sustainability

Article

Geotourism Hazards and Carrying Capacity in Geosites of Sangkulirang-Mangkalihat Karst, Indonesia

Arzyana Sunkar [1,*], Anindika Putri Lakspriyanti [1,*], Eko Haryono [2], Mohsen Brahmi [3,4], Pindi Setiawan [5] and Aziz Fardhani Jaya [5]

1 Faculty of Forestry and Environment, IPB University, Bogor 16001, Indonesia
2 Karst Research Group, Faculty of Geography, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia; e.haryono@geo.ugm.ac.id
3 FEMS Faculty, University of Sfax, Sfax 20655, Tunisia; brahmi.mohsen@gmail.com
4 Faculty of Arts and Design, Bandung Institute of Technology, Bandung 40132, Indonesia
5 Division of Campaign and Public Media, Forest Watch Indonesia, Bogor 16129, Indonesia; pindisp@yahoo.com (P.S.); syah.azizfardh@gmail.com (A.F.J.)
* Correspondence: arzyana@apps.ipb.ac.id (A.S.); anindikapl@gmail.com (A.P.L.); Tel.: +62-251-8621947 (A.S.&A.P.L.)

Abstract: The protection of resources and the safety of visitors are two essential elements in the sustainability of any tourism destination. The Sangkulirang-Mangkalihat karst has the potential to be developed as a UNESCO Global Geopark based on the diversity and unique nature of its geological heritage. Proper management efforts should be carefully planned to ensure sustainability of the geosite. Intact natural conditions can be a potential hazard to visitors and, conversely, the presence of visitors can interfere with the natural preservation of the sensitive karst area. Physical, biological, and human activities that may endanger visitors should be identified and limiting the number of visitors received by each geosite should also be considered. This paper aims to identify the potential tourism hazards of physical, biological, and human activities and to calculate the tourist's carrying capacity of three geosites (Tewet cave, Nyadeng lake, and Bloyot cave) in the Sangkulirang-Mangkalihat karst. The identification of potential hazards was conducted in each geosite and analyzed and assessed using management options referencing UNEP, NPSA, and APEC, whereas the carrying capacity was assessed with reference to the Cifuentes formulation. Meanwhile, the carrying capacity was assessed at three levels, namely physical carrying capacity (PCC), real carrying capacity (RCC), and effective carrying capacity (ECC). The highest physical and biological hazards were the ravines in the Tewet cave, as well as a moderate level of risk, such as slippery, steep terrain and the presence of crocodiles. Meanwhile, the potential hazards faced by Nyadeng lake and Bloyot cave were classified as low risk. The carrying capacity assessments indicated that Bloyot cave is able to accommodate the largest number of visitors on a daily basis. Therefore, the carrying capacity results of each geosite can serve as a reference for managers to limit the number of visitors to the site in order to ensure the sustainability of Sangkulirang-Mangkalihat geosites.

Keywords: cave; geoheritage; geosite; hazard; archaeology; rock art; sustainability; tourism

check for updates

Citation: Sunkar, A.; Lakspriyanti, A.P.; Haryono, E.; Brahmi, M.; Setiawan, P.; Jaya, A.F. Geotourism Hazards and Carrying Capacity in Geosites of Sangkulirang-Mangkalihat Karst, Indonesia. *Sustainability* **2022**, *14*, 1704. https://doi.org/10.3390/su14031704

Academic Editor: Juan Ignacio Pulido-Fernández

Received: 29 November 2021
Accepted: 25 January 2022
Published: 1 February 2022

1. Introduction

Sustainability is the way forward for effective management of natural resources, including in tourism management, since it is an integral part of tourism policy and strategy [1]. Given the interconnectedness of tourism pressure and sustainability, the relevance of tourism sustainability is critical [2]. The sustainability assessment is therefore an increasingly important area of research in the field of tourism. Specifically, it is critical to ensure consistent development of tourist destinations and products [3,4]. The challenge of sustainability is more pronounced on tourism objects or attractions that rely heavily on nonrenewable resources, such as geological resources [5].

A branch of tourism that focuses on geological attractions is known as geotourism, which is a new concept within tourism studies [6] and has gained popularity over the past decades [7]. Geotourism is defined as "Geotourism is tourism of geology and landscape usually undertaken at geosites. It fosters conservation of geological attributes (geoconservation) as well as understanding of geoheritage and geodiversity (through appropriate interpretation). At a higher level the geological knowledge imparted at a geosite may be used to inform its biotic and cultural features so that a more holistic view of the environment can be gained. This should then lead to a more enhanced understanding and appreciation of the world built from its geological foundations" [8] (p.8). Geotourism is expected to foster the protection of geological heritage through public support through the sustainable economic development of the regions [9].

Geological heritage protection is the aim of a Geopark [10–12], defined by UNESCO (United Nations Educational, Scientific and Cultural Organization) as a nationally protected area that contains a number of geological heritage sites of particular importance, rarity, or aesthetic appeal, and is one element in an integrated concept of protection, education, and sustainable development [13]. Geoparks represent a novel approach in natural and geological heritage protection and play important roles in cultural sustainability in rural areas [14–17], while encouraging scientific research, public education, and local economic development [16,17]. Hence, if properly managed, geotourism in Geoparks can be a vehicle for the conservation of a geological area and at the same time, contribute to local economic sustainable development [18,19].

In Indonesia, geopark development began in 2010 when the Ministry of Tourism established six geopark areas, namely Toba, Merangin, Rinjani, Gunung Sewu, Batur, and Raja Ampat, as national geoparks [20], of which some now have developed into UNESCO Global Geoparks (Figure 1). This development is a response to the national policy which recognized Geoparks through the Presidential Decree Number 9 Year 2019 on Geopark. Currently, Indonesia hosts six UNESCO Global Geoparks and 13 national geoparks, as well as several aspiring geoparks (Figure 1), of which the Sangkulirang-Mangkalihat aspiring geopark (see Figure 1) is currently encouraged by the government and diverse practitioners to be established as a UNESCO Global Geopark.

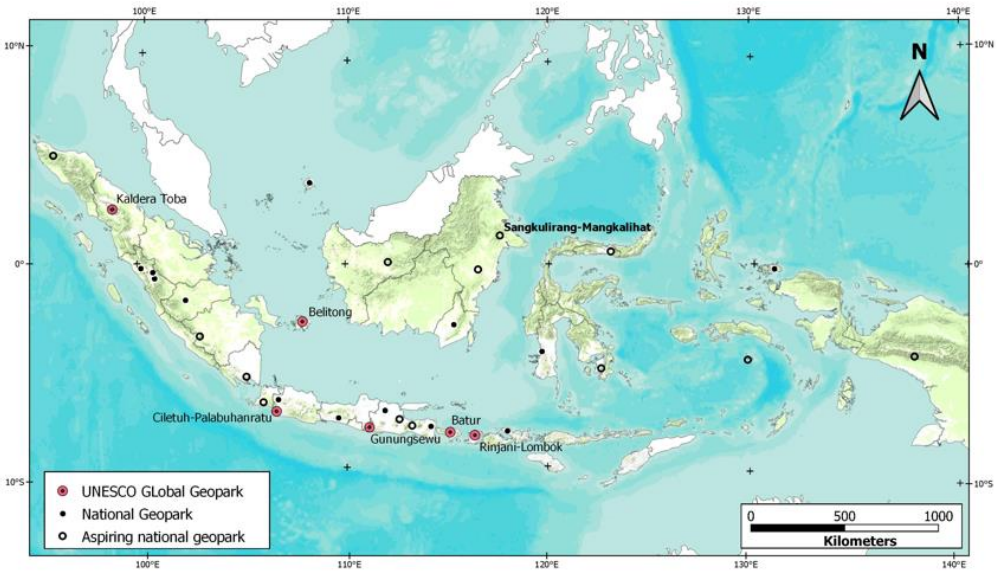

Figure 1. Distribution of geoparks in Indonesia.

The tectonic history of the Sangkulirang-Mangkalihat karst is inseparable from the formation of the Mangkalihat Peninsula and the Kutai Basin. The Mangkalihat at the beginning of its development was one of the microcontinents from North Gondwana (a supercontinent) that crossed the equator in the Late Triassic to Early Cretaceous period

(205–141 Ma) as a result of the widening of the Ceno-Tethys Ocean [21–23], which was part of Sundaland in 150–60 Ma. The Sundaland recounts the history of the growth and disintegration of a continent by accretion and dispersion [22]. The island of Borneo also encompasses the tectonic interaction between the Indian–Australian and Pacific with Asian plates and could be traced from the stratigraphic column and structural patterns. Limestone, as the host rock of Sangkulirang-Mangkalihat karst, was formed when the Makassar Strait extended over the mid-Eocene, which initiated the uplifting process that exposed the limestone into Sangkulirang-Mangkalihat highland [24]. Geomorphologically, the karst area presents high diversity of karst landforms as each karst block (area) is associated with specific type of karst, i.e., labyrinth, conical, and the newly-discovered bottle-shaped karst hills (chimney-like feature) (Figure 2). This unique morphology is a karst cone formation with a circular hole at the top with a depth that reaches the lowest surface layer of the karst tower that resembles a bottle/chimney [25]. These chimney-like features are often found in karst blocks on top of a plateau with a high elevation. The genesis of this feature remains unknown and very little research has ever been conducted to investigate this feature [24]. Another intriguing geomorphological feature in the Karst of Sangkulirang-Mangkalihat is the karst plateau as the indication of folding geoprocess [24].

Figure 2. Chimney-like feature of Sangkulirang-Mangkalihat karst.

Speleologically, the rock-shelter caves are the locations for cave paintings, and they are the main attraction of Sangkulirang-Mangkalihat karst. In addition, the dating of the U-series shows that the oldest parietal art of eastern Borneo dates between 51.8 and 40 ka. The oldest date of 51.8 ka provides the maximum date for the earliest cave painting phase in the Sangkulirang-Mangkalihat Peninsula [26]. Culturally, the maximum date of 51.8 thousand years ago (ka) [26] also marks the oldest cave paintings made by prehistoric modern humans in the world. This has implications for understanding how the first rock art emerged, developed, and spread throughout Southeast Asia during the Late Pleistocene and beyond [26]. A UNESCO Global Geopark status can promote the sustainability of these values of international significance.

Through the tourism experience gained by visitors and the surrounding community, deeper awareness and relationship with the geological heritage can be formed. In this way, geoparks can become an effective medium to bring the wider community closer to the geological heritage [14]. However, the number of visitors can also pose a threat to environmental conditions, as well as reduce comfort of the visitors. The increasing number of visits to a site increases the susceptibility of the site to various potential natural and anthropogenic effects that could degrade these resources [27], leading to negotiation in terms of sustainability [28]. Caves have been demonstrated to be highly susceptible to human activities [29,30], and “caves have unique scientific, recreational, and scenic value, and these values are endangered by both carelessness and intentional vandalism that cannot be recovered once they are gone" [31] (p. 19).

