

Assessing the Geoheritage Significance of Danau Rayo, Indonesia: A Geosite Associated with a Hypothesized Impact Structure in a Humid Tropical Environment

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Abstract

Danau Rayo has been proposed as a candidate impact structure based on previous geomorphological, geophysical, petrographic, mineralogical and geochemical observations, although the impact origin remains unconfirmed. This study aims to assess the significance of Danau Rayo geoheritage as a geosite with a hypothesized impact origin in a humid tropical environment and evaluate its management readiness from a stakeholder perspective. The research uses a mixed-method approach that integrates geological evidence synthesis, stakeholder surveys, and multidimensional assessment of geoheritage. A total of 27 stakeholders representing the government, local communities, tourism groups, business actors, and academics participated in this study. The assessment covers five dimensions of geoheritage, namely Scientific Value, Educational Value, Aesthetic Value, Cultural Value, and Conservation Value, as well as evaluation of geoethics supporters, which include Responsibility, Public Engagement, Sustainability, and Knowledge Integration. The results showed that Danau Rayo has a **Geoheritage Significance Index (GSI) of 2.99**, with **Cultural Value (3.65)** and **Scientific Value (3.38)** as the highest dimensions. On the other hand, **the Conservation Value (2.10)** was the lowest dimension, indicating that there is still limited protection and geoconservation of the area. The supporting evaluation resulted in a **Geoethics Index (GI) of 2.83**, which shows management readiness at the intermediate level. These findings show that Danau Rayo has strong geoheritage potential supported by scientific, cultural, and aesthetic values, but still faces challenges in conservation and governance aspects. This research provides the basis for the development of geoconservation, geoeducation, geotourism, and sustainable geopark planning, while confirming the need for further research to verify the hypothesis of the origin of the impact of Danau Rayo.

1. Introduction

Impact structures are a form of geoheritage with high scientific, educational, and cultural significance, illustrating why geoheritage plays an important role within geodiversity conservation (Brilha, 2016); (Brilha, et al., 2018). Formed by the collision of high-energy extraterrestrial objects with the Earth's surface, these structures are not merely unusual landforms but also valuable geological records that preserve evidence of planetary evolution, crater-forming mechanisms, rock deformation processes, and the interaction between endogenous and exogenous geological processes (French & Koeberl, 2010). Furthermore, impact structures contain evidence of extraterrestrial collisions that have influenced Earth's surface, environmental systems, and the history of life, making them crucial for understanding both planetary evolution and Earth history (Osinski, et al., 2020) (Osinski, et al., 2022). Because of their rarity and their ability to preserve evidence of impact events, they are widely recognized as geoheritage sites of outstanding scientific value (Sanchez & Brilha, 2017) (Chandran, et al., 2022). Consequently, many impact structures have been designated as important geosites and are utilized for scientific research, Earth science education, geotourism, and geoconservation initiatives.

Internationally recognized impact structures such as **Lunar Crater** (India) (Chandran, et al., 2022), **Wolfe Creek Crater** (Australia) (Shoemaker, et al., 2005) and **Pingualuit Crater** (Canada) (Desiage, et al., 2015)

demonstrate that impact-generated landscapes can evolve into high-value geoheritage resources when supported by strong scientific significance, landscape integrity, and effective conservation and management systems. Beyond serving as natural laboratories for understanding high-energy geological processes, these sites also contribute to geoeducation, geotourism, and public awareness of Earth history. From a geoheritage perspective, impact structures are particularly valuable because they represent rare geological phenomena that preserve evidence of planetary evolution and crater-forming processes. Their rarity, scientific relevance, and educational potential often place them among the most significant geosites within geoheritage assessment frameworks (Kenkmann, 2021). In addition, many impact structures have become embedded within local cultural traditions, legends, and collective identities, highlighting the close relationship between geological heritage and cultural heritage (Brilha, 2016) (Sanchez & Brilha, 2017) (Chandran, et al., 2022).

Although impact structures have been widely studied from geomorphological, geophysical, petrographic, mineralogical, and geochemical perspectives, geoheritage research has largely focused on scientifically confirmed impact craters with established conservation status. In contrast, candidate impact structures remain underrepresented in geoheritage and geoconservation studies, particularly those that have not yet achieved formal scientific recognition (Sanchez & Brilha, 2017; Chandran et al., 2022).

This limitation is especially relevant in humid tropical environments, where intensive weathering, erosion, sedimentation, and dense vegetation can progressively modify or obscure impact-related geomorphological features (Quesada-Román, et al., 2025). Consequently, candidate impact structures that retain recognisable basin morphology under such conditions provide valuable opportunities to investigate landscape preservation processes and the geoheritage significance of impact-related landforms in tropical regions (Rochette, et al., 2019).

Danau Rayo represents an important example of this context. Previous studies have identified geomorphological, geophysical, petrographic, mineralogical, and geochemical evidence consistent with its interpretation as a candidate impact structure, although impact origin remains to be conclusively verified (Sari, et al., 2024). At the same time, no study has comprehensively evaluated its geoheritage significance by integrating geological evidence, cultural values, stakeholder perspectives, and management considerations. Therefore, this study assesses the geoheritage significance of Danau Rayo through a multidimensional framework encompassing scientific, educational, aesthetic, cultural, and conservation values, while also evaluating management readiness to support future geoconservation and sustainable development.

This study aims to evaluate the geoheritage significance of Danau Rayo as a geosite with a hypothesized impact origin and distinctive circular basin morphology preserved in a humid tropical environment. By integrating geological evidence, geoheritage assessment, local cultural heritage, and stakeholder perspectives, the study seeks to provide a comprehensive understanding of Danau Rayo's geoheritage potential, examine stakeholder perceptions, identify conservation and governance challenges, and propose recommendations for sustainable geoconservation and site management. To address these

objectives, an integrated approach combining geological evidence, geoheritage assessment, stakeholder perspectives, and geoconservation considerations was adopted to evaluate both the significance and management readiness of Danau Rayo.

2. Geological and Environmental Setting

2.1 Geographic Setting

Danau Rayo is located in North Musi Rawas Regency, South Sumatra Province, Indonesia. This area is located in a lowland to undulating area dominated by tropical vegetation cover and influenced by the hydrological system that develops in the upstream part of the Rawas Watershed. Administratively, Danau Rayo is included in an area with potential for geotourism development and is considered one of the locations that can support the development of the North Musi Rawas Geopark initiative.

Geographically, Danau Rayo is characterized by an almost circular basin filled with a permanent body of water. This area is surrounded by natural vegetation and land that is partly used for community activities. The condition of the landscape that is still relatively maintained makes Danau Rayo have important value both from a geomorphological and landscape perspective.

From an environmental point of view, Danau Rayo is located within a humid tropical climatic setting characterized by high temperatures, relatively constant air humidity throughout the year, and high rainfall. South Sumatra Province has an average annual rainfall of around 2,597 mm per year, resulting in a positive water balance and supporting the existence of permanent water bodies such as Danau Rayo (Ariska, et al., 2024).

The humid tropical environment greatly influences the evolution of the region's landscape. Chemical weathering takes place intensively, vegetation develops rapidly, and erosion and sedimentation occur actively. Under these conditions, many geomorphological features tend to degrade or modify over relatively short geological timescales. These environmental conditions are relevant to the interpretation of Danau Rayo as a candidate impact structure because they provide the geomorphological and climatic context in which the basin has evolved (Osinski & Pierazzo, 2013).

2.2 Geological Characteristics

Danau Rayo has unique geological characteristics compared to most natural lakes in the tropical environment of Sumatra. This uniqueness is mainly reflected in the basin's almost circular morphology, the hydrological system that develops in it, and various geological indications that support the interpretation of this area as a *candidate impact structure*. These characteristics are not only important from a geological perspective, but also form the main basis for assessing the scientific value and significance of the region's geoheritage.

One of the most prominent characteristics of Danau Rayo is the almost perfectly circular morphology of the basin. Analysis of the Digital Elevation Model (DEM), hillshade imagery, and orthomosaic UAV

imagery showed that the lake formed a basin with a diameter of about 777–789 m, surrounded by relatively higher reliefs in some sectors. This shape differs from most fluvial lakes, which generally follow river flow patterns, and from tectonic lakes that develop according to regional geological structures.

From a geoheritage perspective, this circular morphology is an important element that enhances the region's scientific value because it represents a relatively rare landform found in humid tropical environments. The presence of a morphology resembling a *raised rim* and a slope-slope pattern leading to the center of the basin also indicates special geological processes that characterize this area.

Danau Rayo is a permanent body of water that develops in a relatively closed basin. The region's hydrological system shows that surface flows from the surrounding area tend to be concentrated towards the central part of the basin, while natural outlets are relatively limited. The combination of basin morphology and high rainfall causes water accumulation to occur sustainably, so that the lake remains filled throughout the year. The existence of this permanent lake makes an important contribution to the geoheritage value of the area. In addition to improving the visual and aesthetic quality of the landscape, the hydrological system of Danau Rayo provides an opportunity to examine interactions between geomorphology, hydrology, and landscape evolution in a humid tropical environment.

The interpretation of Danau Rayo as a candidate impact structure is based on the integration of various geological evidence obtained from previous research. The evidence includes geomorphological, geophysical, petrographic, mineralogic, and geochemical aspects that collectively exhibit characteristics consistent with the impact structure hypothesis, although it is not yet sufficient to confirm its status as a verified impact crater.

From a geomorphological aspect, Danau Rayo shows an almost circular basin, an indication of rim morphology, and a structural pattern that leads out of the center of the basin. Geophysical data show a pattern of subsurface heterogeneity consistent with depressions filled with different materials compared to the surrounding environment, similar to geophysical anomalies reported from several candidate and confirmed impact structures investigated using resistivity-based methods (Jinmin, et al., 2013); (Lamali, et al., 2016). Petrographic analysis also identified breccia and molten-rock lithology, as well as several deformation features that could potentially be related to high-energy processes (Grieve & Therriault, 2012); (Kenkmann, et al., 2014). In addition, mineralogy and geochemical analyses show compositional variations that indicate a complex geological history.

Although the currently available evidence is insufficient to confirm an impact origin, the combined geomorphological, geophysical, petrographic, mineralogical, and geochemical observations support continued investigation of the impact hypothesis. The geological characteristics of Danau Rayo are marked by an almost circular basin morphology, a permanent lake system, and geological evidence consistent with the impact hypothesis. These features distinguish Danau Rayo from many other lakes in the tropical environment of Sumatra.

