). The RTRW also recognizes the Meratus Mountains as a Provincial Strategic Area for environmental functions and carrying capacity, while emphasizing ecological restoration, nature-based tourism, and geosite preservation (Indonesia, 2023).

Although geopark research has made substantial progress in geosite inventory, geotourism, community participation, and destination governance, GIS-based zoning studies remain fragmented and insufficient for spatial planning applications (Brilha, 2016; Ferreira and Valdati, 2022; Zhuang et al., 2024). Most studies evaluate individual dimensions, such as geosite density, tourism suitability, accessibility, or environmental sensitivity, as separate analytical outputs rather than integrating them into a unified planning framework (Gupta et al., 2024; Quesada-Valverde and Quesada-Román, 2023; Štrba et al., 2023). Consequently, these approaches provide valuable thematic maps but offer limited support for interpreting zoning priorities within legally designated land-use systems. In Indonesia, geopark studies similarly emphasize governance, stakeholder collaboration, and tourism management, yet rarely connect official geosite inventories with statutory spatial planning instruments such as the RTRW (Dwipati et al., 2025; Rahmatin and Nawangsari, 2025; Ristiawan et al., 2023). This disconnect limits the practical use of GIS analyses for supporting zoning decisions and long-term territorial management.

This gap is important because spatial planning does not treat territory as a uniform surface. It differentiates area functions, permissible activities, conditional uses, and restrictions attached to each spatial category (Iukhno et al., 2025; Yanbo et al., 2023). A geopark that overlaps conservation areas, settlements, water bodies, production forests, agricultural landscapes, tourism spaces, and mining-influenced areas cannot be managed as a single tourism zone or as a purely protected area (Ferdowsi and Németh, 2025; Mo et al., 2023; Shiri et al., 2025). Zoning interpretation must consider ecological sensitivity, land suitability, accessibility, carrying capacity, and land-use intensity to ensure that tourism and development do not weaken geoecological integrity (Qi et al., 2023; Shi et al., 2024; Sobhani et al., 2022). Formulating such zoning requires spatial approaches, such as grid-based indexing, to rapidly delineate hotspots (Gathot Harbowo and Siringoringo, 2025). Furthermore, assessing site feasibility requires multi-parameter quantitative methods that cover scientific and economic values (Ansori et al., 2021), alongside functional and social media exposure metrics for targeted tourism planning (Sahara and Setiawan, 2022).

Against this background, this study develops a GIS-based zoning interpretation of Meratus Geopark by positioning official geosite inventories as a spatial planning interface rather than as stand-alone spatial datasets. The framework sequentially combines weighted kernel density estimation to identify concentrations of strategically important geosites, accessibility analysis to evaluate spatial connectivity, RTRW overlay to examine consistency with statutory land-use designations, and sensitivity–suitability assessment to interpret conservation and development priorities. Rather than merely integrating existing GIS techniques, the proposed workflow establishes explicit analytical relationships between geoheritage distribution, accessibility, environmental constraints, and formal planning regulations. This integrated interpretation provides planning-oriented evidence for zoning decisions that cannot be generated by applying each GIS technique independently.

Accordingly, this study aims to develop and demonstrate an operational GIS-based framework for interpreting geopark zoning within the context of statutory spatial planning. Specifically, the study evaluates the spatial concentration of geosites, their accessibility, compatibility with the Provincial RTRW, and environmental sensitivity to produce planning-oriented zoning interpretations for the Meratus Geopark. The proposed framework is intended to strengthen the integration of geoheritage conservation with regional spatial planning and sustainable territorial management.

2. Research Methods

This study applied a spatial-analytical case study design to transform the official Meratus Geopark site inventory into a GIS-based zoning interpretation. The design was descriptive and evaluative rather than causal; therefore, the analysis did not aim to explain cause–effect relationships between geosite location, accessibility, land-use designation, and zoning outcome. Instead, it examined how official geosites, route structure, access networks, spatial planning categories, and field-based contextual evidence jointly inform zoning interpretation. This approach follows geopark and geoheritage studies that emphasize integrating geosite inventory, conservation, territorial management, community development, and spatial planning within a single landscape framework (Brilha, 2016; Dias et al., 2023; UNESCO, 2026; Zhuang et al., 2024). The study was conducted in Meratus Geopark, South Kalimantan, Indonesia. The main unit of analysis was the official geosite point, while route-level aggregation was used to interpret territorial differentiation across the Western, Southern, Eastern, and Northern routes. The study used all 54 official Meratus Geopark sites; therefore, no statistical sampling of geosites was applied. Supporting spatial data were selected purposively based on their relevance to the research objective, namely the interpretation of the relationship between geosite inventory and spatial planning. These data included the delineation of the Meratus Geopark, route attributes, administrative boundaries, BIG toponymy data, road networks, water-access segments, pedestrian access links, urban or service nodes, and the South Kalimantan Provincial Spatial Plan (RTRW) 2023–2042. The RTRW layer was used because it provides formal spatial pattern categories for interpreting whether geosites are associated with protected areas, cultivation areas, settlement spaces, tourism functions, production landscapes, water bodies, or other designated land-use categories (Indonesia, 2023). Field-survey documentation collected in 2025 was used as representative visual and contextual evidence for proposed zoning categories. The field photographs were not treated as a statistically representative sample, but as contextual verification of selected sites and spatial functions.

All spatial layers were checked for geometry validity, standardized into a common projected coordinate system, and organized in a GIS environment. All spatial analyses were performed using ArcGIS Pro version 3.x (Esri, Redlands, CA, USA). Spatial datasets were projected into the Universal Transverse Mercator (UTM) coordinate system, WGS 1984, Zone 50 South, to ensure consistency in distance and area calculations. The principal GIS tools included Kernel Density, Average Nearest Neighbor, Network Analyst (Closest Facility and Service Area), Spatial Join, Intersect, and Raster Calculator, together with standard vector editing and topology validation procedures. The analysis was conducted through seven sequential procedures. First, the official geosite inventory was mapped and grouped by route to identify distribution patterns and administrative context. Second, weighted kernel density estimation was applied to examine the concentration of developmental potential. The kernel density search radius and raster cell size were determined through preliminary sensitivity testing to balance spatial detail with the geopark's regional extent. Several parameter combinations were evaluated to avoid excessive smoothing while maintaining interpretable hotspot patterns across the four geopark routes. The final parameter values were selected because they produced stable density surfaces that accurately represented spatial variation without generating fragmented or overly generalized clusters, consistent with recommendations from previous GIS-based spatial density studies. Official geosite points were treated as the main analytical anchors, while selected toponymy points were incorporated only when they were thematically relevant to geo-geomorphology, hydrology, culture, tourism, or access. Each toponymy point was assigned a weighting score according to its functional relevance to geopark development. Weight values were assigned through a rule-based analytical scheme based on the functional relevance of each toponymy group to geopark interpretation, development-potential density, and spatial planning objectives. The scheme was applied consistently to all 3,647 selected toponymy records. The weighting procedure was not intended to rank the intrinsic scientific value of each toponymy feature, but to differentiate its relative contextual contribution to the weighted development-potential density surface.

To clarify the weighting procedure, the selected toponymy records were grouped into five functional classes before being incorporated into the KDE model. The weighting scheme used in the analysis is summarized in Table 1.

Table 1. Functional weighting scheme for selected toponymy points

Functional group	Examples of features	Weight	Analytical role
Geoheritage and geomorphological features	Caves, waterfalls, hot springs, cliffs, geological formations	5	Main contextual support for geoheritage and geodiversity potential
Hydrological and landscape features	Rivers, reservoirs, lakes, springs, valleys	4	Support for ecological, riverine, and landscape interpretation
Cultural and historical features	Traditional villages, religious sites, old mines, cultural landmarks	3	Support for cultural meaning and place identity
Tourism and visitor-related features	Attractions, viewpoints, recreation sites, visitor facilities	2	Support for visitor-service and interpretation potential
Access and settlement-support features	Road nodes, settlements, landing points, service nodes	1	Support for accessibility and local management context

Source: Authors' rule-based weighting scheme for weighted KDE analysis

Table 2. Decision framework for GIS-based zoning interpretation

Proposed zone	Main spatial evidence	Supporting criteria	Planning interpretation
Core zone	High geosite concentration and/or strong conservation relevance	Protected-area context, high geoheritage value, ecological sensitivity	Protection, interpretation, and controlled visitation
Buffer zone	Transitional space around key geosite clusters	Settlement interface, livelihood context, ecological support function	Interface between geopark assets and community landscapes
Geopark corridor	Spatial linkage between geosite clusters and route systems	Road, river, pedestrian, or route-based connectivity	Mobility, interpretation, and route-based geopark experience
Limited development zone	Accessible sites with visitor-service potential	Settlement, tourism, cultural production, or cultivation context	Controlled visitor services and community-based tourism
Special management zone	Mixed spatial functions or management constraints	Extractive heritage, infrastructure pressure, land-use conflict, cultural sensitivity	Site-specific management, monitoring, and cross-sector coordination

Source: Authors' GIS-based interpretation framework

Table 3. Spatial data, analytical procedures, and outputs

Spatial data/input	Analytical procedure	Main output
Official Meratus Geopark geosite inventory	Route grouping, point mapping, nearest-neighbor analysis	Geosite distribution, route profile, clustering statistics
Meratus Geopark delineation	Boundary standardization and map framing	Study area boundary and spatial analysis extent
BIG toponymy data	Thematic filtering and weighted KDE support	Contextual development-potential density
Road network, water-access segments, and pedestrian links	Network-distance and access-corridor analysis	Accessibility gradient and route-based access classes
Urban and service nodes	Proximity and service-context interpretation	Accessibility context and visitor-service potential
RTRW spatial pattern polygons	GIS overlay with geosite points	Site–RTRW relationship and planning-category interpretation
Sensitivity–suitability criteria	Rule-based synthesis	Zoning interpretation and management implications
Field-survey photographs, 2025	Representative contextual verification	Visual evidence for proposed zoning categories

Source: Authors' GIS compilation and analysis based on official Meratus Geopark geosite data, BIG toponymy data, access-network data, urban/service nodes, geopark delineation, South Kalimantan Provincial RTRW 2023–2042, and field-survey documentation.