Activities conducted in geological areas have the potential to cause accidents that can even lead to damages or death, which, of course, will harm visitors [32]. The fragility of the karst environment makes it highly vulnerable to a variety of different hazards, including physical, biological, human, and geological [33]. Hazards, as well as the number of visitors, need to be managed in order to avoid the risks and losses that will be caused. There are two risks that have the potential to negatively impact resources: vulnerability and fragility. In this context, vulnerability may be defined as a risk related to the likelihood of human impacts, while fragility may be defined as a risk of change (consequences) caused by natural processes [27,34–36]. The number of visitors that can be received (carrying capacity) by the area also needs to be recognized, highlighting the importance of determining the carrying capacity [37].

Since the systematic literature reviews conducted by various researchers [4,6,38], not much has been written on geotourism development that focuses on the assessment of potential physical, biological, and human hazards and the carrying capacity of geosites at the same time. Study on visitor-carrying capacity for geosites development has been carried out by [39]; however, the research was not followed by the identification of potential hazards in karst areas or geosites. This paper identifies and discusses the various types of hazards and carrying capacity of three geosites (tourism attractions within a geopark with remarkable geological or scientific significance) in Sangkulirang-Mangkalihat karst that could accommodate visitors to minimize environmental impacts and discomforts. As suggested by [30], the ecological characteristics and the management capacity should be considered during an increase in the number of visitors. Aspects of visitor safety and tourism objects safety are essential things that need to be considered, as these will greatly affect the sustainability of geotourism development in the Sangkulirang-Mangkalihat karst.

2. Materials and Methods

This study was carried out in Sangkulirang-Mangkalihat karst in the East Kalimantan Province of Indonesia. The karst is located on the Mangkalihat Peninsula, east of Kalimantan Island (Figure 3). The people and residents of the surrounding karst area have used it from generation to generation as a housing site to search for swallow nests and water resources. This karst area is protected under the Government Regulation Number 67 of 2012 concerning the Protection and Management of Sangkulirang-Mangkalihat Karst Ecosystem in Berau and East Kutai Regency [25,40].

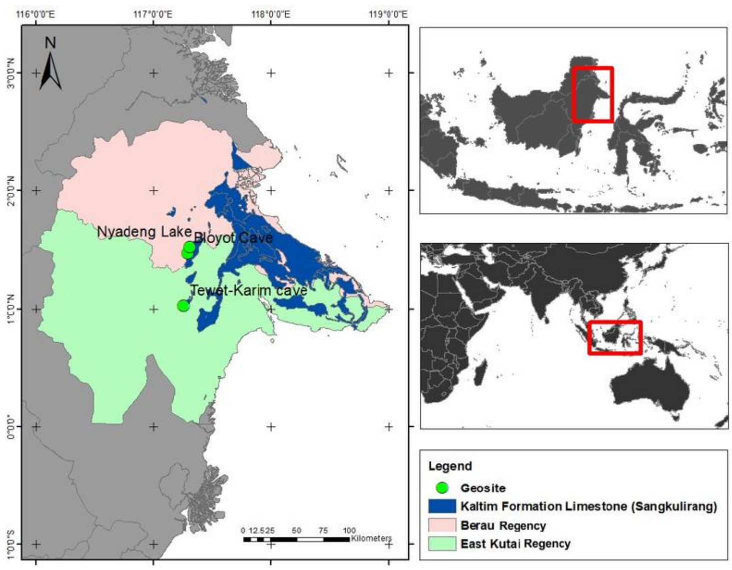

Figure 3. Locations of the three geosites studied.

The data collection took place at three geosites (Figure 3) administratively located in two different villages, namely in (i) Nyadeng lake and Bloyot cave geosites of the village of Merabu, in 2019 inhabited by 234 inhabitants [41], and (ii) Tewet cave geosite located in the village of Tepian Langsat, with 1181 inhabitants in 2018 [42]. These geosites were selected as study locations because they are already open to the public and are more prepared to welcome tourists than other geosites within the Sangkulirang-Mangkalihat karst area. Data collection took place between April and May 2021, which involved interaction with tourists and local guides, and thus this research has been approved by the Human Research Ethics Committee of the IPB University through Ethical Clearance No. 444/IT3.KEPMSM-IPB/SK/2021.

2.1. Potential Hazards

An assessment of potential hazards associated with physical, biological, and human activities was conducted. Analysis of physical and biological hazard data refers to the UNEP (United Nation Environment Programme) [34], while the hazard to human activities refers to the NPSA (National Patient Safety Agency) [35]. Both are also referred by [43] to determine the potential hazard of tourism in mountain areas.

Physical and biological hazards refer to the risk assessment guidelines by calculating the likelihood and severity (consequence), followed by a risk assessment using a risk assessment matrix. Each potential hazard identified is assigned a likelihood weight (Table 1) and severity (Table 2) in accordance with UNEP Guidelines [34]. Information about past events is required to determine the likelihood and severity of each potential hazard at each location.

Table 1. Assessment of the likelihood of physical and biological hazards occurrence [34].

Likelihood	Value	Description
Almost certain	5	Is expected to occur in most circumstances
Likely	4	Will probably occur in most circumstances
Possible	3	Might occur at some time
Unlikely	2	Could occur at some time
Rare	1	May occur in exceptional circumstances

Table 2. Severity of potential physical and biological hazards [34].

Consequences	Value	Description
Catastrophic	10	Disruption inevitably leads to death
Major	8	Disruption sometimes leads to death
Moderate	4	Disruption causes serious (permanent) injury
Minor	2	Minimal disruption/cause minor injury
Insignificant	1	No disruption

Exposure to the potential hazards that present the highest risk is then calculated based on likelihood and consequences using the following formula.

$$\text{Risk} = \text{Likelihood} \times \text{Consequences} \quad (1)$$

The potential risk level is derived by mapping the calculation results of the risk level matrix (Table 3). The options for managing hazards were identified based on the risk assessment provided by APEC [36]. There are four risk reduction management options offered to improve management, namely reduce, avoid, retain, and transfer risks (Figure 4).

Table 3. Risk matrix analysis [34,35].

Risk = Likelihood × Consequences		Likelihood				
		Rare	**Unlikely**	**Possible**	**Likely**	**Almost Certain**
Consequences	Catastrophic	10 High	20 Extreme	30 Extreme	40 Extreme	50 Extreme
	Major	8 High	16 High	24 Extreme	32 Extreme	40 Extreme
	Moderate	6 Moderate	12 Moderate	18 High	24 High	30 Extreme
	Minor	4 Low	8 Low	12 Moderate	16 High	20 High
	Insignificant	2 Low	4 Low	6 Low	8 Moderate	10 High

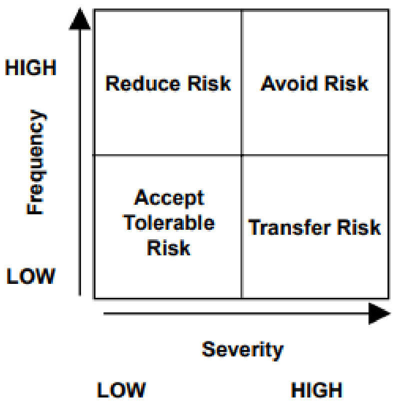

Figure 4. The risk evaluation matrix [34,35].

The risk assessment of potential hazards from human activities is conducted using the Job Safety Analysis (JSA) method [36]. This method may be used to control the potential risk of accidents in geological areas. The data used are tailored to the activities carried out by visitors and the community in the use of the Sangkulirang-Mangkalihat karst. The risk level of potential hazards is divided into four categories: extreme risk (score 15–25), high risk (score 8–12), moderate risk (score 4–6), and low risk (score 1–3) (Table 4).

Table 4. Human activity hazard level matrix.

No.	Category of Risk	Color Code	Score Value
1	Extreme		15–25
2	High		8–12
3	Moderate		4–6
4	Low		1–3

Source: Wilks [36].

The JSA method is an estimate of the hazard before a loss-causing impact occurs. Hazard identification is performed by plotting hazard locations along the path to tourist attractions. The scoring is then established to determine the risk value for each potential hazard according to the risk value matrix (Table 5). The risk grading is obtained by multiplying the severity value (negligible, minor, moderate, major, catastrophic) with the probability of risk occurrence (rare, unlikely, possible, likely, almost certain). The resulting grade is used to determine the risk prevention and control priority scale.

Table 5. Human activity risk value matrix table [36].

Likelihood of Happening		**1 Rare**	**2 Unlikely**	**3 Possible**	**4 Likely**	**5 Almost Certain**
Consequence		This will probably never happen/recur	Do not expect it to happen/recur but it is possible it may do so	Might happen or recur occasionally	Will probably happen/recur, but it is not a persisting issue/circumstances	Will undoubtedly happen/recur, possibly frequently
5 Catastrophic	Death	**5**	**10**	**15**	**20**	**25**
4 Major	Fracture, permanent disability	**4**	**8**	**12**	**16**	**20**
3 Moderate	Unconscious	**3**	**6**	**9**	**12**	**15**
2 Minor	Serious injury	**2**	**4**	**6**	**8**	**10**
1 Negligible	Mild injury	**1**	**2**	**3**	**4**	**5**
Risk score = Consequence × Likelihood						

2.2. Carrying Capacity

The carrying capacity calculation is performed to obtain the number of visitors that can be accommodated in the tourist attraction area. The calculation used is based on a formula that refers to Cifuentes [33,34] with modification of Fandeli and Muhammad [44] and Zacarias et al. [45]. There are three levels of carrying capacity, including physical carrying capacity (PCC), real carrying capacity (RCC), and effective carrying capacity (ECC).

Physical carrying capacity is the maximum number of visitors who are physically satisfied with the space provided in one day, considering the comfort of the tourists. The PCC is calculated by using the following equation:

$$PCC = A \times 1/B \times Rf \tag{2}$$

Information:
PCC = Physical carrying capacity (person/day).
A = The area used for tourism (m^2).
B = The area required for a tourist to travel while still achieving comfort (m^2).
B uses a fixed number referring to Cifuentes [33], which is the area required for one tourist while still obtaining satisfaction is determined at 1 m^2.
Rf = Rotation factor.

Real carrying capacity is the maximum number of visitors that are allowed to visit the object, considering the limiting factor or biophysical correction factor (Cf) of the features of the tourist attraction. RCC is calculated by the following equation:

$$RCC = PCC \times Cf\_1 \times Cf\_2 \times \ldots . \times Cf\_n \tag{3}$$

Information:
RCC = Real carrying capacity (people/day).
Cf = Correction factor.

