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Sustainability Evaluation of Lake Batur Management in Bali Province: A Multidimensional Scaling Approach

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Abstract: Lake Batur has been designated as one of Indonesia's 15 priority lakes to be restored due to significant anthropogenic pressures from aquaculture, agriculture, tourism, and domestic waste. The purpose of this study is to evaluate the sustainability status of Lake Batur management through rapid appraisal techniques combined with a multidimensional scaling (MDS) approach using 18 attributes representing three dimensions, namely ecological, social, and economic dimensions. Data was collected from structured interviews with village leaders, field surveys, and secondary data from PODES 2024 and related agencies. Sustainability status varies significantly between villages and dimensions. In the ecological dimension, three villages showed a less sustainable status (32.75-45.53), while five villages achieved a fairly sustainable level (56.11-62.55). In the social dimension, four villages had a fairly sustainable status (51.04-64.87) and four villages had a less sustainable status (30.86-49.93). The results of the analysis on the economic dimension showed that five villages had a fairly sustainable status (51.39-65.68), two villages had a less sustainable status (33.33-39.90), and one village was not sustainable (22.60). Based on the leverage analysis, the flood frequency attribute is the most sensitive attribute in the ecological dimension, while in the social and economic dimensions, respectively, it lies in population density and the number of MSMEs.

Keywords: Lake sustainability; Multidimensional scalling; Rapfish; Sustainable Lake management

Introduction

Lake ecosystem degradation has become an urgent global environmental challenge, with more than half of the world's lakes experiencing significant quality decline due to anthropogenic pressures (Carpenter et al., 2011). Indonesia, with more than 15,000 lakes, faces similar challenges, with most lakes experiencing degradation with high sedimentation rates and pollution exceeding environmental quality standards (Dewan Sumberdaya Air Nasional, 2020). These conditions have prompted the government to establish a priority lake rescue program through Presidential Regulation No. 60 of 2021.

Based on Presidential Regulation No. 60 of 2021, 15 priority lakes have been designated, namely Lake Toba, Lake Singkarak, Lake Maninjau, Lake Kerinci, Lake Rawa Danau, Lake Rawa Pening, Lake Batur, Lake Tondano, Mahakam Cascade Lake, Sentarum Lake, Limboto Lake, Poso Lake, Tempe Lake, Matano Lake, and Sentani Lake. This designation is based on several assessment indicators: (a) experiencing pressure and degradation such as damage to water catchment areas, damage to lake margins, increased sedimentation, and decreased water quality; (b) having strategic economic, ecological, socio-cultural, and scientific value, (c) being listed in one of the development planning documents, master plans, and/or other technical documents in the water and/or lake sector.

Lakes as freshwater ecosystems play a crucial role despite covering only 3.7% of the land surface. Lakes provide ecosystem services including flood control, biodiversity conservation, climate change mitigation, and water purification (Ho & Goethals, 2019). The link between lakes and the SDGs is evident in SDG 6 on sustainable water management and SDG 15 on life on land through the conservation of freshwater biodiversity.

The concept of sustainable development centers on inter- and intra-generational equity based on three

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interrelated pillars: environmental, economic, and social (Mensah, 2019). The economic dimension includes fair income distribution and resource efficiency, the social dimension relates to equity and community participation, while the environmental dimension emphasizes ecosystem preservation (Fischer et al., 2021).

Anthropogenic activities are a dominant factor affecting the quality of lake ecosystems. The main causes of eutrophication are human activities that produce waste such as fertilizers, pesticides, livestock manure, fish farming, and domestic waste, leading to a decline in biodiversity and water quality (Yusal et al., 2025). Population growth around lakes increases the demand for land for settlements and agriculture, resulting in erosion, sedimentation, and water pollution (Adi et al., 2024).

Lake Batur, located in Kintamani District, Bangli Regency, Bali Province, has been designated as one of 15 national priority lakes. As the largest caldera lake on the island of Bali with an area of 16.05 km^2 and a water volume of 815.38 million m^3, Lake Batur plays a vital role for the ecosystem and surrounding communities (Jaya et al., 2024). The lake is surrounded by eight villages with different geographical and socio-economic characteristics: Kedisan, Buahan, Abang Batu Dinding, Abang Songan, Terunyan, Songan A, Songan B, and Batur Tengah.

The condition of Lake Batur has deteriorated due to various pressures. Sedimentation reached 124.71 million m^3 in 37 years (1975-2012) with a siltation of 7.80 m (Laili et al., 2020). There are 10,902 floating net cages (KJA), which exceeds the optimal capacity, while domestic waste reaches 229,587.84 m^3 per year (Handayani et al., 2011). Research shows that Lake Batur is experiencing eutrophication at the eutrophic level (Kaban et al., 2023; Sunaryani et al., 2023).

