Sustinere
Journal of Environment and Sustainability
Volume 7 Number 3 (2023) 220-233

Print ISSN: 2549-1245 Online ISSN: 2549-1253
Website: https://sustinerejes.com E-mail: sustinere.jes@uinsaid.ac.id

RESEARCH PAPER

Karst ecosystem services and their roles in the management of Gunung Sewu UNESCO global geopark

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Article history:
Received 20 June 2023 | Accepted 19 September 2023 | Available online 31 December 2023

Abstract. As a member of the Global Geopark Network, Gunung Sewu UNESCO Global Geopark is designed to attract tourists, with a focus on the tourism industry to generate revenue. However, this development triggers environmental pressure on the already fragile karstic ecosystem, necessitating the implementation of mitigation measures. This research aims to employ Karst Ecosystem Services (KESs) as a tool for managing the karst area and the Geopark itself, exploring both the concept and its implementation. Two examples of ecosystem services, scenic and habitat quality, are generated using InVEST tools as the representations of Karst Ecosystem Services. In the Karst of Gunung Sewu, the habitat quality of tree covers, ponds, and caves is threatened by limestone mining, agriculture, and large-scale infrastructure, while the scenic quality is degraded by the presence of construction sites, large statues, and unused or abandoned building. These ecosystem services can contribute to strengthening the Geopark's pillars through conserving intactness and maintaining energy flow within the habitat for the Geoconservation pillar. For geoeduaction pillar, scenic landscapes provide visual interpretation, and the integrity of landforms supports morphological interpretation. Lastly, habitat and scenic quality can be developed to enhance tourism attraction while maintaining the environment quality for the Sustainable Local Economic Development pillar.

Keywords: Ecosystem services; Geopark; Karst; Gunung Sewu; Sustainable Development

1. Introduction

Aligned with the emergence of geotourism and a growing appreciation for geological heritage and geodiversity, Indonesia consistently develops its Geopark to promote geoconservation, enhances geological values, and foster local economic growth (Du & Girault, 2018). These Geoparks, dedicated areas showcasing exceptional geological uniqueness and rarity, find a fitting application in Indonesia due to the country's wealth of geological features. In general, Geopark is structured upon three foundational pillars: education, conservation, and sustainable local economic development, all recognized by the presence of geological heritage and geosites within its bounds (Brilha, 2018; Herrera-Franco et al., 2022). Currently, Indonesia boasts 30 Geopark areas, and as per May 2023, 10 of these have successfully integrated into the UNESCO Global Geopark Network.

One of the famous Geopark areas in Indonesia is the Gunung Sewu UNESCO Global Geopark (GSUGGp), which attained its status in 2015 due to its distinctive tropical karstic features. These include thousands of conical hills, caves, underground passages, and a typical karstic coastal

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DOI: https://doi.org/10.22515/sustinere.jes.v7i3.349

landscape, leading to its designation as a Geopark area. Prior to its establishment as a UNESCO Global Geopark, the Karst of Gunung Sewu suffered from various environmental deterioration including drought, water pollution, and alterations to its landforms, significantly impacting economic development and local welfare. However, the spirit of the Geopark has inspired the inhabitants of Karst of Gunung Sewu to actively engage in community-based conservation efforts, empowering themselves to preserve nature to bolster tourism (Sari et al., 2021; Sulistyo et al., 2021). Presently, the Karst of Gunung Sewu has experienced economic benefits following the Geopark establishment, primarily deriving from the tourism sector (Sisharini, 2019).

GSUGGp has experienced a significant surge in visitators numbers (Sulistyadi et al., 2018; Vitrianto et al., 2021), along with infrastructure development such as roads and tourism amenities, although it faced setbacks during the COVID-19 pandemic (Cahyadi & Newsome, 2021). Despite these developments, substantial work remains. The development of tourism sectors burdens the area's delicate ecosystem. Managing the Geopark within its carrying capacity it crucial, especially considering its vulnerability to environmental degradation due to its karstic landscape (Chen et al., 2020; Chen et al., 2021). Both tourism development and large-scale infrastructure projects trigger significant environmental pressures in the already fragile karstic ecosystem through land cover conversion, alteration of morphology, and tourism activities, impacting its water quality, morphology, agriculture sector, and habitat (Sandera, 2019; Soedwiwahjono & Pamardhi-Utomo, 2020).