Effective carrying capacity is the maximum number of visits during which the subject remains at the available management level. Managerial capacity is the sum of all conditions in the Sangkulirang-Mangkalihat karst that can be exploited objectively and according to the management objectives of the area. Managerial capacity is constrained by the criteria of the management system and the number of management employees with the following calculation:

$$ECC = RCC \times MC \tag{4}$$

Information:
ECC = Effective carrying capacity (people/day).
RCC = Real carrying capacity (people/day).

MC = Management capacity.
MC (management capacity) is calculated by approaching the number of area management officers.

$$MC = Rn/Rt \times 100\% \quad (5)$$

Information:
Rn = Number of onsite personnel (people).
Rt = Number of fixed resources manager (person).

3. Results

3.1. General Condition of Sangkulirang-Mangkalihat Karst

Sangkulirang-Mangkalihat karst ecosystem (Figure 5) is located in the province of East Kalimantan, specifically in Berau and East Kutai Regencies with a total area of 1,867,676 ha hectares according to the East Kalimantan Governor Regulation No. 67 Year 2012 out of the total 15.4 million ha of karst across the country [46]. The area enjoys a tropical climate. Out of this total karst area, as much as 403,151.89 ha is delineated as a geological protected area [25]. The area is also inhabited by 120 species of birds, 200 species of arthropods, including insects, 300 species of flora, and 50 species of fish and is the main habitat for endemic animals of Borneo, namely the Bornean orangutan [47]. Pinnacle karst and numerous cave systems are among the uniqueness of the area. The Sangkulirang-Mangkalihat karst features hilly terrain, steep cliffs, and underground caves. The caves in this area have unique features, such as cave paintings (rock art) and different types of animal images that have archaeological significance [48]. Owing to the possession of 240 pieces of rock art distributed over the entire roof of the cave, radiocarbon dating indicates that rock art in the Tewet cave in Sangkulirang-Mangkalihat karst is 40,000 BP (40 ka). It is considerably older than the Lascaux cave (35,400 BP) and the Chauvet cave (32,000) in France [48] and the karst area was presumed as the initial location for Austronesian humans to enter [49,50]. Furthermore, the maximum date for the earliest cave painting phase in the Sangkulirang-Mangkalihat Peninsula is 51.8 ka [26], and this also indicates the oldest cave paintings made by prehistoric modern human.

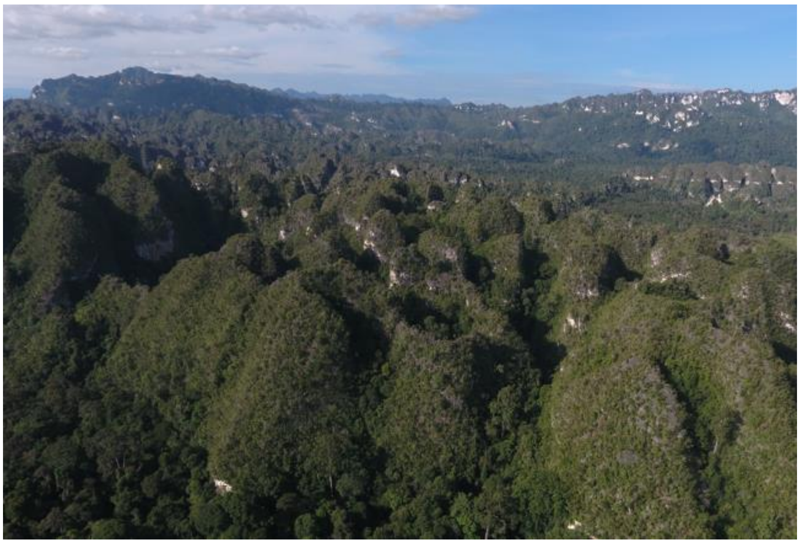

Figure 5. Sangkulirang-Mangkalihat karst landscape.

The Merabu Karst area is approximately 8000 ha [51]. Topographically, it is a lowland on the border of Lesan River, as well as karst plains and karst hills. Merabu is a karst area that is more developed in terms of both exokarst and endokarst. This development is characterized by the presence of both exokarst and endokarst morphological features and hydrological characteristics. The presence of exokarsts in the case of Merabu indicates the formation of tower hills, while the presence of endokarst features indicates the existence of caves. One of the caves with cultural value is the Bloyot cave. In this area, there is a phenomenon of a karst pool filled by springs of large discharge, with a depth of 40 meters, passing through below the water level of the Lesan River. The pool is clear and is called *Telaga Nyadeng* (Nyadeng lake). In the Merabu perikarst zone, it is very easy to find springs and small rivers that go in and out of these karst hills. The alluvial soil between the hills is relatively flat and contains dense forest. The Meranti tree stands straight and fairly tight, and many ironwoods can be seen standing big and tall.

3.2. Current Geotourism Development in the Three Geosites

Geotourism in the three geosites is developing. In 2012, the people of Merabu village, assisted by The Nature Conservancy, submitted a proposal for a village forest. The natural potentials that the community were going to develop were caves and karst lakes. In 2014, Merabu village received a Village Forest Designation from the Ministry of Environment and Forestry through the Minister of Environment and Forestry Decree Number 28/Menhut-II/2014 concerning the Merabu village forest which has an area of 8245 hectares and is managed by the Merabu Village Forest Management Institution (LPHD). Starting in 2018, the management of tourism has been completely handed over to Merabu BUMDES (Village Owned Enterprises). Nothing has changed regarding the tourism arrangements that have been set out in the previous village regulations; however, Merabu village tourism management has become one of the business units in the Merabu BUMDES. Most of the community has been involved in tourism activities by being tour guides, renting homestays, providing catering, and renting accommodation (boats and cars) for tourists. The two geosites that have been developed by the community are Bloyot cave and Nyadeng lake (Figure 6).

(**a**) (**b**)

Figure 6. Geosites that have been developed in the village of Merabu: (**a**) Rock art of hand print, and human at Bloyot cave; (**b**) Nyadeng lake.

Most of the tourists visiting Merabu are local tourists originating from East Kalimantan. Based on the guest book of East Kalimantan Cultural Heritage Preservation Center (Balai Pelestarian Cagar Budaya), it can be seen that the number of visitors to Nyadeng peaked in June and January (Figure 7), in the times of holiday seasons.

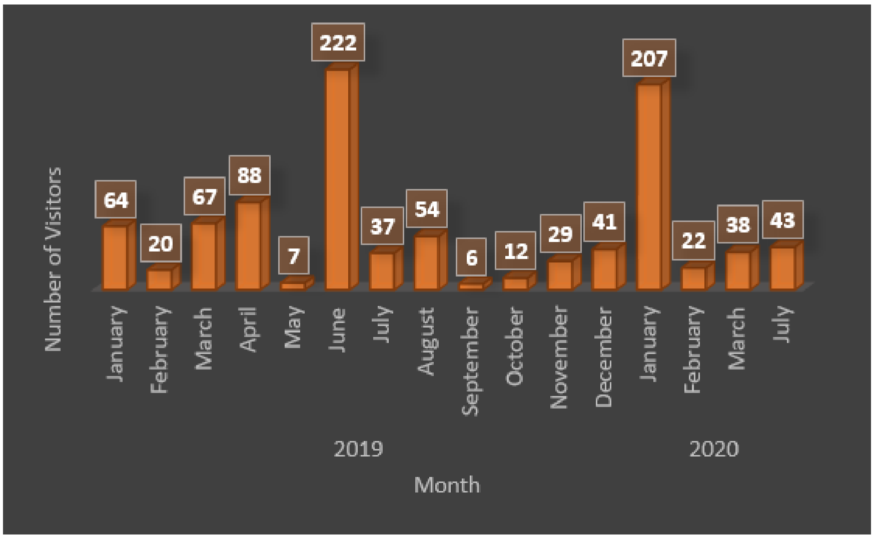

Figure 7. Number of visitors to Nyadeng lake.

Tourism in Tewet is still in its infancy. The Tewet cave (Figure 8) area is part of the Karst landscape of Mount Gergaji. This area is located in the upstream of the Bengalon river. The natural resources potential around the Tewet area is in the form of karst hills with high cliffs and natural caves with hand-printed paintings. Currently, Tewet cave is designated as a national cultural heritage site by the East Kalimantan Cultural Heritage Preservation Center. The Tewet cave area has natural potential that can be developed into natural tourism. This area has been visited mostly for research purposes on rock painting, hence the number of visitors is still very low (Figure 9). Currently Tewet cave is being developed into a natural tourist attraction and will be managed by the community in Tepian Langsat village.

(**a**) (**b**)

Figure 8. Tewet cave: (**a**) Hand printed images on cave roof and walls; (**b**) Scenery from the entrance of Tewet cave.

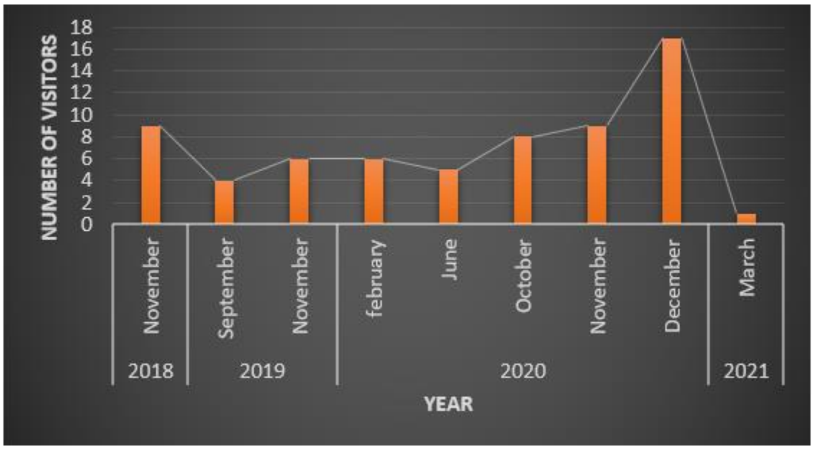

Figure 9. Number of visitors to Tewet cave.

3.3. Sources of Potential Hazards of Sangkulirang-Mangkalihat Geotourism

3.3.1. Sources of Potential Physical Hazard

Karst is the product of karstification process, namely the process of chemical corrosion of rocks by water on limestone [52] resulting in the formation of exokarst features (surface morphology) such as doline/sinkhole, polje, karren [53], dry valleys, lakes, karst hills, and thick-walled beaches [54], and endokarst features (developed underground), such as underground rivers/lakes and caves [53], which can be the source of hazards. Damage to karst can pose a potential hazard, especially to visitors who are on site. Potential hazards can occur, for example rockfall [55,56] and sinkhole [57]. Rockfall can occur due to steep slopes, dislocation of boulders on the slopes, and weathering of rocks [55,56]. Rockfall that occurs may damage important and historic objects. Similar to what happened to the Ajanta caves in India, ancient rock caves that have become historical relics in the area were lost due to rock collapse in the past [56]. Sinkhole is a condition where there is formation of cavities due to increased dissolution of bedrock so that it cracks and erodes vertically [57]. In short, a sinkhole is the collapse of an insoluble cover layer into a cave [58]. These conditions can occur at any time and can threaten the safety of visitors. Karst features found to be the sources of potential physical hazards at the three geosites are rivers, lakes, ravines, sinkholes, and steep cliffs (Table 6).