The Mount Batur area was designated a UNESCO Global Geopark in 2012, adding to the complexity of management, which must integrate conservation with sustainable development. The complexity of multidimensional problems requires a holistic approach that integrates ecological, social, and economic aspects in accordance with the triple bottom line sustainability concept (Purvis et al., 2019)

Lake Batur faces serious pressure from the activities of the surrounding community, including agriculture, settlements, tourism, and KJA fisheries. The number of KJA in 2020 reached 12,200 plots, exceeding the carrying capacity and resulting in pollution from feed waste (Lusia et al., 2023).

Rapid Appraisal for Fisheries Status (Rapfish) was developed by the University of British Columbia as a sustainability evaluation tool using a multidisciplinary approach. Rapfish uses non-parametric ordination techniques with MDS to provide sustainability values relative to predetermined attributes (Pitcher & Preikshot, 2001).

The Multidimensional Scaling (MDS) approach using the Rapfish method allows for the evaluation of the sustainability status of complex socio-ecological systems (Pitcher & Preikshot, 2001). The comparative characteristics of MDS allow for comparisons of sustainability levels between analysis units based on attribute proximity (Kavanagh & Pitcher, 2004).

MDS converts multidimensional data into lower dimensions based on the concept of Euclidean Distance in multidimensional space (Fauzi & Anna, 2002). Rap-Lake is a modification of Rapfish for lake sustainability analysis, adopting the principle of rapid assessment based on attributes using multidimensional ordination methods (Mahida et al., 2019). Leverage analysis identifies sensitive attributes that have a significant effect on sustainability through Root Mean Square (RMS) changes calculations. Monte Carlo analysis validates the model by detecting sources of error from data diversity (Fauzi, 2019).

A key strength of MDS in this context is its capacity for comparative analysis; by calculating relative distances between data points in multidimensional space, it allows for clear comparisons of sustainability levels across different analysis units—in this case, the eight lakeside villages—based on the proximity of their assessed attributes (Kavanagh & Pitcher, 2004). Consequently, this study aims to systematically assess and compare the sustainability status of Lake Batur management across the ecological, social, and economic dimensions within each of the eight villages directly adjacent to the lake, providing a nuanced, location-specific diagnostic to inform targeted intervention strategies.

Method

The research was conducted in the Lake Batur area, Kintamani District, Bangli Regency, Bali Province in August 2024. Lake Batur is located at coordinates 115°22'2.3"-115°25'33" E and 8°13'24"-8°17'13.3" S at an altitude of ~1,000 m above sea level. The units of analysis were the eight villages surrounding the lake: Kedisan, Buahan, Abang Batu Dinding, Abang Songan, Terunyan, Songan A, Songan B, and Batur Tengah.

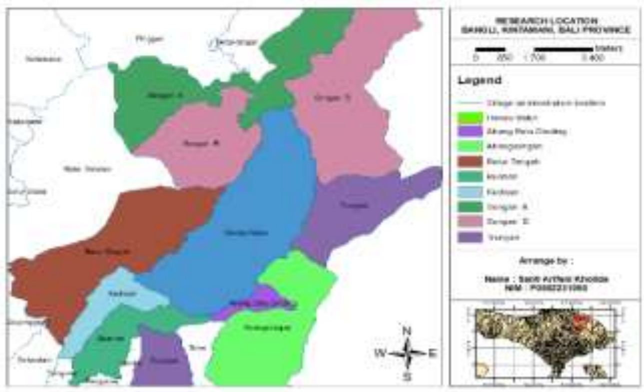


Figure 1. Map of the research location

This study used primary and secondary data. The primary data consisted of (1) water quality data at eight points representing each village for physical and chemical analysis of the water, (2) structured interviews with community/traditional leaders in the eight villages and relevant agencies using purposive sampling. Secondary data was collected from the Central Statistics Agency (BPS) (PODES 2024, Kintamani Subdistrict in Figures), the Bangli District Agriculture Office (KJA data), and planning documents related to the condition of Lake Batur.

Multidimensional Scaling (MDS)

This study uses the *Rapid Appraisal* approach with the MDS method through the *Rapfish* algorithm, which has been adapted into *Rap-Lake* for lake sustainability evaluation. The *rapid appraisal* (RAP) approach is a *multidisciplinary* methodology designed to analyze *comparative sustainability* based on a series of attributes or indicators that can be assessed using a simple scoring system (Fauzi & Anna, 2002). This approach was chosen because of its capacity to comprehensively integrate various sustainability indicators/attributes (Pitcher & Preikshot, 2001).

