

DESIGNING A WEB-BASED INFORMATION SYSTEM FOR MEASURING SUSTAINABLE TOURISM PERFORMANCE IN KARST CAVE GEOTOURISM OF INDONESIA

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Abstract: Karst cave geotourism in Indonesia faces serious threats due to uncontrolled tourism pressure on vulnerable ecosystems. The lack of a data-driven management system leads to environmental degradation, tourist safety risks, and a decline in destination quality. This research aims to design a digital information system to measure tourism performance sustainably, with a case study of Jomblang Cave in Yogyakarta, Indonesia. Its contribution is to present a digital solution to monitor aspects of safety, enjoyment, and support decision-making in sustainable tourism governance. This research uses mixed methods with quantitative and qualitative approaches, and develops an information system based on the Waterfall-type System Development Life Cycle (SDLC) model through the stages of analysis, design, and implementation. Analysis was conducted using Use Case Diagram (UCD), Entity Relationship Diagram (ERD), and Data Flow Diagram (DFD) to design a system that meets the needs. The system can automatically calculate geosite performance values using the Modified Geosite Assessment Model (M-GAM) method, including two additional variables, namely safety and enjoyment. The web-based Jomblang Cave tourist attraction performance measurement information system consists of a home page, a questionnaire, and an assessment matrix that allows users to provide assessments, while the admin and owner monitor the results based on automatically processed inputs. The implementation phase maps the data of 32 tourists and six experts into the M-GAM Matrix, and calculates the MV and AV values to determine the Z-index position. The system automatically generates evaluative recommendations based on the lowest scores and has performed as expected as an evaluation and decision-making tool in tourism management. This research presents a real-time and easily accessible system for measuring tourist attraction performance. The system generates MV 6.37 and AV 16.09, placing the Z-index at a medium level (Z22). The automated system detected major weaknesses in the Education (VSE = 1.82) and functionality (VF_n = 2.87) factors, especially regarding cave protection and tourist safety. Automated recommendations allow managers to focus on improving critical areas and support strategic decisions for geotourism development.

Keywords: geotourism, information system, M-GAM, safety, enjoyment, Jomblang Cave, sustainable tourism

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INTRODUCTION

Karst cave ecosystems in Indonesia face significant pressure due to the development of geotourism that is not matched by an adequate management system (Aly et al., 2021; Kurniati et al., 2020; Putri et al., 2021; Sunkar et al., 2022). Uncontrolled tourism activities have led to speleothem degradation, groundwater pollution, disturbance of endemic fauna, and changes in underground microclimates that threaten ecological balance (Chiarini et al., 2022; Mammola et al., 2022). With more than 2,700 cave mouths and at least 268 of them worth visiting, Indonesia holds tremendous geotourism potential. However, without data-driven management, these potential risks could backfire.

Previous studies point to weak governance, lack of environmental Education programs, lack of adaptive infrastructure, and the absence of long-term monitoring systems as the main obstacles to sustainable geotourism development (Herrera-Franco et al., 2020). In addition, cave tourism is a high-risk category that demands serious attention to the safety aspects of tourists. A clear example can be found in the Sangkulirang-Mangkalihat karst area, where uncontrolled tourist activities have caused damage to cave structures and a decline in their ecological functions (Sunkar et al., 2022).

In the context of managing karst geotourism destinations, a performance evaluation system is needed that is not only normative but also provides quantifiable data and can be monitored regularly. Measurement of tourism sustainability achievements is crucial to ensure that tourism activities are in line with long-term ecological, social, and economic

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principles (Kokinou et al., 2023; Shen et al., 2024). However, conventional approaches based on manual observation and static reporting have proven to be unable to respond to the rapid dynamics in the field (UNWTO, 2024). Therefore, an adaptive, objective, and digital-based assessment model is needed to strengthen evidence-based governance.

In recent years, several studies have explored digital transformation in tourism monitoring systems. Hoffmann et al. (2022) introduced an online data-driven framework for measuring sustainability indicators in real time using digital platform analytics. Rahmadian et al. (2022) developed a digital twin model integrating IoT and big data to monitor environmental impacts and visitor behaviors dynamically in natural tourism areas. Meanwhile, Zhang & Deng (2024) proposed a smart ecotourism model that integrates artificial intelligence and real-time data governance for sustainability assessment. These studies collectively demonstrate the potential of digital technologies to enhance the precision and adaptability of tourism monitoring. However, they remain generic in scope and have not yet been applied to fragile geotourism contexts such as karst caves, which require specialized sustainability indicators and participatory governance frameworks.

The Modified Geosite Assessment Model (M-GAM), as an extension of the GAM method, provides an evaluation framework capable of integrating objective and subjective values of a geosite (Cvetanović et al., 2024). In this study, M-GAM was further modified by including two additional variables of safety and enjoyment to address the real challenges in managing disaster-prone karst cave destinations (Kusuma et al., 2025). Jomblang Cave, as a case study, is a combination of vertical and horizontal caves that demands technical readiness of tourists and managers, and contains anthropogenic risks such as negligence and lack of safety Education. To optimize the application of these methods, a web-based digital information system was developed that enables automatic data collection and analysis. The system was built using the System Development Life Cycle (SDLC) Waterfall approach to ensure systematic development, from the needs analysis to the implementation stage (Saravanos & Curinga, 2023). With digital integration, the evaluation process becomes more efficient and accurate, enabling immediate assessment of the performance of tourist destinations based on inputs from tourists and experts.

In addition to improving monitoring efficiency, the system is also designed to facilitate multi-stakeholder participation of managers, experts, tourists, and local communities in an inclusive and adaptive conservation process (Bekele et al., 2025). It enables visualization of dynamic indicators and early detection of risks of environmental degradation and disruption to the quality of the tourist experience. While recent studies (Hoffmann et al., 2022; Rahmadian et al., 2023; Zhang & Deng, 2024) have proven the advantages of digital systems for monitoring sustainability, they have not yet been combined with geosite-specific evaluation frameworks such as M-GAM or applied in participatory models involving multiple stakeholders. This study therefore bridges that gap by integrating digitalization and M-GAM-based assessment within a single web-based system designed for karst cave geotourism. Accordingly, the main objectives of this study are threefold: (1) to design and develop a web-based information system for measuring sustainable tourism performance in karst cave geotourism using the Waterfall model; (2) to integrate M-GAM indicators expanded with safety and enjoyment into a digital evaluation platform; and (3) to analyze the practical challenges and managerial opportunities that arise from implementing the system in a real-world karst cave setting. Based on this urgency, this research aims to answer two main questions: (1) How can the digitalization system of measuring sustainable tourism achievements in karst destinations be implemented effectively? (2) What are the challenges and opportunities that arise in managing the sustainability of karst geotourism based on the results of measuring achievements? By answering these questions, the research not only contributes to the development of an operational web-based M-GAM framework but also provides an empirical foundation for replicating sustainable, participatory digital monitoring systems in other karst cave destinations across Indonesia.

LITERATURE REVIEW

The distribution of Karst in Indonesia

Most karst areas are composed of carbonate rocks, and almost none are composed of other rocks such as gypsum, mudstone, or evaporite rocks (Covington et al., 2023). Almost all islands in Indonesia have carbonate rocks, but not all of them are classified as karst areas (Haryono et al., 2004; Zamroni et al., 2023). Karst in Indonesia is spread across most of the islands, although the level of development varies. Of these areas, Maros-Pangkep and Gunung Sewu are often considered as prototypes of tropical karst (Sumarga et al., 2024; UNESCO, 2023; Zamroni et al., 2023).

Maros Karst is characterized by the development of Karst Towers (Mogote), which are positive formations with relatively high rock walls (Flora & Fauna International, 2023; UNESCO, 2023). The vertical height from sea level ranges from 300 to 550 meters, while the relief varies between 100 to 250 meters. The limestone in Maros karst was deposited during the Eocene. The total area of Maros karst reaches 650 km², with intikarst around 300 km² (Flora & Fauna International, 2023; UNESCO, 2023). Gunung Sewu Karst is characterized by the development of karst domes (Karst Kegle), which are positive formations that are blunt, not steep, or often called sinusoidal domes (UNESCO, 2025). Vertical heights range from 300 - 500 meters above sea level, and reliefs vary between 50 to 150 meters. The limestone in the Gunung Sewu Karst is Miocene in age and has been karstified since the Late Pliocene to Early Pliocene Reinhart et al. (2023). Gunung Sewu Karst is also characterized by doline formations that are always filled with water every rainy season, which are then called ponds, which number in the hundreds. The area of Gunung Sewu karst reaches 3300 km², covering the provinces of Yogyakarta, Central Java, and East Java (UNESCO, 2025).

The Uniqueness of Karst Cave Landscape and Geotourism: Jomblang Cave Case Study

A karst area is one of the most amazing and complex geological landscapes in the world. Karst landscapes have a high value of beauty and uniqueness, both on the surface (exokarst) and below the surface (endokarst) (Walker & Louys, 2024).

On the surface, karst landscapes are dotted with thousands of towering karst domes or towers, occasionally interspersed with steep canyons, dolines, and doline lakes. Where karst areas border the sea, cliffs are formed that enhance their visual charm. Beauty is not limited to the surface. Below ground, karst cave systems reveal remarkable geological structures with speleothem ornaments such as stalactites, stalagmites, flowstones, and columns formed through thousands of years of geochemical processes. These caves can be vertical, horizontal, or a combination of both, with ornaments that vary greatly in shape, color, and size (Zerga, 2024). Quite often, the caves have large chambers and underground rivers with natural dams, where the underground space can reach hectares even though the diameter of the cave mouth is only one to two meters. One of the most spectacular representations of the beauty and complexity of karst landscapes in Indonesia is Jomblang Cave, located in the Gunungsewu karst region of Yogyakarta. The area has been recognized as a UNESCO Global Geopark since 2015, and covers karst landscapes from Gunungkidul to Pacitan. Distinctive geological characteristics such as limestone hills, cliffs, caves, underground rivers, waterfalls, and basins form an extraordinary karst ecosystem that is important for conservation and educational geotourism.