Table 6. Sources and risk level of physical hazards in Nyadeng lake, Bloyot cave, and Tewet cave.

Geosite	Sources of Physical Hazard	Likelihood Level	Consequence Level	Risk Level
Nyadeng lake	Shallow river Slippery path Lake Flood	Rare Possible Likely Unlikely	Minor Minor Major Minor	Low Low Low Low
Bloyot cave	Ravine Slippery path Muddy ground Sinkhole Rockfall	Rare Possible Possible Rare Rare	Major Minor Not Severe Major Major	Low Low Low Low Low
Tewet cave	Ravine Slippery path Sinkhole Rockfall	Almost certain Likely Rare Rare	Severe A Bit Severe Major Major	Extreme Moderate Low Low

1. River

The Lesan river becomes shallower upstream. Parts of the river on the way to Nyadeng lake experience siltation during the dry season. This represents a potential hazard to passing dugout canoe (ketinting). Ketinting can run aground in the shallow section of a river, of which the passengers on board may be thrown off. Shallow rivers may occur when the river conditions are poor, and there is a point that has potential for siltation. Over the last 5 years, however, shallow rivers can still be crossed by ketinting.

2. Slippery Path

The path that visitors follow from the Nyadeng pier to the Nyadeng lake is a terrain composed of soil and karst rocks sunk in some parts. When it rains, the path becomes damp and slippery (Figure 10). This can become a hazard when visitors are not paying attention and do not use adequate safety equipment, particularly footwear. When the field is wet after the rain, it is possible that visitors slide as a result of the slippery path. This can cause minor discomfort or injury for visitors.

Figure 10. Slippery trail in Nyadeng area.

3. Lake

Nyadeng has two pools, each with a depth greater than 30 meters. Swimming activities at Nyadeng lake are very risky and can cause drowning or even death if tourists are not able to swim due to their poor fitness.

4. Flood

During the past 2 years, specifically during the rainy season in February and March, Nyadeng lake overflowed. Consequently, the land surrounding the lake and the rivers is submerged. The most recent flood occurred in 2020 at about the height of an adult knee, causing minor inconvenience such as itching and damage to the equipment.

5. Ravine

The path to the Tewet cave must pass through different terrains, one of which is a ravine, as the location of the cave is on a cliff of karst hill. It is a potential hazard for visitors to fall as the path has to pass by the edge of a cliff, although in the last 10 years, there has never been any form of accident that caused a visitor to fall from a cliff.

Contrary to the location of the cave of Tewet, the cave of Bloyot is in the middle of a cliff. As a result, the only access to the cave must be by a cliff. The cliff is almost 90° in condition and there is very little seating and handling. Therefore, it can potentially be hazardous to visitors, as it poses a potential risk of falling while climbing without using adequate climbing equipment.

6. Muddy ground

To reach the cave of Bloyot, one must pass by the ground (plain forest) with sloping topography. At the arrival of the rainy season, in some parts of the path, the water is flooded, and the ground becomes muddy. This can be hazardous, as visitors are likely to slide or itch due to their exposure to mud.

7. Sinkhole

One of the geological hazards is a sinkhole, which develops during the dissolution of karst dolomite, anhydrite, gypsum, or salt by groundwater or water enriched with carbon dioxide [57]. Nevertheless, there has been no reported historical sinkhole hazard in the studied geosites.

8. Rockfall

Both Tewet cave and Bloyot cave are located on cliffs, and thus there is a possibility of a rockfall (though categorized as rare). Rockfall occurrences can threaten the lives and safety of visitors during visiting and surveying of the place, as it is one of the most common and dangerous types of slope instability due to its high speed and destructive power [55]. Rockfalls occur when rock masses detach from a cliff (Figure 11) and fall freely as a result of gravity [59].

Figure 11. Steep karst cliffs.

3.3.2. Sources of Potential Biological Hazards

Potential biological hazards are all forms of hazards that originate from biological resources that can cause a variety of health effects. Plants, insects, and animals along the path leading to a tourist attraction may pose a potential hazard to visitors. Potential biological hazards can be found in all the three tourist attractions, including tree roots, gnats, fallen trees, and crocodiles. Tree roots are relatively frequent sources of hazard and are moderate in severity at all three geosites (Table 7).

Table 7. Sources and risk level of biological risk in Nyadeng lake, Bloyot cave, and Tewet cave.

Geosite	Sources of Biological Hazard	Likelihood Level	Severity Level	Risk Level
Nyadeng lake	Tree root Gnat	Possible Possible	Minor Minor	Low Low
Bloyot cave	Tree root Fallen tree	Unlikely Unlikely	Minor Insignificant	Low Low
Tewet cave	Tree root Crocodile	Unlikely Unlikely	Minor Major	Low Moderate

1. Tree roots

The path to Nyadeng lake runs through the lowland tropical forest and contains a lot of tree roots (Figure 12), which can become hazardous as visitors can trip.

Figure 12. Example of tree roots found along the trail.

2. Gnat

Nyadeng lake is a lake located in the middle of the forest. When it becomes dark, many gnats appear and bite the skin. This has the potential to be a hazard, as tourists can itch due to gnat bites.

3. Fallen tree

In several places on the path to the cave of Bloyot, there are fallen trees that cover the path. This can be a potential danger, as it can obscure the way, or visitors can be injured by fallen tree branches.

4. Crocodile

Along the Bengalon River and its tributaries, crocodiles are still present. From 2020 to 2021, there have been several cases of people being attacked by crocodiles, even if the place is not on the tourist path but in the same river.

3.3.3. Sources of Potential Hazards of Human Activities

The danger of human activity is a form of danger that comes from visitors, either due to bad behavior or decision-making prior to and during the visit. Potential hazards from human activities are observed in relation to activities conducted by visitors and the community. There are eight possible hazards in all 11 segments, each segment represents an area between resting spots or points of attraction where visitors might stop or take a break. In Nyadeng lake, there are three potentially hazardous human activities, whose risk levels are composed of two moderate hazards and one low hazard (Figure 13). In the Bloyot cave, there are four types of potentially dangerous human activities—three hazards are in the low category and one of them is in the extreme category (Figure 14). Tewet cave has four types of human activities that are potentially dangerous—two types of hazards are included in the moderate category, and the remaining two are included in the extreme category (Figure 15). All of these segments are presented with their related risks in Table 8.

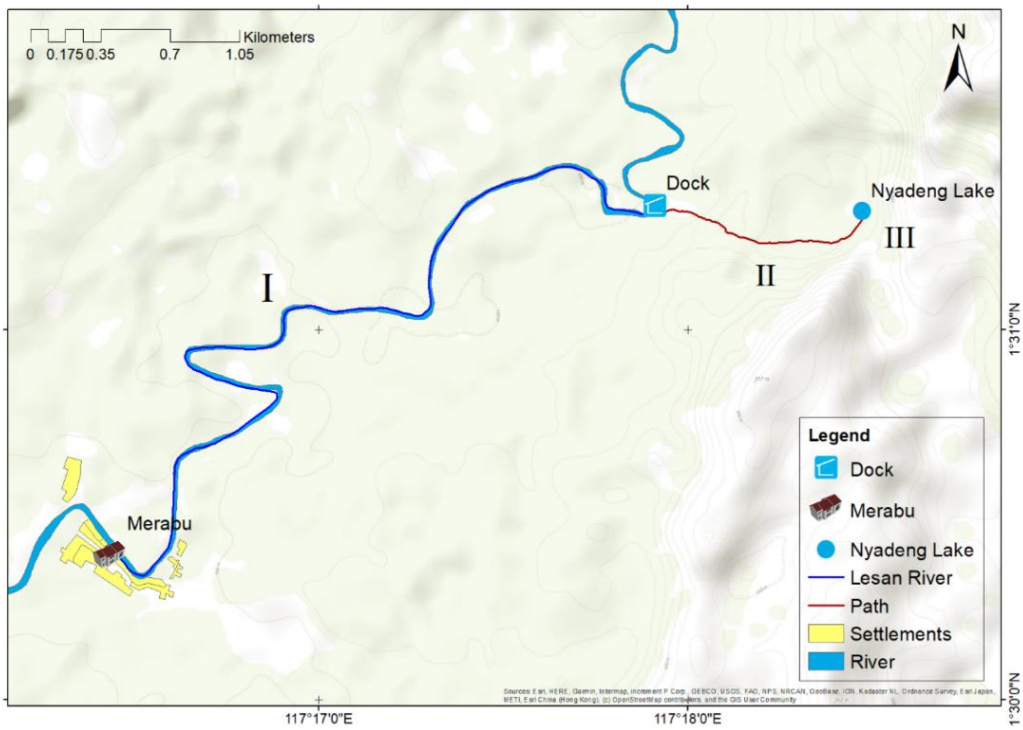

Figure 13. Potential hazard segments linked to human activities along the trail to Nyadeng lake.

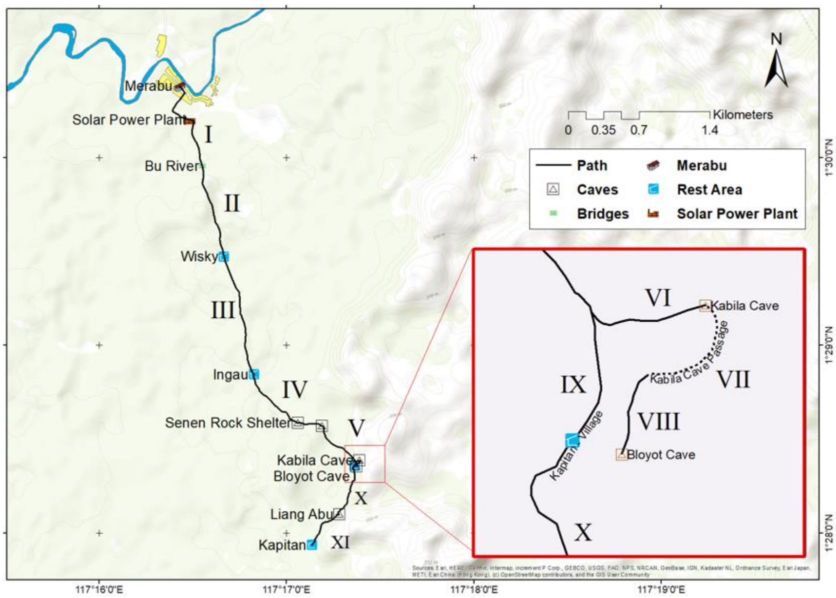

Figure 14. Potential hazard segments linked to human activities along the trail to Bloyot cave.