The application of Rap MDS sustainability analysis requires the fulfillment of certain requirements and principles prior to implementation (Fauzi, 2019). These requirements aim to minimize errors in the measurement process, *scoring* determination, and interpretation of the results obtained. The scoring in *Rapfish* is generally based on three main elements, namely *Peer Review Scoring, Grey Literature,* and *Expert Judgment.*

The *Rapfish* algorithm is designed to measure the status or degree of sustainability of a system on a sustainability spectrum from "*bad*" to "*good*." This evaluation depends on the method of scoring specific attributes. The selected attributes must be able to represent the level of sustainability in each dimension studied and be adjusted to the availability of data that can be obtained from the characteristics of the object of study. Thus, the key element in *Rapfish* lies in the selection of attributes to be evaluated in certain dimensions (Fahly, 2024). The stages involved in the implementation *of Rapfish* can be seen in (Figure 2).

The identification of attributes in the sustainable management of Lake Batur covers three main dimensions: ecological, social, and economic. In this phase, attributes for each dimension of sustainability are reviewed and determined. Attribute selection meets practical parameters, can be evaluated objectively, and extreme values can be clearly categorized as conditions that are beneficial or detrimental to sustainability (Laras et al., 2011). The determination of sustainability attributes is carried out through a literature review approach by collecting theoretical foundations and data from reference sources relevant to the research topic.

The data collection process utilized acAademic sources such as reference books, national and international journal publications, research reports, applicable regulations, and other scientific publications. In this study, the author analyzed the ecological, social, and economic aspects that affect the sustainability of Lake Batur. Based on the results of the literature review, a number of attributes or variables were obtained for each dimension, which were then used to evaluate the sustainability of Lake Batur. variables were obtained for each dimension, which were then used to evaluate the sustainability of Lake Batur.

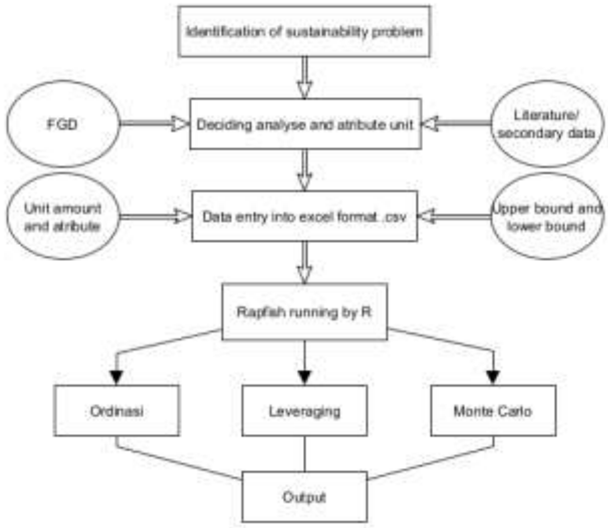


Figure 2. Stages of Rapfish MDS analysis as a method in this study.

Table 1. Index value categories and sustainability status (Kavanagh & Pitcher, 2004)

Category	Sustainability Status
0-25	Bad (Unsustainable)
26-50	Poor (Less sustainable)
51-75	Fair (Moderately sustainable)
76-100	Good (Very sustainable)

Each attribute was given a value or score that reflected the sustainability of Lake Batur according to the dimension used. The scoring system used an ordinal scale based on sustainability parameters that referred to actual conditions. The value range is between 0 (worst condition) and 10 (best condition) according to the observed attribute conditions (Pitcher & Preikshot, 2001).

From the scoring results for each attribute, an MDS analysis was then performed to determine the sustainability status of Lake Batur, expressed on a sustainability index scale (0-100). The sustainability status categories are presented in (Table 1).

Leverage Analysis

Leverage analysis was conducted to identify sensitive attributes that have the greatest influence on the sustainability status of each dimension. This analysis was performed using *Root Mean Square* (RMS) calculations, which show the magnitude of change in the sustainability index when one attribute is removed from the analysis. The greater the change in the RMS value, the more sensitive the role of that attribute is in the sustainability status. The basis of this analysis is the principle of sensitivity in complex systems. The purpose of identifying sensitive attributes is to maximize intervention (Tesfamichael & Pitcher, 2006). The results of this leverage analysis are used as a basis for developing management strategies based on attributes that have high values in the leverage analysis.

Monte Carlo Analysis

Monte Carlo is used to see errors, namely the uncertainty value in MDS. The goodness of fit is determined using the Stress value; a good fit is indicated by a low stress value and vice versa. A stress value of less than 0.25 ($S < 0.25$) indicates a good model, while a good R2 value is close to 1 (Kavanagh & Pitcher, 2004). If the difference between the MDS and Monte Carlo values is small, it can be interpreted that the MDS analysis used to determine the sustainability status of Lake Batur is quite good with a 95% confidence level.