Karst Geotourism Development Strategy

The development of karst geotourism plays a crucial role in encouraging sustainable regional development by increasing geological literacy and promoting environmental ethical values (Vasconcelos et al., 2023). The development strategy of karst geotourism is based on three main dimensions: Education, socioeconomics, and conservation (Roig et al., 2023). Successful management of karst areas relies heavily on the active involvement of local communities, facilitated by synergies between government authorities, educational institutions, and research institutions through an integrated collaborative approach. Geotourism planning and promotion need to be conducted within a sustainability framework by considering the economic contribution of the tourism sector to the community. The Modified Geosite Assessment Model (M-GAM) is one of the models used to assess and evaluate the geotourism potential of a site (Cvetanović et al., 2024). M-GAM classifies the value of a geosite into two main categories, namely core value and added value. Core value comes from the natural characteristics of the site. It is divided into three groups of indicators, namely educational indicators (scientific/educative value - VSE), aesthetic indicators (beauty value - VSA), and conservation indicators (protection value - VPr). Meanwhile, the added value comes from the utilization of the geosite by visitors and is categorized as functional value (VFn) and tourism value (VTr).

This model illustrates the strategic framework of karst geotourism development. The assessment conducted using M-GAM involves collaboration between experts and tourists, so that the assessment results are more comprehensive and applicable (Cvetanović et al., 2024; Juárez et al., 2024). Recent research using M-GAM or similar frameworks, such as Juárez et al. (2024), Roig et al. (2023), and Vasconcelos et al. (2023) has focused on evaluating site potential and stakeholder perception rather than integrating digital monitoring systems. These studies mainly relied on expert judgment and questionnaire-based data, which, while valuable, remain limited by their static and periodic nature. The present study differs by embedding M-GAM indicators within a digital, web-based system that allows continuous and participatory data updating. This integration enhances the responsiveness and objectivity of sustainability assessment in karst geotourism contexts.

Safety and Enjoyment in Tourism

Keselamatan merupakan syarat penting dalam kepariwisataan yang meliputi keamanan dan perlindungan. Safety is an important requirement in tourism which includes security and protection of tourists from the risk of harm. Based on Law Number 10 of 2009 concerning Tourism, article 26 (D), "tourism businesses or tour operators must pay attention to the safety and security of tourists". Each tourism destination has unique characteristics that affect its potential risks, so tourism managers need to conduct in-depth risk estimation. Bichler & Pikkemaat (2021) assert that tourism is an unusual environment, where tourists travel for sightseeing, recreation, entertainment, exploration, or seeking knowledge.

However, safety cannot be separated from the aspect of enjoyment, because a safe tourism experience is a prerequisite for the emergence of feelings of comfort, satisfaction, and happiness during the visit. Enjoyment is a positive experience that arises when tourists engage in activities or experiences that fulfill their wants, goals, or needs. According to Kusuma et al. (2025), enjoyment is "a positive affective state that occurs when someone is involved in an experience or activity that fulfills their wants, goals, or needs". Enjoyment can cover various aspects, including pleasure, meaning, security, safety, self-esteem, and a sense of belonging. As stated by Chen et al. (2020), people usually feel pleasure when doing activities that satisfy and meet basic needs such as physiological needs, safety, belongingness, self-esteem, self-actualization, and a meaningful life. Enjoyment can be learned at different levels of abstractness, ranging from concrete experiences to high-level needs.

Thus, safety and enjoyment are two complementary and equally crucial elements in shaping the quality of a sustainable tourism experience. A destination that is not only safe but also enjoyable will increase traveler satisfaction, extend visit duration, and strengthen the positive image of the destination in the long run. Nevertheless, most studies addressing safety and enjoyment (Bichler & Pikkemaat, 2021) tend to be conceptual or survey-based, focusing on perception rather than system-based monitoring of visitor experiences. This study adds to the literature by incorporating these experiential dimensions into a measurable digital framework that reflects visitor satisfaction dynamically.

Digitalization System

Digital systems are a series of information technology-based mechanisms used to efficiently collect, process, store, and present data in digital form, to support decision-making and improve organizational performance (El-Ebiary & Yousef, 2020). In the context of tourism, digital systems can be applied in various aspects, ranging from destination management, marketing, tracking tourist behavior, to evaluating sustainability through real-time monitoring of indicators. Recent studies support that

this approach yields significant benefits: tracking techniques such as GPS/app-based monitoring help destination managers in decision-making and planning (Julio Guerrero & Dias, 2024); the deployment of digital nudging in media interfaces drives more sustainable visitor behavior (Ni et al., 2025); online platform data allow real-time or near-real-time measurement of sustainability and tourist flows (Hoffmann et al., 2022); digital twin and big data governance frameworks offer monitoring of environmental impact and visitor patterns dynamically (Rahmadian et al., 2023); and smart technologies including IoT and AI are foundational in the sustainable ecotourism model globally (Zhang & Deng, 2024). Thus, the integration of digital systems into tourism management, particularly in geotourism destinations such as karst caves, represents not merely a technological innovation but a strategic approach to enhancing sustainable governance that is transparent, participatory, and adaptive to contemporary environmental and social challenges. Comparatively, Julio Guerrero & Dias (2024) focused on GIS- and GPS-based monitoring of tourist movements, emphasizing mobility optimization; Hoffmann et al. (2022) utilized online behavioral data to infer sustainability patterns; Rahmadian et al. (2023) implemented digital twins for environmental observation in smart ecotourism contexts; and Zhang & Deng (2024) integrated AI for predictive sustainability modeling. However, all of these studies were limited by their lack of domain-specific adaptation for karst ecosystems and did not integrate participatory assessment models such as M-GAM. The present research addresses this gap by designing a web-based information system specifically for karst cave geotourism that combines sustainability indicators (from M-GAM) with digital data collection and visualization mechanisms. Therefore, the novelty of this study lies in its integrative approach: (1) combining M-GAM-based sustainability indicators with a web information system, (2) focusing on the karst cave context in Indonesia, and (3) enabling participatory data input from multiple stakeholders (experts, managers, visitors) for continuous evaluation. This provides a methodological and practical advancement beyond previous static or domain-generic digital tourism models.

Critical Analysis and Research Gap

A review of the recent literature (Hoffmann et al., 2022; Juárez et al., 2024; Rahmadian et al., 2023; Zhang & Deng, 2024) indicates that digitalization has substantially transformed tourism monitoring systems by enabling real-time, data-driven evaluation of sustainability and visitor behavior. However, most of these systems remain general-purpose, lacking domain adaptation for specific natural settings such as karst cave geotourism, where environmental sensitivity and data accessibility are unique challenges. Similarly, assessment models like M-GAM have proven effective for evaluating geosite potential and sustainability indicators but still rely primarily on manual, periodic data collection, which limits their capacity to capture dynamic changes in tourist activities and environmental conditions.

Methodologically, prior studies tend to separate technological innovation from sustainability evaluation digital systems emphasize monitoring efficiency, while geotourism frameworks emphasize multidimensional assessment without automation. This disconnection creates a research gap in developing an integrated, web-based system that operationalizes sustainability indicators within a participatory and adaptive digital environment. Addressing these gaps, the present study contributes by designing and implementing a web-based information system tailored to karst cave geotourism in Indonesia, structured using the Waterfall model (analysis–design–implementation). The system embeds M-GAM sustainability indicators within a dynamic data architecture that allows continuous input from multiple stakeholders (managers, experts, and visitors). This integrative design offers a novel framework for real-time performance measurement in sustainable tourism, overcoming the limitations of static, manual, and domain-generic approaches previously documented in the literature.

MATERIALS AND METHODS

Study Area

Jomblang Cave is located in Semanu District, Gunungkidul Regency, Yogyakarta Special Region, Indonesia, approximately 50 km southeast of Yogyakarta City (Figure 1).

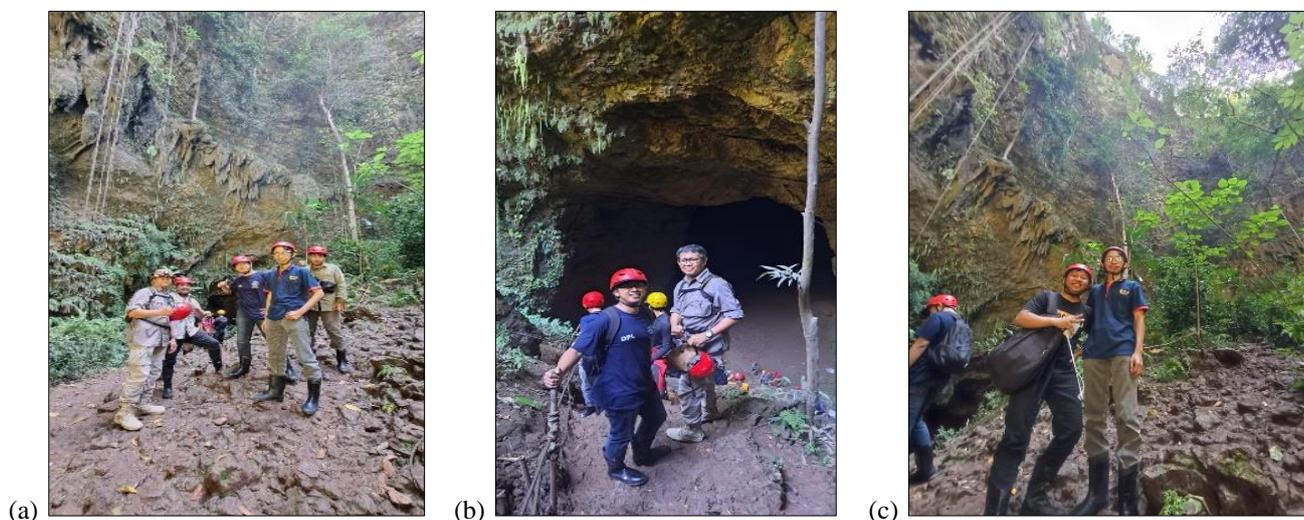


Figure 1(a). The appearance of a vertical cave seen from below (b). The front of the horizontal cave (c). Appearance of stalactites on the cave wall (Source: Authors, 2025 - Jomblang Cave, Semanu District, Gunungkidul Regency, Yogyakarta, Indonesia)

Geographically, it lies between 7°59'–8°05' S and 110°38'–110°45' E within the Gunung Sewu UNESCO Global Geopark. The area is characterized by a karst landscape formed by Miocene limestone, featuring vertical sinkholes, underground rivers, and rich speleothems. Jomblang Cave is a vertical-type cave with a depth of about 60 meters and a horizontal passage connecting to Grubug Cave. Visitors must descend the cave vertically using a rope-based pulley system operated by licensed and trained guides (as shown in Figure 2). At the bottom of the cave, tourists will find a thriving ancient forest. From there, a ±260-meter-long horizontal passageway connects Jomblang Cave with Grubug Cave, which features stunning views of speleothem, including giant stalactites and stalagmites, as well as natural light effects dubbed "heavenly light" (as illustrated in Figure 3). The combination of surface and underground landscape beauty makes Jomblang Cave an excellent geotourism destination that combines elements of conservation, Education, and adventure. However, this extraordinary potential also demands serious attention to aspects of safety, carrying capacity, and ecological preservation to ensure that this geological heritage can be enjoyed sustainably by future generations.