2.3 Cultural Context

In addition to its unique geological characteristics, Danau Rayo also has strong cultural values that have developed through long-term relationships between the community and the surrounding landscape. From a geoheritage perspective, the relationship between geological and cultural elements is an important component that enriches the significance of a geosite because it allows the formation of a relationship between *natural heritage* and *cultural heritage*. The cultural value inherent in a geosite can increase public appreciation of the area while strengthening support for conservation and sustainable management efforts.

One of the most well-known cultural elements in Danau Rayo is the legend of Bujang Kurap, which is still passed down from generation to generation by the local community. The legend became part of the local identity and shaped the way people understood the existence of the lake and the surrounding environment. In addition, the existence of the Batu Meja site and various other folklore shows that Danau Rayo is not only understood as a physical landscape, but also as a cultural space that has social and historical significance for the community.

In the context of geoheritage, the relationship between the landscape and local culture makes a significant contribution to **the Cultural Value** of the region. Cultural value does not only come from the existence of legends or traditions, but also from the community's emotional attachment to the landscape, which they consider part of regional identity. This condition shows that the geoheritage of Danau Rayo was built through the interaction between geological characteristics and cultural meanings that develop in the community.

The connection between geology and culture also has important implications for geoeducation and geotourism activities. The cultural narrative that develops around Danau Rayo can be used as an interpretive medium to explain the area's geological characteristics to the community and visitors. Through this approach, scientific information about basin morphology, geological processes, and candidate hypotheses of impact structures can be communicated more easily because they are associated with stories and traditions known to the local community.

From a geoconservation perspective, cultural values can serve as social capital that supports the protection of geoheritage. Studies have shown that communities tend to be more supportive of conservation when a landscape is not only seen as scientifically important, but also has cultural significance and local identity. Therefore, the existence of the legend of Bujang Kurap, Batu Meja, and various other forms of local knowledge is an important asset that can be used to strengthen the management and conservation strategy of Danau Rayo.

3. Methodology

3.1 Research Design

This study uses a mixed-method exploratory research approach that integrates geological analysis, geoheritage assessment, and stakeholder perception evaluation to assess the significance of the Danau Rayo geoheritage as a geosite with a hypothesized impact origin preserved in a humid tropical environment. This approach was chosen because the assessment of geoheritage depends not only on the geological characteristics of a site but also on the educational value, culture, conservation, and stakeholder perception and engagement in the area.

The research was carried out through four main stages. The first stage is a **literature review and geological data synthesis**, which includes a review of the results of geomorphology, geophysics, petrography, mineralogy, and geochemical research that has been carried out previously on Danau Rayo. The second stage is **the collection of stakeholder data** through structured interviews involving elements of the government, village governments, tourism awareness groups (Pokdarwis), MSME actors, academics, and local communities. The third stage is **data coding and analysis, which involves converting interview results** into Likert scale-based scores to measure perceptions of geoheritage indicators and aspects of area management. The fourth stage is **statistical analysis and interpretation**, which includes descriptive statistics, reliability analysis, assessment of geoheritage significance, and evaluation of conservation readiness and area management.

Through this approach, this study not only evaluates the geological characteristics of Danau Rayo, but also assesses how geoheritage values are perceived by stakeholders and how these values can support geoconservation, geoeducation, geotourism, and future geopark development.

3.2 Stakeholder Survey

The assessment of the significance of the geoheritage of Danau Rayo was carried out through a stakeholder-based survey involving various stakeholder groups that have a direct relationship with the management, utilization, conservation, and development of the area. The stakeholder approach is used because the value of geoheritage is not only determined by the geological characteristics of a site, but also by how it is understood, utilized, and protected by the communities and institutions that interact with the area.

A purposive sampling approach was adopted because the study aimed to obtain informed assessments from stakeholders directly involved in the management, utilization, conservation, and promotion of Danau Rayo. The selected participants represented key stakeholder groups with relevant knowledge, decision-making roles, or direct interactions with the site, including government agencies, local communities, tourism awareness groups (Pokdarwis), MSMEs, and academics. Given the exploratory nature of the study and the emerging status of Danau Rayo as a geoheritage site, purposive sampling was considered more appropriate than probability-based sampling because it enabled the inclusion of individuals with specific expertise and experience relevant to geoheritage assessment. This approach prioritizes depth of stakeholder knowledge over statistical representativeness and is commonly applied in exploratory geoheritage, geoconservation, and stakeholder perception studies (Patton, 2002) (Creswell, 2009).

Respondents were purposively selected to represent groups that have a role in natural resource management, regional development, tourism development, local economic activities, and cultural preservation. The groups include local government agencies, village governments, tourism awareness groups (*Pokdarwis*), micro, small, and medium enterprises (MSMEs), local communities, and academics.

A total of **27 stakeholders** were interviewed using semi-structured instruments designed to explore perceptions of scientific, educational, aesthetic, cultural, conservation, management, and protection aspects of Danau Rayo. The interview results were then coded into a five-level Likert-scale-based score to allow statistical analysis and quantitative evaluation of the geoheritage significance of the region.

Table 1
Characteristics of Stakeholders Participating in the Study

Stakeholder group	Number Of Respondents	Percentage (%)
Government Agencies	18	66.7
Pokdarwis	2	7.4
MSMEs	2	7.4
Local Community	3	11.1
Academic	2	7.4
Total	27	100.0

Most of the respondents came from government groups (66.7%), reflecting the involvement of various agencies in regional management and development. Local community groups, Pokdarwis, and MSMEs contributed 25.9% of the total respondents, thus allowing the accommodation of the perspective of the community that interacts directly with Danau Rayo. In addition, the involvement of academics provides important input from a scientific and educational point of view.

The diverse composition of stakeholders allows the research to obtain a more comprehensive picture of the geoheritage value of Danau Rayo while identifying opportunities and challenges in area management from a multi-stakeholder perspective. This approach is also in line with the principles of geoconservation and geopark management, which emphasize the importance of stakeholder participation in conservation and sustainable development efforts.

3.3 Geoheritage Assessment Framework

The geoheritage assessment of Danau Rayo was carried out using an evaluation framework developed based on the concept of geoheritage assessment introduced by Brilha (2016) and refined in the geoheritage framework described by Reynard and Brilha (2018). This framework is used to evaluate the significance of geoheritage in a multidimensional manner, thus considering not only the scientific value of a geosite, but also the educational, aesthetic, cultural, and conservation aspects.

The multidimensional approach was chosen because geoheritage reflects the interaction between geological characteristics, socio-cultural values, and management and conservation needs (Kubalikova, 2013). In the context of Danau Rayo, this approach allows for a more comprehensive evaluation of areas that are still in the stage of scientific verification as impact structure candidates.

Based on the synthesis of literature and the results of stakeholder interviews, this study uses five main dimensions of geoheritage, namely Scientific Value (SV), Educational Value (EV), Aesthetic Value (AV), Cultural Value (CV), and Conservation Value (CoV). The five dimensions were chosen because they represent the main characteristics that determine the significance of a geosite and are relevant to the condition of Danau Rayo as a geosite with a hypothesized impact origin. Because this study adopts a stakeholder-based and exploratory assessment approach, equal weighting was assigned to all geoheritage dimensions. This decision was made to evaluate stakeholder-perceived geoheritage significance rather than intrinsic geological significance. The approach assumes that scientific, educational, aesthetic, cultural, and conservation dimensions collectively contribute to stakeholder appreciation of geoheritage and therefore were considered equally in the calculation of the Geoheritage Significance Index (GSI).

Table 2
Geoheritage Indicators Used in this Study

Dimension	Code	Indicator
Scientific Value (SV)	Q1	Geological uniqueness
	Q2	Distinctive geological features
	Q3	Utilization of geoheritage for scientific and tourism purposes
Educational Value (EV)	Q4	Educational potential
	Q5	Interpretation quality
	Q6	Availability of educational and interpretation media
	Q7	Educational barriers and limitations
Aesthetic Value (AV)	Q8	Landscape beauty
	Q9	Environmental comfort
	Q10	Visual quality and landscape management
Cultural Value (CV)	Q11	Emotional attachment
	Q12	Memorable visitor experience
	Q13	Storytelling significance
	Q20	Cultural authenticity
	Q21	Relationship between culture and geoheritage
	Q22	Authentic local experience
Conservation Value (CoV)	Q14	Conservation efforts
	Q15	Protection policies
	Q16	Conservation challenges

To reinforce the conceptual validity of the instrument, each dimension was developed based on geoheritage literature widely used in geosite research and geoconservation.

Table 3
Theoretical Basis of the Geoheritage Assessment Framework

Dimension	Main Reference	Conceptual Focus
Scientific Value	Brilha (2016)	Scientific significance and geological relevance
Educational Value	Reynard & Brilha (2018)	Geoeducation and interpretation potential
Aesthetic Value	Brilha (2016); Gordon (2018)	Landscape quality and visual attractiveness
Cultural Value	Gordon (2012, 2018)	Relationship between geoheritage and cultural landscape
Conservation Value	Brilha (2016); Henriques et al. (2015)	Protection and geoconservation needs

The value of each indicator is assessed using a five-level Likert scale and then averaged to obtain a score for each dimension. Furthermore, all dimensions of geoheritage are used to calculate the **Geoheritage Significance Index (GSI)**, which represents the overall significance of Danau Rayo.

Through this framework, the geoheritage of Danau Rayo is evaluated not only based on geological evidence supporting its interpretation as a candidate impact structure, but also on the educational, aesthetic, cultural, and conservation values that contribute to the area's importance for research, society, and sustainable geotourism development. The resulting GSI therefore represents stakeholder-perceived geoheritage significance rather than an expert-based assessment of intrinsic geoheritage value.

3.4 Supporting Geoethics Assessment

Although the main focus of this study is the assessment of the significance of Danau Rayo's geoheritage, a comprehensive geoheritage evaluation requires an understanding of the conditions of management, conservation, and stakeholder engagement that support the sustainability of the area. Therefore, this study complements the geoheritage assessment with **a supporting geoethics assessment**, which evaluates management *readiness* and regional governance conditions.

In this study, geoethics is not positioned as the main goal or an evaluation framework equivalent to geoheritage, but rather as a supporting instrument to understand the extent to which the value of Danau Rayo's geoheritage has been supported by conservation practices, governance, community participation, and local knowledge integration. This approach aligns with geoethics principles that emphasize responsibility for geological heritage, sustainable use of natural resources, and community involvement in area management (Gordon, 2019) (Castro, et al., 2021).

Based on the principles of geoethics developed by the International Association for Promoting Geoethics (IAPG) and the Cape Town Statement on Geoethics, this research uses four supporting dimensions, namely **Responsibility (R)**, **Public Engagement (PE)**, **Sustainability (S)**, and **Knowledge Integration (KI)**. The four dimensions were chosen because they are relevant for evaluating the readiness of Danau Rayo

management as a geoheritage area that has the potential to be developed for conservation, education, and geotourism purposes.