Pragmatically, tourism development must comply with the Geopark guidelines and the three pillars upon which it is built. Operationally, this objective could be achieved by implementing several instruments or frameworks, such as carrying capacity, sustainable development, regulations and policies, spatial planning, and ecosystem services (Hamilton-Smith, 2006; Putri & Ansari, 2021; Rahma et al., 2020). The Karst Ecosystem Services (KESs), specifically, have benefited GSUGGp in numerous ways. Providing cultural, recreational, and provisioning values that support tourism activities and products, including attractions and amenities as integral elements.

This study utilizes two examples of ecosystem services - habitat quality and scenic quality, to highlight the contributions of the karstic ecosystem, especially the Karst of Gunung Sewu, as pivotal factors in the development and management of the Geopark. The ecosystem services within the karstic area are from the foundation of human activities, providing essential support and regulation for livelihood. Several studies indicate that karst ecosystem services play important roles in tourism activities within karst-type Geopark and, particularly influencing cultural and aesthetic values (Golob, 2019; Miao et al., 2022; Zhang et al., 2023). We aim to comprehend the role of ecosystem services especially in terms of scenery and habitat, and explore their relationship with Geopark management. Additionally, we aim to address key research questions: why are karst ecosystem services crucial to Geopark operation and how should they be effectively implemented in GSUGGp?

2. Methods

This paper conducts an ecosystem service study using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software created by the Natural Capital Project, offering 16 ecosystem services models and calculations. We specifically select two ecosystem services, namely habitat quality (Bhagabati et al., 2014; Terrado et al., 2016), and scenic quality (Griffin et al., 2015), which are more relevant to the karstic ecosystem. The selection process considers several considerations such as alignment with the Geopark concept, the urgency of the threats, and also considering technical limitations like InVEST modeling, data availability, and geographic coverage.

2.1. Research area

This research was conducted in the Karst Landscape area, part of GSUGGp located in Gunungkidul Regency, Special Region of Yogyakarta, covering the southern region of the regency. Two different area of interest (AOIs) were selected for each ecosystem service. For scenic quality assessment, the AOI boundaries stretched from Nguluran Beach to Sadeng Beach, encompassing the eastern coastal area of Gunungkidul Regency, aligning with the modeling tool designed by InVEST. Whereas, the AOI for habitat quality was nested within the Pegunungan Sewu Zone, following the delineation by the Ministry of Mineral and Energy Resources for the Karst Lansdcape Area. This delineation holds significance for analyzing KESs, as the GSUGGp border encompasses several non-karst areas, including the Nglanggeran Ancient Volcano, identified as one of its geosites. The AOIs and research locations are illustrated in Figure 1.