Figure 2. (a). Installation of rope pulleys for tourists before descending the vertical cave (b). Tourists accompanied by a team prepare to descend the vertical cave (c). Tourists use a pulley to descend the vertical cave (Source: All photos were taken at Jomblang Cave, Semanu District, Gunungkidul Regency, Yogyakarta, Indonesia, on April 2025 by the authors.)



Figure 3. Sunlight entering through the vertical shaft, known as the "Light of Heaven," illuminating the end of the horizontal passage in Jomblang Cave, Gunungkidul, Yogyakarta, Indonesia (Source: Photo by the authors, April 2025)

Research Design

This research uses mixed methods that combine quantitative and qualitative approaches to assess the performance and sustainability of geotourism in Jomblang Cave. Mixed methods design is considered effective in tourism studies as it integrates the subjective experience of tourists with data-driven objective analysis (Creswell & Clark, 2017; Fuchs, 2025). The quantitative approach was conducted through a structured survey of visitors to Jomblang Cave who were above 18 years old and had visited the site within the past year. The questionnaire covered three main aspects: geotourism assessment with the Modified Geosite Assessment Model (M-GAM), perception of safety (infrastructure, guide competence, and risk management), and enjoyment level (accessibility, beauty, and experience satisfaction).

Data were analyzed with descriptive statistics such as averages and percentages. The qualitative approach was conducted through in-depth interviews with tourists, managers, local government, and conservation experts.

The interviews aimed to explore their experiences, expectations, and challenges. In addition, participatory observations were conducted to record visitor behavior, environmental impacts, and infrastructure conditions. Qualitative data were analyzed using thematic techniques, using manual coding. The integration of the two approaches was done through data triangulation, comparing survey results with interviews and observations. This research also uses an explanatory sequential design, where survey results are used as the basis for developing further interview questions. This approach provides a comprehensive picture of the condition and management of Jomblang Cave geotourism.

Data Collection Techniques

Data was collected through a combination of questionnaires, interviews, direct observation, and document analysis. Primary data included tourist and expert assessments of geosite quality, along with data flow and information system (IS) requirements. Secondary data included documentation of tourism management entities, Standard Operating Procedures (SOPs), tourism guidelines, and related supporting documents. Questionnaire items were first validated through face validity tests by ecology and conservation experts and the Yogyakarta Tourism Office.

1. Observation: Observation is a method of observing an object or subject matter of a problem (Fix et al., 2022; Ishtiaq, 2019; Seim, 2024; Smit & Onwuegbuzie, 2018). Observation activities focused on: (1) the physical condition of the cave environment, (2) tourist activities during exploration, and (3) interactions between visitors and tourist facilities. These direct observations allowed researchers to record in detail technical aspects such as the quality of tourist paths, lighting, safety levels, and the impact of tourist activities on the cave environment. The results of these field observations then became the basis for mapping problems and developing a comprehensive geotourism evaluation model.

2. Interviews: This research conducted face-to-face interviews with three groups of key informants, namely: (1) the manager of Jomblang Cave tourist attraction, (2) tourists who have visited, and (3) experts in the field of ecology and tourism. According to Rutledge & Hogg (2020) an interview is a method of collecting information by conducting an interactive question and answer process between the interviewer and the source, either directly or indirectly via telephone. Interviews with managers focused on the operational and management aspects of tourist areas, while interviews with tourists aimed to find out the experiences and perceptions of tourists. Interviews with ecology and tourism experts were conducted to obtain expert assessments related to conservation and sustainable development aspects in Jomblang Cave. Data obtained from these three groups of informants complement each other in providing a comprehensive picture of the performance of Jomblang Cave geotourism.

3. Documentation: The documentation method in this research collects various data related to the management of the Jomblang Cave tourist attraction. Based on Hoffmann et al. (2022); Chiarini et al. (2022), the data collected include: (1) answers to tourist questionnaires regarding their travel experiences, (2) notes from discussions with tourism and geology experts, and (3) tourist attraction manager reports regarding the applicable management system. Other supporting data include administrative documents, photos of field conditions, and visitor archives. All of this documentation data serves as analytical material in designing the geotourism information system, especially for modeling the Entity Relationship Diagram (ERD) and Data Flow Diagram (DFD) that will be developed. The data obtained through this method is categorized as secondary data that complements and strengthens the findings from observation and interview methods.

4. Literature Study: The process of collecting data sourced from books, library data, literature, or notes related to existing problems is called a literature study (Smela et al., 2023). References and previous research are needed related to the creation of information systems as a basis for conducting the research process and as a reinforcement of arguments when research is carried out.

Information System Design Method and Type of Data Used

The information system in this study was designed using the Waterfall model, which consists of three main stages, namely analysis, design, and implementation. In the analysis stage, information needs identification was carried out, which included tourism entity data, data flow diagrams (DFD), business processes, and information system specifications. These elements are collected through interviews with tourism managers and analysis of relevant documents.

This research utilizes primary and secondary data to support the design process and performance assessment of Jomblang Cave geotourism. Primary data includes assessment results from experts, tourist perceptions, business process flow, and information system data specifications. Meanwhile, secondary data includes information on management entities, standard operating procedures (SOPs), tourism guidebooks, and geotourism documentation.

Variables and Indicators in Geosite Assessment

The geosite assessment process in this study adapts the Modified Geosite Assessment Model (M-GAM) mechanism developed by Tomić & Božić (2014). This approach combines two main perspectives, namely expert assessments and visitor perceptions, to produce a more holistic geosite assessment. The indicators used refer to the Geosite Assessment Model (GAM) formulated by Vujičić et al. (2011), which in this study was expanded by adding two new indicators, namely safety and enjoyment. All sub-indicators in the two main categories, Main Value (MV) and Additional Value (AV), were assessed based on two components: expert scores and Importance Factor (Im) assigned by tourists. This importance factor reflects how relevant and important each sub-indicator is from the visitor's perspective about their geotourism experience.

1. Main Value (MV): Main Value component evaluates the intrinsic features of the geosite through three variables: Scientific/Educational Value (VSE), which measures geological significance and educational potential (Cvetanović et al., 2024); Aesthetic Value (VSA), which evaluates the visual appeal and attractiveness of the landscape (Cvetanović et al., 2024); and Protection Value (VPr), which assesses conservation status and preservation needs (Cvetanović et al., 2024)

2. Added Value (AV): Added Value (AV) includes variables that reflect geosite functionality, tourism utility, and visitor satisfaction, with two additional subcomponents in this study: Safety Value (VSf) and Enjoyment Value (VEj). This component captures the tourism-related functions of a geosite using four variables: Functional Value (VFn), which assesses the usefulness of infrastructure and support facilities (Cvetanović et al., 2024); Tourist Value (VTr), which captures tourist-centered perspectives including accessibility, services, and site interpretation (Cvetanović et al., 2024); Safety (VSf), which evaluates the sense of physical and psychological safety experienced by visitors at a geosite (Kusuma et al.,

2025; Mawby & Ozascilar, 2024); and Enjoyment (VEj), which refers to visitors' overall level of satisfaction and emotional engagement during the tourism experience (Kusuma et al., 2025; Prayag et al., 2017).

Each variable consists of specific sub-indicators that help measure the performance of the geosite in detail. These assessments are conducted by experts and tourists, allowing for a more comprehensive and balanced evaluation that is in line with the development of sustainable geotourism (Reinhart et al., 2023).

Table 1. GAM Sub-indicator Value (Source: Personal Documentation of the Researchers, 2025)

Sub-indicators	Grade				
	0	0.25	x0.5	0.75	1
		Main Values (MV).		Scientific/Educational value (VSE).	
(1). rarity	Common	Regional	National	International	The only occurrence
(2). Representativeness	None	Low	Moderate	High	Utmost
(3). knowledge of geoscientific issues	None	Local publications	Regional publications	National publications	International publications
(4). level of interpretation	None	Processes are moderate level, but the detection is difficult to interpret for non-experts	Good examples of processes, but difficult to interpret for non-experts	Processes are moderate level, but easy to interpret for the average visitor	Good examples of processes and easy to interpret for the average visitor
Scenic/Aesthetic values (VSA).					
(5). Viewpoints	None	1	2 - 3	4 - 6	> 6
(6). surface	Small	-	Medium	-	Large
(7). Surrounding landscape and nature	-	Low	Medium	High	Utmost
(8). Environmental fitting of sites	Unfitting	-	Netral	-	Fitting
Protection Value (VPr).					
(9). Current condition	Completely damaged (due to the various activities of humans)	Extremely damaged (due to the natural processes).	Moderate level of damaged (with necessary geomorphological features preserved).	Slightly damaged	No damage
(10). Protection level	None	Local	Regional	National	International
(11). Vulnerability	Irrevocable (with the probability of total loss).	High (can be damaged).	Moderate (can be damaged by any of the natural processes or human activity).	Less (can only be harmed by human activity)	None
(12). A Suitable number of visitors	0	0 - 10	10 - 20	20 - 50	> 50
		Additional Values (AV).		Functional values (VFn).	
(13). accessibility	Unreachable	Low (walking with special equipment through an expert tourist guide).	Moderate (via bicycles and other means of transport that use muscle power).	High (by car).	Utmost (by bus, train, helicopter, etc.).
(14). Additional natural values	None	1	2 hingga 3	4 hingga 6	> 6
(15). Additional anthropogenic values	None	1	2 hingga 3	4 hingga 6	> 6
(16). Vicinity of emissive centers	>10km	100-50km	50-25km	25-5km	<2km
(17). Vicinity of an important road network	None	Local	Regional	National	Internasional
(18). Additional functional values	None	Low	Medium	High	Utmost
Touristic values (VTr).					
(19). Promotion	None	Local	Regional	National	Internasional
(20). Organised visits	None	< 12 per year	12-24 per year	24-48 per year	> 48 per year
(21). Vicinity of visitors centers	>50 km	20-50 km	20-5 km	5-1 km	<1 km
(22). Interpretative panels	None	Low Quality	Medium Quality	High Quality	Utmost quality
23) Number of visitors	None	Rendah (<5000).	Sedang (5001-10000).	Tinggi (10001-1000000).	Utmost (>1000000).
(24) Tourism infrastructure	None	Low	Medium	High	Utmost
(25). Tour guide service	None	Low	Medium	High	Utmost
(26). Hostelry service	> 50 km	25-50 km	10-25 km	5-10 km	<5 km
(27). Restaurant service	>25 km	10-25 km	10-5 km	1-5 km	<5 km