Monte Carlo analysis is applied to identify sources of *error* in data variability. Errors in the implementation of RAPFISH can be caused by various factors, including: (1) Errors in determining attribute values. This problem can arise due to inaccurate understanding of the unit of analysis being studied, lack of in-depth knowledge related to attributes and their scores, differences in perspective or assessment between researchers, and errors in data input. (2) Imperfect convergence of MDS results, indicated by high *stress* values. (3) The possibility of using attributes that are less suitable for the unit of analysis being studied (Fauzi, 2019).

There are two types of Monte Carlo results in Rapfish R: *uniform distribution and triangular distribution*. In Monte Carlo uniform distribution, each value has an identical probability of occurrence, while in *triangular distribution*, the values have characteristics similar to a triangle, namely a minimum value, a possible value, and a maximum value. If the Monte Carlo results graph shows a distribution of units that tends to be concentrated at the initial value. This can be interpreted as indicating that the disturbance in this unit is minor. Conversely, if the distribution of units spreads away from the initial point, this indicates a significant disturbance (Fauzi, 2019).

Results and Discussion

The unit of analysis used in this study was eight villages directly adjacent to Lake Batur. From the results of the Rapfish MDS analysis, the values and sustainability status of each village in relation to its impact on the sustainability of Lake Batur were obtained in three dimensions, namely ecology, social, and economy, with 18 attributes (Table 2).

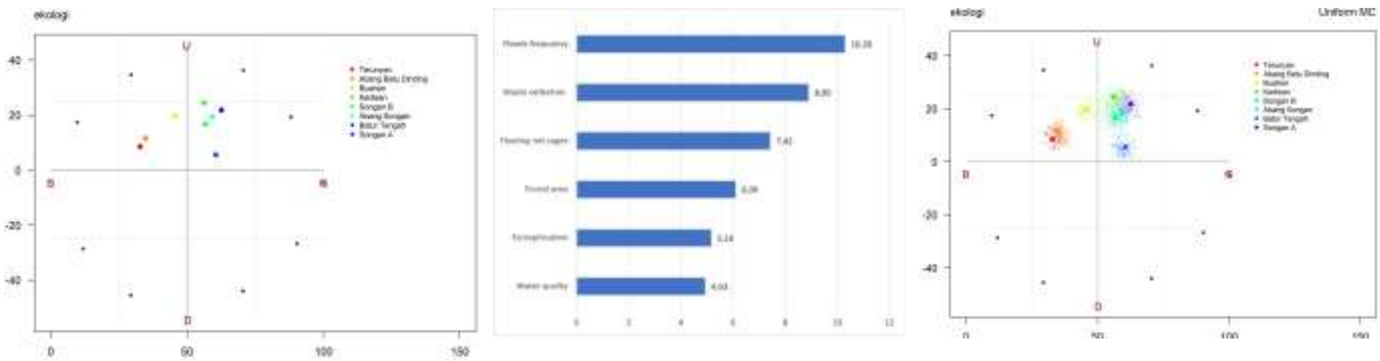
Table 2. Dimensions and attributes used.

Dimension	Attribute	Assessment	Reference
Ecology	Lake water quality	0-2 = Severely polluted (IP > 15.0); 3-4 = Heavily polluted (10.0 < IP ≤ 15.0); 5-6 = Moderately polluted (5.0 < IP ≤ 10.0); 7-8 = Slightly polluted (1.0 < IP ≤ 5.0); 9-10 = Good (0 ≤ IP ≤ 1.0)	(Kementerian Lingkungan Hidup dan Kehutanan Republik Indonesia, 2021; Mahida et al., 2019)
	Number of KJA	0-2 = Very poor (> 1,765); 3-4 = Poor (1,510-1,764); 5-6 = Moderate (1,255-1,509); 7-8 = Good (1,000-1,254); 9-10 = Very good (< 1,000)	(Iriadi, 2015; Lusia et al., 2023)
	Number of flood incidents (last 5 years)	0-3 = Very high (≥ 7 times in 5 years); 4-5 = High (6-5 times in 5 years); 6-7 = Moderate (4-3 times in 5 years); 8-9 = Low (1-2 times in 5 years); 10 = Very low (never)	(Kementerian Kehutanan Republik Indonesia, 2014; Mahida et al., 2019)
	Waste collection (per week)	0-2 = 0-2 times; 3-4 = 3-4 times; 5-6 = 5-6 times; 7-8 = 7-8 times; 9-10 = 9-10 times	(Fajri, 2025)
	Eutrophication level	0-2 = Hypertrophic (> 80); 3-4 = Eutrophic (51-80); 5-6 = Mesotrophic (41-50); 7-8 = Oligotrophic (31-40); 9-10 = Ultraoligotrophic (< 30)	(Iriadi, 2015; Sulastri et al., 2019)
	Forest area	0-2 = ≤ 10%; 3-4 = 10.01-20%; 5-6 = 20.01-30%; 7-8 = 30.01-40%; 9-10 = > 40%	(Hasim, 2012; Pemerintah Republik Indonesia, 1999)
Social	Population density	0-2 = > 300; 3-4 = 251-300; 5-6 = 201-250; 7-8 = 151-200; 9-10 = 100-150	(Rendrarpoertri, 2025)
	Number of poor people	0-2 = 76-100; 3-4 = 76-100; 5-6 = 51-75; 7-8 = 26-50; 9-10 = ≤ 25	(Rendrarpoertri, 2025)
	Level of community dependence on the lake	0-2 = very high; 3-4 = high; 5-6 = moderate; 7-8 = low; 9-10 = very low	(Imran, 2023; Iriadi, 2015)
	Length of schooling	0-2 = < 6; 3-4 = 6-8; 5-6 = 9-11; 7-8 = 12-15; 9-10 =	(Fajri, 2025)