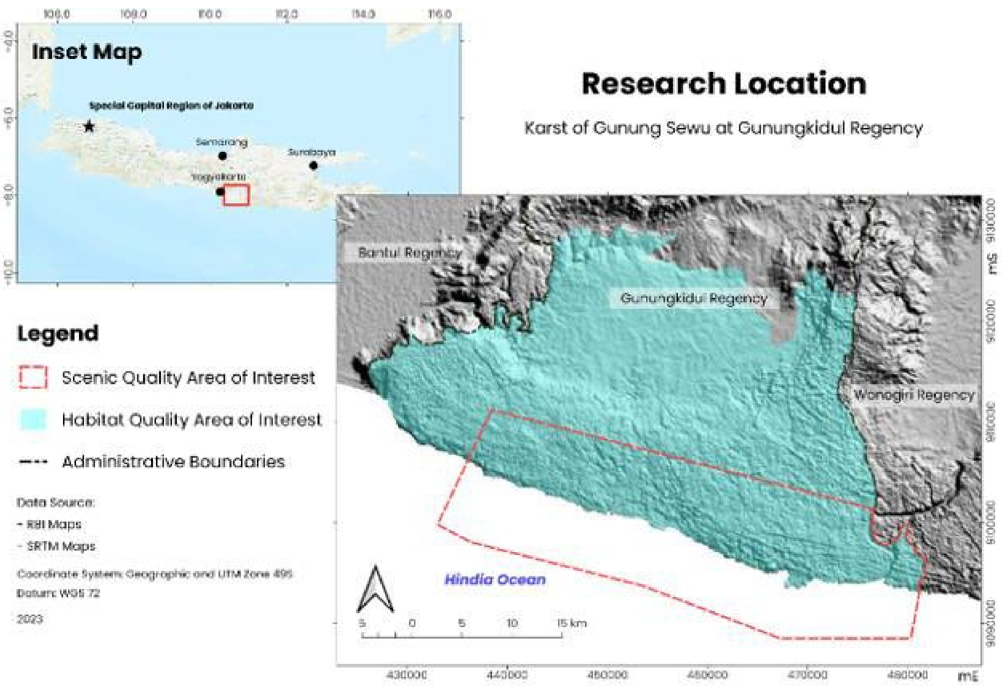

Figure 1. Research area in Karst of Gunung Sewu

2.2. Data acquisition

The analysis of ecosystem services in InVEST requires specific data depending on the type of analysis employed. We utilized two types of data: primary and secondary. Primary data were attained through direct observation and surveys, while secondary data were obtained from national and global datasets. The preparation and compilation of pre-processed data conducted using QGIS software. Subsequently, after data preparation and verification, we proceeded with ground checks and field observations to validate the data. The comprehensive list of data used is detailed in Table 1.

Table 1. Data required and acquisition method

Ecosystem services	Data	Source
Habitat Quality	Land Cover	ESA World Cover V2 2022
	Threats (agriculture, limestone quarries, urban area, tourism area, roads)	Field observation
Scenic Quality	Scenic disturbances	Field observation
	Topography	National DEM

Habitat and scenic quality require different data approaches. To model scenic quality, our focus was on identifying scenic disturbances within the coastal area, achieved by observing the landscape from specific viewpoints such as the hills and highlands in the coastal region. During fieldwork, we documented these observations and provided rationale for the presence of such obstructions. Scenic quality in InVEST requires the input of various parameters for each scene obstruction, including radius, height, and weight for each point. We utilized default values for these parameters, assuming the height of obstructions to be equivalent to ground elevation, with no specific criteria allocated for each type of obstruction.

2.3. Data analysis

The data analysis in this study consists of both data calculation and visualization. We employed InVEST and QGIS software for these tasks. InVEST conducted calculations and generated raw inputs in raster and polygon formats, while QGIS assisted in managing and visualizing the produced data. Following InVEST generation of ecosystem services such as habitat and scenic quality as the KESs, we analyzed the results within the Geopark framework to evaluate their roles in Geopark management.

2.3.1. Habitat quality

The calculation of habitat quality based on the identification of land cover and threats within a landscape. InVEST estimates ecosystem services, by assuming that a higher threat level corresponds to lower habitat quality. In this calculation, the threat used in InVEST consists of four components: the impact proportion relative to other impacts, the maximum distance from the threat impact, efforts made to mitigate the threat, and the ecosystem's sensitivity to the threat. These four components are created in a raster format, with each grid cell containing a hazard value. The parameter's score, obtained from previous research (Li et al., 2022; Wang et al., 2021; Xu et al., 2019; Zhang et al., 2022), were summarized in Tables 2 and 3 respectively.

Table 2. Properties of threats to habitat

Threats to habitat	Maximum distance (km)	Weight	Decay over distance
crops	5	0.6	linear
urban	5	1	exponential
tourism	5	0.7	exponential
mining	6	1	linear
roads1	3	1	linear
roads2	1	0.7	linear

Table 3. Sensitivity of habitat to a certain threat

Name	Habitat	Crops	Urban	Tourism	Mining	Roads 1	Roads 2
Tree Cover	1	0.8	0.8	0.4	0.9	0.8	0.3
Shrubland	0.25	0.5	0.4	0.5	0.5	0.6	0.3
Grassland	0.5	0.5	0.3	0.4	0.5	0.5	0.4
Cropland	0.3	0	0.2	0.2	0.5	0.5	0.3
Built-up	0.1	0.05	0.1	0.1	0.1	0.1	0.1
Bare vegetation	0.1	0.1	0.2	0.2	0.3	0.3	0
Permanent water bodies	1	0.4	0.5	0.3	0.9	0.5	0.3
Herbaceous wetland	1	0.3	0.4	0.4	0.5	0.5	0.3
Caves	1	0.3	0.9	0.9	0.9	0.7	0.3

InVEST generates two types of raster outputs for hub: degradation scores and levels of habitat quality. These scores for each pixel are computed using equation (1) and equation (2) (Natural Capital Project, n.d.).