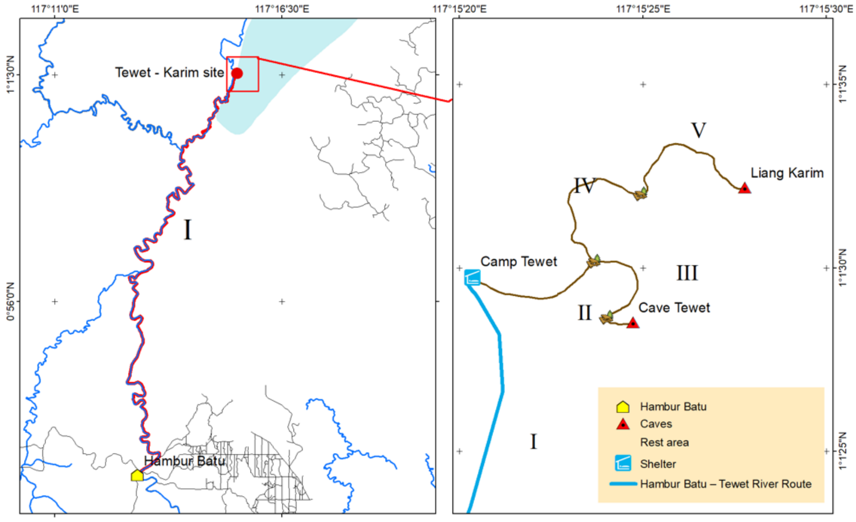

Figure 15. Potential hazard segments from human activities on the trail to Tewet cave.

Table 8. Level of risk associated with human activities in Nyadeng lake, Bloyot cave, and Tewet cave.

Geosite	Human Activities	Segment	Potential Hazard	Risk Level
Nyadeng lake	Swimming in a state of physical weakness	I, III	Drowning/death	Moderate Score: 5
	Not using adequate gears	I, II, III	Falls/minor injuries	Low Score: 3
	Riding a boat/ketinting at night	I	Crash/bounce/drowning/death	Moderate Score: 5
Bloyot cave	No adequate footwear	I-XI	Stumbled/ minor injuries/ itching	Low Score: 3
	Running downhill	VI	Falls/minor injuries/serious injuries	Low Score: 2
	Not using caving equipment (head-lamp, helmet)	VII	Lost/fallen/slightly injured	Low Score: 3
	No safety climbing equipment used	VIII	Falls/broken bones, handicaps/death	Extreme score: 20
Tewet cave	Not using safety climbing equipment	II, III	Falls/broken bones, handicaps/death	Extreme Score: 20
	Running downhill	II, III, IV, V	Falls/broken bones, handicaps/death	Moderate Score: 5
	Climbing up the cave during rains	II, III, IV, V	Falls/broken bones, handicaps	Moderate Score: 4
	Swimming in the river	I	Drowning/attacked by crocodiles/death	Extreme Score: 15

1. Swimming in a state of physical weakness

Nyadeng lake has a depth of more than 30 meters. Therefore, tourists need to be able to swim when participating in activities within the lake. Meanwhile, swimming in a state of physical weakness can cause muscle cramps and unconsciousness.

2. Not using proper gear

Access to Nyadeng lake requires caution in several areas. While crossing the Lesan river, it is necessary to use equipment such as a life jacket, as some portions of the river are deep. This should also be applicable when swimming. Nyadeng can be accessed through forest terrain, hence it is necessary for tourists to use proper footwear in order not to stumble or fall due to the slippery surface. Failure to use this equipment may jeopardize the safety of tourists.

Access to the Bloyot cave involves several terrains that require caution, including the crossing of the forest and the slippery ground. It is necessary to use proper gears such as shoes and covered clothing to avoid tripping or falling, as it is slippery or impeded by tree branches. Failure to use this equipment may jeopardize the safety of tourists.

3. Riding the boat/ketinting at night

Sometimes, there are tourists who force themselves to travel to Nyadeng at night to catch the morning sunrise in Ketepu. They must travel through the Lesan river to reach Nyadeng lake. Although the river itself is shallow, the current is quite strong. It takes special skills for motorists to pass through this tributary. This has the potential to be dangerous as it can cause the boat to lose steering and thus crash.

4. Running downhill

Running as one descends from the Bloyot cave in segment VI, namely the mouth of Kabila cave to the intersection in front of Bloyot, can potentially be dangerous as one can fall. The rocky, slippery, and steep terrain enables this hazard to occur. This is similar to running when going down to the camp, and thus can place tourists' safety in jeopardy. A slippery and steep terrain makes it possible for tourists to fall when they choose to run downhill.

5. Not using caving equipment

Access to the Bloyot cave goes through and enters the Kabila cave. Kabila cave is one of the longest cave systems in Merabu. It takes gear to access the cave. Therefore, if you do not use caving equipment, dangerous situations can occur, e.g., becoming lost, falling from rocks, or rockfall.

6. Not using safety climbing equipment when climbing

Not using safety climbing equipment while passing through the cliffs of Kabila Cave to Bloyot cave can be dangerous. The narrow path adjacent to the ravine must be traversed with climbing safety equipment. Failure to do so may result in a risk, such as falling into a ravine. The paths to the caves of Tewet and Karim are made of cliffs. If secured climbing equipment is not used, it can endanger tourists.

7. Climbing up to the cave when it rains

Climbing when it rains can be hazardous for tourists. As the terrain is slippery, some cliffs are very difficult to access. This can be hazardous to tourists as they may fall.

8. Swimming in the river

Swimming in the river can pose a risk of being attacked by crocodiles. Crocodile habitats are found alongside the Bengalon River and its tributaries.

3.4. Carrying Capacity

3.4.1. PCC

Nyadeng lake has a land area of 600 m^2 that can be used for lounging or recreational activities. Visitors typically engage in activities in Nyadeng lake for 1 to 2 h. Tourist operating time in the area occurs from 07.00–17.00 local time, although occasionally there were tourists who came here during the night. Considering the space and time available, the number of visitors who can be physically accommodated in Nyadeng Lake is 3000 people per day, while for Bloyot cave, the time normally spent by visitors is from 30 min to 1 h, to look around and appreciate the cave paintings. Bloyot cave has an area of 497.5 m^2. The number of visitors who can be physically accommodated in Bloyot cave is 4975 people/day (Table 9).

Table 9. Physical carrying capacity of the three geosites in Sangkulirang-Mangkalihat karst.

Geosite	Area Provided by Manager (A)	Area Required by Visitors (B)	Rotation Factor (Rf)	PCC
	(m^2)	(m^2)	(Times)	(Person/Day)
Nyadeng lake	600	1	5	3.000
Bloyot cave	498	1	10	4.975
Tewet cave	137.76	1	12	1.653

Tewet cave has an area of 137.76 m^2. To reach the Tewet cave, visitors must hike for 60–120 min. Meanwhile, to enjoy the tourist attraction, visitors spend 30–60 min. To enter the cave, visitors have to climb, as the entrance or the mouth of the cave is on the edge of the cliff. Therefore, visitors visiting the Tewet cave must possess special skills. In the Tewet cave, visitors typically observe and document images of rock arts, and enjoy the natural landscape around the mouth of the cave.

3.4.2. RCC

1. Rainfall (Cf1)

Based on rainfall data obtained from BMKG through the data from the Berau station, the rainfall for Berau Regency and its surroundings for the last five years was two dry months and 52 wet months. As a result, a rainfall index of 0.038 (Mn) was obtained. The highest value in the Schmidt–Ferguson climate classification is 7 (Mt), while the precipitation correction factor for Merabu and Tepian Langsat is 0.98 (Table 10).

Table 10. Real carrying capacity of Bloyot cave, Nyadeng lake, and Tewet cave.

Geosite	Correction Factor					RCC
	Cf_1	Cf_2	Cf_3	Cf_4	Cf_5	
			Merabu			
Bloyot cave	0.98	0.60	0.20	0.22	0.83	108
Nyadeng lake	0.98	0.60	0.20	0.22	0.83	65
			Tepian Langsat			
Tewet cave	0.98	0.60	0.20	0.10	0.50	10

2. Slope (Cf2)

The slope is a limiting factor that can affect the number of visitors at the site of a tourist attraction center. The higher the slope, the more restricted the visitors' movement to access the tourist attraction. Bloyot cave, Nyadeng lake, and Tewet cave are all located in an area that has mountainous topography. Although the path to the three geosites must pass through steep cliffs, the three sites have a quite gentle slope, making it easy for visitors to enjoy the tourist attraction. Referring to the classification of slope classes and the Decree of the Minister of Agriculture No. 837/KPTS/UM/11/1980, the gentle slope class has a value of 20 (Mn) and the maximum value of the slope class is 100 (Mt). Therefore, the slope correction factor in Merabu and Tewet is 0.60 (Table 10).

3. Soil Erodibility (Cf3)

Bloyot cave, Nyadeng lake, and Tewet cave have Eutrudepts soil composition. Based on soil taxonomy, limestone soil ranges in classification from Eutrudepts and is often found in karst areas. It is distributed in molded reliefs with a slightly flat to undulating relief. This type of cambisol soil is classified as a podzolic soil type, which is sensitive to erosion. Referring to the classification of soil types and the Decree of the Minister of Agriculture No. 837/KPTS/UM/11/1980, the soil type has a value of 60 (Mn), and the maximum value of the soil type is 75. Therefore, the correction factor for soil erosion at the two locations is 0.20 (Table 10).

4. Landscape potential (Cf4)

The landscape factor is essentially one of the correction factors that determine the carrying/bearing capacity of the area as related to the physical space available [45]. The development of a natural tourist area that exceeds the carrying capacity will lead to disruption of the landscape elements in the area. Using the guidelines from the Bureau of Land Management in Fandeli and Muhammad [45], the landscape potential indexes for the Merabu area and the Tepian Langsat area are 0.22 and 0.10, respectively (Table 11).

Table 11. Merabu and Tewet landscape potential element scores.

Landscape Elements	Average Score	
	Merabu	**Tepian Langsat**
Landform	5.0	5.0
Vegetation	4.3	5.0
Color	3.7	5.0
Scenery	3.7	3.7
Distinctiveness	3.7	5.0
Modification	0.7	0.7
Location Scoring Score (Mn)	21	24,3 $\approx$ 24
Maximum Scoring Score (Mt)	27	27
Cf_4 (1-Mn/Mt)	0.22	0.10

5. Presence of animals (Cf5)

Bornean orangutans (*Pongo pygmaeus*) and proboscis monkeys (*Nasalis larvatus*) are two endemic species of Borneo and are protected species. According to the IUCN Red List, proboscis monkeys are considered endangered (EN), whereas Bornean orangutans are critically endangered (CR). Consequently, the presence of humans should be monitored to avoid the extinction of both animals in their habitat. Based on the field observations and information obtained from local officials, Bornean orangutans are often found in Merabu and Tewet, while proboscis monkeys are only found in Tewet. The breeding season of the animals is a limiting factor for tourist activities. During the mating season, animals become more susceptible, and thus the presence of humans can act as a disturbance for animals. The mating season for the Bornean orangutan occurs twice a year, in March and October. It is estimated that the reproduction season for proboscis will be January, June, August, and November [60].