Table 4
Geoethics Indicators Used in this Study

Dimension	Code	Indicator
Public Engagement (PE)	Q17	Community participation
	Q18	Community involvement in tourism activities
	Q19	Community capacity development
	Q23	Tourist-community interaction
	Q24	Intensity of interaction
	Q25	Drivers of participation
	Q26	Economic benefits
	Q27	Benefit distribution
	Q28	Support for local products
Responsibility (R)	Q29	Environmental responsibility
	Q30	Participation in decision-making
	Q31	Governance transparency
Sustainability (S)	Q32	Revisit intention
	Q33	Factors influencing revisit intention
	Q34	Recommendation intention
	Q35	Visitor loyalty drivers
	Q40	Challenges in sustainable tourism development
	Q41	Management recommendations
Knowledge Integration (KI)	Q36	Geoheritage and community-based tourism integration
	Q37	Geoeducation potential
	Q38	Stakeholder collaboration
	Q39	Institutional support

Table 5
Theoretical Basis of the Geoethics Assessment Framework

Dimension	Main Reference	Conceptual Focus
Responsibility	Cape Town Statement on Geoethics; Peppoloni & Di Capua (2021)	Ethical responsibility and governance
Public Engagement	Di Capua et al. (2017); UNESCO (2021)	Community participation and stakeholder involvement
Sustainability	UNESCO (2021); Wang et al. (2019)	Sustainable management and long-term development
Knowledge Integration	Peppoloni & Di Capua (2021); UNESCO (2021)	Integration of scientific and local knowledge

The value of each indicator is measured using a five-level Likert scale and then averaged to obtain a score for each geoethics dimension. The results of this evaluation are not used to determine the significance of geoheritage directly, but are used to identify opportunities and challenges in area management that can affect the sustainability of Danau Rayo as a geoheritage.

Thus, the supporting geoethics assessment serves as a complement to the geoheritage assessment, which helps to clarify whether the scientific, educational, aesthetic, cultural, and conservation value of Danau Rayo has been supported by adequate management and governance capacity.

3.5 Reliability Analysis

To ensure the internal consistency of the instruments used in this study, reliability testing was carried out using **Cronbach's Alpha** coefficient. Reliability analysis aims to evaluate the extent to which the indicators in the instrument provide consistent and stable measurement results in representing the construct being studied.

Cronbach's Alpha is one of the most widely used measures of reliability in social research, education, and stakeholder perception studies. An alpha value approaching 1 indicates a better level of internal consistency, while a value above 0.70 is generally considered adequate for exploratory research and instrument development.

In this study, reliability testing was carried out on all indicators used in the geoheritage assessment framework and the supporting geoethics assessment. This approach was chosen because the main objective of the research is to evaluate the significance of the geoheritage of Danau Rayo through instruments that integrate various interrelated dimensions.

Table 6
Reliability Analysis of the Assessment
Instrument

Dimension	Cronbach's Alpha
Overall Instrument	0.785

The results of the analysis showed that the instrument as a whole had a **Cronbach's Alpha value of 0.785**, which indicates a good level of reliability. These values show that the indicators used in the study have adequate internal consistency to support the analysis of geoheritage significance and the evaluation of aspects of area management.

This reliability value provides confidence that the data obtained from stakeholders can be used to analyze various dimensions of geoheritage consistently. Thus, the assessment results not only reflect the respondents' perceptions but are also supported by instruments with acceptable measurement quality.

In addition to strengthening the methodological validity of the research, reliability analysis is also important to address potential criticism of reviewers related to the use of stakeholder perception-based instruments. With Cronbach's Alpha values being above the threshold commonly used in exploratory research, this instrument is considered feasible for use in the evaluation of the geoheritage of Danau Rayo. According to commonly accepted reliability criteria, Cronbach's Alpha values between 0.70 and 0.79 indicate good internal consistency. Therefore, the obtained alpha value of 0.785 suggests that the assessment instrument demonstrates satisfactory reliability for exploratory geoheritage research.

Based on this classification, the alpha value of **0.785** indicates that the research instrument is in the **Good Reliability category**. Reliability was assessed at the overall instrument level because the study evaluates geoheritage significance as an integrated multidimensional construct. Given the exploratory nature of the study and the relatively limited sample size, dimension-level reliability coefficients were not emphasized.

3.6 Statistical Analysis

Statistical analysis was carried out to evaluate stakeholder perceptions of the significance of Danau Rayo geoheritage and the conditions of area management. This analysis includes descriptive statistics, instrument reliability testing, geoheritage index calculation, and comparison of perceptions between stakeholder groups.

Descriptive statistics are used to describe the general tendency of respondents' responses to each indicator and dimension of the study. The parameters calculated include the mean, standard deviation, minimum, and maximum. The average score was used to identify the level of stakeholder perception of each aspect of geoheritage and geoethics, while the standard deviation was used to describe the variation in responses between respondents.

The value of each geoheritage dimension is calculated as the average score of the indicators that compose the dimensions, namely: Scientific Value (SV), Educational Value (EV), Aesthetic Value (AV), Cultural Value (CV), and Conservation Value (CoV). Furthermore, all dimensions are used to calculate the **Geoheritage Significance Index (GSI)** as an indicator of the overall significance of Danau Rayo.

$$GSI = \frac{SV + EV + AV + CV + CoV}{5}$$

The use of equal weighting follows the exploratory nature of the present study and is intended to provide an integrated stakeholder-based evaluation of geoheritage significance. Future studies may incorporate expert-based weighting methods, such as the Analytic Hierarchy Process (AHP) or Delphi approaches, to examine the sensitivity of the resulting index.

As a supporting assessment, the geoethics score is calculated based on four dimensions: Responsibility (R), Public Engagement (PE), Sustainability (S), and Knowledge Integration (KI). The overall value is calculated using **the Geoethics Index (GI)**:

$$GI = \frac{R + PE + S + KI}{4}$$

This index is used to evaluate the readiness of management, conservation, and governance of the area that supports the sustainability of Danau Rayo's geoheritage.

The internal consistency of the instrument was tested using **Cronbach's Alpha** coefficient. This test was carried out to ensure that the indicators used can measure the research construct consistently. Alpha values are interpreted based on criteria commonly used in social and behavioral research.

To evaluate possible differences in perceptions between stakeholders, **the Mann–Whitney U Test** was used, a nonparametric method suitable for ordinal data and unbalanced sample sizes. This analysis compares two main groups of stakeholders:

1. **Government Stakeholders**
2. **Local Community Stakeholders** (Pokdarwis, MSMEs, and local communities)

Testing was carried out on all dimensions of geoheritage and geoethics, as well as the GSI and GI indices.

The hypotheses used are:

H0

There is no significant difference in perception between government groups and local communities.

H1

There is a significant difference in perception between government groups and local communities.

The significance level was set at 95% ($p < 0.05$).

4. Results

4.1 Descriptive Statistics

Descriptive statistics were used to provide an overview of stakeholder perceptions of each indicator included in the geoheritage and supporting geoethics assessment frameworks. The analysis comprised the mean, standard deviation, minimum value, and maximum value for each indicator. The mean score indicated the general tendency of stakeholder perceptions, while the standard deviation reflected the degree of variation in responses among participants. The minimum and maximum values provided information on the range of responses, allowing the identification of indicators that received relatively high or low evaluations as well as the degree of consensus among respondents.

Descriptive statistics were calculated for all 41 indicators used in this study. To improve readability and focus the discussion on the most relevant findings, the complete descriptive statistics dataset is provided in **Supplementary Table S1**. The main text highlights only the indicators with the highest and lowest scores, which represent the principal strengths and weaknesses identified by stakeholders in relation to the geoheritage significance and management readiness of Danau Rayo.

The five highest-scoring indicators highlight the strong cultural, aesthetic, and educational significance of Danau Rayo (Table 7). Emotional Attachment and Landscape Beauty obtained the highest ratings, indicating that stakeholder appreciation is strongly rooted in the relationship between the landscape and local identity. Geological Uniqueness and Educational Potential further demonstrate recognition of the site's scientific and educational relevance. These findings suggest that the principal strengths of Danau Rayo lie in the integration of geological features, landscape quality, and cultural connections.

Table 7
Top Five Indicators Identified by Stakeholders

Rank	Indicator	Mean $\pm$ SD	Interpretation
1	Emotional Attachment (Q11)	4.46 $\pm$ 0.90	Strong emotional connection between local communities and Danau Rayo.
2	Landscape Beauty (Q8)	4.42 $\pm$ 0.70	High visual attractiveness and landscape appreciation.
3	Memorable Experience (Q12)	4.12 $\pm$ 1.03	Danau Rayo provides a distinctive and memorable visitor experience.
4	Geological Uniqueness (Q1)	3.85 $\pm$ 1.01	Stakeholders recognize the uniqueness of Danau Rayo's geological characteristics.
5	Educational Potential (Q4)	3.77 $\pm$ 1.07	The site is perceived as having strong geoeducational potential.

The five lowest-scoring indicators are primarily associated with conservation and governance. Protection Policies recorded the lowest score, reflecting stakeholder concerns regarding the absence of adequate protection mechanisms for Danau Rayo. Similarly, Conservation Challenges, Governance Transparency, and Benefit Distribution indicate weaknesses in governance, institutional capacity, and equitable benefit-sharing. These results suggest that the key challenge for Danau Rayo is not a lack of geoheritage value, but rather the limited conservation framework and management capacity required to ensure its long-term sustainability.

Table 8
Bottom Five Indicators Identified by Stakeholders

Rank	Indicator	Mean $\pm$ SD	Interpretation
1	Protection Policies (Q15)	1.58 $\pm$ 0.76	Lack of formal protection and regulatory support.
2	Sustainable Tourism Challenges (Q40)	1.77 $\pm$ 0.71	Challenges related to sustainable tourism management remain inadequately addressed.
3	Conservation Challenges (Q16)	2.00 $\pm$ 0.69	Conservation measures and management efforts remain limited.
4	Benefit Distribution (Q27)	2.04 $\pm$ 0.92	Tourism and development benefits are perceived as unevenly distributed.
5	Governance Transparency (Q31)	2.08 $\pm$ 1.09	Stakeholders perceive weaknesses in governance transparency and accountability.

4.2 Geoheritage Significance Assessment

The assessment of the significance of the geoheritage of Danau Rayo is carried out based on five main dimensions, namely **Scientific Value (SV)**, **Educational Value (EV)**, **Aesthetic Value (AV)**, **Cultural Value (CV)**, and **Conservation Value (CoV)**. The score of each dimension is obtained from the average of the indicators that make up each dimension, then used to calculate the **Geoheritage Significance Index (GSI)** as a measure of overall geoheritage significance. The geoheritage dimension scores are summarized in Table 9.