Table 1 shows the Jomblang Cave geotourism value evaluation framework using the Modified Geosite Assessment Model (M-GAM), which consists of four main groups and 27 sub-indicators. Each sub-indicator is rated using a 5-level Likert scale: 0 (very low), 0.25 (low), 0.5 (medium), 0.75 (high), and 1 (very high), to give objective weight to the quality of each aspect assessed. The Major Value Group (MV) includes: (1) Scientific/Educational Value (VSE) which assesses rarity, representation, geological knowledge, and interpretation; (2) Scenic Value (VSA) includes visual beauty, area, surrounding landscape, and environmental suitability; (3) Protection Value (VPr) assesses existing conditions, level of protection, Vulnerability, and visitor capacity. The Additional Value (AV) group consists of: (1) Functional Value (VF_n), which includes accessibility, additional value (natural/artificial), and distance from main access; and (2) Tourism Value (VTr), which assesses promotion, facilities, infrastructure, and visitation numbers. The model enables a comprehensive assessment of geotourism potential and performance based on quantitative data.

Table 2. Safety and Enjoyment Sub-indicator Values (Source: Personal Documentation of the Researchers, 2025) (Source: (Pei et al., 2020; U.S. Department of Labor, n.d.-b, n.d.-a; World Tourism Organization (UNWTO), 1996; World Tourism Organization (UNWTO) et al., 2024)

No.	Subindicators	Grade				
		0	0.25	0.5	0.75	1
Safety Values (Vsf).						
28	Risk	Life threatening	Accidents are possible	Relatively safe	Safe destination conditions	Very safe destination conditions
29	Preparedness	None	Incomplete	Present and complete	Complete and effective	Very complete, effective, and updated.
30	Infrastructure maintenance	None	Irregular	Regular	Very effective	Very effective and updated
31	Conflict level	Utmost	High	Medium	Low	None
32	Procedure	None	Incomplete	Present and complete	Complete and effective	Very complete, effective, and updated.
33	Clarity of instruction	None	Hard to understand	Safety instructions are there	Very clear	Very clear and accompanied by illustrations
34	Health infrastructure	None	Incomplete	Present and complete	Very effective	Very effective and updated
Enjoyable Values (VEj).						
35	Pleasure	Unhappy	A little happy	Quite happy	Very happy	Excited
36	Experience	Usual	Slightly different	New and different	Very new and different	Unforgettable
37	Relation	Uncomfortable	Little interaction	Interact	Mutual respect	Very comfortable
38	Feelings flow	Stress	Slightly entertained	Entertained	Forgetting the routine	Very relaxed
39	Recommendation intention	Do not want	Slightly want	Want	Strongly want	Definitely
40	Return intention	None	A little bit	Want to come back	Very much want to come back	Come back
41	Calm	Uncomfortable	A little worried	Quiet	Very quiet	Very comfortable

Table 2 was used to evaluate two important aspects of the geotourism experience at Jomblang Cave, namely safety (Vsf) and enjoyment (VEj). The safety aspect is assessed through seven indicators that include the level of risk, preparedness, infrastructure maintenance, safety procedures, and availability of health facilities. Each indicator is scored on a Likert scale from 0 (life-threatening) to 1 (very safe). Meanwhile, the enjoyment aspect is evaluated based on seven indicators, such as tourist experience satisfaction, quality of social interaction, comfort, and intention to return. The enjoyment assessment also uses a Likert scale from 0 (unhappy) to 1 (very much enjoyed or excited). This evaluation provides an overall picture of the quality of the tourism experience in terms of visitor safety and satisfaction. The weighting of GAM values with the addition of safety and comfort variables will be the basis for assessing the Main Value (MV) and Added Value (AV) of a geosite by tourists and expert evaluators. After all questionnaires have been prepared and filled out by respondents, the next step is to calculate the GAM value first (Vujičić et al., 2011; Antić et al., 2020; Cvetanović et al., 2024).

$$GAM = MV + AV \quad (1)$$

MV represents the Main Value, and AV represents the Additional Value. Main Value (MV) and Additional Value (AV) are the primary and complementary values of a geosite, respectively. As part of the development of the tourism site assessment, two additional indicators—Safety Value (VSf) and Enjoyment Value (VEj)—were included in the AV component, as shown in Tables 4 and 5. Since MV and AV consist of three and four indicator groups, respectively, the calculation of values can be expressed through the following two equations (Vujičić et al., 2011; Antić et al., 2020):

$$MV = VSE + VSA + VPr \quad (2)$$

$$AV = VF_n + VTr + VSf + VEj \quad (3)$$

Where VSE refers to Scientific/Educational Value, VSA to Aesthetic Value, VPr to Protection Value, VF_n to Functional Value, VTr to Travel Value, VSf to Safety Value, and VEj to Enjoyable Value. The Importance Factor (*Im*) is an opportunity for visitors to express their opinion on the significance of each sub-indicator included in the assessment

model. After that, the importance factor (Im) is multiplied by the score given by experts (ranging from 0.00 to 1.00) who assess the current condition and status of each sub-indicator. Finally, the Modified Geosite Assessment Model (M-GAM) equation is defined and can be presented through the following formula (Tomić & Božić, 2014; Antić et al., 2020):

$$MGAM = Im(n). (GAM) = Im(n). (MV + AV) ; Im = \frac{\sum_{k=1}^K IV_k}{K} \quad (4)$$

Where: Im = Important Factor, n = the n -th data, representing the total number of visitors who participated in the assessment. The Importance Score (Im) is calculated as the average of these assessments, reflecting the perceived relevance of each sub-indicator from the tourist perspective. Im values range between 0.00 and 1.00 (inclusive), ensuring a standardized weighting mechanism that integrates visitor opinions into the overall geosite assessment process.

This approach enhances the objectivity of the Modified Geosite Assessment Model (M-GAM) by combining expert evaluations and visitor perceptions, thus providing a more comprehensive understanding of geosite performance.

RESULTS

Information System Design

The process of designing an information system uses the waterfall method through several types of stages, namely analysis, design, and implementation. The following are the stages in designing an information system for measuring the performance of the Goa Jomblang tourism objects.

1. Analysis

Based on the data obtained, three types of diagrams are made, each of which represents the flow of data and business.

a. Use Case Diagram (UCD): The UCD diagram represents the number of actors involved and all types of activity processes in accessing the information system, which is designed with three actors, each having specific roles. The roles of the user include viewing gallery contents, reading travel guides, inputting M-GAM scores, reading safety riders, and downloading safety riders. Figure 4 explains the role of the admin actor, which includes uploading image files, uploading guides, uploading safety rider files, receiving M-GAM calculations, and reporting tour performance. The role of the third actor, the tour owner, is to receive all types of incoming reports.

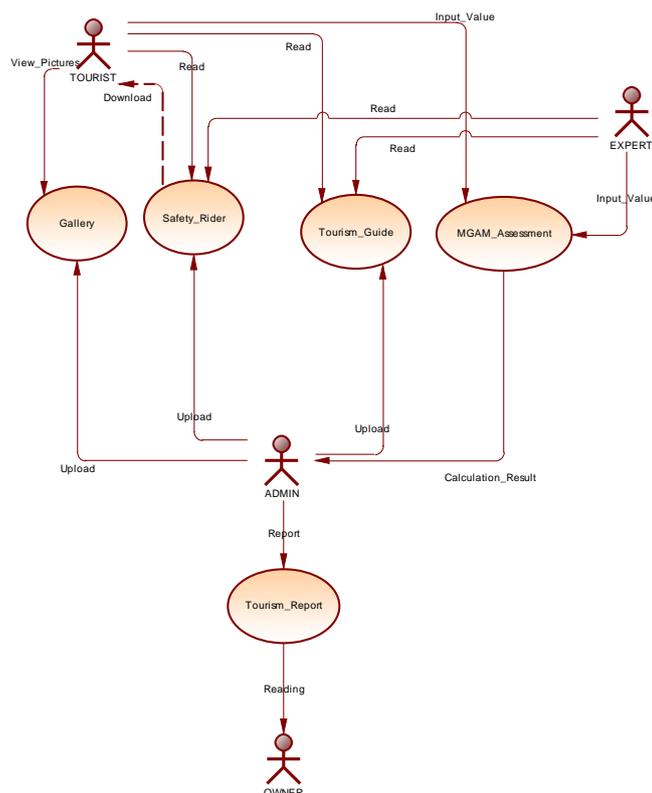


Figure 4. Diagram UCD (Source: Personal Documentation of the Researchers, 2025)

b. Entity Relationship Diagram (ERD): The ERD diagram illustrates the relationship between entities in the system. Six entities are interconnected, and each has visualized data. Figure 5 explains that the user entity requires two pieces of data to perform the questionnaire data input process, namely, the ID and the M-GAM assessment input.

c. The New M-GAM entity contains all M-GAM assessment variables in the form of seven values, namely VSE, VSA, VPr, VF_n, VTr, VSf, and VE_j. In addition to the assessment variable values, the M-GAM entity has MV and AV values obtained from the calculation process of the seven variables, resulting in a Zindex whose results will be sent to the Admin and Owner entity. The admin and Owner entity has the same role and data variables. The Tour Guide, Gallery, and Safety Rider entities depend on the Admin and Owner entity.