Table 11 presents the carrying capacity results by considering the biophysics of the geosites. The results show that the area can accommodate 108 people/day in Bloyot cave, 65 people/day in Nyadeng lake, and 10 people/day in Tewet cave. Biophysical characteristics, such as rainfall, slope, and soil erodibility in Merabu and Tewet are similar; however, they have different landscape potentials and disturbances to animals.

3.4.3. Effective Carrying Capacity (ECC)

Effective carrying capacity (ECC) is the maximum number of visits ensuring the object remains sustainable in accordance with the capacity of existing managers [61]. The management capacity used is the approach to the number of available personnel [61,62].

Bloyot cave and Nyadeng lake already have specific tourist management tools. The manager is assisted or cooperates with the local community to provide services, such as guides and the rental of boats or ketinting—both for Bloyot cave and Nyadeng lake. For the Tewet cave, there is no management that specifically manages tourism in the area. To date, seven custodians have been tasked with taking care of cultural heritage sites in and around Tewet. Officers or guides may increase as visitors' number increases. Hence, the number of employees fluctuates. On the three geosites, the guides were not permanent staff, but they were members of the local community that voluntarily acted as guides, hence there were no fixed number of permanent staff that were regularly on standby. Due to the fluctuating number of officers [61], the calculation of effective carrying capacity cannot be carried out.

4. Discussion

4.1. Risk Management for Hazard Reduction

Hazard risk reduction management for tourism in karst areas is carried out by evaluating each hazard risk contained in the area, and then making recommendations for management options that must be carried out (Table 12). This management step is a strategy to overcome the dangers contained in a tourist area. There are four risk reduction options that can be considered and adjusted to the severity, frequency of occurrence, and the level of risk of a type of hazard: accepting tolerable risk, avoiding risk, reducing risk, and transferring risk [32].

Table 12. Physical and biological hazards management recommendations for Nyadeng lake, Bloyot cave, and Tewet cave.

No.	Location	Source/Potential Hazard (Physics and Biology)	Risk Level	Management Option	Management Action
1	Nyadeng lake	Shallow river/siltation	Low	Accept tolerable risk	Applying rules/ temporarily closing
2		Slippery terrain/tripping, falling	Low	Accept tolerable risk	Adding safety straps/equipment Implementing SOPs for using shoes
3		Lake/drown	Low	Transferring risk	Create a warning board/ Provide rescue workers/onsite life guard who are experts in swimming
4		Flood/drown	Low	Accept tolerable risk	Applying rules/ temporarily closing
5		Tree root /tripping	Low	Accept tolerable risk	Adding a safety rope
6		Gnat/spread disease	Low	Avoiding risk	Provide education/ Bring insect repellent
1	Bloyot cave	Ravine/falling	Low	Transferring risk	Adding a safety rope/ Implementing SOP
2		Slippery and steep terrain/falling, tripping	Low	Accept tolerable risk	Adding a safety rope
3		Mud/slide	Low	Avoiding risk	Provide education/ Implement SOP
4		Tree root /tripping	Low	Accept tolerable risk	Adding a safety rope
5		Fallen tree/injured	Low	Accept tolerable risk	Providing education to tourists
6		Sinkhole/ damage, could result in death	Low	Accept tolerable risk	Regular sinkhole hazard assessment
7		Cliff/rockfall	Low	Accept tolerable risk	Providing rockfall barrier with fixed or hinged connection
1	Tewet cave	Ravine/falling	Extreme	Accept tolerable risk	Adding a safety rope/ Implementing SOP
2		Slippery and Steep Terrain/tripping, falling	Moderate	Avoiding risk	Adding a safety rope
3		Tree root /tripping	Low	Accept tolerable risk	Adding a safety rope
4		Crocodile/attack	Moderate	Transferring risk	Make a warning board Daily monitoring
6		Sinkhole/damage, could result in death	Low	Accept tolerable risk	Regular sinkhole hazard assessment
7		Cliff/ rockfall	Low	Accept tolerable risk	Providing rockfall barrier with fixed or hinged connection

Shallow rivers, slippery terrain, floods, and tree roots are natural occurrences due to natural phenomena that cannot be avoided. At Nyadeng lake, the risk level of each potential hazard is low risk, with management options accepting risk, transferring risk, and avoiding risk. Without onsite management, there may be a moderate or high risk of drowning. To overcome this, management actions need to be taken by performing or applying temporary closures and strict rules in conditions that allow these events to occur. For example, by closing or prohibiting visitors from accessing tourist attractions at night and during the rainy season, especially in February and March, when the intensity of rain increases and floods often occur in Nyadeng lake, and in the dry season, when the Lesan river is silted up. Alternatively, access to this area may be accessible through hiking. To avoid the potential danger from tree roots, the manager can add safety ropes that visitors can use to help them when walking. The presence of gnats is unavoidable and often annoying to make visitors uncomfortable. Nevertheless, the risk is low, and this can be avoided by reminding visitors of the presence of insects such as gnats and urging them to wear long sleeves, long pants, and come along with insect repellent.

In Bloyot cave, the risk level for each potential hazard is low, with management options accepting risk, transferring risk, and avoiding risk. Similar to Tewet cave, the potential danger of slippery and steep terrain, the presence of tree roots, and fallen trees is a natural occurrence that cannot be avoided, so you must accept the risk. Installing or adding safety ropes on slippery and steep terrain needs to be carried out to make it easier for visitors to pass through the path. In addition to that, it is also important to ensure that every visitor who enters uses shoes that are suitable for the terrain to be traversed. The path to Bloyot cave is very narrow and is directly adjacent to a ravine. This condition has high severity, although the chances of occurrence are rare. Nevertheless, the potential for ravine hazards still needs to be watched out for and the management needs to provide ropes along the path bordering the ravine and apply SOPs for visitors who will visit the Bloyot cave tourist attraction.

In the Tewet cave, each potential hazard has a low to high risk. The potential for ravine hazards to occur very often with major consequences is high. Therefore, management has the option to reduce risk by taking action to install safety ropes and apply SOPs. A moderate level of risk can lead to slippery surfaces, steep terrains, and the presence of crocodiles. The management option for slippery and steep terrain is to avoid risk, as the chances of occurrence are often of rather high severity. One of the actions that can be taken by managers to avoid these risks is to add safety ropes at locations with slippery and steep terrain. The management option for the potential presence of crocodiles is to transfer the risk, and the action that can be taken is to provide warning signboards to visitors so that they can be more careful and alert.

Potential hazards of human activities can be controlled by informing visitors and setting up warning signs, applying strict and effective rules, especially for equipment for caving or climbing, and conducting regular monitoring on a daily basis. Establishing visitor restrictions may also help managers overcome the threat of danger that may present itself to visitors.

The highest risk level before control is 20 in the extreme category and can drop to 12 in the high category, and the lowest risk level before control is two in the low category and can drop to one, as shown in Table 13.

Table 13. Recommendations for human activities hazard management in Nyadeng lake, Bloyot cave, and Tewet cave.

No.	Location	Human Activities	Risk Level	Control	Risk after Control
1	Nyadeng lake	Swimming in a state of physical weakness	Moderate Score: 5	Provide education with warnings and warning boards	Low Score: 3
2		Not using adequate gears	Low Score: 3	Applying rules and checking SOP	LowScore: 2
3		Riding a boat/ *ketinting* at night	Moderate Score: 5	Provide education with warnings and warning boards	LowScore: 3
1	Bloyot cave	Not using adequate footwear	Low Score: 3	Applying rules and checking SOP	Low Score: 2
2		Running downhill	Low Score: 2	Provide education with warnings and warning boards	Low Score: 1
3		No caving equipment used (head-lamp, helmet)	Low Score: 3	Applying rules and checking SOP	Low Score: 2
4		No safety climbing equipment used	Extreme Score: 20	Applying rules and checking SOP	High Score: 12
1	Tewet Cave	No safety climbing equipment used	Extreme Score: 20	Applying rules and checking SOP	High Score: 12
2		Running downhill to camp	Moderate Score: 5	Provide education with warnings and warning boards	Moderate Score: 4
3		Climb up to the cave when it rains	Moderate Score: 4	Provide education with warnings and warning boards	Low Score: 3
4		Swimming in the river	Extreme Score: 15	Provide education with warnings and warning boards	Moderate Score: 6

4.2. Importance of Tourism Carrying Capacity in the Sustainability of the Geosites

The three tourist attractions, namely Bloyot cave, Nyadeng lake, and Tewet cave, each have their own characteristics. Different characteristics will result in different carrying capacities. Therefore, it is necessary to determine wise management efforts by considering the condition of the tourist attraction, such as facing challenges or the level of uniqueness [29]. Karst areas and caves, in particular, have a fragile nature. The caves are known as natural laboratories that have significant value because they store climatic archives such as speleothems (calcite formations such as stalactites, stalagmites, etc.), sediments, fauna with special adaptations to cave life (ability to adapt to cave environments), and fossil remains [63]. The use of caves as a tourism attraction also has a negative impact that can damage the cave's ecosystem. A major cause of damage to ecosystems is the massive visitation of humans. The caves are subject to rapid transfer of pollutants, in which the slightest pollution may alter their value and require costly and lengthy repairs. The human presence can affect several things, namely, to modify the microclimate of the cave, to disturb the biota of the cave, to compact the ground, and to disturb the hydrological flow. Therefore, the number of visitors needs to be balanced with conservation value to avoid excessive use of the cave in the short term [64,65].

Historical relics (relics in the form of cave paintings or rock art) can be found in Bloyot cave and Tewet cave. The images contained in the two caves are in the form of animal and human handprints. Pictures are scattered on the walls and roof of the caves. Local residents believe that the handprints are a relic of ancient humans. The local community also understands that the relics depict a history of how ancient humans used the forest for their daily needs. These paintings show the life and epoch of the people who lived in the caves. Animal paintings on cave walls show the types of animals that can and cannot be eaten. This is in line with the hunting activities of the surrounding community to meet their food needs.

However, it is known that the cave paintings have been damaged, one of which is due to human touch. The damage that occurred in the image is peeling and discoloration. The touch of a human can indeed change the cave ornaments, including those in the form of paintings. Tourists entering the cave indirectly become carbon carriers attached to their body parts, which then come in contact with the cave ornaments [66]. In the Gong cave, damage to the cave's ornaments was caused by visitor contact. As a result of the visitor contact, either intentionally or involuntarily, the decorations of the cave became dark/black. Discoloration occurs because of the dirt that sticks to the palms that moves to the surface of the ornament [66]. The Paleolithic paintings of the UNESCO sites of Altamira (Spain) and Lascaux (France) also had to be closed due to the degradation of the painting caused by aerosolization of fine soil particles, including bacteria and fungal spores [63].