Average nearest-neighbor analysis was then used to assess whether the official geosite pattern was clustered, random, or dispersed. Third, accessibility was evaluated using a network-based approach, with *Tugu Nol* Banjarmasin as the provincial origin node. The analysis considered road access, primary access corridors, water-based access, pedestrian links, and urban or service nodes, because accessibility in Meratus Geopark includes riverine, peri-urban, upland, and last-mile mobility contexts. Fourth, geosite points were overlaid with RTRW spatial pattern polygons to identify their relationship with formal spatial planning categories. Fifth, sensitivity–suitability interpretation was developed by combining geosite context, accessibility condition, RTRW category, conservation relevance, visitor-service potential, and management constraints. Sixth, representative field-survey photographs were used to support the interpretation of core, buffer, corridor, limited development, and special management zones. Seventh, all results were synthesized into a GIS-based zoning interpretation and a conceptual model of Meratus Geopark as a spatial planning interface. Zoning interpretation followed an explicit decision framework rather than subjective visual interpretation. Core zones were assigned to geosites characterized by high geoconservation significance, strong spatial concentration, and dominant overlap with protected spatial functions. Buffer zones included areas surrounding core geosites that support ecological integrity and visitor management. Corridor zones connected clusters of geosites through existing transportation or river networks. Limited development zones represented areas suitable for controlled tourism development under existing land-use regulations. Special management zones were identified where multiple planning constraints, environmental sensitivity, or land-use conflicts required site-specific management strategies.

To make the zoning interpretation more transparent, each proposed zone was derived from a combination of spatial evidence rather than from a single criterion. The decision framework is presented in Table 2. The categories should be read as analytical planning interpretations, not as legally binding zoning designations.

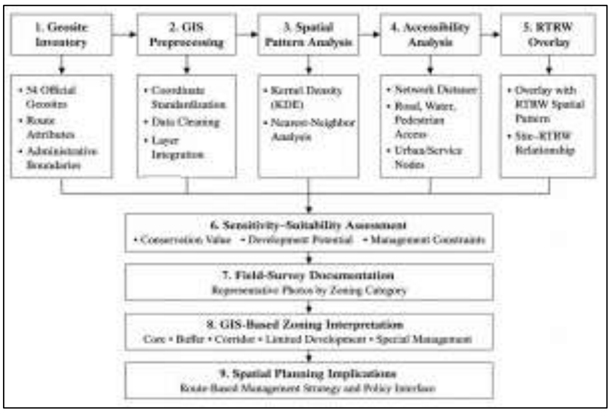

Fig 1. Research workflow for GIS-based zoning interpretation of Meratus Geopark

The selected methods were appropriate because the research question required spatial interpretation rather than causal modeling. Kernel density analysis was used to identify concentration surfaces; nearest-neighbor analysis provided statistical support for spatial clustering; network-distance analysis captured realistic access conditions;

RTRW overlay linked geopark sites with formal planning categories; and field-survey documentation strengthened contextual interpretation. The resulting zoning interpretation should therefore be read as an analytical planning interface, not as a legally binding zoning map. The complete methodological workflow, from data collection through GIS-based spatial analysis to zoning interpretation, is illustrated in Figure 1. The workflow links geosite inventory, GIS preprocessing, clustering analysis, accessibility analysis, RTRW overlay, sensitivity–suitability assessment, field-survey documentation, zoning interpretation, and spatial planning implications. The spatial datasets, analytical procedures, and expected outputs associated with each stage of the workflow are summarized in Table 3.

3. Research Results

3.1. Route-Based Spatial Distribution of Meratus Geopark Sites

The distribution of the 54 official Meratus Geopark sites shows a clear route-based spatial structure. The sites are not evenly distributed across the geopark territory, but are organized into four routes with distinct territorial characteristics. The Western Route contains 9 sites and is closely associated with the urban-river system of Banjarmasin and Barito Kuala. The Southern Route contains 14 sites and forms a peri-urban transition corridor linking Banjarbaru, Cempaka, Kiram, Mandiangin, and surrounding conservation-oriented landscapes. The Eastern Route contains the largest number of sites, with 17 sites concentrated within one regency, one district, and six villages or urban wards. The Northern Route also includes 14 sites, distributed across three regencies, eight districts, and 14 villages or urban wards, indicating a wider, more fragmented territorial pattern.

This route-based distribution shows that Meratus Geopark is not a single homogeneous destination. Each route has a different spatial role. These differences indicate that the territorial organization of Meratus Geopark is inherently heterogeneous rather than spatially uniform. Consequently, each route requires different planning priorities, management strategies, and zoning approaches, depending on its dominant landscape characteristics, accessibility, and socio-ecological functions. The Western Route is shaped by river mobility and cultural settlement landscapes. The Southern Route is linked to urban services, cultural interpretation, and access to conservation. The Eastern Route forms a compact conservation and lake-reservoir cluster, while the Northern Route represents a peripheral upland landscape with mixed cultural, historical, geological, and management characteristics. A detailed summary of the route-based distribution and territorial characteristics of the geopark sites is presented in Table 4.

Table 4. Route-based distribution and territorial characteristics of Meratus Geopark sites

Route	Number of sites	Dominant spatial setting	Main territorial role
Western Route	9	Urban-river, water-cultural, and settlement landscape	Urban-river cultural corridor
Southern Route	14	Peri-urban, cultural, service, and conservation transition landscape	Peri-urban interpretation and service corridor
Eastern Route	17	Reservoir, lake, conservation, and geoheritage landscape	Conservation and lake-reservoir geosite cluster
Northern Route	14	Upland, customary-cultural, religious-historical, and extractive heritage landscape	Peripheral upland mixed-management landscape
Total	**54**	**Multi-route geopark territory**	**Spatial planning interface**

Source: Authors' compilation based on the official Meratus Geopark site inventory, route attributes, and administrative boundary data.

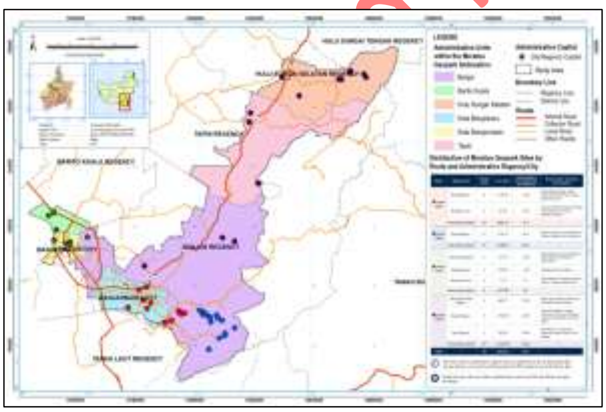

Fig 2. Spatial distribution of Meratus Geopark sites by route and administrative location. Source: Compiled by the authors based on the Meratus Geopark site inventory, route attributes, and administrative boundary data

Building on the route classification in Table 4, the geosite distribution was mapped to examine its spatial configuration within the Meratus Geopark. The resulting map illustrates the relationship between geosite distribution, route networks, and administrative boundaries Figure 2.

Figure 2 demonstrates that the spatial organization of Meratus Geopark is structured around four territorial corridors rather than a single centralized destination. This differentiated spatial configuration provides the basis for subsequent analyses of clustering, accessibility, and zoning interpretation.

3.2. Spatial Clustering and Development-Potential Density

The weighted kernel density analysis indicates that the spatial pattern of Meratus Geopark is strongly clustered. The KDE surface was generated from 54 official geosite points and 3,647 selected toponymy points, producing 3,701 weighted input points. Official geosites were used as the main analytical anchors, while selected toponymy points were included as contextual evidence of place-based development potential. The KDE model used a 10,000 m search radius and a 250 m raster cell size.

The average nearest-neighbor result confirms the clustered pattern. The nearest-neighbor index was 0.184, with a z-score of -11.478 and a p-value below 0.001. These values indicate that the official geosite distribution is statistically clustered rather than random. High- and very-high-density areas are located where official geosites are reinforced by surrounding toponymy related to hydrology, culture, access, geomorphology, and tourism. The resulting surface therefore represents a weighted development-potential density, not merely a map of point concentration. From a spatial planning perspective, the identified hotspot areas indicate locations where geoheritage resources, supporting landscape features, and visitor accessibility converge within the same territorial context. These areas therefore represent strategic priorities for integrated conservation and tourism management because they concentrate both development opportunities and potential visitor pressure. Conversely, lower-density areas should not be interpreted as having lower geoheritage importance, but rather as requiring different planning strategies that emphasize territorial connectivity and landscape conservation. The parameters used in the weighted kernel density analysis and the statistical results of the nearest-neighbor analysis are summarized in Table 5.

Table 5. Weighted KDE parameters and nearest-neighbor statistics

Component	Result	Analytical meaning
Official geosite points	54	Main geosite anchors
Selected toponymy points	3,647	Contextual support for development-potential analysis
Total weighted input points	3,701	Final KDE input
KDE search radius	10,000 m	Spatial bandwidth for density estimation
Raster cell size	250 m	KDE output resolution
Nearest-neighbor index	0.184	Strong clustering
z-score	-11.478	Strong departure from random distribution
p-value	< 0.001	Statistically significant clustering
Main output	Weighted development-potential density	Analytical surface, not a legal zoning boundary

Source: Authors' GIS analysis based on official Meratus Geopark geosite data, selected BIG toponymy data, weighted KDE processing, and nearest-neighbor analysis.