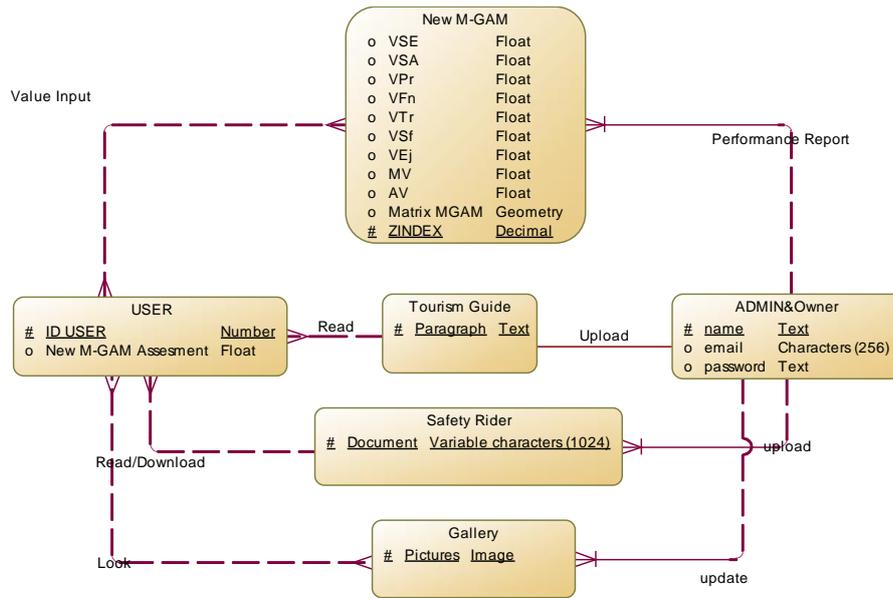


Figure 5. Diagram ERD (Source: Personal Documentation of the Researchers, 2025)

d. Data Flow Diagram (DFD): The DFD diagram explains the process of data flow circulating in the information system. The DFD diagram has two levels, namely level 0 and level 1. At DFD level 0, the general or outline data flow between entities or the origin of the data is explained. It (Figure 6) can be seen that the entity circulates data, but only a general circulation process occurs. To describe the data circulation that is happening specifically, a level 1 DFD diagram is used.

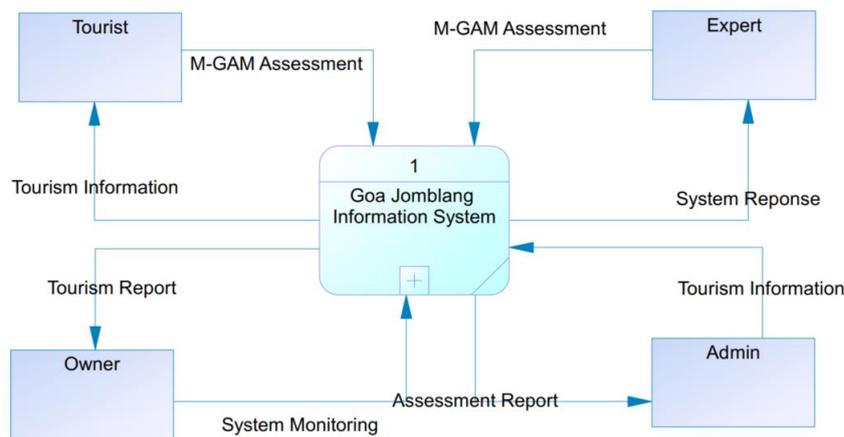


Figure 6. Diagram DFD Level 0 (Source: Personal Documentation of the Researchers, 2025)

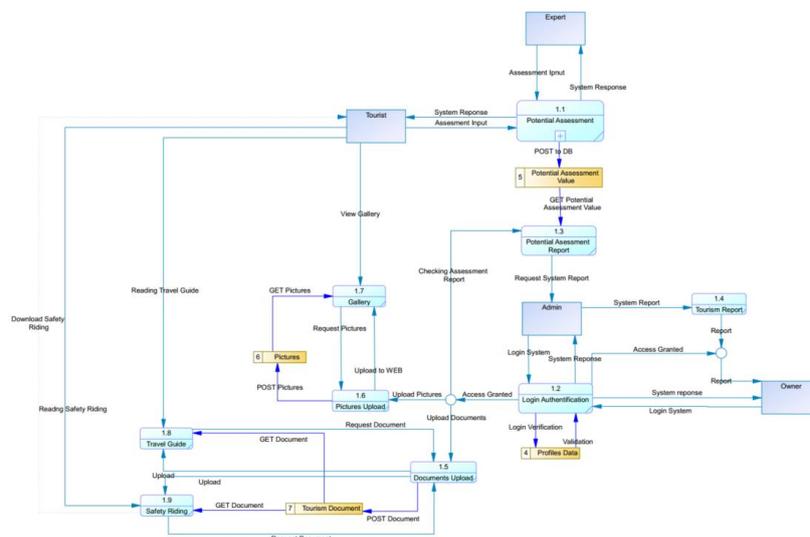


Figure 7. Diagram DFD level 1 (Source: Personal Documentation of the Researchers, 2025)

The data flow process and the types of data stored can be seen in the DFD level 1 diagram. Figure 7 shows the data flow process from tourists to other entities, specifically. The Tourist and Expert entities will input the M-GAM values received by the system and store them in the database. The data will be sent for processing and will be sent to the admin in the form of calculation results and tourism performance reports. The calculation results in a report that the Admin and Owner can access.

The admin's job is to upload files such as images, tour guides, and safety riders for users to read. All files will be stored in the database so that users can access them in the web system. Admin and Owner entities cannot access all files and reports unless they go through a login or registration process to gain access. The User entity does not need a login process because the M-GAM value input process can be done without an account. Figure 8 explains that tourists assess the importance level of each indicator through questionnaires (importance factor/Im), while experts evaluate the actual condition to reflect the geosite's performance. Both assessments cover *main values* (scientific, aesthetic, conservation) and *additional values* (tourist, functional, safety, enjoyment). The data are then processed using a weighted formula that combines importance and performance scores, by the M-GAM mechanism, producing final results visualized in a quadrant matrix and radar chart. These outcomes are presented in an interactive dashboard and automated reports to support data-driven decision-making and continuous monitoring of sustainable geotourism management in Jomblang Cave.

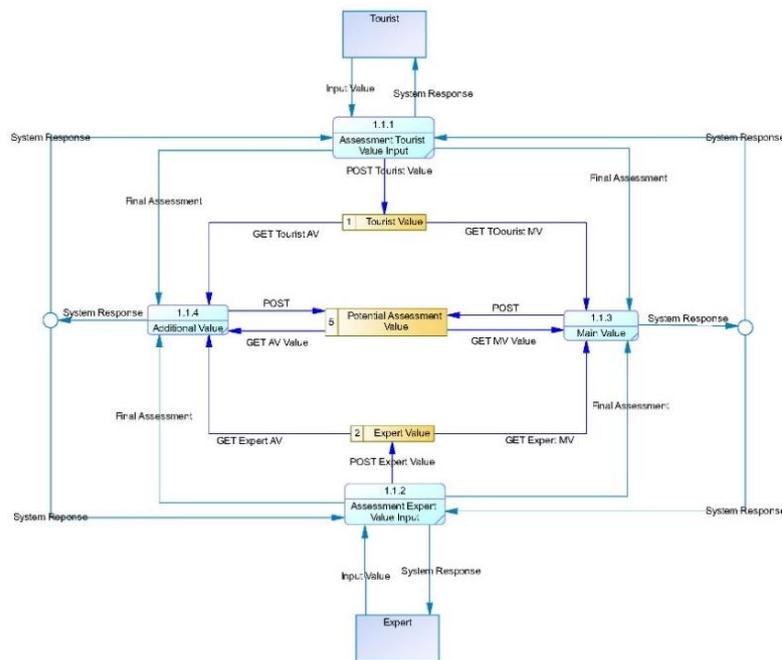


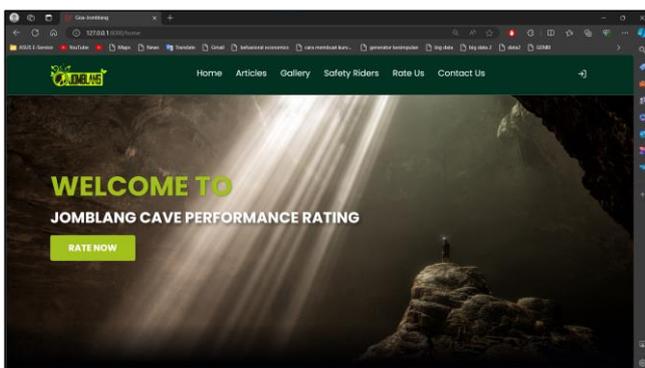
Figure 8. Diagram DFD level 2 (Source: Personal Documentation of the Researchers, 2025)

2. Design

The design process can be done once all requirements are met. The stages in the design are in the form of a web coding process that matches the requirements criteria that have been described. The web designs that have been made include the following:

a. Homepage

Figure 9 shows the homepage of the Goa Jomblang website. The Goa Jomblang homepage uses dark colors to represent the cave's interior. The Rate Now button, when hovered by the pointer, will change color to a darker one. The color change on the button gives a dynamic accent to the web. The Rate Now button will take users to the Rate Us page.