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r}\right) r_y i_{rxy} \beta_x S_{jr} \quad (1)$$

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^2}{D_x^2 + k}\right) \quad (2)$$

Equation (1) determined the D_{xj}, denoted the total threat level in grid x of habitat type j. Variable Y_r represented the set of grid cells in the raster map of r and w_r, r_y, β_x referred to the weight, the effect, and the mitigating factor of the threat in grid y, respectively (in this case, β_x = 1). S_{jr} represented in sensitivity of the habitat to a certain threat. In the context of habitat quality, Equation (2) was employed. Q_{xj} stood for the habitat quality of LULC j in grid x, and H_j represented the variable for the habitat suitability of LULC j. Equation (2) incorporated k as the half-saturation constant and z as the normalized constant, where z was set 0.5 and k to 2.5.

2.3.2. Scenic quality

This type of ecosystem service involves analyzing viewpoints from the Digital Elevation Model and identifying any scene disturbances that may affect the natural view of particular location. Scene disturbances comprise anything that may degrade the natural scenery. By evaluating the location, elevation, and scene disturbances, this ecosystem service evaluates the viewpoint that offers the best scenery. In InVEST, the scenic quality calculation results in two outputs: visual quality and visual viewpoints in raster format. The visual quality categorizes pixel values into five classes, each representing a percentile level of visual impact - from totally unaffected (0) to heavily impacted (5). On the other hand, the visual viewpoints raster illustrates the number of visible viewpoints within each raster cell.

The scenic quality model in InVEST derived the visual quality calculation within each cell by employing the reference-plane viewshed algorithm (Wang et al., 2000) for visibility assessment. Subsequently, the model aggregated the visibility data into a valuation raster, which was further categorized into 5 quartiles. The process involved weighted and assumming the visibility raster to determine the number of visible points from a certain cell within the raster.

3. Results

The InVEST calculation of the data generates the current state and conditions of existing karstic ecosystem services within GSUGGp. Regarding scenic quality, we discovered several obstructions affecting the scenery along the beaches in the coastal area of GSUGGp, evaluating their impact on visibility and visual quality. Similarly, in the assessment of habitat quality, we selected several threats that could be potentially disrupt the habitat as represented by the LULC, as detailed the following explanation.

3.1. Gunung Sewu UNESCO Global Geopark habitat quality

The KES within the karst area of GSUGGp are contingent on the LULCs categories, and the characteristic habitats within the Karst of Gunung Sewu are facing pressures from tourism, pollution, limestone mining, and urban activities. These factors have been selected as an input for the model we have generated. The resulting Habitat Quality as KES in GSUGGp is depicted in Figure 2.

Figure 2 contains two different raster maps: one displaying degradation scores and the other showcasing levels of habitat quality. The degradation scores are computed using Equation (1), while the Level of Habitat Quality is derived from Equation (2). Examining the Level of Habitat Quality map shows that the Wonosari City vicinity exhibits a darker blue shade, indicating lower habitat quality as unsuitable habitat types and the heightened threats. This particular area comprises urban and agricultural zones, both classified as unsuitable habitats with low scores, posing significant threats to the habitat.