Table 6. Route-based accessibility gradient and planning interpretation

Route	Average distance from Tugu Nol Banjarmasin	Dominant access structure	Accessibility interpretation	Planning implication
Western Route	8.2 km	Urban roads, river corridors, and water-based access	Very high accessibility	River-cultural interpretation, water mobility, urban tourism, and community-based services
Southern Route	45.6 km	Primary and collector roads connecting Banjarmasin–Banjarbaru–Kiram–Mandiangin	High to moderate accessibility	Interpretation facilities, education, visitor services, and conservation-based tourism
Eastern Route	60.1 km	Banjarbaru–Aranio–Riam Kanan corridor and lake-reservoir access	Moderate accessibility	Controlled access, carrying-capacity management, and conservation-oriented tourism
Northern Route	121.1 km	Long-distance arterial/collector roads, local roads, and last-mile access	Low to peripheral accessibility	Selective development, field verification, safety control, and special management

Source: Authors' GIS network-distance analysis based on official geosite locations, Tugu Nol Banjarmasin as the provincial origin node, road network data, selected access corridors, water-based access segments, pedestrian links, and urban/service nodes.

Based on the parameters in Table 5, weighted Kernel Density Estimation (KDE) was applied to identify the spatial intensity of geosite distribution in the Meratus Geopark. The resulting density surface provides the basis for interpreting development potential and conservation priorities Figure 3.

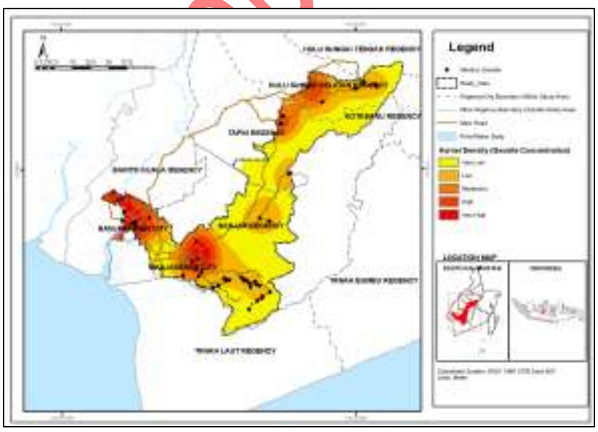

Fig 3. Spatial clustering and concentration pattern of Meratus Geopark sites based on nearest-neighbor and kernel density analysis.

Source: Authors' GIS analysis based on geosite point data and selected toponymy data. Note: The figure reports the nearest-neighbor index of 0.184, z-score of -11.478, p-value < 0.001, and weighted kernel density output.

Figure 3 provides quantitative evidence that the distribution of geosites is spatially organized rather than random. The statistically significant clustering supports the interpretation that zoning should be based on spatial concentration systems instead of individual geosite locations.

3.3. Accessibility Gradient Across the Geopark Network

The accessibility analysis shows a strong gradient among the four routes. Accessibility was interpreted using a network-based approach that included road access, water-based access, pedestrian access, primary access corridors, and urban or service nodes. This approach was used because several sites in Meratus Geopark are connected through riverine, peri-urban, upland, and last-mile mobility systems.

The Western Route is the most accessible route, with an average distance of 8.2 km from Tugu Nol Banjarmasin. Banjarmasin shapes its accessibility through the Barito Kuala urban-river system, where road access and water mobility are both relevant. The Southern Route has an average distance of 45.6 km and is supported by the

Banjarmasin–Banjarbaru–Kiram–Mandiangin corridor. The Eastern Route has an average distance of 60.1 km and is linked to the Banjarbaru–Aranio–Riam Kanan access structure. The Northern Route is the least accessible, with an average distance of 121.1 km. Its peripheral position, upland setting, and reliance on longer arterial, collector, local, and last-mile access corridors indicate higher management complexity. These accessibility differences have important planning implications. Highly accessible routes are more likely to experience higher visitor intensity and therefore require stronger visitor management, interpretation facilities, and carrying capacity controls. In contrast, relatively remote routes should prioritize landscape conservation, selective infrastructure provision, and emergency access planning to maintain ecological integrity while ensuring visitor safety. A summary of the route-based accessibility characteristics and their implications for spatial planning is presented in Table 6.

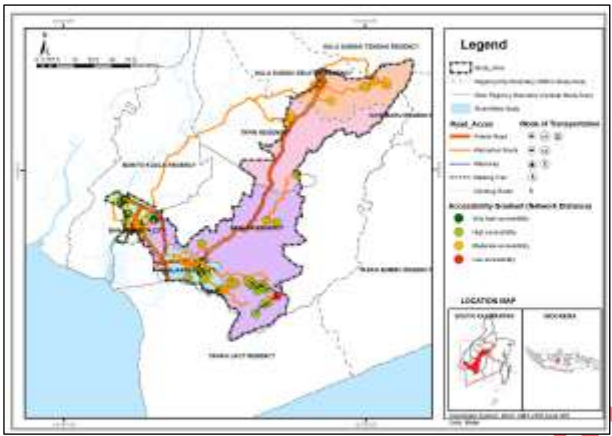

Fig 4. Accessibility gradient of Meratus Geopark sites from provincial urban nodes and transport corridors.

Source: Authors' GIS network-distance analysis based on geosite locations, road network data, selected access corridors, water-based access, pedestrian links, and urban/service nodes.

Based on the accessibility indicators in Table 4, the spatial accessibility of geosites was mapped to illustrate their connectivity to the provincial transportation network. Figure 4 shows the resulting accessibility gradient and variations in transport connectivity.

Figure 4 illustrates that accessibility is not only a transportation attribute but also a determinant of conservation priorities, infrastructure investment, and visitor management across the geopark.

3.4. Relationship Between Geosites and RTRW Spatial Pattern Categories

The overlay between geosite locations and the South Kalimantan Provincial Spatial Plan shows that Meratus Geopark intersects multiple RTRW spatial pattern categories. The geopark sites are associated not only with tourism or conservation spaces, but also with settlements, water bodies, production landscapes, cultural landscapes, and mixed-use areas. This finding indicates that geopark planning cannot be reduced to a single spatial function.

The route-level pattern also differs. The Western Route is more closely related to riverine, settlement, and cultural landscape functions. The Southern Route intersects peri-urban service spaces and conservation-linked areas. The Eastern Route is more strongly associated with conservation and reservoir-lake settings. The Northern Route shows the most mixed spatial relationship, reflecting its upland, customary-cultural, religious-historical, production, and heritage-related contexts. A comprehensive summary of the relationships between the geopark sites and RTRW spatial pattern categories, together with their planning implications, is presented in Table 7.

Table 7. RTRW spatial pattern relationship and planning relevance

Spatial relationship	Main planning meaning	Management implication
Protected or conservation-related areas	High ecological or heritage sensitivity	Conservation priority, visitor control, and carrying-capacity management
Water bodies and riverine landscapes	Water-based cultural and ecological functions	River-cultural interpretation and water-mobility planning
Tourism and settlement-related areas	Higher visitor-service potential	Controlled visitor services, interpretation facilities, and community-based tourism
Production forest or agricultural landscapes	Mixed land-use and livelihood context	Selective development and land-use compatibility review
Extractive or infrastructure-influenced spaces	Potential pressure on geoheritage values	Special management, monitoring, and planning control
Mixed-space relationships	Multiple overlapping spatial functions	Integrated zoning interpretation and cross-sector coordination

Source: Authors' GIS overlay based on official Meratus Geopark geosite data and South Kalimantan Provincial RTRW spatial pattern polygons 2023–2042.

To evaluate the relationship between Meratus Geopark sites and the regional spatial planning framework, geosite locations were overlaid with the Provincial Spatial Plan (RTRW) land-use categories. Figure 5 presents the distribution of geosites across the different planning zones, while Table 5 summarizes their planning implications. The results indicate that geosites intersect a wide range of spatial planning categories, with protected areas and water-related landscapes having high conservation significance. In contrast, tourism, settlement, and productive land-use zones provide greater opportunities for sustainable geotourism development under appropriate management. Overall, the findings highlight the need to integrate geoheritage conservation with statutory spatial planning to support balanced environmental protection and sustainable land use.

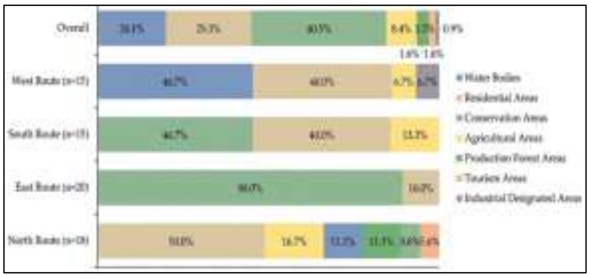

Fig 5. Composition of RTRW spatial pattern categories associated with Meratus Geopark sites, overall and by route. Source: Authors' calculation based on unique site–RTRW spatial pattern relationships.

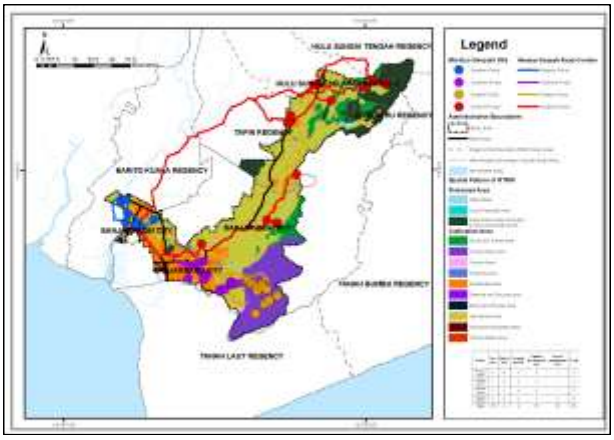

Fig 6. Spatial planning interface between Meratus Geopark sites and RTRW spatial pattern categories.

Source: Authors' GIS overlay based on geosite point data and RTRW spatial pattern polygons.

Figure 5 demonstrates that the distribution of geosites among RTRW categories varies substantially across routes, reinforcing the need for differentiated zoning strategies that accommodate multiple statutory land-use functions.

The spatial relationship between Meratus Geopark sites and the RTRW spatial pattern categories is illustrated in Figure 6.

Rather than simply illustrating spatial overlap, Figure 6 demonstrates how official geosite inventories can be translated into planning-relevant information by integrating them with statutory spatial planning categories.