Dimension	Attribute	Assessment	Reference
		> 15	
	Number of village regulations	0-2 = 0-3; 3-4 = 4-7; 5-6 = 8-11; 7-8 = 12-15; 9-10 = >15	(Fajri, 2025)
	Number of local institutions	0-2 = ≤ 2 units, 3-4 = 3-5 units; 5-6 = 6-8 units; 7-8 = 9-11 units; 9-10 = > 11 units	(Hasim, 2012)
Economy	Number of markets	0-2 = < 2 units; 3-4 = 2-3 units; 5-6 = 4-5 units; 7-8 = 6-7 units; 9-10 = ≥ 8 units	(Hasim, 2012)
	Distance to market	0-2 = > 20 km; 3-4 = 16-20 km; 5-6 = 11-15 km; 7-8 = 6-10 km; 9-10 = 0-5 km	(Rendrarpoertri, 2025)
	Number of accommodations	0-2 = < 7 units; 3-4 = 7-12 units; 5-6 = 13-18 units; 7-8 = 19-24 units; 9-10 = ≥ 25	(Rendrarpoertri, 2025)
	Number of SMEs	0-2 = < 25 units; 3-4 = 26-40 units; 5-6 = 41-55 units; 7-8 = 56-70 units; 9-10 = > 70 units	(Rendrarpoertri, 2025)
	Number of cooperatives	0-2 = ≤ 2 units; 3-4 = 3-4 units; 5-6 = 5-6 units; 7-8 = 7-8 units; 9-10 = 9-10 units	(Rendrarpoertri, 2025)
	Marketing of fishery products	0-2 = consumed locally; 3-4 = marketed in several villages within one subdistrict; 5-6 = marketed in several subdistricts within a district; 7-8 = marketed in several districts within a province; 9-10 = marketed outside the province	(Iriadi, 2015)

Ecological Dimension

The results of the ecological dimension analysis show variations in the sustainability index with a range of values between 32.75 and 62.55. Through multidimensional ordination techniques, the ecological dimension classifies the sustainability levels of villages around Lake Batur into two classes, less sustainable and moderately sustainable.



(a) (b) (c)

Figure 3. (a) MDS ordination graph (b) Leverage graph (c) Monte-Carlo

In (Figure 3 a), three villages were identified as belonging to the less sustainable category, namely Terunyan Village (32.75), Abang Batu Dinding Village (34.72), and Buahan Village (45.53). Meanwhile, five other villages are classified as moderately sustainable, including Kedisan (56.11), Abang Songan (59.20), Songan A (62.55), Songan B (56.71), and Batur Tengah (60.52).