Expert Data																													
No	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Q25	Q26	Q27		
1	0.75	0.75	0.75	0.75	0.75	1	0.75	0.75	0.25	0.75	0.75	1	1	0.75	0.75	0.75	1	0.75	0.75	0.5	1	0.75	0.75	0.5	1				
2	0.75	0.75	0.75	0.75	0.75	0.75	0.5	1	0.25	0.75	0.75	0.75	0.75	0.75	0.5	1	1	0.75	1	1	1	1	1	1	1	1	1	1	1
3	0.75	0.75	0.75	0.75	0.5	1	1	0.75	0.5	0.75	0.5	0.5	0.25	0.5	0.5	0.5	0.5	0.5	0.75	0.75	0.75	0.5	0.7						
4	1	0.75	0.75	0.25	0.75	1	1	1	0.75	1	0.25	0.75	1	1	0.75	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5	0.75	0.5	0.75	0.75	0.75	0.5	0.75	0.25	0.75	0.25	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.5	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
6	0.75	1	1	0.25	0.75	0.25	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Tourist Data																														
No	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Q25	Q26	Q27			
1	1	0.25	0	0.5	1	1	0.75	1	0.75	0.5	0.5	0.75	0.25	0.5	0.5	0.25	0	0.25	0.25	0.5	1	0.75	0	1						
2	0.75	0	0.25	0	0.5	0.5	0.75	1	0.75	0.75	0.75	1	0.5	0.5	0.25	0.75	1	1	0.5	0.75	1	1	0.25	0.75						
3	1	0	0.5	0	0.75	0.75	0.5	1	0.5	0.5	0.5	0.5	0.5	0.5	0.25	0.25	0.25	0.5	0.5	0.75	0.75	0.5	0.75							
4	0.75	0.5	0.25	0.75	1	0.75	1	1	1	0.75	0.75	0.5	0.75	0.5	1	0.5	0.5	0.5	1	1	0.5	1	1	0.5	1					
5	1	1	0.25	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 9. Homepage (Source: Personal Documentation of the Researchers, 2025)

Figure 10. Questionnaire Data Page Display (Source: Personal Documentation of the Researchers, 2025)

b. Questionnaire Data Page

Figure 10 shows all questionnaire data from both experts and tourists. If the tourist fills in the Rate Us page, it is different from the expert who fills in the questionnaire on the Expert page. Only the page name is different, but the content remains the same as the Rate Us page. This distinction is made to distinguish the database used by experts and tourists.

The data displayed is a record of data from the traveler and expert databases. The value owned by the expert will be multiplied by the value owned by the traveler. The calculation of the M-GAM value will be done on the Matrix Data page.

c. Matrix Data Page

The Matrix Data page shows the calculated data from the questionnaire values provided by experts and tourists. At the top of the page, you will find basic knowledge about the M-GAM assessment process on tourism objects. The system will automatically calculate the average value owned by experts and tourists. The results of the system calculation will then be displayed in the table, showing the total value obtained.

M-GAM Calculation Mechanism

In evaluating the performance of tourism objects using M-GAM, assessment data from tourists and experts are needed. The questionnaire data provided by tourists will be an important factor that will be multiplied by the assessment of the expert. MV and AV value data were obtained from filling out 38 questionnaires with a total of 32 tourist respondents who became importance factor variables and six expert respondents who became GAM variables. The assessment carried out is divided into seven different types of value. The calculation of MV and AV has a total of seven values, with three values in MV and four values in AV, as the development of AV values.

Table 3. Total Average of Each Value MV (Source: Personal Documentation of the Researchers, 2025)

Value	VSE				VSA				VPr			
	1	2	3	4	5	6	7	8	9	10	11	12
Expert	0.83	0.75	0.79	0.58	0.71	0.75	0.88	0.67	0.63	0.88	0.42	0.71
Importance	0.88	0.44	0.57	0.52	0.79	0.81	0.85	0.95	0.83	0.83	0.44	0.84
Value	0.74	0.33	0.45	0.30	0.56	0.61	0.75	0.63	0.52	0.72	0.18	0.59

Table 3 shows the evaluation results of the three main variables in the Modified Geosite Assessment Model (M-GAM), namely scientific/educational value (VSE), scenic value (VSA), and protection value (VPr), each of which consists of four indicators in the questionnaire (indicators 1-12). On the VSE variable (indicators 1-4), the scores given by experts ranged from 0.58 to 0.83. Indicator 1 obtained the highest expert score (0.83) and the highest level of importance (0.88), resulting in the highest final score of 0.74. In contrast, indicator 4 had the lowest final score (0.30) as it had the lowest expert score and importance level. For the VSA variable (indicators 5-8), expert scores ranged from 0.71 to 0.88, with indicator seven being the highest. Indicator 8 had the highest importance (0.95), while indicator 7 obtained the highest final score (0.75) thanks to the optimal combination of expert scores and indicator importance. As for the VPr variable (indicators 9-12), expert scores were in the range of 0.42-0.88. Indicator 10 received the highest expert score (0.88) and the highest final score (0.72). In contrast, indicator 11 recorded the lowest expert score and importance, which resulted in a very low final score (0.18), indicating its insignificant contribution to the overall assessment.

Table 4. Total Average AV Value VF_n and VT_r (Source: Personal Documentation of the Researchers, 2025)

Value	VF _n						VT _r					
	13	14	15	16	17	18	19	20	21	22	23	24
Expert	0.75	0.83	0.79	0.79	0.79	0.75	0.92	0.83	0.79	0.88	0.79	0.92
Importance	0.66	0.55	0.55	0.52	0.70	0.68	0.62	0.79	0.91	0.78	0.59	0.88
Value	0.50	0.46	0.44	0.41	0.56	0.51	0.57	0.66	0.72	0.68	0.46	0.80

Table 4 displays the assessment results of two AV variables in the M-GAM model, namely function value (VF_n) and tourism value (VT_r), based on indicators 13-24. On VF_n, expert scores ranged from 0.75 to 0.83, indicating a moderately positive perception. Indicators 14 and 16 had the highest scores (0.83 and 0.79), while indicators 13 and 18 had the lowest (0.75). The level of importance is relatively low (average 0.61), with indicator 17 being the most important (0.70) and indicators 14 and 15 the least (0.55). Final scores ranged from 0.41 to 0.56, with indicator 17 the highest and indicator 16 the lowest. On VT_r, expert scores were very high (0.79-0.92), emphasizing the importance of the tourism aspect. Indicators 19 and 24 were the highest (0.92). In terms of importance, indicators 21 (0.91) and 24 (0.88) were the most important, while indicator 19 was the least important (0.62). The highest final scores are for indicators 24 (0.80) and 21 (0.72), while indicator 19 is the lowest (0.57) due to its low importance despite its high expert score.

Table 5. Total Average AV Value VF_n and VT_r Total Average AV Value VS_f and VE_j (Source: Personal Documentation of the Researchers, 2025)

Value	VS _f							VE _j						
	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Expert	0.54	0.83	0.83	0.83	0.83	0.83	0.83	0.88	0.88	0.71	0.71	0.83	0.75	0.79
Importance	0.59	0.83	0.85	0.95	0.81	0.88	0.80	0.91	0.92	0.85	0.90	0.88	0.66	0.87
Value	0.32	0.69	0.71	0.79	0.68	0.73	0.66	0.80	0.81	0.60	0.64	0.74	0.49	0.69

Table 5 displays the ratings of two AV variables, namely VSf (Safety) and VEj (Enjoyment), based on indicators 25-38. For VSf, most indicators received high expert scores (0.83), except for indicator 25 (0.54). This indicates that experts rated almost all aspects of VSf as excellent. Indicator 28 had the highest level of importance and final score (0.95 and 0.79), while indicator 25 had the lowest (0.59 and 0.32). The final scores of other indicators ranged from 0.66 to 0.73, indicating good performance. On VEj, expert scores were mostly high (0.83-0.88), with indicator 33 standing out (expert score 0.88; important 0.92; final 0.81). Indicators 34 and 35 had lower values (0.71), and indicator 37 had the lowest final value (0.49) due to low importance. Other indicators showed positive contributions (final values 0.60-0.80). From the values obtained from the expert and tourist questionnaires, the next stage is the M-GAM calculation process.

1. MV Assessment

In assessing MV, questionnaire data from tourists and experts is needed in the form of a total average of the values of VSE, VSA, and VPr. The first step to finding the MV value is to get the total average on each questionnaire from both tourists and experts. An example of calculating the VSE value on question number 1 is as follows:

Given the known values—Importance Factor 1 = 0.88 and GAM = 0.83, the calculation of VSE₁ is obtained using the equation $VSE_1 = Im_1 \times GAM$, resulting in $VSE_1 = 0.88 \times 0.83 = 0.74$. This value applies to subsequent calculations, and once all VSE values from 1 to 4 are determined, they are summed as $VSE = VSE_1 + VSE_2 + VSE_3 + VSE_4 = 0.74 + 0.33 + 0.45 + 0.30 = 1.82$. The next step is to calculate MV by adding VSE to the values of VSA and VPr, resulting in $MV = VSE + VSA + VPr = 1.82 + 2.54 + 2.02 = 6.38$, where 6.38 represents the final MV value.

2. AV Assessment

In assessing AV, questionnaire data from tourists and experts is needed in the form of a total average of the values VF_n, VTr, VSf, and VEj. The first step to finding the AV value is to get the total average on each questionnaire from both tourists and experts. An example of calculating the VF_n value on question number 13 is as follows:

The calculation begins with the importance factor for question 13 (Im_{13}) of 0.66 and a GAM value of 0.75, so the VF_n for question 13 is obtained using the formula $VF_{n13} = Im_{13} \times GAM = 0.66 \times 0.75 = 0.50$. This value applies to the subsequent questions, and once all VF_n values are calculated, they are summed as follows: $VF_n = VF_{n13} + VF_{n14} + VF_{n15} + VF_{n16} + VF_{n17} + VF_{n18} = 0.50 + 0.46 + 0.44 + 0.41 + 0.56 + 0.51 = 2.87$. The obtained VF_n value of 2.87 is then used in the AV calculation: $AV = VF_n + VTr + VSf + VEj = 2.87 + 3.89 + 4.58 + 4.76 = 16.10$.

Visualization of Calculation Results on information Systems

Figure 11 shows the M-GAM Value Calculation Process. From the calculation table performed by the system, the MV value is 6.37, and the AV value is 16.09. The MV and AV values will be used as coordinates in the M-GAM Matrix to determine the Z-index position. After all values are obtained, the next step is to represent the MV and AV values in an M-GAM matrix. The MV coordinate is located on the x-axis, and the AV coordinate is located on the y-axis. After determining the MV and AV coordinates, the Z-index will be obtained.