3.5. GIS-Based Zoning Interpretation and Field-Survey Evidence

The synthesis of geosite distribution, KDE clustering, accessibility gradient, RTRW overlay, and sensitivity–suitability assessment produced five proposed zoning categories: core zone, buffer zone, geopark corridor, limited development zone, and special management zone. These categories do not replace formal RTRW zoning. They serve as analytical tools to support geopark planning and management.

The core zone refers to sites with high geoheritage or conservation significance where protection and controlled use are the main priorities. The buffer zone represents transitional areas that connect key geopark assets with local settlements and everyday land-use contexts. The geopark corridor refers to spaces where mobility, connectivity, and route-based experience are central. The limited development zone identifies areas suitable for controlled visitor services, interpretation, and local cultural economy. The special management zone refers to sites or landscapes where heritage value overlaps with extractive history, infrastructure pressure, or mixed spatial functions. Field-survey documentation collected in 2025 supports the interpretation of these proposed categories. Representative sites include the Kiram Bamboo Mosque Site as a core-area representation, the Traditional Herbal Medicine Village Site as a buffer-area representation, the Lok Baintan Floating Market as a geopark corridor, the Traditional Sasirangan Village Site as a limited development area, and the Nassau Oranje Mine and Tahura Meratus Geopark Information Center Site as special management area representations. These photographs provide contextual evidence of the physical and functional characteristics of each zoning category, although they should be read as representative documentation rather than statistical field samples. A comprehensive summary of the GIS-based zoning interpretation and the planning characteristics of each zone is presented in Table 8.

Table 8. GIS-based zoning interpretation of Meratus Geopark

Proposed zone	Main evidence	Planning meaning	Representative field-survey evidence
Core zone	High geoheritage or conservation significance	Protection and controlled use	Ancient Submarine Volcano Site / Kulit Ular Rock Site / Orchid Conservation Park Site
Buffer zone	Transitional settlement and local livelihood context	Interface between geopark assets and everyday local space	Belangian Village Site / Riam Kanan Lake Fisheries Site / Lakeside Stilt House Site
Geopark corridor	Mobility, connectivity, and route-based experience	Corridor for movement, interpretation, and spatial linkage	Lok Baintan Floating Market Site
Limited development zone	Accessibility, visitor services, and local cultural economy	Controlled development for interpretation and community-based services	Traditional Sasirangan Village Site / Kiram Bamboo Mosque Site / Traditional Herbal Medicine Village Site
Special management zone	Mixed heritage, extractive history, infrastructure, or complex spatial context	Specific management arrangement and monitoring	Oranje Nassau Mine Site / Cempaka Traditional Diamond Mining Site / Sacred Mosque Site

Source: Authors' GIS-based zoning interpretation derived from geosite inventory, accessibility analysis, RTRW overlay, sensitivity–suitability assessment, and field-survey documentation, 2025.

Building upon prior spatial suitability and accessibility analyses, a GIS-based zoning framework was established to delineate management priorities for the Meratus Geopark. This framework integrates geosite inventories, accessibility metrics, regional spatial planning (RTRW), environmental sensitivity, and field verification data. Consequently, distinct functional zones were defined to support geoconservation, sustainable tourism, and long-term territorial management, as illustrated in Figure 7.

Source: Authors' GIS-based zoning interpretation derived from geosite inventory, accessibility analysis, RTRW overlay, and sensitivity–suitability assessment.

Figure 7 shows that the proposed zoning framework represents a planning-oriented interpretation rather than a replacement for the statutory RTRW zoning system. The resulting zones integrate geoheritage significance with accessibility, environmental sensitivity, and spatial planning considerations.

Figure 8 presents selected field-survey documentation illustrating different management contexts within Meratus Geopark.

Figure 8 provides contextual field support for the GIS-derived zoning interpretation. The photographs illustrate differences in landscape setting, accessibility, visitor facilities, cultural functions, and surrounding land-use context among selected Meratus Geopark sites. The figure presents six field-survey examples observed in 2025: (a) Kiram Bamboo Mosque Site, (b) Traditional Herbal Medicine Village Site, and (d) Traditional Sasirangan Village Site as examples of limited development contexts; (c) Lok Baintan Floating Market Site as a geopark corridor associated with river-based mobility and cultural interpretation; and (e–f) Oranje Nassau Mine Site and Tahura Meratus Geopark Information Center Site as examples of sites requiring specific management, interpretation, or visitor-orientation considerations. These photographs provide site-level contextual evidence and should not be interpreted as a statistical sample of all 54 geosites. Source: Author's field survey documentation, 2025.

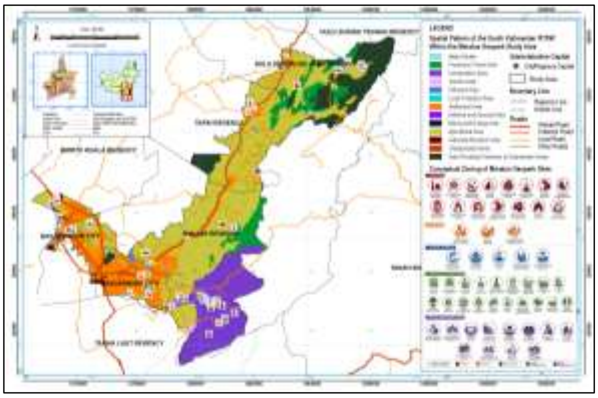

Fig 7. GIS-based zoning interpretation of Meratus Geopark sites.

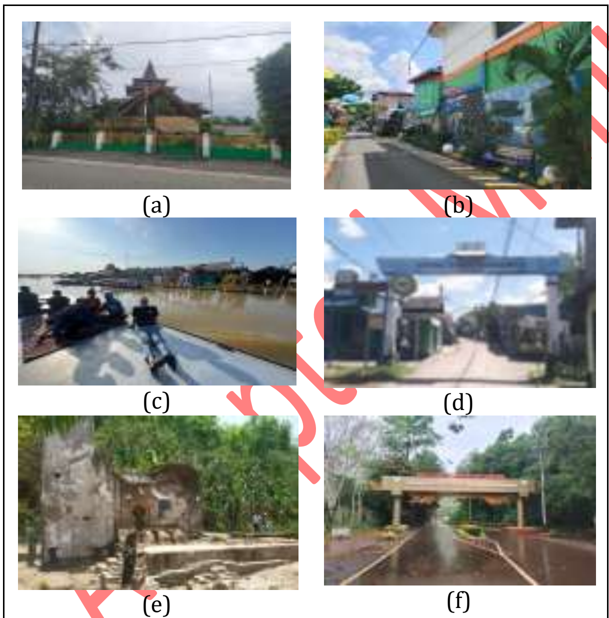

Fig 8. Field-survey documentation of selected Meratus Geopark sites illustrating different management contexts.

3.6. Route-Based Zoning Composition and Spatial Planning Interface

The route-based zoning composition shows that each route contains a distinct combination of spatial functions. The Western Route is mainly associated with corridor and limited development functions, reflecting its river-cultural and urban-service context. The Southern Route combines core and limited development functions, indicating a balance between conservation, interpretation, and visitor services. The Eastern Route contains the strongest concentration of core and buffer functions, consistent with its conservation and reservoir-lake setting. The Northern Route is dominated by special management and limited development functions, reflecting its peripheral upland context and higher management complexity. The route-level and overall distribution of the proposed zoning categories is summarized in Table 9.

Overall, the results show that Meratus Geopark functions as a spatial planning interface. The differentiated zoning composition across the four routes further demonstrates that geopark management cannot rely on a uniform planning strategy. Instead, route-specific priorities are required to balance conservation objectives, visitor management, infrastructure provision, and community development, based on local territorial characteristics. The geosite inventory provides the starting point, but the planning interpretation emerges only after combining clustering, accessibility, the RTRW overlay, a sensitivity–suitability assessment, and field-based contextual evidence. The final model indicates that geopark planning should differentiate between protected spaces, lived spaces, connectivity spaces, visitor-service spaces, and spaces requiring special management arrangements. The spatial distribution of these zoning categories across the four routes is illustrated in Figure 9. The figure should be read together with Table 9, because the table provides the numerical composition, while the figure highlights the proportional dominance of each zoning category by route.

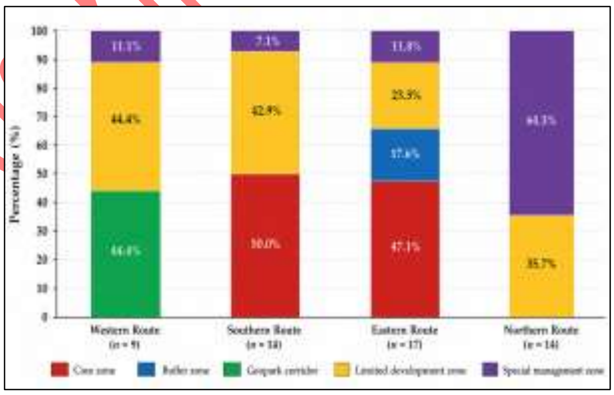

Fig 9. Route-based zoning composition of Meratus Geopark. Source: Authors' calculation based on GIS-based zoning interpretation and route classification.

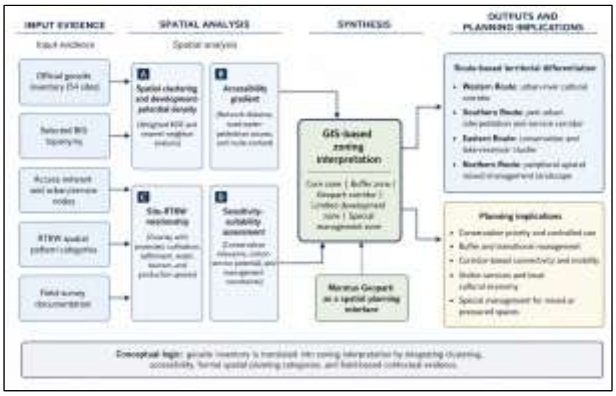

Fig 10. Conceptual model of Meratus Geopark as a spatial planning interface.

Figure 9 highlights substantial variation in zoning composition among the four routes, confirming that territorial differentiation constitutes a fundamental characteristic of Meratus Geopark planning.