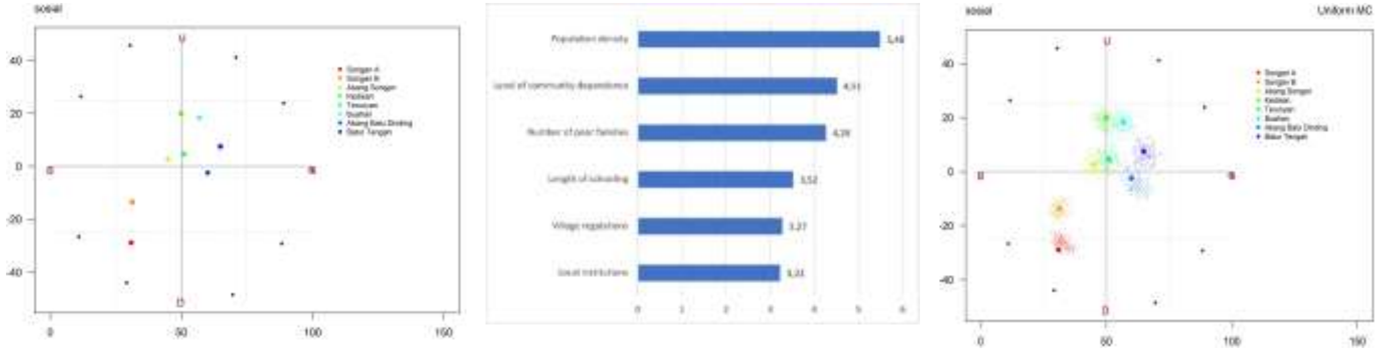
The results of the leverage analysis show that there are three attributes whose values exceed the RMS, namely flood frequency, waste transportation, and the number of KJA. Based on data from 2020-2024, four villages have experienced flooding, with 2022 being the worst period, affecting three villages at once.

The frequency of waste transportation varies between villages, ranging from 1-4 times a week, with some villages managing waste independently. According to data from the Bangli Regency Office of Agriculture, Food Security and Fisheries, currently there are 10,902 cages in Lake Batur.

To determine the *error* in the calculation of sustainability values using Rapfish, a Monte Carlo analysis was conducted. In this study, a uniform distribution Monte Carlo analysis was used with 200 iterations (Figure 3 c) shows that the points cluster close to the starting point on the MDS ordination.

Social Dimension

The results of the social dimension analysis show variations in the sustainability index with a range of values between 30.86 and 64.87. Through multidimensional ordination techniques, the social dimension classifies the sustainability levels of the villages around Lake Batur into two classes, less sustainable and quite sustainable. Four villages are fairly sustainable: Terunyan (51.04), Buahan (56.87), Abang Batu Dinding (60.04), and Batur Tengah (64.87). Four less sustainable villages: Songan A (34.94), Songan B (35.37), Abang Songan (40.83), and Kedisan (49.93).



(a) (b) (c)

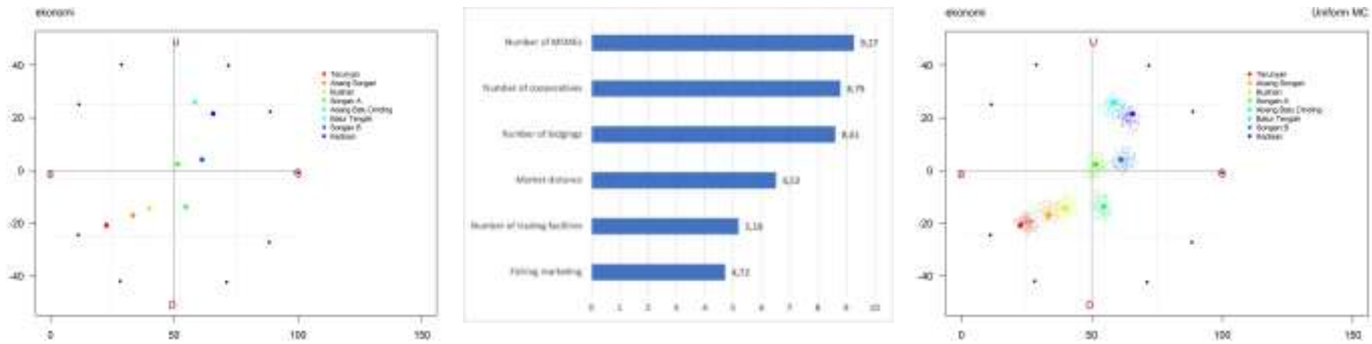
Figure 4. (a) MDS ordination graph (b) Leverage graph (c) Monte-Carlo

Based on the leverage analysis results (Figure 4 b), the attributes of population density (5.48%), the community's dependence on the lake (4.51%), and the number of poor families (4.26%) are the three most influential attributes in the social dimension.

The results of the Monte Carlo analysis on the social dimension (Figure 4c) show that the distribution of units tends to be dense and not spread out, indicating that there are no significant disturbances related to the social dimension.

Economic Dimension

The results of the analysis on the economic dimension show that the sustainability value ranges from 22.60 to 65.68. These sustainability values are divided into three sustainability categories for the eight villages. Five villages achieved a fairly sustainable status, namely Kedisan (65.68), Songan B (61.19), Batur Tengah (58.41), Abang Batu Dinding (54.73), and Songan A Village (51.39). While, two villages have a less sustainable status, namely Buahan Village (39.90) and Abang Songan Village (33.33). Meanwhile, Terunyan Village has the lowest sustainability score among the seven villages, namely 22.60, with an unsustainable status.