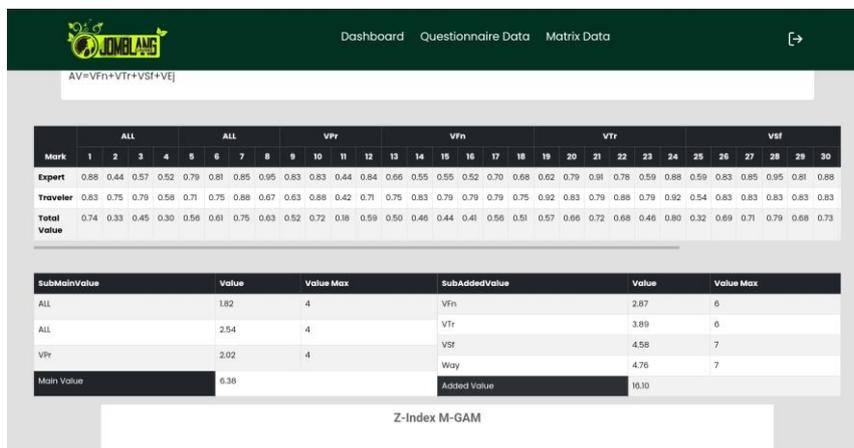


Figure 11. M-GAM Value Calculation Process (Source: Personal Documentation of the Researchers, 2025)

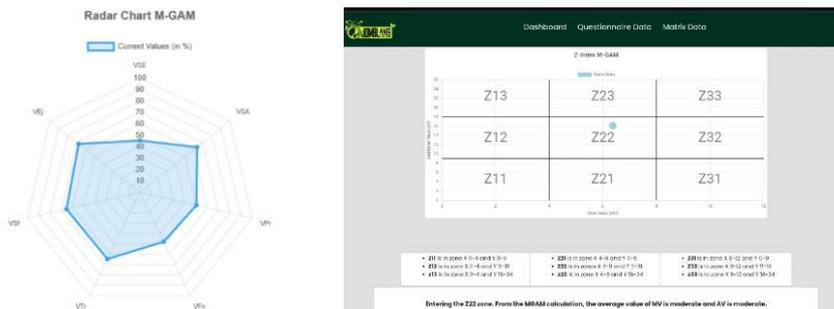


Figure 12. (a) Matrix M-GAM; (b) Radar M-GAM (Source: Personal Documentation of the Researchers, 2025)

Figure 12 shows the coordinates of MV and AV that have been obtained, which can be used to determine the Z-index position. By using the MV and AV coordinates, the M-GAM matrix Zindex is obtained at position Z22. At Z-index Z22, the middle area has an average value of MV and AV at a moderate level. So there is still a need for evaluation to improve the performance of tourism objects. It can be seen in the M-GAM calculation that the lowest value is in the VSE value of 1.82. It can be seen on the radar chart that the VSE value has the smallest percentage compared to the others, which is 45.40%. The VSE value is an MV variable that focuses on the educational aspect. There needs to be an increase in educational insights to tourists about the Jomblang Cave tourism object.

The lowest value in AV is value VF_n with a value of 2.87. Value VF_n is an AV variable that focuses on the functionality aspect. There needs to be an increase in infrastructure that supports the attractiveness of the Jomblang Cave tourism object. There needs to be cooperation between the tourism object manager and the local government in the development process.

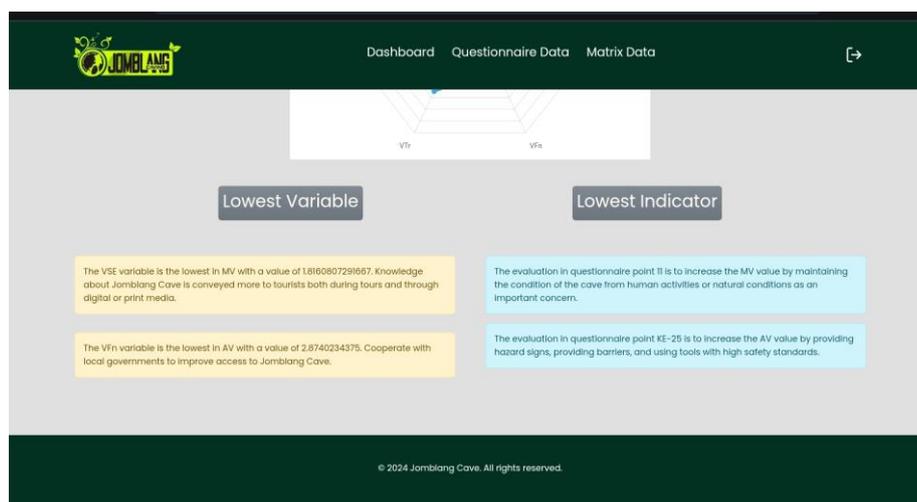


Figure 13. M-GAM Zindex Notification Display and Evaluation Action (Source: Personal Documentation of the Researchers, 2025)

Figure 13 shows the results of the M-GAM assessment performed by the system, which will automatically generate evaluation actions. The evaluation action given is by the results of the smallest calculation. For example, in MV, the lowest value is VSE. Then, the system will notify that VSE has the lowest value, and the action taken to overcome this is to enhance knowledge about Jomblang Cave. In AV, the lowest value is VF_n, and the action taken to overcome this is to improve the infrastructure aspect, which can work with the local government to improve access to Jomblang Cave. The notification given by the system on the right tells that the lowest average value is on one of the questionnaire points. For example, in the MV aspect, there is one question that has the lowest score. This indicates that maintaining the cave's condition from human activities or natural conditions is an important concern.

3. Implementation

The information system that has been created has passed testing and can run according to the M-GAM assessment method. The results of the assessment from the system can be used as a reference in developing the Jomblang Cave tourism object. The evaluation given by the system can help the manager to follow up on the low assessment of tourists and experts.

DISCUSSION

This research answers the main problem raised in the introduction, namely, the lack of a data-based and adaptive karst cave geotourism management system. The M-GAM-based digital information system developed in this study is proven to be able to integrate evaluative, educational, and participatory aspects in the management of risk-prone geotourism destinations such as Jomblang Cave. The system design results demonstrate that the modified M-GAM evaluation model can be systematically integrated into a digital information system, enabling a more structured and automated assessment process. By combining MV (Main Values) and AV (Additional Values) collected from both tourists and experts, the model allows for a dynamic and responsive quantitative evaluation. This dual-source approach ensures that the final assessment reflects not only expert technical judgments but also the perceptions, preferences, and priorities of tourists as end-users. Such integration represents a significant advancement over static, manually observational methods, which have been criticized for their subjectivity, inflexibility, and limited capacity to reflect real-time changes in tourism dynamics (Beynen & Philip, 2011; Chen & Chen, 2016; Staab et al., 2021).

One of the core advantages of the digitalized M-GAM approach lies in its evidence-based evaluation framework. The system offers interactive visualization tools that allow stakeholders to explore and interpret the data intuitively, fostering greater transparency in decision-making. This visualization capability not only improves accessibility for non-technical audiences but also facilitates more effective communication among policymakers, tourism managers, local communities, and investors. As a result, the evaluation outcomes can be used directly to support targeted interventions, monitor progress, and adapt management strategies in response to evolving circumstances.

The automation of the M-GAM calculation further enhances its utility. By embedding the weighting process, which balances the importance factors derived from tourist inputs with technical values assessed by experts, into the system, the model eliminates the manual computation burden. This automation reduces the potential for human error, speeds up the evaluation cycle, and enables continuous monitoring. Moreover, by integrating both quantitative scoring and qualitative interpretation, the platform strengthens the validity and Reliability of the results, ensuring that they are robust enough to support real-time, data-driven decision-making.

This capability aligns strongly with recommendations from global tourism governance bodies such as the UNWTO (2024) and the GSTC Global Sustainable Tourism Council (2023), which advocate for the use of digital tools and data-driven methodologies in sustainable tourism management. By adhering to these guidelines, the system contributes to the broader agenda of sustainable tourism, supporting the balance between conservation objectives, visitor satisfaction, and local economic benefits. In doing so, it provides a replicable model that can be adapted to different destinations, thereby enhancing its relevance and scalability in the global tourism sector. Building on these capabilities, it becomes clear that the system also provides critical insights for addressing site-specific challenges in karst cave management.

Through the results of the M-GAM calculation, which place the Z-index position at Z22 (medium category), it is evident that the sustainability performance of Jomblang Cave is not yet optimal. A medium Z-index indicates that while certain aspects of the site meet acceptable standards, there remain significant gaps in fully realizing its geotourism potential. This outcome aligns with the concerns expressed by Sunkar et al. (2022), who emphasized that karst cave destinations in Indonesia frequently encounter ecological pressures, largely as a consequence of management practices that are not sufficiently adaptive to changing environmental and tourism dynamics.

In the case of Jomblang Cave, such pressures may manifest in the form of visitor overcapacity, inadequate environmental monitoring, and an imbalance between conservation and tourism needs. The MV variable highlights a particularly concerning aspect: the lowest score is recorded for VSE (Scientific/Educational Value), at only 1.82 (45.40%). This low percentage reflects the limited integration of geoscience knowledge into the visitor experience. Geotourism, by definition, is intended not only to provide recreational opportunities but also to promote understanding of geological processes, landscape evolution, and environmental stewardship. In Jomblang Cave, however, this educational component appears underdeveloped. Potential reasons include the absence of interpretive materials such as detailed geological information boards, guided tours led by geoscience-trained guides, or educational programs tailored to different visitor groups, from school students to professional researchers. Without these, visitors may appreciate the cave's visual beauty but leave without gaining a deeper understanding of its geological and ecological significance.

This situation echoes wider trends observed in Indonesian karst geotourism, where interpretation is often minimal, leading to missed opportunities for public science engagement and conservation advocacy.

Similarly, the AV variable reveals that the lowest value belongs to VFn (Functional Value), pointing to weaknesses in the practical and utilitarian aspects of the tourist infrastructure. Functional value encompasses facilities and services that directly affect visitor comfort, safety, and accessibility. In the case of Jomblang Cave, this may involve inadequacies such as poorly maintained trails, limited or uneven resting points, insufficient safety measures (e.g., handrails, lighting in darker sections), or the lack of strategically placed information panels. Such shortcomings can discourage visitors with physical disabilities, increase the risk of accidents, and reduce the overall perceived quality of the site. As Herrera-Franco et al. (2020) suggest, geotourism destinations with low functional value often struggle to compete internationally, even when they possess exceptional natural features, because visitor satisfaction depends as much on infrastructure as it does on natural beauty.