The conceptual integration of these components into a spatial planning framework is illustrated in Figure 10. Source: Synthesized by the authors based on spatial clustering, accessibility gradient, RTRW overlay, mixed-space analysis, GIS-based zoning interpretation, and field-survey evidence.

Table 9. Overall composition of proposed zoning categories for Meratus Geopark

Proposed zoning category	WR n=9; (%)	SR n=14; (%)	ER n=17; (%)	NR n=14; (%)	Total sites	Total (%)	Main planning implication
Core zone	0;(0)	7;(50)	8;(47.1)	0;(0)	15	27.8%	Protection, controlled use, and conservation-oriented interpretation
Buffer zone	0;(0)	0;(0)	3;(17.6)	0;(0)	3	5.6%	Transitional management between geosites and community landscapes
Geopark corridor	4;(44.4)	0;(0)	0;(0)	0;(0)	4	7.4%	Route-based movement and spatial linkage
Limited development zone	4;(44.4)	6;(42.9)	4;(23.5)	5;(35.7)	19	35.2%	Controlled visitor services and local economic support
Special management zone	1;(11.1)	1;(7.1)	2;(11.8)	9;(64.3)	13	24.1%	Site-specific management and cross-sector coordination
Total	9;(100)	14;(100)	17;(100)	14;(100)	54	100%	Differentiated geopark zoning framework

Source: Authors' calculation based on GIS-based zoning interpretation of the 54 official Meratus Geopark sites.
WR: Western Route; SR: Southern Route; ER: Eastern Route and NR: Northern Route

Figure 10 summarizes the principal scientific contribution of this study by demonstrating how spatial clustering, accessibility analysis, RTRW overlay, and sensitivity–suitability assessment can be integrated into an operational GIS-based framework for geopark zoning and spatial planning.

Overall, these results indicate that the zoning structure of the Meratus Geopark does not rest on a single spatial category, but on a combination of protected spaces, lived spaces, connectivity spaces, visitor-service spaces, and spaces requiring specific management arrangements. This finding reinforces the view that geopark zoning should be read as a territorial synthesis rather than as a simple extension of tourism or conservation categories alone. To maintain the focus and concision of the main text, detailed site-level zoning allocations for each route are not presented here; the complete distribution is provided in Appendices A–D.

4. Discussion

The results show that the planning value of a geosite inventory emerges only when it is interpreted together with spatial concentration, accessibility, statutory land-use categories, field evidence, and management constraints. In the Meratus case, the official geosite list is not only a catalogue of heritage locations, but also an entry point for constructing a differentiated spatial planning interface. This finding supports the need to move beyond site-based inventory toward territorial interpretation in geopark planning.

The clustering analysis provides an important basis for this argument. The significant nearest-neighbor result and the weighted KDE surface indicate that the official geosites are not randomly distributed. However, the meaning of clustering in this study goes beyond the statistical concentration of points. Because the KDE incorporated selected toponymy, the density surface reflects the interaction between formal geosite locations and surrounding landscape names, hydrological features, cultural places, access-related elements, and geo-geomorphological contexts. This expands the conventional role of geosite inventories, which have often focused on identification, scientific value, and conservation assessment (Brilha, 2016). In the Meratus case, the inventory becomes more useful for planning when read alongside the territorial setting in which the sites are embedded. Unlike many previous international geopark studies, which generally applied GIS for geosite inventory, tourism suitability assessment, or geoheritage mapping as separate analytical tasks (Brilha, 2016; Ferreira and Valdati, 2022; Zhuang et al., 2024), the workflow proposed in this study integrates weighted kernel density estimation, accessibility analysis, statutory spatial planning overlay, and sensitivity–suitability assessment into a sequential planning framework. The scientific contribution therefore lies not in the individual GIS techniques themselves, but in their systematic integration to translate official geosite inventories into operational spatial planning evidence that can directly support zoning interpretation and territorial management.

This finding is broadly consistent with the view that geoparks integrate geoheritage protection, education, tourism, local development, and territorial governance (Dias et al., 2023; Zhuang et al., 2024). However, the Meratus case also shows that such integration is not spatially uniform. These route-specific differences demonstrate that development potential should be interpreted within its territorial context rather than being inferred solely from the spatial concentration of geosites. Its reservoir and conservation context require a more cautious approach to access, visitor pressure, and ecological sensitivity.

Accessibility further clarifies why route-based interpretation is necessary. The Western and Southern routes are closer to urban and peri-urban service systems. At the same time, the Northern Route depends on longer arterial and collector corridors, local roads, and last-mile access. Nevertheless, accessibility should not be interpreted as a simple justification for development. A highly accessible site may still require restrictions if it is culturally or ecologically sensitive.

In contrast, a less accessible site may require special support for safety, community access, or heritage protection. The inclusion of road, water, and pedestrian access is therefore important because Meratus Geopark contains riverine, upland, reservoir, and settlement-based mobility systems that cannot be captured by road distance alone. This supports more recent arguments that geopark management must balance visitor access, conservation, livelihood opportunities, and territorial governance (Dias et al., 2023; Henriques and Brilha, 2017). This finding also suggests that accessibility should be interpreted as a management variable rather than merely a transportation indicator. In geopark planning, improved accessibility may increase tourism opportunities while simultaneously intensifying ecological disturbance and visitor pressure. Consequently, accessibility analysis should be integrated with conservation priorities and spatial regulations to identify where infrastructure expansion is appropriate and where visitor access should remain limited.

The RTRW overlay provides a further contribution by connecting geopark interpretation with formal spatial planning. The analysis shows that Meratus sites intersect with conservation areas, water bodies, settlements, cultivation landscapes, production spaces, tourism areas, and mixed spatial contexts. This confirms that geopark zoning cannot be separated from the existing spatial planning regime (Ferdowsi and Németh, 2025; Zhuang et al., 2024). At the same time, RTRW categories alone are not sufficient to explain how geosite value, cultural meaning, access pressure, community function, and management risk should be handled together. Formal spatial categories can indicate regulatory context, but they do not automatically provide site-level management interpretation. The GIS-based zoning interpretation proposed in this study therefore acts as an analytical bridge between official planning categories and the practical needs of geopark management. This planning-oriented interpretation extends the role of conventional GIS overlay analyses, which typically identify spatial coincidence between geosites and land-use categories without explicitly translating these relationships into management recommendations. By integrating regulatory information with accessibility, spatial concentration, and environmental sensitivity, the proposed framework provides a more operational basis for planning decisions at both regional and site levels.

Field-survey documentation adds contextual support to this interpretation. The selected photographs do not function as a statistical sample. However, they help demonstrate that the proposed zones correspond to observable spatial functions: protected or high-value spaces, transitional community landscapes, mobility corridors, controlled visitor-service areas, and sites requiring specific management. This evidence strengthens the argument that zoning should be understood as a territorial synthesis, rather than simply as an extension of tourism or conservation zoning. In this sense, the study contributes to geopark scholarship by making the planning role of geosite inventories more operational. It shows that geosite data can be organized into a spatial interface that helps identify where conservation, interpretation, mobility, community-based services, and special management should be given different degrees of emphasis. Because the framework relies on readily available spatial datasets, it can also be transferred to other geoparks with different geological settings, governance systems, and planning contexts. However, the weighting scheme, accessibility criteria, and zoning thresholds should be recalibrated according to local geological characteristics, conservation priorities, statutory planning regulations, and socio-economic conditions before implementation.

The practical implication is that Meratus Geopark should avoid a uniform management strategy across all routes. The Western Route may prioritize river-cultural interpretation and water-based mobility; the Southern Route may support education, services, and controlled visitor facilities; the Eastern Route may require stronger conservation and carrying-capacity considerations; and the Northern Route may require selective intervention, field verification, safety management, and special arrangements for culturally or spatially sensitive sites. These implications should be read as planning guidance rather than legally binding zoning decisions. In practice, provincial and district governments may use the proposed zoning framework as supporting spatial information during the preparation or revision of regional spatial plans (RTRW), detailed spatial plans (RDTR), geopark management plans, and tourism development strategies. Geopark managers can also apply the framework to prioritize conservation measures, visitor management, infrastructure investment, and community-based tourism programs based on the spatial characteristics of each route, while remaining consistent with existing statutory planning regulations.

The workflow is transferable as an analytical structure because it relies on spatial datasets commonly available in many geopark regions, including geosite inventories, access networks, administrative boundaries, spatial planning layers, and field-based contextual evidence. However, transferability requires local calibration. KDE parameters, accessibility criteria, weighting values, and zoning thresholds should be adjusted to the geological setting, governance context, community conditions, and planning regime of each geopark.

Several limitations define the scope of this study. First, the design is spatial-analytical and does not test causal relationships among accessibility, land-use designation, geosite value, and development outcomes. The results therefore provide planning interpretation, not causal explanation. Second, the analysis relies on secondary spatial datasets that may differ in scale, positional accuracy, update period, and attribute completeness. Such differences may influence overlay results, network-distance estimates, and route-level classification. Third, the weighted KDE depends on selected parameters, including search radius and raster resolution, toponymy classification, and weighting rules. These choices were applied transparently, but different parameter settings may produce some variation in density patterns. In addition, the spatial resolution and quality of the input datasets may influence the analytical results. Differences in raster resolution, positional accuracy, network precision, and toponymy classification can introduce uncertainty into hotspot delineation, accessibility analysis, and spatial overlay, particularly when the framework is applied at finer planning scales. Fourth, accessibility analysis represents network structure rather than actual travel time, transport availability, road surface quality, seasonal water conditions, or visitor movement. Fifth, field photographs were used as representative contextual evidence, not as a statistically designed field sample of all 54 geosites.