(a) (b) (c)

Figure 5 (a) MDS ordination graph (b) *Leverage* graph (c) Monte-Carlo

Based on the economic dimension leverage analysis graph in (Figure 5 b), there are three attributes whose values exceed the RMS value: the number of MSMEs (9.27), the number of cooperatives (8.79), and the number of lodgings (8.61).

Podes 2024 data confirms that the cooperatives available in the villages around Lake Batur are savings and loan cooperatives. The data shows that Kedisan, Songan B, and Batur Tengah have the highest number of lodgings compared to other villages.

Multidimensional Analysis

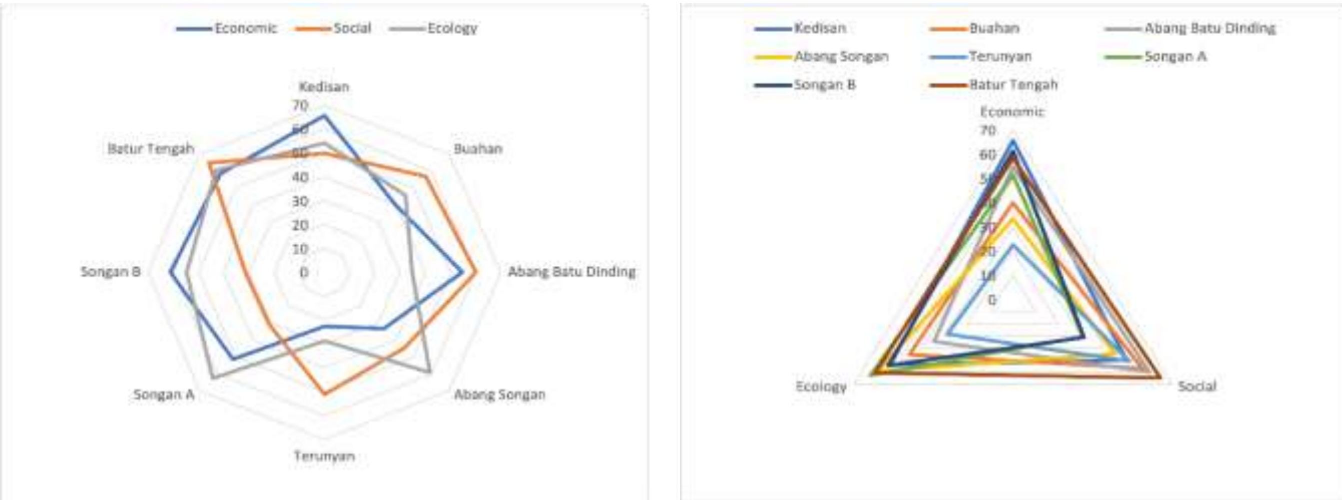
The results of the multidimensional analysis in this study cover three dimensions, namely ecology, social, and economy, with 8 analysis units, which are villages directly adjacent to Lake Batur. These analysis results integrate the three dimensions of sustainability (ecology, social, and economy) to provide a comprehensive picture of the sustainability status of Lake Batur management.

The sustainability status for all villages in each dimension is presented in (Table 3). The economic dimension shows the widest range of variation (22.60-65.68). The social dimension shows moderate variation (30.86-64.87). Meanwhile, the ecological dimension shows a narrower range (32.75-62.55).

The results of the multidimensional analysis show that only Batur Tengah consistently achieved a moderately sustainable status in all three dimensions (ecology: 60.52; social: 64.87; economy: 58.41), making it a model of sustainable village in the Lake Batur area. In contrast, Terunyan shows a paradoxical pattern with a less sustainable status in the ecological (32.75) and economic (22.60) dimensions, but a fairly sustainable status in the social dimension (51.04).

Table 3. Sustainability status of villages in three dimensions

Village			Sustainability Status
	Ecological	Social	Economic
Kedisan	56.11 (adequate)	49.93 (poor)	65.68 (adequate)
Buahan	45.53 (below average)	56.87 (adequate)	39.90 (insufficient)
Abang batu dinding	34.72 (insufficient)	60.04 (adequate)	54.73 (fair)
Abang songan	59.20 (adequate)	44.86 (below average)	33.33 (poor)
Terunyan	**32.75 (below average)**	**51.04 (adequate)**	**22.60 (bad)**
Songan A	62.55 (sufficient)	30.86 (below average)	51.39 (adequate)
Songan B	56.71 (adequate)	31.31 (below average)	61.19 (adequate)
Batur Tengah	**60.52 (adequate)**	**64.87 (fair)**	**58.41 (fair)**



(a) (b)

Figure 6. (a) Sustainability radar diagram (b) Sustainability kite diagram

The sustainability analysis also produced a radar diagram and a sustainability kite diagram. These diagrams illustrate the interaction between the three dimensions used and the sustainability status of the eight villages. The radar diagram in (Figure 6a) visualizes the relative position of each village to the center of the radar.