The number of visitors can also cause damage to the tourist area. The high number of tourist visits has become a problem in several tourist sites in Indonesia, one of which is Pindul cave, Gunung Kidul Regency in Yogyakarta. The number of tourists in Pindul cave exceeds the carrying capacity of the environment every weekend, and during holidays has a negative impact on these tourist destinations, namely the fragility of the cave walls and disruption of the growth of stalactites and stalagmites, and water pollution from tourism activities and waste [67,68]. Meanwhile, Gong cave also experienced the same thing. The intensity of tourist visits to the cave is quite high. Based on data on the number of tourists in 2016, more than 2800 people visited the cave within a day and as many as 710 people entered the cave simultaneously in just one hour. In addition, the maximum capacity limit is 20–50 people per exploration [65].

As mentioned earlier, it is very important to pay special attention to cave tourism objects. In addition to protecting the preservation of historical heritage, it is also important to protect the cave environment from damage and avoid harm to visitors. Management efforts that can be carried out are adjusted to the characteristics and uniqueness of the tourist attraction location. For example, the Tewet cave has characteristics that are more fragile and sensitive to disturbance and damage and has a higher potential danger to visitors. As a result, Tewet cave has a low carrying capacity of 10 people/day. Therefore, this cave can only be accessed by those who have a special interest in cave painting and rock climbing. In contrast, Bloyot cave, which has a larger cave space and easier access than the Tewet cave, has a higher carrying capacity of 108 people/day, and thus this cave can be visited by general visitors. It is important for managers to consider the ability of natural resources needed to be recovered after a disturbance in visitors' activities. The number of visitors who are below the value of the ecological carrying capacity will be under pressure and provide more opportunities for nature to recover [29].

Sites of geocultural excellence, such as Sangkulirang-Mangkalihat Karst, are presently in increasing demand in Indonesia as nature-based tourist destinations related to geopark development. This offers the possibility of maximizing the conservation benefits of nature tourism. Cultural attractions are also a statistical highlight of Indonesian tourism [60]. Community engagement is often driven by local culture, which is the foundation of the values, attitudes, and ways of life that contribute to the preservation of the community's heritage [69]. With this in mind, the conservation of the geological site should be centered on the conservation of the geoheritage, knowledge, and geotourism, which constitute the three objectives of a geopark: conservation, education, and geotourism [69] that highlights sustainability.

5. Conclusions

The potential hazards found along the way to the three tourist attractions in the karstic region of Sangkulirang-Mangkalihat consist of physical, biological, and human activities. The most hazardous physical and biological hazards are the ravines of the Tewet Cave. In the cave of Tewet–Karim, there is also a potential hazard with a moderate level of risk, namely the slippery and steep ground and the presence of crocodiles. Meanwhile, in two other locations, Nyadeng lake and Bloyot cave, the potential for danger is low.

Depending on the conditions and characteristics of the karst of Sangkulirang-Mangkalihat, the number of visitor limits to be received by each tourist attraction is obtained. The three attraction areas and their tourism carrying capacities are as follows: PCC Bloyot cave (4975 people/day), Nyadeng lake (3000 people/day), and Tewet cave (1653 people/day). The RCC of Bloyot cave is 108 people/day, Nyadeng lake is 65 people/day, and Tewet cave is 10 people/day, while the ECC cannot be calculated due to the fluctuating number of officers. This information will provide local risk management with the information required for the development of a strategic plan within the geopark.

Author Contributions: Conceptualization, A.S., A.P.L. and E.H.; methodology, A.S. and A.P.L.; investigation, A.F.J.; resources, E.H. and P.S.; formal analysis, A.S. and A.P.L.; writing—original draft, A.S. and A.P.L.; writing—review and editing, A.S., A.P.L., E.H., P.S. and M.B.; supervision, E.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by WORLD CLASS UNIVERSITY (WCU) for Indonesia Collaboration Research (PPKI) Funding Scheme of IPB University, Grant Number: 1381 /IT3.L1/PN/2021. The APC was also funded by WORLD CLASS UNIVERSITY (WCU) for Indonesia Collaboration Research (PPKI) Funding Scheme of IPB University.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study through Ethical Clearance No. 444/IT3.KEPMSM-IPB/SK/2021 approved by the Human Research Ethics Committee of the IPB University.

Acknowledgments: The authors would like to give credit to the Regional Office for Cultural Properties Preservation in East Kalimantan and the local communities that support the field survey.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Holden, A. *Environment and Tourism*; Routledge: Abingdon, UK, 2016.
2. Gogonea, R.M.; Baltălungă, A.A.; Nedelcu, A.; Dumitrescu, D. Tourism pressure at the regional level in the context of sustainable development in Romania. *Sustainability* **2017**, *9*, 698. [CrossRef]
3. Garrigos-Simon, F.J.; Narangajavana-Kaosiri, Y.; Lengua-Lengua, I. Tourism and sustainability: A bibliometric and visualization analysis. *Sustainability* **2018**, *10*, 1976. [CrossRef]
4. Buonincontri, P.; Micera, R.; Murillo-Romero, M.; Pianese, T. Where Does Sustainability Stand in Underground Tourism? A Literature Review. *Sustainability* **2021**, *13*, 12745. [CrossRef]
5. UN Environment World Conservation Monitoring Centre (UNEP-WCMC); International Union for Conservation of Nature (IUCN); National Geographic Society (NGS). *Protected Planet Report 2018*; United Nations Environment Programme: Cambridge, UK, 2018.
6. Ólafsdóttir, R.; Tverijonaite, E. Geotourism: A systematic literature review. *Geosciences* **2018**, *8*, 234. [CrossRef]

7. Wang, L.L.; Tian, M.Z.; Wang, L. Geodiversity, geoconservation and geotourism in Hong Kong Global Geopark of China. *Proc. Geol. Assoc.* **2015**, *126*, 426–437. [CrossRef]
8. Dowling, R.; Newsome, N. (Eds.) Geotourism: Definition, characteristics and international perspective. In *Handbook of Geotourism*; Edward Elgar Publishing Limited: Cheltenham, UK, 2018; p. 520.
9. Zouros, N.; Valiakos, I. Geopark management and assessment. *Bull. Geol. Soc. Greece* **2010**, *43*, 965–975. [CrossRef]
10. da Glória Garcia, M.; do Nascimento, M.A.L.; Mansur, K.L.; de Araújo Pereira, R.G.F. Geoconservation strategies framework in Brazil: Current status from the analysis of representative case studies. *Environ. Sci. Policy* **2022**, *128*, 194–207. [CrossRef]
11. Prabhakar, B.C.; Radhika, K.N. Recognizing new geoheritage sites in Karnataka, India. *Geoheritage* **2022**, *14*, 1–24. [CrossRef]
12. Mucivuna, V.C.; da Garcia, M.D.G.M.; Reynard, E. Criteria for Assessing Geological Sites in National Parks: A Study in the Itatiaia National Park, Brazil. *Geoheritage* **2022**, *14*, 1–19. [CrossRef]
13. Tičar, J.; Tomić, N.; Valjavec, M.B.; Zorn, M.; Marković, S.B.; Gavrilov, M.B. Speleotourism in Slovenia: Balancing between mass tourism and geoheritage protection. *Open Geosci.* **2018**, *10*, 344–357. [CrossRef]
14. Guo, W.; Chung, S. Remarking tourism carrying capacity frameworks for geoparks. In Proceedings of the 4th International Conference on Advances in Social Science, Humanities, and Management, Guangzhou, China, 24–25 December 2016; pp. 197–205.
15. United Nations Educational, Scientific and Cultural Organization (UNESCO). Global Geoparks. Available online: http://www.unesco.org/new/en/natural-sciences/environment/earth-sciences/unesco-global-geoparks/ (accessed on 27 November 2021).
16. Komoo, I. Geopark sebagai peraga pembangunan lestari wilayah. *Akademika* **2010**, *80*, 9–18.
17. Fauzi, N.S.M.; Misni, A. Conserving Geo-diversity: The importance of valuing the heritage elements at Langkawi Geopark. *J. Des. Nat. Ecodynamics* **2017**, *12*, 303–313. [CrossRef]
18. Dowling, R.; Newsome, D. *Geotourism*; Elsevier: Oxford, UK, 2006.
19. Hose, T.A. The English origins of geotourism (as a vehicle for geoconservation) and their relevance to current studies. *Acta Geogr. Slov.* **2011**, *51*, 343–359. [CrossRef]
20. Hidayat, T.W.; Nasution, I. Persepsi Publik Tentang Destinasi Pariwisata Danau Toba Sebagai Global Geopark Kaldera UNESCO. *Publikauma J. Adm. Publik Univ. Medan Area* **2019**, *7*, 88–102. [CrossRef]
21. Metcalfe, I. Gondwanaland dispersion, Asian accretion and evolution of eastern Tethys. *Aust. J. Earth Sci.* **1996**, *43*, 605–623. [CrossRef]
22. Satyana, A.H. Accretion and dispersion of Southeast Sundaland: The growing and slivering of a continent. In Proceedings of the Joint Convention of Indonesian Association of Geologists, 32nd Annual Convention and Indonesian Association of Geophysicists (IAGI) and the 28th Annual Convention (HAGI), Jakarta, Indonesia, 15–17 December 2003.
23. Guritno, E.; Muller, W.; Drajat, D.; Purnama, M. The nature of the Mangkalihat Terrane–NE Borneo Indonesia. In Proceedings of the Indonesian Petroleum Association Thirty-Sixth Annual Convention & Exhibition, Jakarta, Indonesia, 23–25 May 2012.
24. Haryono, E.; Reinhart, H.; Hakim, A.A.; Sunkar, A.; Setiawan, P. Linking geodiversity and cultural diversity in geoheritage management: Practice from karst of Sangkulirang-Mangkalihat, Indonesia. *GTG J.* 2022; *submitted*.
25. Tropical Forest Conservation Act Kalimantan; Indonesia Biodiversity Conservation Trust Fund; Kelompok Studi Karst Fakultas Geografi Universitas Gadjah Mada; Dinas Lingkungan Hidup Provinsi Kalimantan Timur. *Rencana Induk Pengelolaan Kawasan Karst Sangkulirang-Mangkalihat, Kalimantan Timur 2018*; Dinas Lingkungan Hidup Kalimantan Timur: Kalimantan Timur, Indonesia, 2018.
26. Aubert, M.; Setiawan, P.; Oktaviana, A.A.; Brumm, A.; Sulistyarto, P.H.; Saptomo, E.W.; Istiawan, B.; Ma'rifat, T.A.; Wahyuono, V.N.; Atmoko, F.T.; et al. Palaeolithic cave art in Borneo. *Nature* **2018**, *564*, 254–257. [CrossRef]
27. Miller, A.E.; Steele, N.; Tobin, B.W. Vulnerability and fragility risk indices for non-renewable resources. *Environ. Monit. Assess.* **2018**, *190*, 1–11. [CrossRef]
28. Parga-Dans, E.; Gonzalez, P.A.; Enriquez, R.O. The social value of heritage: Balancing the promotion-preservation relationship in the Altamira World Heritage Site, Spain. *J. Destin. Mark. Manag.* **2020**, *18*, 100499. [CrossRef]
29. Afrasiabian, A.; Mahmoudi Sivand, S.; Dogančić, D.; Plantak, L.; Đurin, B. Geological features for geotourism in the Zanjan and Hamadan area, Northern Iran. *Sustainability* **2021**, *13*, 6587. [CrossRef]
30. Putri, I.A.; Ansari, F. Managing nature-based tourism in protected karst area based on tourism carrying capacity analysis. *J. Lands. Ecol.* **2021**, *14*, 46–64. [CrossRef]
31. National Speleological Society (NSS). *A Guide to Responsible Caving*; National Speleological Society: Huntsville, AL, USA, 2016.
32. Utami, S.U.; Muntasib, E.K.S.H.; Samosir, A.M. Hazard management in Karang Hawu beach, Sukabumi District, West Java. *Media Konservasi* **2019**, *24*, 322–333. [CrossRef]
33. Cifuentes, A.M. *Determination of Tourist Carrying Capacity in Protected Areas*; CATIE: Turrialba, Costa Rica, 1992.
34. United Nation Environment Programme (UNEP). *Disaster Risk Management for Coastal Tourism Destinations Responding to Climate Change. A Practical Guide for Decision Maker*; UNEP: Paris, France, 2008.
35. National Patient Safety Agency (NPSA). *A Risk Matrix for Risk Managers*; National Patient Safety Agency: London, UK, 2008.
36. Wilks, J. *Tourism Risk Management for the Asia-Pacific Region: An Authoritative Guide for Managing Crises and Disasters*; APEC: Gold Coast, Australia, 2004.
37. Telbisz, T.; Mari, L. The significance of karst area in European national parks and geoparks. *Open Geosci.* **2020**, *12*, 117–132. [CrossRef]