Future research should therefore move in several targeted directions. Field-based validation should be expanded to verify site condition, access quality, safety constraints, conservation sensitivity, and visitor-service readiness. Participatory GIS involving local communities, geopark managers, planners, and tourism actors would help calibrate the proposed zoning interpretation and identify local meanings that may not appear in formal spatial datasets. Accessibility modeling should also incorporate travel time, road quality, public transport, seasonal river conditions, and visitor movement data. Finally, applying the same workflow to other Indonesian and international geoparks would test whether the proposed geosite-to-planning-interface approach is transferable across different territorial and governance contexts. Future applications across geoparks with different geological, environmental, and governance contexts would help evaluate the robustness and transferability of the proposed framework while refining its weighting scheme, zoning criteria, and planning indicators.

5. Conclusion

This study demonstrates that Meratus Geopark is more appropriately understood as a spatial planning interface than as a simple inventory of tourism sites. By integrating official geosite inventories with multiple GIS-based analytical components, the study demonstrates that geoheritage information can be systematically translated into planning-oriented spatial evidence that supports zoning interpretation beyond conventional inventory-based approaches. The four routes do not share a single planning logic: the Western Route functions as an urban-river cultural corridor, the Southern Route as a peri-urban interpretation and service corridor, the Eastern Route as a conservation and lake-reservoir cluster, and the Northern Route as a peripheral upland mixed-management landscape.

The main methodological contribution of this study is the development of an integrated GIS workflow for translating official geosite inventories into planning-relevant spatial evidence. By combining weighted KDE, accessibility analysis, RTRW overlay, sensitivity–suitability interpretation, and field-based contextual verification, the study shows how geosite data can support zoning interpretation beyond point-based inventory. The proposed zoning interpretation does not replace statutory spatial planning, but provides an analytical bridge between geoheritage data and practical planning decisions.

For Meratus Geopark, the findings indicate that planning priorities should be differentiated across route-based territorial contexts. Core and buffer zones require stronger conservation and visitor-control measures, corridor zones require mobility and interpretation planning, limited development zones require controlled visitor-service provision, and special management zones require site-specific monitoring and cross-sector coordination. Future research should expand field validation, include participatory assessment, and test the workflow in other geoparks with different geological and governance contexts.

CRediT authorship contribution statement

Rusdasopia Fahriani: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. Usman Firdaus: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Muhammad Yusuf Ridhani: Methodology, Investigation, Formal analysis, Validation, Writing – review & editing. Defin Leliana: Data curation, Visualization, Investigation, Formal analysis, Writing – review & editing. Kiky Permana Setiawan: Conceptualization, Methodology, Supervision, Validation, Project administration, Writing – review & editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Declaration of AI use

The authors used ChatGPT (OpenAI) as a language support tool during manuscript preparation to improve the clarity, structure, grammar, and readability of the text. The authors take full responsibility for all content, data interpretation, arguments, results, and conclusions presented in this manuscript. No AI tool was used to generate, analyze, or interpret the study data independently.

Acknowledgements

The authors would like to express their sincere appreciation to all scholars and researchers whose published works have provided important intellectual foundations and references for this study. The authors also acknowledge various scientific databases and literature sources that facilitated access to the references required for this research. Special appreciation is extended to the Department of Urban and Regional Planning, Faculty of Engineering, Muhammadiyah University of Banjarmasin, for its institutional support, academic facilities, and conducive scholarly environment that enabled the completion of this study. The authors are also grateful to all individuals and institutions who provided valuable assistance, insights, and support throughout the research and manuscript preparation process.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Adhi, Y., Dewi, I., Turisno, B., 2022. Ecological Impacts and Socio-Legal Infrastructure as an Approach to Environmental Management in Ex-Mining Land Reclamation. Int. J. Sustain. Dev. Plan. https://doi.org/10.18280/ijsdp.170729

Afkarina, K.I.I., Wardana, S., Damayanti, P., 2019. COAL MINING SECTOR CONTRIBUTION TO ENVIRONMENTAL CONDITIONS AND HUMAN DEVELOPMENT INDEX IN EAST KALIMANTAN PROVINCE. J. Environ. Sci. Sustain. Dev. https://doi.org/10.7454/jessd.v2i2.1025

Ansori, C., Warmada, I.W., Setiawan, N.I., Yogaswara, H., 2021. Geomorphosite Assessment at North Karangsambung -Karangbolong Geopark Kebumen, as Tools of Geotourism Development. J. Geosci. Eng. Environ. Technol. 6, 164–171. https://doi.org/10.25299/jgeet.2021.6.3.6753

Briggs, A., Newsome, D., Dowling, R., 2022. A proposed governance model for the adoption of geoparks in Australia. Int. J. Geoheritage Park. 10, 160–172. https://doi.org/10.1016/j.ijgeop.2021.12.001

Brilha, J., 2016. Inventory and Quantitative Assessment of Geosites and Geodiversity Sites: a Review. Geoheritage 8, 119–134. https://doi.org/10.1007/s12371-014-0139-3

Cahyadi, H.S., Newsome, D., 2021. The post COVID-19 tourism dilemma for geoparks in Indonesia. Int. J. Geoheritage Park. https://doi.org/10.1016/j.ijgeop.2021.02.003

Cahyadi, M., Aufa, N., 2022. PUSAT INFORMASI GEOPARK MERATUS DI BANJARBARU. J. TUGAS AKHIR Mhs. LANTING. https://doi.org/10.20527/jtamlanting.v11i1.1399

De Castro, E., Loureiro, F., Patrocinio, F., Gomes, H., Castel-Branco, J., Cezar, L., Fernandes, M., Azevedo, P., 2022. The Estrela UNESCO Global Geopark Territorial Development Strategy: A Holistic Vision for the Twenty-First Century. Tour. Hosp. Event Manag. https://doi.org/10.1007/978-3-030-89839-7_2
Dias, A., Robina-Ramírez, R., Sánchez, M.S.-O., 2023. Territorial planning and sustainable development—case study: Protected areas in the territory of the Aspiring West Geopark, Portugal 11. https://doi.org/10.3389/fenvs.2023.1132162
Dwipati, U., Ibrahim, M.A., Abdullah, M.T., 2025. Assessing and initiating collaborative governance for sustainable geotourism development: A case study of Maros-Pangkep Geopark in Indonesia. Edelweiss Appl. Sci. Technol. 9, 1406–1412. https://doi.org/10.55214/25768484.v9i5.7173
El Hamidy, M., Errami, E., 2025. The geosites of Safi province (Marrakech-Safi region, Morocco): Inventory and assessment for geoconservation, geotourism, geoeducation, geoparks, and local sustainable development. Int. J. Geoheritage Park. 13, 68–91. https://doi.org/10.1016/j.ijgeop.2025.01.001
Farsani, N., Coelho, C., Costa, C., 2010. Geotourism and geoparks as novel strategies for socio-economic development in rural areas. Int. J. Tour. Res. 13, 68–81. https://doi.org/10.1002/jtr.800
Ferdowsi, S., Németh, K., 2025. Geoparks Management in Tourism Destinations: Integrating Development and Conservation. Sustain. Dev. 34, 1034–1056. https://doi.org/10.1002/sd.70334
Ferreira, D.R., Valdati, J., 2022. Geoparks and Sustainable Development: Systematic Review. Geoheritage 15. https://doi.org/10.1007/s12371-022-00775-9
Frey, M.-L., 2021. Geotourism—Examining Tools for Sustainable Development. Geosciences. https://doi.org/10.3390/geosciences11010030
Gathot Harbowo, D., Siringoringo, L.P., 2025. Locating Geodiversity Hotspots through Grid-Based Spatial Indexing: Lombok Island, Indonesia. J. Geosci. Eng. Environ. Technol. 10, 215–223. https://doi.org/10.25299/jgeet.2025.10.02.18898
Gupta, V., Anand, S., Wei, D., Wang, G., Tripathi, S.C., 2024. Exploring applied sustainable strategies through geoheritage and geotourism: A systematic literature review. Int. J. Geoheritage Park. 12, 660–677. https://doi.org/10.1016/j.ijgeop.2024.11.009
Hafidhah Nurul Haq, Rosana, M.F., Endyana, C., Nugraha, K.S.A., Alamsyah, I., 2024. Geochemistry of Igneous Rocks of Citirem Formation and Its Implications for the Tectonic Setting in Ciletuh – Palabuhanratu UNESCO Global Geopark Area. J. Geosci. Eng. Environ. Technol. 9, 58–68. https://doi.org/10.25299/jgeet.2024.9.1.14367
Henriques, M., Brilha, J., 2017. UNESCO Global Geoparks: a strategy towards global understanding and sustainability. Episodes 40, 346–355. https://doi.org/10.18814/epiiugs/2017/v40i4/017036
Indonesia, P.K.S., 2023. Perda Kalsel Th 2023 No 6 (1).
Iukhno, A., Knyaz, O., Sadovyy, I., Hrek, M., 2025. Comprehensive spatial development plan as basis for urban territorial planning, forecasting and land use. Actual Probl. Innov. Econ. law. https://doi.org/10.36887/2524-0455-2025-4-10
Khan, M., Chen, R., 2025. Assessing the Impact of Land Use and Land Cover Change on Environmental Parameters in Khyber Pakhtunkhwa, Pakistan: A Comprehensive Study and Future Projections. Remote Sens. https://doi.org/10.3390/rs17010170
Lee, Y., Jayakumar, R., 2021. Economic impact of UNESCO Global Geoparks on local communities: Comparative analysis of three UNESCO Global Geoparks in Asia. https://doi.org/10.1016/j.ijgeop.2021.02.002
Lestari, F., Indrayati, I., 2022. Pengembangan Kelembagaan dan Pembiayaan Geopark di Indonesia: Tantangan dan Strategi. J. Reg. Rural Dev. Plan. https://doi.org/10.29244/jp2wd.2022.6.2.102-122
Magriaty, R., 2025. Strategi Pengembangan Pariwisata Kawasan Geopark Meratus Provinsi Kalimantan Selatan, Studi Kasus: Kecamatan Piani Kabupaten Tapin. J. Reg. Rural Dev. Plan. https://doi.org/10.29244/jp2wd.2025.9.1.87-111
Martínez-Martín, J.E., Mariñoso, P.E., Rosado-González, E., Sá, A., 2023. UNESCO Global Geoparks vs. Education: a 10-Year Bibliometric Analysis. Geoheritage 15. https://doi.org/10.1007/s12371-023-00802-3
Mo, J., Sun, P., Shen, D., Li, N., Zhang, J., Wang, K., 2023. Simulation Analysis of Land-Use Spatial Conflict in a Geopark Based on the GMOP–Markov–PLUS Model: A Case Study of Yimengshan Geopark, China. Land 12. https://doi.org/10.3390/land12071291
Naydenov, K., 2022. GEOPARKS AS A BASIS FOR THE INTEGRATED CONSERVATION OF ECOSYSTEMS, CULTURAL HERITAGE, AND DEVELOPMENT OF ECOTOURISM, in: SGEM International Multidisciplinary Scientific GeoConference� EXPO Proceedings. https://doi.org/10.5593/sgem2022/5.1/s20.026
Nikolova, V., Sinnyovsky, D., 2018. Geoparks in the legal framework of the EU countries. Tour. Manag. Perspect. https://doi.org/10.1016/j.tmp.2018.11.007
Popa, R., Popa, D.-A., Andrășanu, A., 2017. The SEA and Big-S Models for Managing Geosites as Resources for Local Communities in the Context of Rural Geoparks. Geoheritage 9, 175–186. https://doi.org/10.1007/s12371-016-0192-1
Qi, W., Hu, Y., Zhong, L., Hui, W., 2023. Optimising the relationship between ecological protection and human development through functional zoning. Biol. Conserv. https://doi.org/10.1016/j.biocon.2023.110001
Quesada-Valverde, M., Quesada-Román, A., 2023. Worldwide Trends in Methods and Resources Promoting Geoconservation, Geotourism, and Geoheritage. Geosciences. https://doi.org/10.3390/geosciences13020039
Rahmatin, L.S., Nawangsari, E.R., 2025. Analysis of Sustainable Tourism Development in the Ijen UNESCO Global Geopark Area. E-Journal Tour. https://doi.org/10.24922/eot.v12i1.124262
Ristiawan, R., Huijbens, E., Peters, K., 2023. Projecting Development through Tourism: Patrimonial Governance in Indonesian Geoparks. Land 12. https://doi.org/10.3390/land12010223
Sahara, R., Setiawan, B., 2022. Assessment of Geosite and Geomorphosite at South Solok Aspiring Geopark Area. J. Geosci. Eng. Environ. Technol. 7, 110–116. https://doi.org/10.25299/jgeet.2022.7.3.9520
Shen, F., Yang, L., Zhang, L., Guo, M.-Y., Huang, H., Zhou, C., 2022. Quantifying the direct effects of long-term dynamic land use intensity on vegetation change and its interacted effects with economic development and