Table 9
Geoheritage Dimension Scores

Dimension	Mean Score
Scientific Value (SV)	3.38
Educational Value (EV)	2.81
Aesthetic Value (AV)	2.99
Cultural Value (CV)	3.65
Conservation Value (CoV)	2.10
Geoheritage Significance Index (GSI)	2.99

The assessment results show that **Cultural Value (3.65)** is the dimension with the highest score. These findings indicate that cultural values make a very important contribution to the geoheritage significance of Danau Rayo. The high score is supported by the community's strong attachment to the area, the existence of the Bujang Kurap legend, and the close relationship between the landscape and local cultural identity. The Scientific **Value dimension (3.38)** also obtained a relatively high score. These results show that stakeholders recognize the distinctive geological characteristics of Danau Rayo, particularly its near-circular basin morphology and its scientific interest as a site where an impact origin has been proposed. This score reflects stakeholder recognition of the site's scientific importance rather than an expert-based geological evaluation.

Aesthetic Value (2.99) and **Educational Value (2.81)** are in the middle category. This value shows that Danau Rayo has good landscape attraction and considerable educational potential, but still needs to strengthen interpretation, educational media, and visitor experience management so that the benefits of education and tourism can develop optimally. In contrast, **the Conservation Value (2.10)** is the dimension with the lowest score. This value shows that aspects of area protection, conservation policies, and geoconservation implementation are still relatively weak compared to the scientific and cultural value that Danau Rayo has. The low scores on *the Protection Policies* (Q15 = 1.58) and *Conservation Challenges* (Q16 = 2.00) indicators indicate that conservation is a major challenge in area management.

Overall, the Geoheritage Significance Index (GSI) of 2.99 suggests a generally positive stakeholder perception of the geoheritage significance of Danau Rayo, with the strongest contributions derived from

Cultural Value and Scientific Value. However, the low conservation value shows that strengthening geoconservation, area protection, and governance are urgent needs to ensure the sustainability of Danau Rayo's geoheritage in the future.

4.3 Supporting Geoethics Assessment

As a complement to the geoheritage assessment, this study evaluates the management conditions and readiness for conserving Danau Rayo through **a supporting geoethics assessment**. The assessment is carried out based on four main dimensions, namely **Responsibility (R)**, **Public Engagement (PE)**, **Sustainability (S)**, and **Knowledge Integration (KI)**. The results of the evaluation were used to understand the extent to which the geoheritage value of Danau Rayo has been supported by governance, stakeholder participation, and sustainable management efforts. The geoethics dimension scores are presented in Table 10.

Table 10
Geoethics Dimension Scores

Dimension	Mean Score
Responsibility (R)	2.37
Public Engagement (PE)	2.65
Sustainability (S)	3.16
Knowledge Integration (KI)	3.13
Geoethics Index (GI)	2.83

The results of the assessment showed that **Sustainability (3.16)** obtained the highest score among all geoethics dimensions. These findings indicate that stakeholders in general have a fairly positive view of the potential for the sustainability of Danau Rayo's development, especially related to the prospects for geotourism development, education, and long-term benefits of the area.

The **Knowledge Integration dimension (3.13)** also shows a relatively high value. These results reflect an opportunity to integrate scientific knowledge about geoheritage with local knowledge, culture, and community experiences. The existence of the Bujang Kurap legend and the community's connection with Danau Rayo are important assets in supporting the interpretation of geoheritage and geoeducation.

Public Engagement (2.65) is at the intermediate level. This value shows that community involvement in tourism activities and area utilization has grown, but participation in the planning, decision-making, and area management processes can still be improved.

In contrast, **Responsibility (2.37)** obtained the lowest score. These findings show that aspects of management responsibility, governance transparency, area protection, and stakeholder involvement in decision-making are still challenges that need attention. The low scores on *the indicators Governance*

Transparency (Q31 = 2.08) and *Participation in Decision-Making* (Q30 = 2.12) strengthen this indication. Overall, the **Geoethics Index (GI) of 2.83** shows that the readiness of Danau Rayo management is at a medium level. Although there is good potential in the aspects of sustainability and knowledge integration, strengthening governance, accountability, and stakeholder participation is still needed to support sustainable geoheritage management.

Compared to the Geoheritage Significance Index (GSI = 2.99), the **Geoethics Index value (GI = 2.83)** shows that stakeholder recognition of the value of Danau Rayo geoheritage is relatively higher than the readiness of its management and conservation. This difference indicates a gap between the geoheritage potential of the region and the institutional capacity needed to ensure the sustainability of its management.

4.4 Stakeholder Comparison

To understand whether there is a difference in perception between the main stakeholder groups, an analysis was carried out using **the Mann-Whitney U Test**. This nonparametric test was chosen because the data came from the Likert scale and involved two independent groups, namely **Government Stakeholders** and **Local Community Stakeholders**. Analysis was carried out on all geoheritage dimensions, geoethics dimensions, and aggregate indices generated from the two assessment frameworks. The results of the Mann-Whitney U Test are presented in Table 11.

Table 11
Mann-Whitney U Test Results

Dimension	Government	Local Community	U	p-value
Scientific Value	3.30	3.05	79.5	0.328
Educational Value	2.82	2.75	66.5	0.854
Aesthetic Value	2.98	3.10	53.0	0.557
Cultural Value	3.49	3.95	38.5	0.144
Conservation Value	2.07	2.00	73.5	0.531
Public Engagement	2.62	2.77	49.0	0.412
Sustainability	3.10	3.36	36.5	0.112
Knowledge Integration	3.07	2.32	102.5	0.017
GSI	2.93	2.97	50.5	0.467
GI	2.75	2.68	61.0	0.928

The results of the analysis showed that **most dimensions did not differ significantly** between government groups and local communities ($p > 0.05$). These findings indicate that the two stakeholder groups have relatively similar perceptions regarding the significance of Danau Rayo's geoheritage,

including in scientific, educational, aesthetic, cultural, conservation, and sustainable aspects of regional management. In the geoheritage dimension, no significant differences were found for **Scientific Value**, **Educational Value**, **Aesthetic Value**, or **Conservation Value**. Similarly, the **Geoheritage Significance Index (GSI)** does not show a meaningful difference between the two stakeholder groups.

However, one dimension shows a significant difference: **Knowledge Integration** ($p = 0.017$). These results show that the government and local communities have different views regarding the integration of scientific knowledge, local knowledge, stakeholder collaboration, and institutional support in the management of Danau Rayo. In addition, although not statistically significant, local community groups tend to score higher on **Cultural Value** and **Sustainability**, while government groups score higher on **Knowledge Integration**. This pattern shows different emphases: communities highlight more cultural values and long-term benefits of the region, while governments place more emphasis on institutional aspects and management integration.

Overall, no statistically significant differences were detected for most dimensions between stakeholder groups, although Knowledge Integration showed a significant difference. However, differences in the Knowledge Integration dimension point to the need for increased communication, collaboration, and integration between scientific and local knowledge in future management and development processes for the region. These findings should be interpreted cautiously given the relatively limited sample size and the exploratory nature of the stakeholder-based assessment.

4.5 Visual Comparison

To facilitate interpretation of the geoheritage assessment results, the scores of each dimension are visualized using a radar chart. To facilitate interpretation of the geoheritage assessment results, the scores of each geoheritage dimension are visualized in Fig. 2. The radar chart provides a graphical representation of the relative strengths and weaknesses of Danau Rayo across the five geoheritage dimensions.

The radar chart shows a relatively unbalanced pattern between the dimensions of geoheritage. **Cultural Value (3.65)** forms the highest peak, followed by **Scientific Value (3.38)**. These findings suggest that the geoheritage significance of Danau Rayo is primarily supported by the strong linkages between the landscape and local culture as well as by its geological uniqueness as a candidate for impact structures. The **dimensions of Aesthetic Value (2.99)** and **Educational Value (2.81)** are at the medium level, showing that Danau Rayo has a fairly good visual appeal and geoeducational potential, but still requires strengthening interpretation facilities, educational media, and visitor experience management.

In contrast, the **Conservation Value (2.10)** forms the lowest part of the radar chart. This low score indicates that efforts to protect the region, conservation policies, and geoconservation have not developed in proportion to the region's high scientific and cultural value. Overall, this visualization shows that the main challenge of Danau Rayo lies not in the lack of geoheritage value, but in the lack of robust conservation and protection mechanisms needed to ensure the long-term sustainability of the region.

To visualize the management readiness and geoethics conditions of Danau Rayo, the score of each geoethics dimension is displayed as a radar chart. This visualization shows the balance and inequality between aspects of governance, participation, sustainability, and knowledge integration. The figure highlights the balance and disparities among responsibility, public engagement, sustainability, and knowledge integration.

The radar chart shows that the **Sustainability (3.16)** and **Knowledge Integration (3.13)** dimensions have the highest scores. These results indicate that stakeholders see a good potential for sustainable development of the area as well as opportunities to integrate scientific knowledge and local knowledge in the management of Danau Rayo. The **Public Engagement dimension (2.65)** is at a medium level, indicating that community involvement in activities related to Danau Rayo has grown, but is still not fully integrated in the planning and decision-making process. In contrast, **Responsibility (2.37)** is the dimension with the lowest score. These findings show that aspects of governance, transparency, and institutional responsibility are still the main challenges in regional management.

Overall, the radar chart shows that Danau Rayo has a good enough foundation for sustainable development through knowledge integration and stakeholder support. However, the successful implementation of geoconservation and long-term geoheritage management still requires strengthening responsibility, governance, and institutional accountability.

5. Discussion

5.1 Danau Rayo as a High-Value Geoheritage in a Humid Tropical Environment

The results showed that Danau Rayo has a **Geoheritage Significance Index (GSI) of 2.99**, with the highest score in the dimensions of **Cultural Value (3.65)** and **Scientific Value (3.38)**, followed by **Aesthetic Value (2.99)** and **Educational Value (2.81)**. In contrast, **Conservation Value (2.10)** obtained the lowest score. This pattern shows that the geoheritage significance of Danau Rayo is primarily supported by a strong combination of scientific, cultural, and aesthetic values, while the conservation and protection aspects of the area are still relatively weak. The observed pattern demonstrates that geoheritage significance is not solely determined by geological attributes, but also reflects the interaction between scientific, cultural, aesthetic, and conservation dimensions. This multidimensional character is consistent with contemporary geoheritage assessment frameworks that emphasize integrating geoscientific and socio-cultural values in evaluating geosites (Brilha, 2016); (Sanchez & Brilha, 2017) (Pestacore, et al., 2023).