38. Herrera-Franco, G.; Montalván-Burbano, N.; Carrión-Mero, P.; Apolo-Masache, B.; Jaya-Montalvo, M. Research trends in geotourism: A bibliometric analysis using the scopus database. *Geosciences* **2020**, *10*, 379. [CrossRef]
39. Carrion-Mero, P.; Morante-Carballo, F.; Palomeque-Arevalo, P.; Apolo-Masache, B. Environmental assessment and tourist carrying capacity for the development of geosites in the framework of geotourism, Guayaquil, Ecuador. *WIT Trans. Ecol. Environ.* **2021**, *253*, 149–160.
40. Reinhart, H.; Labib, M.A.; Haryono, E. Speleogenetic process of Suaran Block, karst of Sangkulirang–Mangkalihat, East Kalimantan. *E3S Web Conf.* **2020**, *200*, 06011. [CrossRef]
41. Statistic Indonesia. *Kecamatan Kelay Dalam Angka 2020*; Badan Pusat Statistik: Jakarta, Indonesia, 2020.
42. Statistic Indonesia. *Kecamatan Bengalon Dalam Angka 2019*; Badan Pusat Statistik: Jakarta, Indonesia, 2019.
43. Muntasib, E.K.S.; Nadhira, N.; Meilani, R. Hazard Management in Tourism: A Case of The Senaru-Sembalun Hiking Trail, Mount Rinjani National Park, Indonesia. *J. Man. Hut. Trop.* **2019**, *25*, 199–208. [CrossRef]
44. Muhammad, F.C. *Prinsip-Prinsip Dasar Mengkonservasi Lanskap*; Gadjah Mada University Press: Yogyakarta, Indonesia, 2009.
45. Zacarias, D.A.; Williams, A.T.; Newton, A. Recreation carrying capacity to support beach manage-ment at Praia de Faro, Portugal. *Appl. Geogr.* **2011**, *31*, 1075–1081. [CrossRef]
46. Yogi, I.B.P.P. Pelestarian gua-gua prasejarah di Kawasan Karst Sangkulirang Mangkalihat (berbasis pemberdayaan masyarakat lokal). *Forum Arkekologi* **2020**, *33*, 65–76. [CrossRef]
47. Haryono, E.; Reinhart, H.; Effendi, E.; Irianto, P.A.; Fathoni, W.A.; Ardi, T.E.; Putera, A.; Setiawan, T.; Dayatullah, M.; Rinding, Y.S.; et al. Cave Exploration in Sangkulirang-Mangkalihat Peninsula, East Kalimantan-Indonesia. In Proceedings of the 17th International Congress of Speleology Volume One, Sydney, Australia, 22–28 July 2017.
48. Nurdini, N.; Maryanti, E.; Ilmi, M.M.; Setiawan, P.; Saiyasombat, C.; Kadja, G.T.; Ismunandar. Physicochemical investigation of prehistoric rock art pigments in Tewet Cave, Sangkulirang-Mangkalihat Sire, East Kalimantan-Indonesia. *J. Archaeol. Sci. Rep.* **2020**, *30*, 102345. [CrossRef]
49. Sumantri, D.I.G.; Atmadja, D.A.S.S.; Setiawan, P. Sangkulirang Mangkalihat: The Earliest Prehistoric Rock-Art In The World. In Proceedings of the 28th International Cartographic Association, Washington, DC, USA, 2–7 July 2017.
50. Setiawan, P.; Haryono, E. *Karst Merabu*; Badan Lingkungan Hidup Provinsi Kalimantan Timur: Kalimantan Timur, Indonesia, 2013.
51. Soedwiwahjono; Utomo, R.P. A strategy for the sustainable development of the karst area in Wonogiri. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *447*. [CrossRef]
52. Ford, D.C.; Williams, P. *Karst Hydrogeology and Geomorphology*; John Wiley & Sons, Ltd.: West Sussex, UK, 2007.
53. Hertanto, H.B.; Ramelan, A.H.; Budiastuti, S. The development of karst area ecoutourism object potency in the West Pacitan regency of East Java Province. *J. Ekosains* **2011**, *3*, 1–25.
54. Momeni, A.; Heidari, M. Rockfall hazard analysis in the Ganjnameh tourist area, west of Iran. *J. Nat. Environ. Hazards* **2021**, *10*, 1–14.
55. Bagde, M.N. Assessment of rockfall hazard and stabilization of rock slope surface at the World Heritage Ajanta Cave. *Geotech. Geol. Eng.* **2021**, *39*, 3101–3114. [CrossRef]
56. Yordkayhun, S. Geophysical characterization of a sinkhole region: A study toward understanding geohazards in the karst geosites. *Sains Malays.* **2021**, *50*, 1871–1884. [CrossRef]
57. Parise, M. Karst geo-hazards: Causal factors and management issues. *Acta Carsol.* **2015**, *44*, 401–414. [CrossRef]
58. Youssef, A.M.; Pradhan, B.; Al-Kathery, M.; Bathrellos, G.D.; Skildoimou, D. Assessment of rockfall hazard at Al-Noor Mountain, Makkah city (Saudi Arabia) using spatio-temporal remote sensing data and field investigation. *J. Afr. Earth Sci.* **2015**, *101*, 309–321. [CrossRef]
59. Atmoko, T.; Mardiastuti, A.; Iskandar, E. Strategi adaptasi Bekantan (Nasalis larvatus Wurmb 1787) dalam aktivitas harian dan pemilihan pakan di habitat terfragmentasi. *J. Primatol. Indones.* **2017**, *14*, 14–21.
60. Hardoyo, D.; Muhammad, F.; Taruna, T. Perencanaan kegiatan wisata pendidikan di dalam kawasan Geopark Rinjani Lombok berbasis daya dukung lingkungan (studi daerah Air Berik). *J. Ilmu Lingkung.* **2016**, *14*, 103–107. [CrossRef]
61. Purwanto, S.; Syaufina, L.; Gunawan, A. Kajian potensi dan daya dukung Taman Wisata Alam Bukit Kelam untuk strategi pengembangan ekowisata. *J. Pengelolaan Sumberd. Alam dan Lingkung.* **2014**, *4*, 119. [CrossRef]
62. Constantin, S.; Mirea, I.C.; Petculescu, A.; Arghir, R.A.; Mantoiu, D.S.; Kenesz, M.; Robu, M.; Moldovan, O.T. Monitoring human impact in show caves. A study of four Romanian caves. *Sustainability* **2021**, *13*, 1619. [CrossRef]
63. Smith, M.J.; Burns, G.L. Australia's crystalline heritage: Issues in cave management at Jenolan Caves. *Helicite* **2011**, *40*, 27–34.
64. Kurniawan, I.D.; Rahmadi, C. *Ekologi Gua Wisata: Dampak Aktivitas Wisata Terhadap Lingkungan Dan Biota Gua Serta Upaya Konservasinya*; Graha Ilmu: Yogyakarta, Indonesia, 2019.
65. Sunkar, A.; Rachmawati, E.; Cereno, R. Ecotourism Development in Brunei Darussalam, Indonesia, Lao PDR, Myanmar, Singapore and Philippines. In *Opportunities and Challenges of Ecotourism in ASEAN Countries*; Kim, S., Kang, M., Sukmajaya, D., Eds.; Jungmin Publishing: Seoul, Korea, 2013; pp. 52–87.
66. Pujani, L.P.K.; Sanjiwani, P.K. Eksploitasi Goa Pindul sebagai Speleo Tourism di Gunung Kidul, Yogyakarta. *J. Anal. Pariwisata* **2017**, *17*, 17–23.
67. Putra, E.B.D.; Haryono, E.; Nurjani, E. Cave carrying capacity: Lesson learned from Pindul Cave and Baru Cave, Gunung Sewu Geopark-Indonesia. In Proceedings of the DMR-CCOP-TNCU Technical Seminar on "Biostratigraphy and Karst Morphology of Satun Aspiring Geopark", Bangkok, Thailand, 13–14 July 2017; pp. 43–49.

68. Sunkar, A.; Muntasib, E.K.S.H.; Setiadi, I.N.D. Recognition of the potential for cultural conservation philosophies of Tri Hita Karana to promote community participation in Batur Caldera Geopark heritage tourism development. In Proceedings of the International Tourism Conference: Promoting Cultural and Heritage Tourism, Bali, Indonesia, 1–3 September 2016.
69. Sunkar, A.; Brahmantyo, B. Eco-Geotourism in Indonesia. In *Ecotourism and Sustainable Tourism Development in Indonesia: Potentials, Lessons and Best Practices*; Frans, T., Avenzora, R., Eds.; Ministry of Tourism and Creative Economics: Jakarta, Indonesia, 2013.