climate change in jiangsu, China. J. Environ. Manage. 325 Pt B, 116562. https://doi.org/10.1016/j.jenvman.2022.116562
Shi, Y., Gao, H., Tan, S., Qin, H., Tian, Z., Meng, J., Zheng, X., 2024. Pattern change and ecological risk analysis of Shilin World Geopark landscape. Front. Ecol. Evol. https://doi.org/10.3389/fevo.2024.1341969
Shiri, Z., Le, Q.B., Ouerghemmi, H., Rejeb, H., 2025. Landscape approaches for sustainable land systems: A critical systematic review of frameworks, governance, and socio-ecological outcomes. Landsc. Archit. Sustain. 2, 100007. https://doi.org/10.1016/j.las.2025.100007
Sobhani, P., Esmaeilzadeh, H., Sadeghi, S.M.M., Marcu, M. V, 2022. Estimation of Ecotourism Carrying Capacity for Sustainable Development of Protected Areas in Iran. Int. J. Environ. Res. Public Health 19. https://doi.org/10.3390/ijerph19031059
Štrba, Ľ., Vravcová, A., Podoláková, M., Varcholová, L., Kršák, B., 2023. Linking Geoheritage or Geosite Assessment Results with Geotourism Potential and Development: A Literature Review. Sustainability. https://doi.org/10.3390/su15129539
Sulistyadi, Y., Demolingo, R.H., Latif, B.S., Indrajaya, T., Adnyana, P.P., Wiweka, K., 2024. The Implementation of Integrated Coastal Management in the Development of Sustainability-Based Geotourism: A Case Study of Olele, Indonesia. Sustain. 16. https://doi.org/10.3390/su16031272
Syaban, A.S.N., Appiah-Opoku, S., 2024. Unveiling the Complexities of Land Use Transition in Indonesia's New Capital City IKN Nusantara: A Multidimensional Conflict Analysis. Land 13. https://doi.org/10.3390/land13050606
Meratus Geopark, 2023. Meratus Geopark. Indonesian Geoparks Network. Available at: https://meratusgeopark.org/overview/?lang=en.
Utama, H.W., Heriberta, H., Adriadi, A., Emilia, 2025. Geodiversity on the Great Sumatran Fault on Sungai Penuh Aspiring for the Geopark Designation, Jambi, Indonesia. J. Geosci. Eng. Environ. Technol. 10, 376–387. https://doi.org/10.25299/jgeet.2025.10.3.16610
Varriale, R., Genovese, L., Aldighieri, B., 2022. "Diffused Geoparks": Territorial Integration as Solution for a Shared Sustainable Growth Based on Geotourism in Italy, Japan and Tunisia. Heritage 5, 2083–2105. https://doi.org/10.3390/heritage5030109
Wibisono, R.R.S.F., Mahreda, E.S., Biyatmoko, D., Hafiziannor, H., 2023. Analisis Kesesuaian Rtrw Pada Bidang Pertambangan Berdasarkan Rtrwp Kalimantan Selatan Dan Rtrwk Di Kabupaten Tapin. EnviroScienteae 19, 112. https://doi.org/10.20527/es.v19i4.17816
Yanbo, Q., Shilei, W., Yaya, T., Guanghui, J., Tao, Z., Liang, M., 2023. Territorial spatial planning for regional high-quality development – An analytical framework for the identification, mediation and transmission of potential land utilization conflicts in the Yellow River Delta. Land use policy. https://doi.org/10.1016/j.landusepol.2022.106462
Zhuang, A., Stoffelen, A., Meijles, E., Groote, P., 2024. The complex governance of protected areas: Insights from geoheritage and geopark management in China. Environ. Policy Gov. 34, 679–690. https://doi.org/https://doi.org/10.1002/eet.2118

Appendices

Appendix A. Site-level zoning interpretation for the Western Route of Meratus Geopark

No.	Geopark site	Administrative setting	RTRW spatial pattern	Suggested zoning class	Planning rationale
1	Floating Sasirangan Gallery Site	Sungai Jingah, North Banjarmasin, Banjarmasin City	Water bodies/settlement area	Limited development zone	A river-oriented cultural and creative-economy site where visitor use can be supported through small-scale interpretation and community-based services.
2	Traditional Sasirangan Village Site	Sungai Jingah, North Banjarmasin, Banjarmasin City	Settlement area	Limited development zone	A living cultural-production settlement that is suitable for controlled interpretation, craft-based learning, and local economic activities.
3	Curiak Bekantan Conservation Site	Marabahan Baru, Anjir Muara, Barito Kuala Regency	Agricultural area / industrial allocation area	Special management zone	A faunal conservation location situated within a mixed cultivation and allocation context, requiring site-specific safeguards and coordination.
4	Wasaka Museum Site	Sungai Jingah, North Banjarmasin, Banjarmasin City	Settlement area	Limited development zone	An urban heritage and educational node that can accommodate interpretation functions within an already built-up environment.
5	Lok Baintan Floating Market Site	Lok Baintan, Sungai Tabuk, Banjar Regency	Water bodies/settlement area	Geopark corridor	A river-based cultural landscape where mobility, trade, tourism experience, and everyday settlement life form the main spatial logic.
6	Coal Barge Viewpoint Site	Beringin, Alalak / Marabahan Baru, Anjir Muara	Water bodies	Geopark corridor	A waterway-viewing location that represents river connectivity and visual interpretation of the broader fluvial landscape.
7	Sewangi Traditional Boatbuilding Site	Pulau Sewangi, Alalak, Barito Kuala Regency	Water bodies/settlement area	Limited development zone	A traditional riverbank production site where cultural interpretation and local livelihood activities can be accommodated at limited intensity.
8	Kembang Island Site	Pulau Alalak, Alalak, Barito Kuala Regency	Water bodies	Geopark corridor	A river-island site that functions as a movement, visitation, and interpretation point within the western water-based corridor.
9	Traditional Banjar House Site	Seberang Mesjid, Central Banjarmasin, Banjarmasin City	Water bodies/settlement area	Geopark corridor	A riverside cultural-heritage site embedded in a historic urban-river network and connected to corridor-based interpretation.