The relatively high **Scientific Value** shows that stakeholders recognize the importance of Danau Rayo as an object of geological research. This assessment is in line with various geomorphological, geophysical, petrographic, mineralogical, and geochemical findings that show characteristics consistent with interpreting Danau Rayo as a **candidate impact structure**. Although the available evidence is not yet

sufficient to classify the region as a *confirmed impact crater*, the presence of an almost circular basin, indications of rim-like morphology, and various geological anomalies provide significant scientific value. Impact-related landforms are widely recognized as geosites of exceptional scientific significance because they preserve evidence of rare and high-energy geological processes. Studies from recognized impact geoheritage sites such as Lonar Crater, India, have demonstrated their importance for Earth science research, geoeducation, and geotourism development (Chandran, et al., 2022). Therefore, despite its current status as a candidate impact structure, Danau Rayo possesses characteristics that justify consideration as an emerging geoheritage site with potential relevance to future impact-related research.

From a geoheritage perspective, the impact structure candidate has special value because it represents a relatively rare geological phenomenon and has great potential for multidisciplinary research. The presence of Danau Rayo in a humid tropical environment provides an opportunity to investigate the preservation of circular basin morphology under conditions of intensive weathering and erosion, regardless of whether the impact hypothesis is ultimately confirmed (Rochette, et al., 2019) (Quesada-Román, et al., 2025). Thus, the scientific value of Danau Rayo comes not only from the possible origins of its impact, but also from its potential as a natural laboratory for research on tropical geomorphology, subsurface geophysics, landscape evolution, and geoheritage preservation (Spray, et al., 2010).

The **Cultural Value** dimension obtained the highest score in all geoheritage assessments. These findings show that the relationship between the community and Danau Rayo is one of the main factors shaping the area's significance. The high scores on **the indicators of Emotional Attachment (4.46), Memorable Experience (4.12)**, and cultural relationship with geoheritage indicate that the community views Danau Rayo not only as a landscape, but also as part of local identity. The existence of the legend of Bujang Kurap, the Batu Meja site, and various cultural narratives that are still developing in the community strengthen the region's cultural value. In the context of geoheritage, the linkage between landscapes and culture is an important asset because it can increase public appreciation of geoheritage while strengthening support for conservation efforts. The high cultural value also shows that Danau Rayo has the potential to be developed as a geoheritage model that integrates geology and cultural heritage. This integration is very important in the development of geoeducation, geosite interpretation, and community-based geotourism (Zafeiropoulos, et al., 2021).

The **Aesthetic Value** dimension received a score of 2.99, while the **Landscape Beauty indicator (4.42)** was one of the highest scores among all instruments. These findings show that the landscape of Danau Rayo has a strong visual appeal and is one of the main reasons for the increase in stakeholder appreciation for the area. The combination of permanent water bodies, distinctive basin morphology, natural vegetation, and a relatively preserved environmental atmosphere creates an attractive landscape for both tourism and educational activities. In many geoheritage studies, aesthetic value is often the gateway for the public to recognize and understand the scientific value of a geosite. The same pattern is also seen in Danau Rayo, where the beauty of the landscape plays an important role in building awareness of the area's importance.

The combination of scientific, cultural, and aesthetic values suggests that Danau Rayo has strong characteristics as a **geosite with a hypothesized impact origin**. Unlike many geosites that have only geological value, Danau Rayo shows a close connection between geology, culture, and local people. This condition produces a form of geoheritage that is multidimensional and has wide relevance for research, education, conservation, and regional development.

However, the results of the study also showed that **the Conservation Value** was still at a low level (2.10). These findings indicate that the recognition of the geoheritage value of Danau Rayo is growing faster than its protection and management capacity. Therefore, the region's main challenge lies not in the lack of geoheritage significance, but in the need to strengthen geoconservation, protection policies, and regional governance so that the recognized scientific, cultural, and aesthetic values can be maintained in the long term.

Overall, the results show that Danau Rayo meets many of the characteristics that are common to high-value geosites, namely geological uniqueness, strong cultural linkages, landscape attractiveness, and significant educational potential. With the support of advanced research to verify the impact structure hypothesis as well as the strengthening of geoconservation, Danau Rayo has the potential to develop as one of the important geoheritages in Sumatra and support the development of sustainable geoparks in the future.

5.2 Comparison with Other Geoparks

Danau Rayo occupies a distinctive position within the broader Southeast Asian geoheritage context. Unlike many established geoparks such as Batur, Kelimutu, Ciletuh, Langkawi, and Satun, whose geological significance is primarily associated with volcanic, tectonic, or karst systems, Danau Rayo derives much of its scientific interest from a hypothesized impact origin and its well-preserved circular basin morphology. This characteristic provides a different geoheritage theme and highlights the diversity of geological landscapes that may contribute to future geopark development.

Similar to many successful geoparks, the geoheritage significance of Danau Rayo is not based solely on geological characteristics. The high Cultural Value score (3.65) demonstrates the importance of local narratives, community attachment, and cultural identity in shaping stakeholder appreciation of the site. The Bujang Kurap legend, Batu Meja site, and other local cultural narratives strongly support the integration of geoheritage, geoeducation, and community-based geotourism. This pattern is consistent with contemporary geoheritage approaches that recognize the close relationship between geological and cultural values in sustainable geoconservation.

Despite these strengths, Danau Rayo remains at an early stage of geoheritage recognition and development. The relatively low Conservation Value score (2.10) and intermediate Geoethics Index (2.83) indicate that conservation mechanisms, governance structures, and management capacity have not yet developed at the same pace as stakeholder recognition of its geoheritage significance. Therefore, future efforts should prioritize geoconservation planning, stakeholder collaboration,

institutional strengthening, and site protection to support the sustainable development of Danau Rayo as a geosite with a hypothesized impact origin.

5.3 Conservation and Governance Challenges

Although the results show that Danau Rayo has a relatively high level of geoheritage significance (**GSI = 2.99**), various indicators show that the area's conservation and governance capacity is still disproportionately underdeveloped. This finding is reflected in the low Conservation Value score (2.10) in the geoheritage assessment and the Responsibility score (**2.37**) in the geoethics assessment.

One of the most important findings in the study was the low **score of Protection Policies (Q15 = 1.58 ± 0.76)**, which was the lowest score among all the indicators evaluated. These findings show that stakeholders consider formal protection of Danau Rayo to be very limited.

This condition indicates that adequate protection policies have not fully reflected the region's scientific, cultural, and aesthetic values. In fact, geosites that have high scientific significance, especially those related to rare geological phenomena such as impact structure candidates, require protection to maintain the integrity and sustainability of their geoheritage value (Prosser, et al., 2011) (Gordon, et al., 2018).

The **Conservation Value dimension (2.10)** is the lowest score in the geoheritage assessment. These values indicate that various aspects related to area conservation, including geosite protection, conservation management, and mitigation of threats to the area, remain at low levels.

These results show an imbalance between stakeholder recognition of the importance of Danau Rayo as a geoheritage and the readiness of the conservation system that supports it. Conceptually, these conditions show that the process of identifying and appreciating geoheritage develops faster than the implementation of geoconservation needed to ensure the sustainability of the region.

If this condition is not strengthened through more systematic geoconservation policies and programs, then various geoheritage values that have been identified have the potential to be degraded due to environmental pressures and human activities.

Another challenge that arises in this study is governance. The **indicators of Governance Transparency (Q31 = 2.08 ± 1.09)** and **Participation in Decision-Making (Q30 = 2.12 ± 1.18)** show that stakeholders consider management transparency and involvement in the decision-making process to be relatively low. These findings are reflected in the low Responsibility dimension score (**2.37**) in the geoethics assessment. In general, these results show that the regional governance mechanism has not fully integrated the interests of various stakeholders within the framework of coordinated geoheritage management. In many geoheritage areas and geoparks that have developed, the success of conservation is determined not only by the scientific value of the geosite, but also by the existence of institutions that can coordinate the protection, education, research, and sustainable use of tourism

(Gordon, et al., 2021). Therefore, strengthening institutional capacity is one of the main needs for Danau Rayo.

The comparison between the dimensions of geoheritage and geoethics shows a fairly clear imbalance. On the one hand, Danau Rayo obtained high scores on **Cultural Value (3.65)** and **Scientific Value (3.38)**, which indicates that the area has a strong geoheritage foundation. On the other hand, low scores on **Conservation Value (2.10)**, **Responsibility (2.37)**, and several governance indicators indicate that the management system is still in the early stages of development. These findings reinforce the study's main argument that the main challenge of Danau Rayo lies not in the lack of geoheritage significance, but in the limited capacity to protect and manage the area. In other words, the geoheritage value of Danau Rayo has gained relatively high recognition from stakeholders, but the conservation and governance framework necessary to support its sustainability still needs significant strengthening.

Based on these results, there are several priorities to consider in the future management of Danau Rayo:

1. Preparation of a more formal geosite protection policy.
2. Development of a structured and sustainable geoconservation program.
3. Increased transparency and coordination between stakeholders.
4. Strengthening community participation in decision-making.
5. Integration of research, geoeducation, geotourism, and conservation activities in one regional management framework.

With these steps, Danau Rayo has the opportunity to bridge the gap between the high value of geoheritage and the limited conservation and governance capacity, so that it can develop as **an geosite with a hypothesized impact origin** that is managed sustainably.

5.4 Geoethical Readiness for Future Geoconservation

In this study, geoethics is positioned as **a management readiness assessment**, which is a supporting instrument to evaluate the extent to which the geoheritage value of Danau Rayo is supported by management capacity, stakeholder participation, and regional governance. Thus, geoethics is not used to determine the significance of geoheritage directly, but to assess the region's readiness to support geoconservation and sustainable development.

The results of the study showed that **the Geoethics Index (GI)** reached **2.83**, slightly lower than the **Geoheritage Significance Index (GSI)** of **2.99**. This difference indicates that the recognition of the geoheritage value of Danau Rayo is growing faster than its management capacity. In other words, the main challenge of the region lies not in the lack of geoheritage value, but in the institutional and governance readiness needed to maintain the continuity of these values.

The **Responsibility dimension** obtained the lowest score (**R = 2.37**) among all geoethics dimensions. These findings show that aspects of management responsibility, transparency, and stakeholder involvement in decision-making still need greater attention. This low score is also reflected in the

indicators of Participation in Decision-Making (Q30 = 2.12) and Governance Transparency (Q31 = 2.08), which show that stakeholders have not fully felt the existence of a participatory and transparent management mechanism. In the context of geoconservation, institutional responsibility is an important factor because the success of geoheritage protection is determined not only by the scientific value of a geosite, but also by the ability of institutions to coordinate conservation, research, education, and sustainable tourism use.