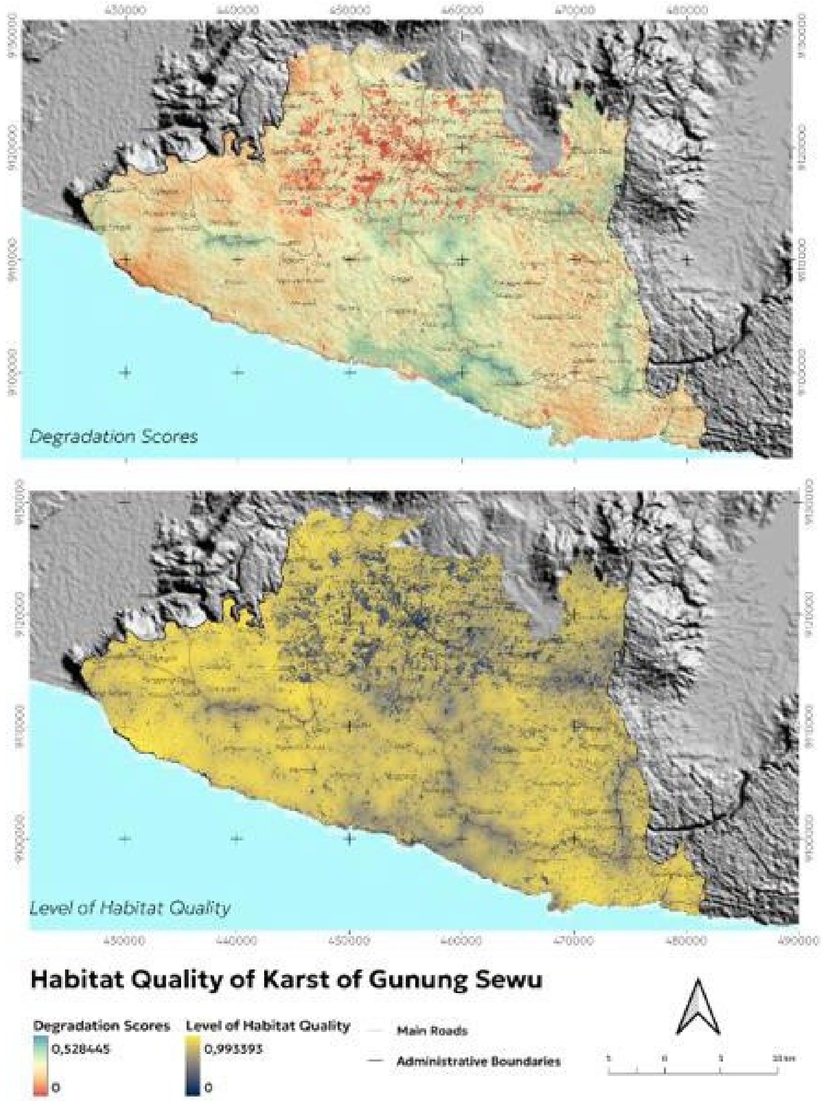

Figure 2. Habitat quality map of research location

Another notable visual cue is the darker shading along the main road and the southern part coastal area, coinciding with the presence of the *Jalan Lintas Selatan* (JLS) infrastructure and the coastal tourism center, both posing significant threat to habitat quality. The JLS infrastructure may impact habitat quality by disrupting integrity through habitat fragmentation, reducing ecological areas, and increasing built-up areas (Astuti & Haryono, 2022). This impact is evident in dense tree-covered regions in the western and southern parts of Karst of Gunung Sewu. Additionally, Ponjong exhibits a darker shade due to the presence of several limestone extraction sites. Contrary to the built-up and agricultural LULCs types that exhibit low suitability scores, area such as tree covers, caves, and permanent water like polje or karst ponds have high suitability scores, albeit situated amidst high threats. Hence, this area was heightened attention. Figure 3 provides an illustration of the habitat type and threat in Karst of Gunung Sewu.

Figure 3. Habitat illustration in Karst of Gunung Sewu: (a) dry field habitat and tree cover on the conical hill, (b) tree covers and agroforestry in the karst of Gunung Sewu. Threats of habitat: (c) limestone mining, (d) construction of Jalan Lintas Selatan

3.2. Gunung Sewu UNESCO Global Geopark scenic quality

Situated in the southern part of Java Island, GSUGGp was formed as the collision between two main tectonic plates, resulting in gradual uplifting. This geological process has sculpted cliffs and hilly coastal areas, featuring numerous conical hill peaks that provide scenic viewpoints overlooking the open ocean. This condition renders a great scenic quality, blending the karstic conical hills in the northern part with an oceanic view featuring a contrasting white sand beach. During field observations, we identified several visual disturbances obstructing the viewpoints towards both the open ocean and the conical hills. These obstructions have the potential to hinder and degrade the "sense of naturality" in the coastal area of GSUGGp, encompassing massive statues, unused buildings, and construction sites, as depicted in Figure 4.