Addressing these gaps will require a more integrated management approach that blends conservation science, visitor experience design, and community involvement. For educational value, this could involve partnerships with universities and research institutions to develop content-rich interpretation strategies, including digital apps, guided talks, and interactive displays. For functional value, investment in sustainable and safe infrastructure is crucial, with careful design to minimize ecological disturbance while enhancing accessibility. If these measures are systematically implemented, Jomblang Cave could move beyond the medium Z-index classification, strengthening both its sustainability profile and its reputation as a world-class geotourism destination. This leads directly to another important aspect of the M-GAM framework: the role of safety and enjoyment in shaping visitor experience and site sustainability.

The addition of two new variables in the Modified Geosite Assessment Model (M-GAM), namely VSf (Safety) and VEj (Enjoyment), represents a significant advancement in adapting the evaluation framework to the unique challenges posed by karst cave tourism. Karst caves, while offering remarkable geological and aesthetic value, are inherently high-risk environments due to factors such as complex underground passages, unstable rock formations, sudden water level changes, and limited natural lighting. By integrating VSf, the model acknowledges that visitor safety is not merely a supplementary consideration but a critical determinant of the overall tourism quality. This inclusion aligns with risk management principles in geotourism, where proactive identification and mitigation of hazards directly influence both the sustainability of the site and the well-being of its visitors (Stella-Watts et al., 2012).

The VSf variable specifically addresses aspects such as structural stability of cave ceilings and walls, adequacy of handrails or guide ropes, presence of proper signage, and clarity of emergency evacuation procedures. A low VSf score in certain indicators, such as poor visitor knowledge of evacuation routes or insufficient preparedness for vertical descents, reflects gaps in management practices that could escalate into serious incidents. These findings suggest the need for targeted interventions, including improved staff training, enhanced safety briefings for visitors, and the installation of better safety infrastructure. The emphasis on VSf also ensures that safety considerations are not

overlooked in favor of purely economic or aesthetic development, thereby supporting a more holistic and responsible approach to cave tourism. On the other hand, the VEj (Enjoyment) variable captures the qualitative aspects of the visitor experience, focusing on emotional satisfaction, recreational fulfillment, and the perceived uniqueness of the site. A high VEj score generally indicates that tourists find the experience memorable and rewarding, which can boost word-of-mouth promotion and repeat visitation. However, the study's observation that VEj is high while VSf reveals weaknesses is particularly significant as it suggests that positive visitor perceptions may mask underlying safety deficiencies. This discrepancy underscores the importance of balancing thrill and enjoyment with rigorous safety measures. For instance, while adventurous elements like narrow passages or vertical climbs may enhance the enjoyment factor, they should be paired with adequate risk communication and protective equipment to prevent accidents.

Ultimately, the introduction of VSf and VEj into M-GAM provides a more nuanced and comprehensive evaluation of geosites, particularly those with inherent hazards like karst caves. It ensures that management strategies address not only the educational, aesthetic, and functional dimensions of geotourism but also the experiential satisfaction and physical safety of visitors. This dual focus can guide policymakers, site managers, and tourism developers in designing interventions that maintain high visitor enjoyment without compromising safety standards, thereby fostering sustainable and responsible geotourism in sensitive and high-risk environments. In ensuring that such management strategies are implemented effectively, the role of participatory and transparent systems becomes critical.

The system design that involves multiple stakeholders, including tourists, experts, managers, and tour owners, embodies the principles of collaborative and participatory management, as recommended by Bekele & Raj (2025). This multi-stakeholder approach ensures that the evaluation and management of geosites are not limited to a single perspective, but instead integrate diverse viewpoints, experiences, and expectations.

By including both professional expertise and public perception, the system captures a more holistic understanding of site value and management needs. Such inclusivity is essential in geosite management, where the balance between conservation and tourism development often requires reconciling the interests of various parties.

One notable feature of the M-GAM system is its value input interface, which does not require a user login. This design choice significantly lowers participation barriers, allowing a wide range of contributors, particularly tourists and casual visitors, to provide their assessments quickly and conveniently. In the context of geosite evaluation, public engagement is not merely a supplementary component; it provides valuable insight into visitor satisfaction, aesthetic appreciation, and perceived safety, which are often overlooked in purely expert-driven assessments. This openness not only increases the quantity of feedback but also enhances its representativeness, making the data more reflective of real user experiences.

In parallel, the system incorporates an access control mechanism in which only administrators and site owners can retrieve full reports. This ensures that while data collection remains public and participatory, data management is secure, and information integrity is maintained. Such selective access fosters accountability, as stakeholders with direct responsibility for site management can base their decisions on reliable, consolidated information.

At the same time, it supports transparency by ensuring that decision-makers can trace and justify their actions through documented evaluation data, reducing the risk of bias or mismanagement.

This integrated design is particularly significant given the long-standing issue of inadequate long-term monitoring systems, as highlighted by Herrera-Franco et al. (2020). Many geosites suffer from inconsistent evaluation and fragmented records, which hinder the ability to track changes in site condition, visitor perceptions, and conservation effectiveness over time. By combining continuous public participation with centralized expert oversight, the proposed M-GAM implementation offers a sustainable solution for ongoing monitoring. It creates a feedback loop in which site conditions and visitor experiences are systematically recorded, analyzed, and used to inform adaptive management strategies, thereby strengthening the resilience and sustainability of geosite operations in the long run. To ensure that these insights translate into practical action, effective visualization tools become essential in decision-making processes.

The representation of evaluation results in the form of the M-GAM Matrix and Radar Chart serves as an effective tool for both spatial and quantitative-based decision making. These visualizations enable stakeholders to identify which aspects of a geosite perform well and which require improvement, thereby facilitating more informed and targeted management actions. This is consistent with the spatial data and geographic information system (GIS)-based methodology proposed by Archi et al. (2023), which emphasizes spatial intelligence in tourism management. However, the approach in this study offers a distinct advantage in terms of accessibility and usability.

Being web-based, it removes the barrier of complex software installation and operation, allowing non-technical managers, local authorities, and community stakeholders to interpret and act upon the data with minimal training.

In addition, the digital information system developed within this framework streamlines the process of evaluating the sustainability of karst cave geotourism by automating calculations, storing historical records, and providing real-time visualization. This not only improves efficiency but also enhances objectivity, as the evaluation process becomes less reliant on subjective interpretations and more grounded in standardized metrics. Such objectivity is essential for minimizing bias, ensuring transparency, and building trust among stakeholders who may have different priorities or perspectives.

Beyond its role in measurement, the system contributes to proactive management by supporting early detection of potential risks. For instance, sudden declines in protection value or safety indicators can be flagged immediately, allowing managers to respond before these issues escalate into critical problems. In this way, the system does not merely serve as a diagnostic tool but also functions as a preventive mechanism that strengthens the resilience of geotourism destinations. The scalability of this system is another significant advantage. Its adaptable architecture allows it to be implemented at various

karst cave destinations across Indonesia, serving as a replicable prototype for M-GAM-based adaptive geotourism management. By providing a standardized yet flexible evaluation model, the system supports national objectives in balancing conservation with sustainable tourism development. This addresses a pressing need in Indonesia, where many geosites face pressures from tourism growth, climate variability, and human activities, but lack consistent monitoring and adaptive management tools. In the long term, integrating this web-based M-GAM evaluation platform into regional and national tourism strategies could foster more sustainable, data-driven, and community-inclusive geotourism practices.

CONCLUSION

This research developed and implemented a digital information system based on the Modified Geosite Assessment Model (M-GAM) to evaluate geotourism sustainability in karst areas, using Jomblang Cave as a case study. The system integrates tourist perceptions, expert assessments, and field observations, enhanced with safety and enjoyment variables, to provide comprehensive, data-driven evaluations and recommendations. Applying the Waterfall method, it produced an accessible questionnaire platform with real-time monitoring through an interactive dashboard.

Results show $MV = 6.37$, $AV = 16.09$, and a Z-index of 22, indicating medium performance with weaknesses in Education, functionality, protection, and safety. The study demonstrates the potential of M-GAM in a digital format for inclusive, collaborative, and evidence-based geotourism management, while noting limitations such as a single case study, reliance on internet connectivity, and lack of long-term validation. Future work should expand to other sites, integrate mobile and AI technologies, and increase community involvement.

Although this study successfully demonstrates the feasibility of a web-based information system for evaluating sustainable tourism performance in karst cave geotourism, several limitations should be acknowledged. The research focuses solely on Jomblang Cave in Yogyakarta, which, while representative of typical karst environments, may differ from other sites in terms of geological, managerial, and visitor characteristics; thus, its findings and indicator weightings (MV and AV) may not be fully generalizable. The system's evaluation also relies on subjective input from respondents and experts, introducing potential response bias; incorporating environmental sensor data or visitor tracking could strengthen objectivity. Furthermore, the limited observation period prevents long-term validation of system performance and sustainability outcomes, suggesting the need for longitudinal implementation. Technical constraints such as dependence on stable internet connectivity and centralized storage may hinder application in remote karst areas, underscoring the importance of developing offline or mobile-compatible modules.

Additionally, while the Modified Geosite Assessment Model (M-GAM) was enhanced with safety and enjoyment variables, other critical dimensions such as community participation, economic equity, and climate resilience remain unexplored. The absence of artificial intelligence (AI) and geospatial analytics also restricts predictive and spatial decision-support potential. Collectively, these limitations indicate that the current system serves as a prototype phase, and future studies should aim to extend multi-site testing, incorporate sensor-based and AI-driven data integration, and evaluate long-term adaptability to advance sustainable and evidence-based geotourism management.

The web-based M-GAM information system provides practical implications for managing sustainable karst cave geotourism by integrating technology, governance, and participatory evaluation. The system enables managers to identify performance gaps in real time and supports proactive, evidence-based decision-making aligned with UNWTO (2024) and GSTC Global Sustainable Tourism Council (2023) guidelines. Its participatory structure encourages inclusivity and transparency by involving tourists, experts, and managers, fostering shared responsibility for conservation. Moreover, the platform's standardized indicators allow replication across different geosites, facilitating benchmarking and comparative assessments. The system's visualization features also serve educational functions, promoting awareness of geological and environmental values among visitors. By aligning ecological preservation with improved visitor experience, this tool strengthens the synergy between conservation and economic sustainability. Overall, the web-based M-GAM framework provides a practical digital model for adaptive and data-driven management, ensuring long-term sustainability of karst cave destinations such as Jomblang Cave.

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