The **Public Engagement** dimension obtained a medium score (**PE = 2.65**), indicating that community engagement has begun to grow, but is still not optimal. Indicators related to community participation, involvement in tourism activities, and interaction between tourists and the community show that there is a good enough social foundation to support the development of community-based geoheritage. However, the benefit distribution (*Benefit Distribution*, Q27 = 2.04) still received a low score, indicating that the economic and social benefits of regional development have not been felt evenly. These findings suggest that strengthening community participation needs to be followed by mechanisms that can ensure a more inclusive and equitable distribution of benefits.

The **Knowledge Integration dimension** obtained a relatively high score (**KI = 3.13**), making it one of the most promising aspects of Danau Rayo's management readiness. This high value indicates an opportunity to integrate scientific knowledge about the geology of Danau Rayo with local knowledge, culture, and community experiences. The existence of the Bujang Kurap legend, cultural sites, and the community's attachment to the landscape provide a strong foundation for developing geoeducational programs and contextual interpretation of geoheritage. The results of the Mann-Whitney U Test also showed that **Knowledge Integration was the only significant difference between the government and local communities (p = 0.017)**. These findings indicate that there are different perspectives on knowledge integration and institutional collaboration, so more intensive dialogue and communication between stakeholders are needed.

Overall, the results of the geoethics assessment show that Danau Rayo already has several important prerequisites to support future geoconservation, especially in terms of sustainability and knowledge integration. However, the low score on the responsibility and governance dimensions shows that the readiness is still not fully mature. Therefore, the development of Danau Rayo geoconservation not only requires the protection of its geological characteristics, but also requires strengthening governance, increasing stakeholder participation, and better integration between scientific and local knowledge. With this approach, Danau Rayo has the opportunity to develop as **a geosite with hypothesized impact origin** to a geoheritage area that is managed sustainably and can support the goals of conservation, education, and regional development in the long term.

5.5 Limitations of the Study

A key limitation of this study is that the impact origin of Danau Rayo remains a working geological hypothesis rather than a confirmed interpretation. Consequently, the geoheritage significance assessed

in this study reflects the site's current scientific interest, geomorphological distinctiveness, cultural importance, and stakeholder perceptions, rather than verification of an impact crater.

A second limitation relates to the stakeholder-based assessment approach. The results are derived from perceptions of 27 stakeholders and therefore should not be interpreted as a direct measure of intrinsic geological significance. Instead, they provide insight into how geoheritage values are recognized and perceived by relevant stakeholder groups.

In addition, the relatively limited sample size and unequal representation among stakeholder categories may influence the statistical robustness of some comparisons. Future studies should incorporate a larger and more balanced stakeholder sample together with expert-based geoheritage assessment to strengthen the evaluation framework.

6. Implications

The results show that Danau Rayo has a strong combination of scientific, cultural, and aesthetic values, but still faces challenges in conservation and governance aspects. The findings have important implications for the development of science, geoconservation, geotourism, and area management policies.

This research contributes to the development of geoheritage studies on geosites that are still in the scientific verification stage. Most geoheritage research focuses on geosites that have been widely identified and recognized, while this study shows that the geoheritage approach can also be applied to **candidate impact structures** that still require further scientific proof. In addition, Danau Rayo provides an opportunity to expand understanding of landscape preservation allegedly related to collisions in humid tropical environments. The high **Scientific Value (3.38)** indicates that this area has the potential as a natural laboratory for geomorphology, geophysics, petrography, mineralogy, and geochemical research. This research also shows that a multidimensional approach that integrates geoheritage, culture, and stakeholder perspectives can be used to evaluate the significance of geosites more comprehensively.

The most important finding of this study is the imbalance between the high value of geoheritage and the area's low conservation capacity. Although **Cultural Value (3.65)** and **Scientific Value (3.38)** show a high level of significance, **Conservation Value (2.10)** is the dimension with the lowest score. This condition indicates the need for a more systematic geoconservation strategy, consistent with the broader objective of conserving geological and geomorphological resources that support science, education, and society (Prosser, et al., 2011) (Gordon, 2019) (Gordon, et al., 2021). The results of the research can be used as an initial basis for preparing **geoconservation planning** for Danau Rayo as a developing geoheritage area.

The high scores of **Landscape Beauty (4.42)**, **Emotional Attachment (4.46)**, and **Educational Potential (3.77)** show that Danau Rayo has great potential to be developed as a community-based geoeducation and geotourism destination, where geological, cultural, and aesthetic values collectively contribute to

visitor experience and interpretation (Kubalikova, 2013) (Zafeiropoulos, et al., 2021) (Sapah, et al., 2026). This approach has the potential to increase public understanding of the value of geoheritage while strengthening the economic benefits for local communities.

From a policy perspective, this study shows the need to strengthen regional regulations and governance. The low scores **for Protection Policies (1.58), Governance Transparency (2.08), and Responsibility (2.37) indicate that formal protection and institutional capacity remain** major challenges. Future policy initiatives should focus on designating Danau Rayo as a regional priority geosite, implementing geoheritage protection regulations, promoting collaborative multi-stakeholder governance, enhancing community participation in decision-making processes, and incorporating geoheritage into the strategic development planning of the North Musi Rawas Geopark. The development of interpretive and educational facilities should also be considered to improve public understanding, geoeducation, and visitor engagement (Sapah, et al., 2026).

Thus, the results of this study show that the success of the development of Danau Rayo does not depend only on its scientific and cultural value, but also on the ability of the government and stakeholders to build a conservation and governance system that can ensure the long-term sustainability of the region.

7. Conclusions

This study evaluates the significance of the Danau Rayo geoheritage as a as a geosite with a hypothesized impact origin. that is preserved in a humid tropical environment through the integration of geological evidence, geoheritage value, and stakeholder perspectives. The results of the study show that Danau Rayo has a **Geoheritage Significance Index (GSI) of 2.99**, which indicates a relatively high level of geoheritage significance. This value is mainly supported by the dimensions of **Cultural Value (3.65)** and **Scientific Value (3.38)**, which reflect the strong link between the geological characteristics of the area, local cultural heritage, and public perception of the importance of Danau Rayo.

From a scientific perspective, Danau Rayo exhibits geological and geomorphological characteristics that have led previous studies to propose a possible impact origin, including the morphology of the nearly circular basin, the potential for multidisciplinary research, and the relatively good level of preservation of the landscape in a humid tropical environment. These findings show that Danau Rayo has significant value as an object of geoheritage research and has the potential to contribute to the study of tropical impact structures, which are still relatively limited.

In addition to scientific value, the results of the study underscore the importance of cultural aspects in shaping the significance of regional geoheritage. The high scores on *the Emotional Attachment, Landscape Beauty, and Memorable Experience indicators* indicate that the geoheritage of Danau Rayo is not only determined by its geological characteristics, but also by the strong relationship between the landscape, culture, and identity of the local community.

Nevertheless, the study also identified important challenges that need attention. The **Conservation Value dimension (2.10)** is the lowest score in the geoheritage assessment. At the same time, the **Protection Policies (1.58)** and **Governance Transparency (2.08)** indicators show that area protection, geoconservation, and governance are still relatively weak compared to the geoheritage values recognized by stakeholders.

The **Geoethics Index (GI) result of 2.83** further strengthens these findings. Although Danau Rayo shows good potential in terms of sustainability and knowledge integration, management capacity, institutional responsibility, and stakeholder participation still need to be strengthened. Thus, the main challenge of Danau Rayo lies not in the lack of geoheritage significance, but in the limited conservation and governance capacity needed to ensure the sustainability of the area.

Overall, this study shows that Danau Rayo has strong potential to be developed as an emerging geoheritage site in Sumatra due to its distinctive geomorphology, cultural significance, educational potential, and ongoing scientific interest concerning its origin. Strengthening geosite protection policies, developing structured geoconservation programs, increasing stakeholder participation, and integrating geoheritage into regional development planning are important steps to support the region's long-term management. With support for advanced research to verify the collision structure hypothesis, as well as institutional and conservation strengthening, Danau Rayo has the potential to develop into an important geoheritage that supports scientific research, geoeducation, geotourism, and sustainable geopark development in the future.

Declarations

Author Contribution

Budhi Setiawan: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis, Visualization, Writing – Original Draft Preparation, Writing – Review and Editing, Project Administration. Sajinkumar K.S.: Validation, Supervision, Writing – Review and Editing. Ayu Krisna Yuliawati: Methodology, Formal Analysis, Data Interpretation, Writing – Review and Editing. Muhamad Sapari Dwi Hadian: Investigation, Validation, Geological Interpretation. Harnani: Investigation, Resources, Validation

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whose contributions were essential to completing data collection and analysis and to preparing the research outputs.