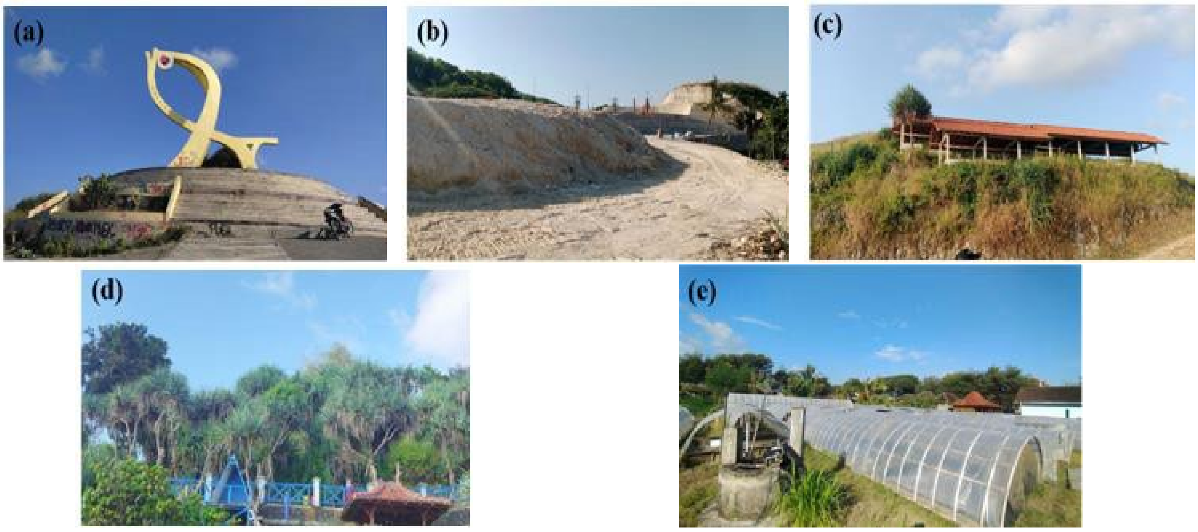

Figure 4. Scenery obstructions in coastal area: (a) Large statue, Krakal Beach (b) Drini park construction, Drini Beach (c) Unused building, Midodaren Beach (d) Selfie spot, Kukup Beach (e) Salt production, Sepanjang Beach

The most disruptive obstructions are the construction sites, scattered across various locations, significantly decreasing the scenic quality by altering viewpoints and changing the landform, hence disturbing the intactness and integrity of the landscape. Following the construction sites, additional disturbances arise from unnecessary structures such as large statues and abandoned or unfinished buildings, contributing unnatural elements to the scenery. Furthermore, the presence of salt production fields and several energy constructions also contributes to disruptions, especially considering that some of these structures have been abandoned and no longer utilized for production.