Source for Appendices: Authors' synthesis from the Meratus Geopark site–RTRW overlay dataset and South Kalimantan Provincial Regulation No. 6/2023 concerning the Provincial Spatial Plan 2023–2042

Appendix B. Site-level zoning interpretation for the Southern Route of Meratus Geopark

No.	Geopark site	Administrative setting	RTRW spatial pattern	Suggested zoning class	Planning rationale
1	Kulit Ular Rock Site	East Mandiangin, Karang Intan, Banjar Regency	Conservation area	Core zone	A geologically important site located within a protected spatial context, making conservation and controlled access the primary concern.
2	Endemic Wildlife Habituation Site	East Mandiangin, Karang Intan, Banjar Regency	Conservation area	Core zone	An ecologically sensitive site where habitat protection and low-impact visitation should

No.	Geopark site	Administrative setting	RTRW spatial pattern	Suggested zoning class	Planning rationale
					dominate management decisions.
3	Traditional Herbal Medicine Village Site	South Loktabat, South Banjarbaru, Banjarbaru City	Settlement area	Limited development zone	A community-based cultural and productive site suitable for interpretation, local knowledge promotion, and controlled visitor activities.
4	Kiram Bamboo Mosque Site	Kiram, Karang Intan, Banjar Regency	Agricultural area	Limited development zone	A religious-cultural landmark in a cultivation landscape, appropriate for managed visitation rather than strict core-zone protection.
5	Prince Suryanata Legend Monument Site	Kiram, Karang Intan, Banjar Regency	Conservation area / agricultural area	Core zone	A culturally significant site located in a mixed spatial setting where heritage protection should guide visitor use.
6	Lambung Mangkurat Museum Site	Komet, North Banjarbaru, Banjarbaru City	Settlement area	Limited development zone	An urban education and interpretation facility that supports geopark knowledge dissemination within a service-oriented area.
7	Sultan Adam Tahura Peak Viewpoint Site	East Mandiangin, Karang Intan, Banjar Regency	Conservation area	Core zone	A protected scenic landscape where high landscape value and ecological sensitivity require controlled use.
8	Purun Handicraft Site	Palam, Cempaka, Banjarbaru City	Settlement area	Limited development zone	A cultural-craft site within a settlement context, suitable for local economic support and low-intensity visitor engagement.
9	Cempaka Traditional Diamond Mining Site	Sungai Tiung, Cempaka, Banjarbaru City	Settlement area	Special management zone	An extractive-heritage site in a built-up context that requires careful interpretation, safety control, and management oversight.
10	Mandiangin Dutch Rest House Site	East Mandiangin, Karang Intan, Banjar Regency	Conservation area	Core zone	A historical structure within a protected landscape, requiring conservation-oriented interpretation and restricted development intensity.
11	Tahura Meratus Geopark Information Center Site	East Mandiangin, Karang Intan, Banjar Regency	Conservation area	Core zone	A principal orientation and interpretation node located inside a conservation setting, requiring visitor management aligned with protection goals.
12	Tropical Rain Garden Site	Cempaka, Banjarbaru City	Settlement area	Limited development zone	An educational and recreational facility that can support controlled public learning activities within a settlement environment.
13	Orchid Conservation Park Site	East Mandiangin, Karang Intan, Banjar Regency	Conservation area	Core zone	A conservation-focused site with specific ecological value and sensitivity, making protection and careful access regulation necessary.
14	Sasirangan Shop Site	Cempaka, Banjarbaru City	Settlement area	Limited development zone	A cultural-economic support site that contributes to visitor services and local product circulation at limited development intensity.

Source for Appendices: Authors' synthesis from the Meratus Geopark site–RTRW overlay dataset and South Kalimantan Provincial Regulation No. 6/2023 concerning the Provincial Spatial Plan 2023–2042

Appendix C. Site-level zoning interpretation for the Eastern Route of Meratus Geopark

No.	Geopark site	Administrative setting	RTRW spatial pattern	Suggested zoning class	Planning rationale
1	Sirang Island Archaeological Site	Belangian, Aranio, Banjar Regency	Conservation area	Core zone	An archaeological site within a protected landscape where heritage safeguarding should take precedence over intensive use.
2	Sei Kambang Schist Rock Site	Aranio, Aranio, Banjar Regency	Conservation area/settlement area	Core zone	A geologically significant site whose scientific value remains central despite its mixed conservation–settlement setting.
3	Diamond-Bearing Sandstone Site	Kalaan, Aranio, Banjar Regency	Conservation area	Core zone	A geological site in a protected area that requires conservation-oriented interpretation and limited disturbance.
4	Riam Kanan Dam Site	Tiwingan Lama, Aranio, Banjar Regency	Conservation area	Limited development zone	A water-infrastructure site that also functions as a visitation and interpretation point, requiring controlled service provision.
5	Matang Kaladan Hill Site	Tiwingan Lama, Aranio, Banjar Regency	Conservation area	Core zone	A high-value scenic and geological landscape where sensitivity and visitor pressure need careful management.
6	Belangian Village Site	Belangian, Aranio, Banjar Regency	Conservation area/settlement area	Buffer zone	A local living space that mediates between protected geosites, settlement activity, and community-based geopark functions.
7	Ancient Submarine Volcano Site	Tiwingan Baru, Aranio, Banjar Regency	Conservation area	Core zone	A major geoheritage site with strong scientific significance, making protection and controlled interpretation essential.
8	Kahung Tropical Rainforest Site	Belangian, Aranio, Banjar Regency	Conservation area	Core zone	A high-ecological-value rainforest site located in a protected landscape and requiring strict conservation attention.
9	Tiwingan Hill Landslide Trace Site	Tiwingan Lama, Aranio, Banjar Regency	Conservation area	Core zone	A geomorphological feature with strong interpretive value and a protected spatial setting.
10	Submerged Sacred Tomb Site	Belangian, Aranio, Banjar Regency	Conservation area	Special management zone	A spiritual-memory site in an inundated landscape, requiring sensitive management beyond ordinary tourism zoning.
11	Submerged Settlement Site	Belangian, Aranio, Banjar Regency	Conservation area	Special management zone	A memory landscape associated with spatial transformation and displacement, requiring culturally sensitive interpretation.
12	Riam Kanan Lake Fisheries Site	Tiwingan Lama, Aranio, Banjar Regency	Conservation area	Buffer zone	A local livelihood activity within the reservoir landscape that supports transition between conservation and community use.
13	Ba'ah Silent Witness Tree Site	Belangian / Pa'au, Aranio, Banjar Regency	Conservation area	Core zone	A symbolic and ecological site whose value is linked to both natural heritage and collective memory.

No.	Geopark site	Administrative setting	RTRW spatial pattern	Suggested zoning class	Planning rationale
14	Bekantan Island Site	Tiwingan Baru, Aranio, Banjar Regency	Conservation area	Limited development zone	An interpretive island site where visitation may be allowed under controlled conditions within the lake landscape.
15	Pinus Island Site	Tiwingan Baru, Aranio, Banjar Regency	Conservation area	Limited development zone	A nature-based visitation point that requires limited-use management due to its protected setting.
16	Ulin Island Site	Tiwingan Lama, Aranio, Banjar Regency	Conservation area	Limited development zone	A controlled nature-visitation site within the reservoir landscape, appropriate for low-intensity interpretation.
17	Lakeside Stilt House Site	Tiwingan Lama, Aranio, Banjar Regency	Conservation area	Buffer zone	A lakeside settlement feature that represents socio-ecological transition between local life and protected landscapes.

Source for Appendices: Authors' synthesis from the Meratus Geopark site–RTRW overlay dataset and South Kalimantan Provincial Regulation No. 6/2023 concerning the Provincial Spatial Plan 2023–2042

Appendix D. Site-level zoning interpretation for the Northern Route of Meratus Geopark

No.	Geopark site	Administrative setting	RTRW spatial pattern	Suggested zoning class	Planning rationale
1	Kilat Api Waterfall Site	Hulu Banyu, Loksado, Hulu Sungai Selatan Regency	Production forest area	Special management zone	A sensitive natural attraction located in a production landscape, requiring site-specific control and environmental safeguards.
2	Bamboo Raft Whitewater Rafting Site	Loksado, Hulu Sungai Selatan Regency	Settlement area	Limited development zone	A community-based tourism activity that can support local services when visitor intensity and safety are managed.
3	Malaris Customary Hall Site	Lok Lahung, Loksado, Hulu Sungai Selatan Regency	Settlement area	Special management zone	A customary site with high cultural sensitivity, requiring respectful interpretation and locally grounded management.
4	Kalayangan Dandang Dengung Village Site	Kupang, North Tapin, Tapin Regency	Settlement area	Limited development zone	A cultural village that can function as an interpretation node within a living settlement context.
5	Kandangan Dodol Site	Telaga Bidadari, Sungai Raya, Hulu Sungai Selatan Regency	Settlement area	Limited development zone	A local-product and identity-based site that supports cultural economy and controlled visitor engagement.
6	Batu Hapu Cave Site	Batu Hapu, Hatungun, Tapin Regency	Settlement area	Limited development zone	A visitor-oriented cave site connected to local service functions and requiring managed access.
7	Sacred Mosque Site	Banua Halat Kiri, North Tapin, Tapin Regency	Settlement area	Special management zone	A religious-historical site where cultural sensitivity and visitor conduct require specific management arrangements.
8	Tanuhi Hot Spring Site	Hulu Banyu, Loksado, Hulu Sungai Selatan Regency	Settlement area	Special management zone	A geothermal-related resource and visitor site requiring attention to safety, resource protection, and use intensity.
9	Bukit Kantawan Viewpoint Site	Lumpangi, Loksado, Hulu Sungai Selatan Regency	Conservation area	Special management zone	A scenic site in a protected landscape where visitor access and ecological

No.	Geopark site	Administrative setting	RTRW spatial pattern	Suggested zoning class	Planning rationale
					sensitivity must be closely controlled.
10	Bukit Langgara Viewpoint Site	Lumpangi, Loksado, Hulu Sungai Selatan Regency	Tourism area	Special management zone	A nature-tourism location that requires management of visitor intensity, landscape protection, and site capacity.
11	Bubungan Tinggi and Gajah Baliku Traditional House Site	Teluk Selong Ulu, West Martapura, Banjar Regency	Settlement area	Limited development zone	A traditional-house heritage site embedded in a living cultural landscape and suitable for controlled interpretation.
12	Tanjung Formation Coal Outcrop Site	Sungai Langsat / Sungai Raya, Simpang Empat, Banjar Regency	Agricultural area	Special management zone	A geological feature in a cultivation landscape, requiring interpretation that accounts for surrounding land-use pressures.
13	Oranje Nassau Mine Site	Pengaron, Banjar Regency	Production forest area/settlement area	Special management zone	An extractive-heritage site in a mixed spatial context, requiring historical interpretation, safety consideration, and monitoring.
14	Batu Laki Limestone Cliff Site	Batu Laki / Malutu, Padang Batung, Hulu Sungai Selatan Regency	Water bodies / agricultural area	Special management zone	A geological landscape located in a mixed and sensitive setting, requiring careful access and site-specific management.

Source for Appendices: Authors' synthesis from the Meratus Geopark site–RTRW overlay dataset and South Kalimantan Provincial Regulation No. 6/2023 concerning the Provincial Spatial Plan 2023–2042.