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Figures

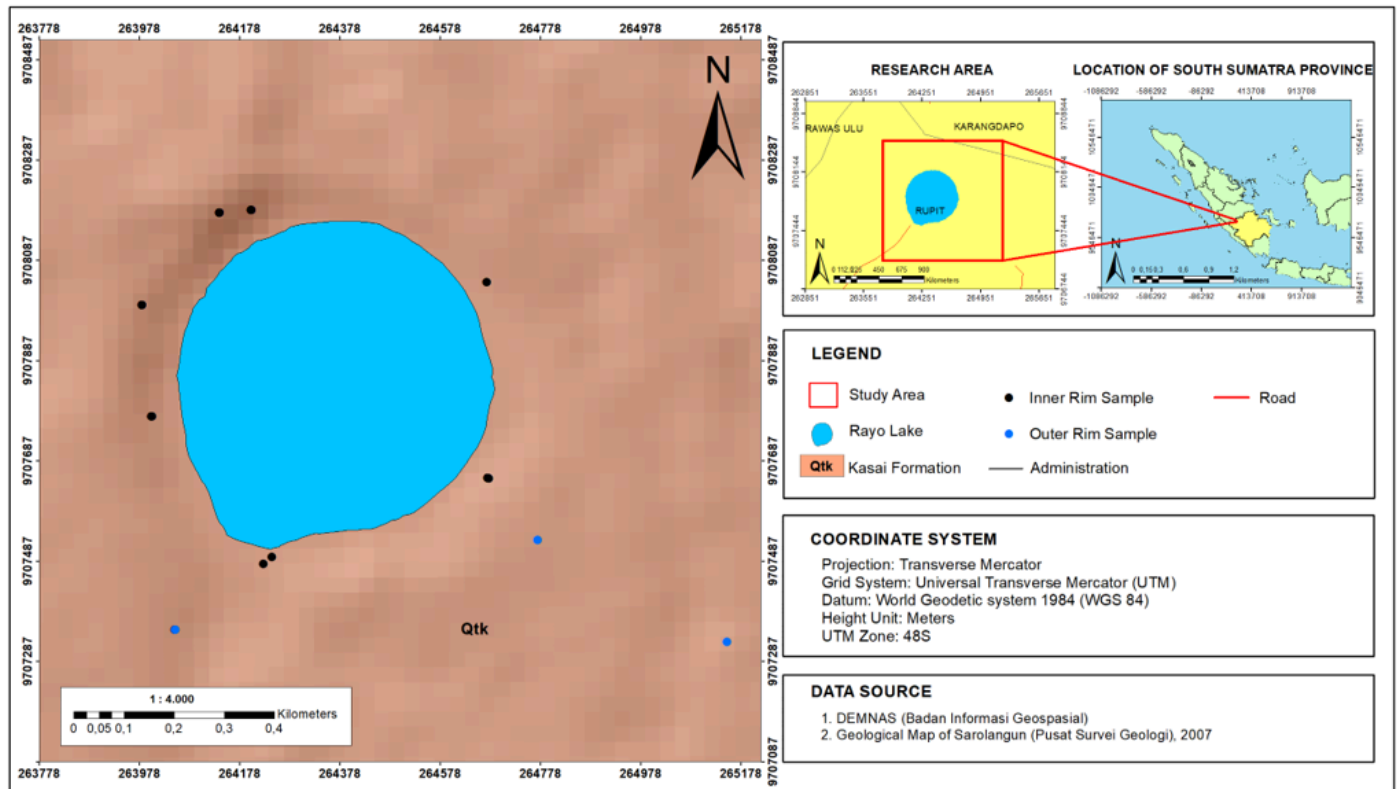


Figure 1

Location of Danau Rayo in Musi Rawas Utara Regency, South Sumatra, Indonesia

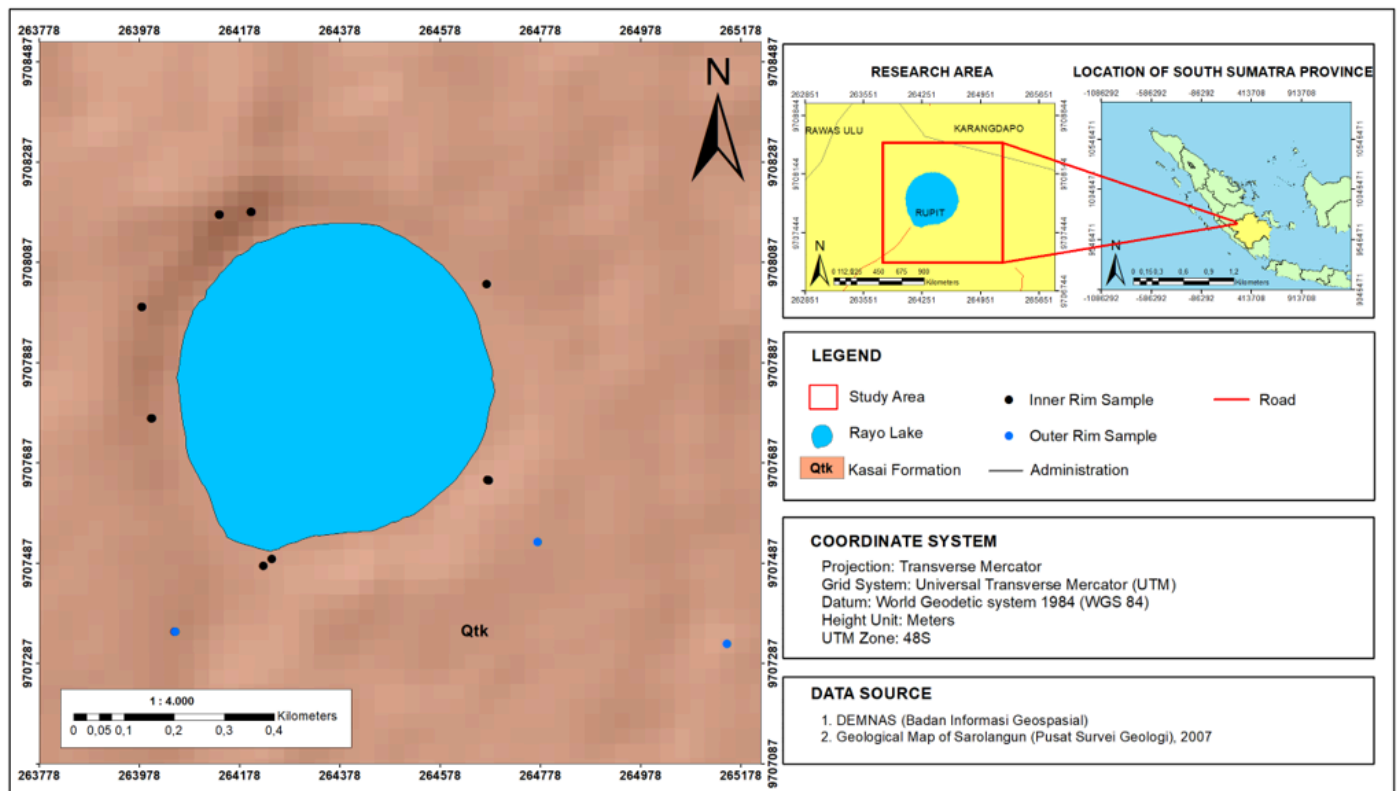


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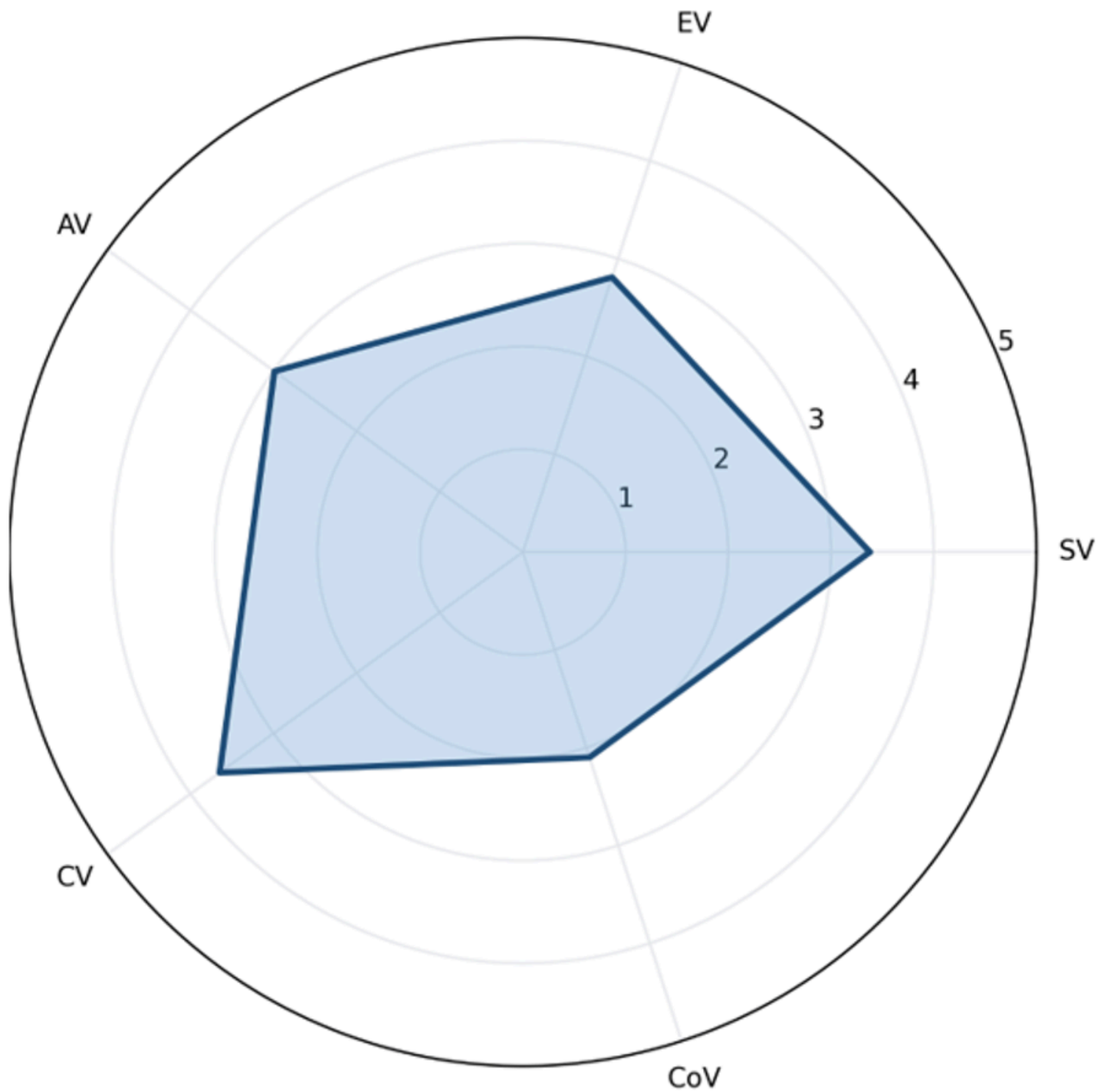


Figure 2

Radar chart showing the distribution of geoheritage dimension scores for Danau Rayo. Cultural Value and Scientific Value recorded the highest scores. In contrast, Conservation Value showed the lowest score, indicating that the geoheritage significance of Danau Rayo is strongly supported by cultural and scientific attributes but constrained by relatively weak conservation and protection measures.