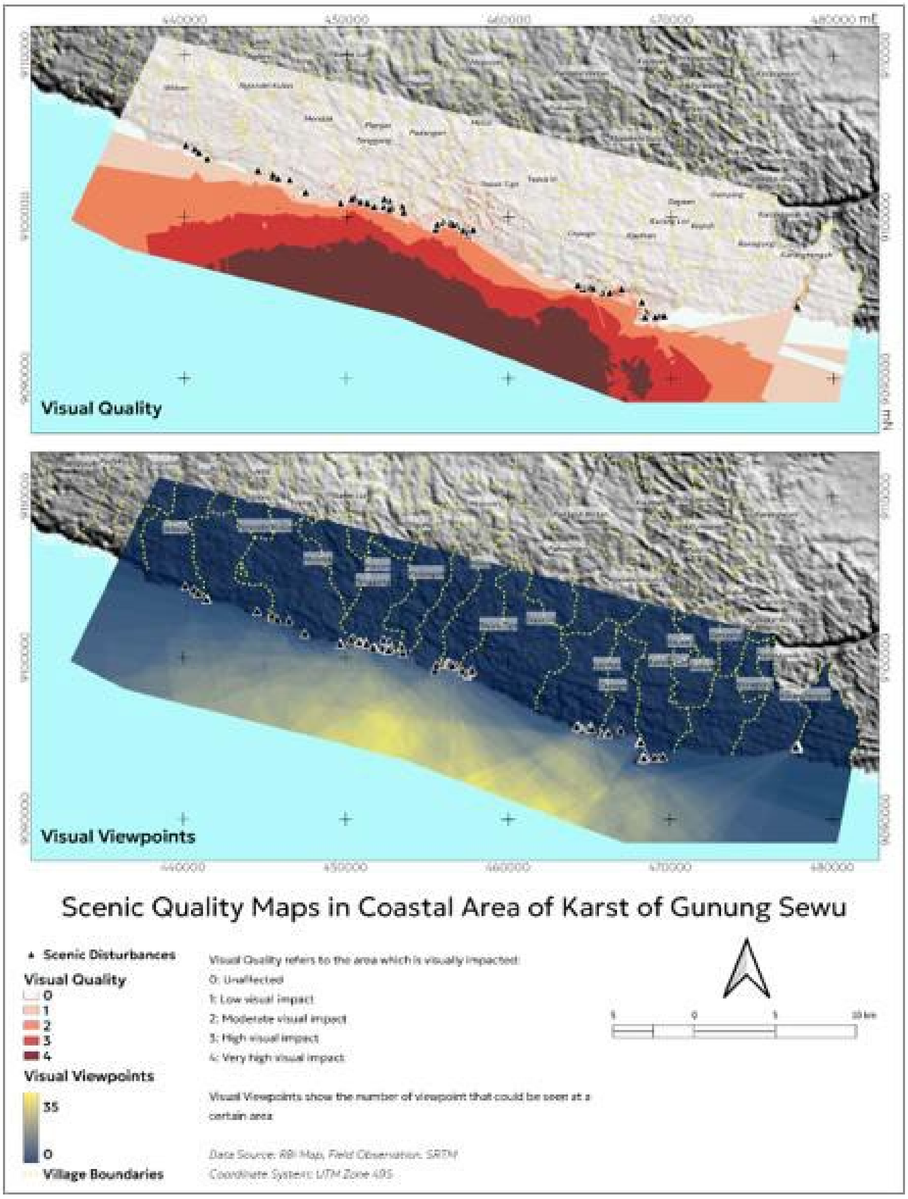

Figure 5. Scenic quality maps of the coastal area of Karst of Gunung SewuDiscussion

Figure 5 highlights several noteworthy aspects. It comprises two maps illustrating visual quality and visual viewpoints. The visual quality map indicates aggregated visual obstructions in multiple spots along the coastal area, disrupting the ocean scenery; conversely, from the ocean, various viewpoints exhibit scenery obstructions. Another focal point is the obstruction towards the northern part of the coastal land. While some viewpoints offer sufficient height for visitors to enjoy the conical hills of Karst of Gunung Sewu from the coastal area, the presence of scenery disturbances, indicated by red specks on the visual quality maps, may hinder this view.

3.3. KESs of habitat and scenic quality: How and why?

In the case of habitat quality, coral reefs, caves, and forests serve as vital living spaces for a diverse myriad of biota, hosting essential biodiversity for inhabitants in the karst area. Caves, specifically, warrant heightened attention as habitats since they provide shelter for bat colonies, acting as both pollinators and pest controllers (Schäckermann et al., 2022; Tremlett et al., 2020). Mijiarto et al. (2014) assessed the services of bat colony in Gudawang Cave, Bogor, estimating economic value generated through guano production. Beyond their utilitarian and economic value, cave habitat holds significant scientific value by providing an environment for unique biota evolution processes (Juan et al., 2010; Romero, 2011).

As a designated Geopark area, the Karst of Gunung Sewu heavily relies on the tourism sector as its primary economic driver. This reliance has led to significant LULC changes (Baixue et al., 2021; Reinhart, et al., 2023) in the region, potentially deteriorating habitat quality and posing increased threats due to the construction of large infrastructure. Research conducted in the Wuling Mountain Karst Plateau in China shows that topographic plays a pivotal role in controlling LULC dynamics and subsequently impact habitat quality (Xie et al., 2022). Consistent with this finding, the Karst of Gunung Sewu agrees that the plateau area in the northern part of the Wonosari urban area experiences more pronounced LULC changes, resulting in a lower level of habitat quality.

Scenic quality, especially concerning the Geopark pillars, plays a critical role preserving the integrity and intactness of landforms through the visual landscapes. GSUGGp has experienced various geological forces over millions of years, sculpting the landforms evident in recent times. Visualization and morphology serve as key features in distinguishing and comprehending the geological process that have shaped the landscape (Haryono & Day, 2004; Tjia, 2013). Another noteworthy observation pertains to the scenic view of the hills in the northern part of the coastal area and its lush greenery. A study conducted in the Proposed Appalachian Geopark in West Virginia supports the notion that visitors exhibit a preference for forest landscapes, akin to those found in the Sewu Mountain zone (Nakarmi et al., 2023).

Scenic quality is also associated with coastal accessibility and the privatization of beaches, as examined by Mooser et al (2023). Mooser's study highlighted extensive beach concession practices in the Southern Italy, and a similar phenomenon is emerging the coastal area of GSUGGp. Our field observations reveal that numerous hilltops have already been claimed by private resorts. This finding holds critical related to the scenic quality, as these visual resources could potentially be commodified as tourism attractions, aligning with the local community aspect – one of Geopark's pillars.

From a technical modeling perspective, the effectiveness of a model is contingent upon the quality of its inputs. The habitat quality InVEST model relies heavily on the input of LULCs data, a reliance shared with other ecosystem services engine such as ARIES (Reinhart, , 2023; Villa et al., 2014). This research utilized LULC data primarily sources from the ESA World Cover datasets to illustrate habitat quality. While this approach is practical and straightforward, it possesses limitations and weaknesses, particularly in its inability to capture the unique habitats within karst areas (Hu et al., 2020; Li & Geng, 2022). To address this, more comprehensive and detailed LULC maps should be used, considering the unique characteristics of karst influenced by its climate, morphology, and human intervention.

3.4. KESs: Foundation of the three pillars of geopark

The results have demonstrated how two examples of ecosystem services in the karst area provide an extent of value, encompassing tangible aspects along with intangible cultural and scientific significance. It triggers the urgency to preserve these values, given their importance to various facets, and highlights their pivotal role in a conservation and management framework. In short, Geopark management is as an all-encompassing endeavor aimed to enforce the pillars of Geopark, which serve as its defining characteristics. While some resources may emphasize sustainability (Henriques & Brilha, 2017; Pásková & Zelenka, 2018) and institutional aspects (Lestari & Indrayati, 2022) as fundamental to Geopark management, fundamentally, the sustainability and institutional framework of a Geopark are anchored in its three pillars.

At GSUGGp, an embodiment of the pillars of Geopark, various efforts have been carried out, aligning with the principles of sustainable development. These conservation endeavors predominantly focus on community empowerment by strengthening Micro, Small, and Medium Enterprises (MSMEs) (Priyono et al., 2020) and educational initiatives (Sulistiyowati et al., 2021). In particular, geoconservation initiatives target mining, recognized as a threat to the conserving the rocks and geological richness in the Karst of Gunung Sewu Area (Pratiwi, 2021). UNESCO Global Geopark stands as a sustainable development model, largely attributable to geotourism element (Da Silva, 2020; Yuliawati et al., 2016). The interrelation between ecosystem services and the pertinent Geopark's pillars is presented in Table 4.

Table 4. Ecosystem services and related geopark pillars

Ecosystem Services	Geoconservation	Geoeducation	Sustainable LED
Habitat Quality	Geoecosystem dynamics and the flow of energy within the habitat	Quality of habitat represents the relation between elements of the ecosystem and serves as educational material	Habitat in Karst of Gunung Sewu provides raw materials for local products (*thiwul* from cassava or grasshopper as gastronomical attraction)
Scenic Quality	The integrity of the landscape as a visual resource.	Morphology is the educational material to show the scientific value	Intactnes and naturality of the landscape to be used as an attraction

KESs play a significant contribution, offering both quantitative and spatial guidelines. The convergence of KESs with Geopark management aligns notably with the Sustainable Development Goals (SDGs), as explained by Li, et al (2021). This intersection reveals how KESs and sustainability interwine, particularly in the fragility of the karst ecosystem. This fragility implies the challenge of achieving sustainability, given that ecosystem dynamic can be easily impacted by development and construction activities. In the case of Karst of Gunung Sewu, the Geopark status mandates development in the tourism sector to attract more visitors and enhance regional income from tourism revenue. KESs serve as a boundary and support for determining carrying capacity, doubling as a spatial planning indicator encompassing both economic and non-economic values (Arany et al., 2018; Riechers et al., 2019; Zhu, 2022).

4. Conclusion

Given the fragility of the karst area, development must proceed with the stringent precautions. The Karst of Gunung Sewu in Gunungkidul Regency has experienced massive tourism infrastructure development, particularly following the tourism surge in the 2010s, which peaked upon its inclusion in the UNESCO Global Geopark Network in 2015. Since then, the focus of development has been geared towards sustaining the tourism industry while aligning with the three pillars of Geopark framework. Leveraging advanced modeling technology like InVEST software enables the generation of ecosystem services models to steer development in line with the Geopark status. Two crucial KESs: habitat quality and scenic quality, directly linked to the

Geopark's pillars. They strengthen the geoconservation pillar by preserving habitat intactness and ecosystem dynamic, contribute to the geoeducation pillar by interpreting the integrity and intactness of visual landscapes, and further the Local Economic Development pillar by enhancing habitat and scenic quality, thereby attracting tourism.

Acknowledgement

This research is funded by Faculty of Geography UGM through *Hibah Penelitian Mandiri* Grant stated at Keputusan Dekan Fakultas Geografi Universitas Gadjah Mada Nomor 80/UN1/FGE/KPT/SETD/2023. The authors would also like to express gratitude to the surveyor team.

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