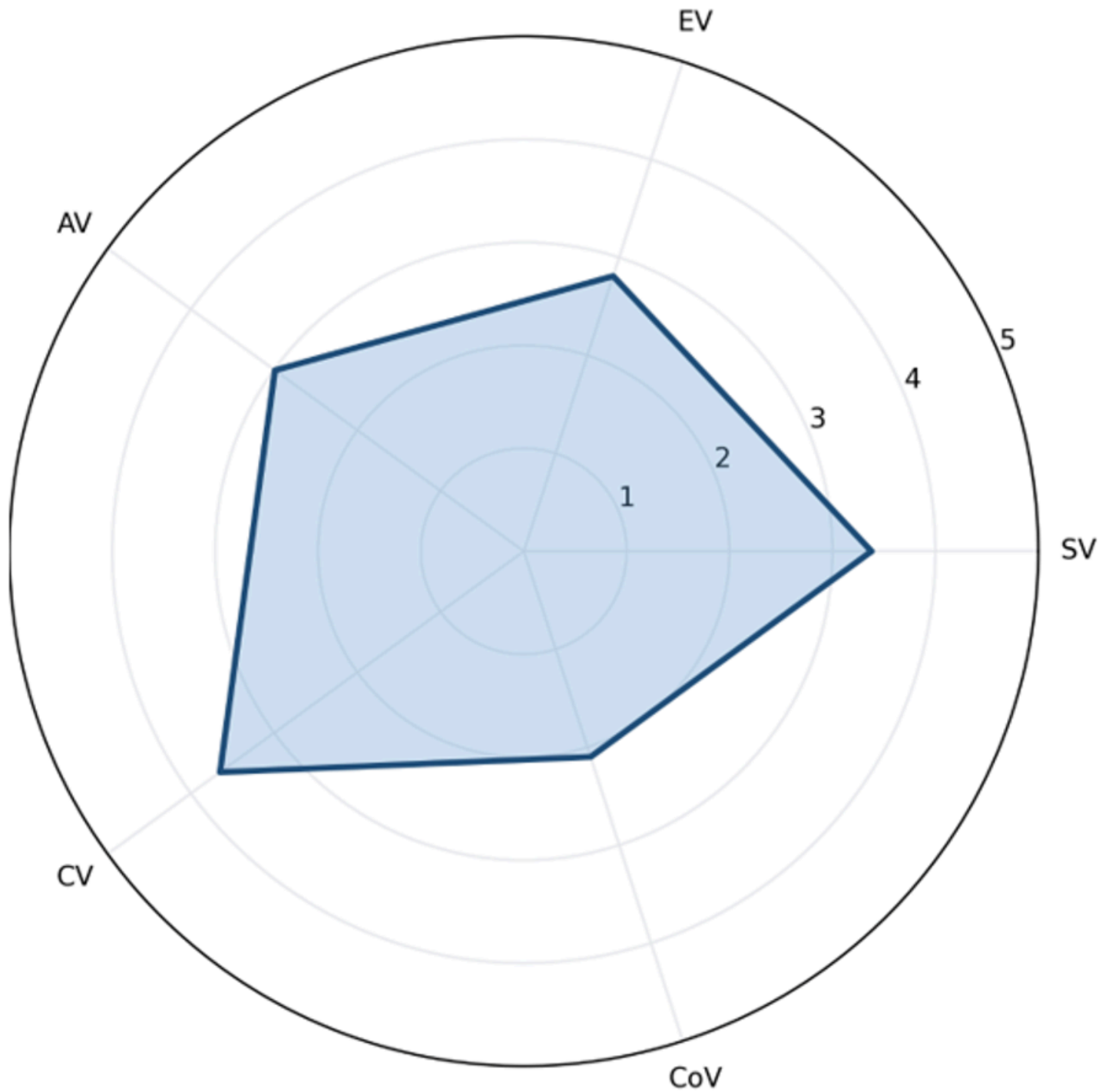


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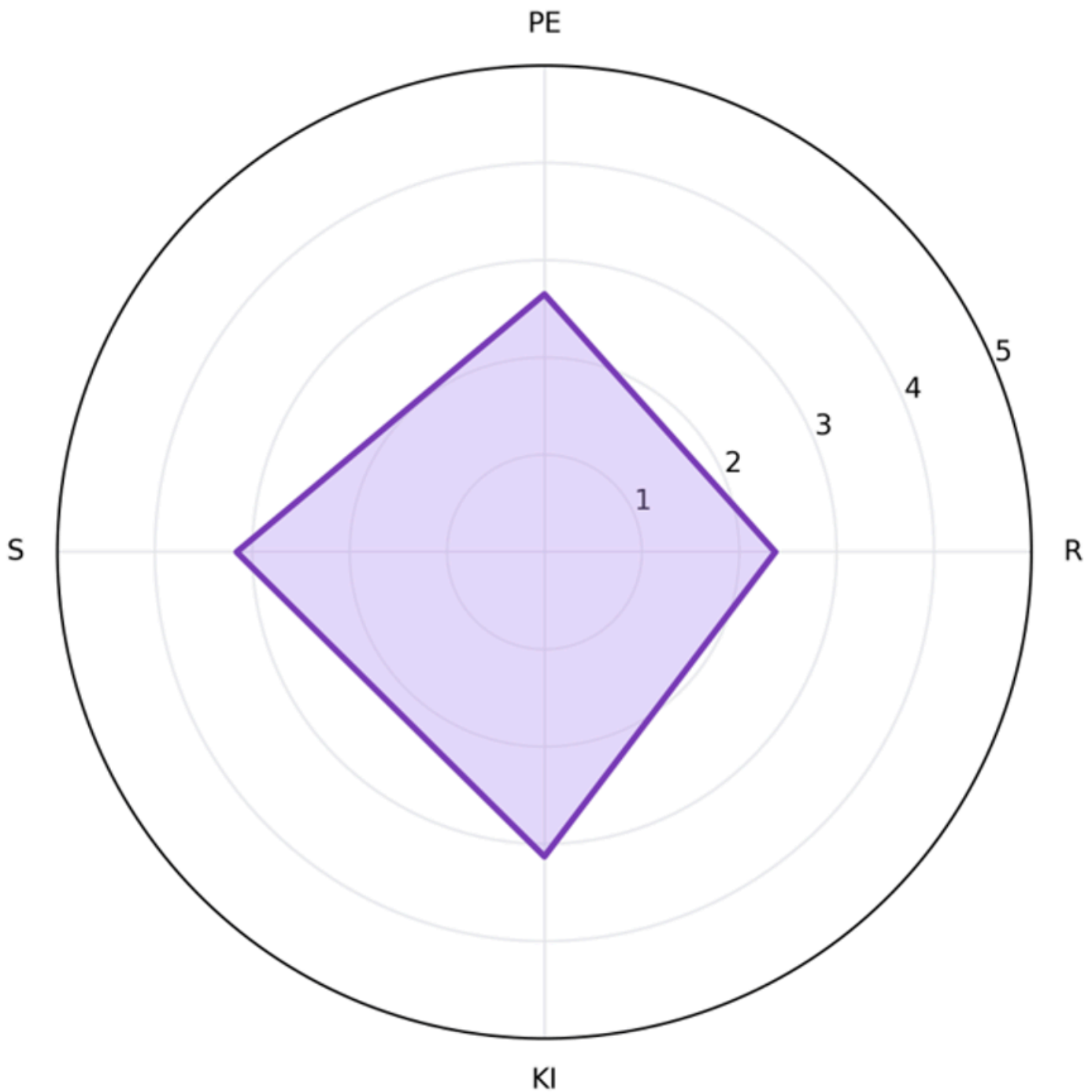


Figure 3

Radar chart of geoethics dimension scores for Danau Rayo. Sustainability (S) and Knowledge Integration (KI) recorded the highest scores, indicating favorable conditions for long-term development and integration of scientific and local knowledge. In contrast, Responsibility (R) showed the lowest score, highlighting weaknesses in governance, accountability, and management responsibility.

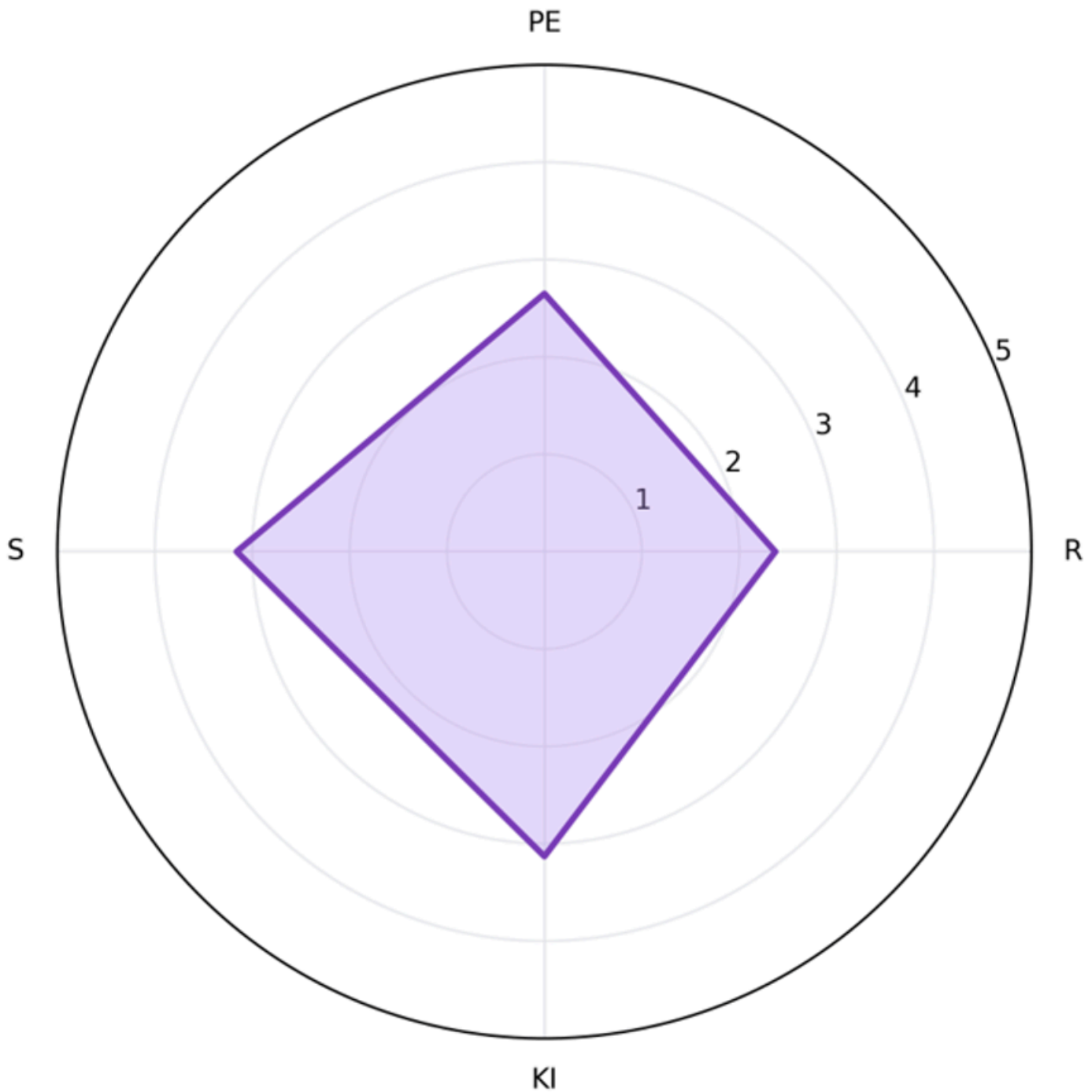


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