Terunyan shows sharp asymmetry with a position very close to the center on the economic dimension, reflecting a structural economic crisis, but relatively distant on the social dimension.

The kite diagram in (Figure 6b) presents an aggregation of the sustainability status of the entire Lake Batur area in the form of a triangle. This triangular shape reflects the integration of the three dimensions of sustainability: ecology, social, and economy. The irregular triangular shape indicates imbalances between dimensions in lake management. Based on the triangle diagram shown, the economic dimension shows the lowest average value, reflected in the "concave" or "narrow" shape of the triangle.

Interpretation of Ecological Sustainability

The variation in ecological sustainability scores among the villages can be attributed to differential exposure and management of environmental pressures, with three attributes emerging as particularly influential. The identification of flood frequency as the most sensitive attribute (leverage value 10.96%) underscores its catastrophic impact, which extends beyond mere statistical occurrence. Although data from 2020-2024 shows flood events are not excessively frequent, field interviews reveal they have severe consequences, including increased sedimentation levels in Lake Batur as floodwaters carry substantial amounts of mud into the lake. This process not only degrades water quality but also severs community access roads, isolates residents, causes casualties, and damages homes and public facilities. These compounded effects align with global findings on how climate-induced disasters impact freshwater systems (Carpenter et al., 2011), and the role of extreme weather events in mobilizing pollutants and sediments from catchments into water bodies is well-documented (Syvitski et al., 2005). The intensification of such hydrological extremes is increasingly linked to anthropogenic climate change, which alters precipitation patterns and increases runoff intensity (Milly et al., 2008).

The second key attribute, waste transportation frequency, highlights a critical infrastructure gap in the region. While communities generally dispose of waste at temporary disposal sites (TPS) for transport to final processing sites (TPA), several villages lack this service entirely. In these areas, residents resort to independent waste management through burning or burial in yards, practices that present secondary pollution risks through atmospheric emissions and soil/water contamination, contradicting the principles of integrated waste management. These informal disposal methods are significant diffuse sources of microplastics and chemical leachates, perpetuating contamination cycles even when visible waste is removed (He et al., 2019). This challenge reflects a common issue observed in the management of other Indonesian lakes (Dewan Sumberdaya Air Nasional, 2020) and is consistent with global studies on the negative environmental impacts of inadequate waste management in developing regions (Guerrero et al., 2013).

The persistent issue of KJA numbers exceeding the lake's carrying capacity represents a clear example of the "tragedy of the commons" (Hardin, 1968). Although the number of KJA has decreased significantly from 12,200 plots in 2020 to the current 10,902 plots, this still exceeds the calculated carrying capacity of approximately 10,031 plots by about 870 units (Lusia et al., 2023). This overcapacity directly contributes to feed waste accumulation and accelerated eutrophication, a problem similarly documented in Lake Maninjau (Mahida et al., 2019). The resulting nutrient loading from excess aquaculture, particularly nitrogen and phosphorus, is a primary driver of cultural eutrophication in lakes worldwide (Smith & Schindler, 2009). Effective management of such aquaculture systems requires frameworks that integrate clear ecological carrying capacities with socio-economic incentives for compliance, as top-down regulation alone often fails (Bennett et al., 2021).

The robustness of these ecological findings is confirmed by the Monte Carlo analysis, which showed points clustering close to the starting point on the MDS ordination. This indicates minimal error in scoring, a stable MDS iteration process, and reliable data input (Fauzi, 2019), confirming that these findings are robust and not artifacts of data variability. This statistical stability is crucial for translating research findings into credible evidence for environmental policy and management decisions (Boteler et al., 2019).

Interpretation of Social Sustainability

The social dimension analysis reveals complex socio-ecological dynamics, with three attributes demonstrating particular significance in determining sustainability outcomes. Population density emerged as the most sensitive attribute (leverage value 5.48%), indicating its crucial role in determining social sustainability. High demographic pressure creates a domino effect on various aspects of social life around Lake Batur, where continuous population growth with its associated activities becomes a major contributor to lake water pollution. This ultimately reduces water quality and impacts the quantity of natural resources provided by the lake, particularly evident in high-density villages like Songan A and Songan B that face challenges in providing social infrastructure, managing domestic waste, and handling pressure on natural resources. Such concentrated human pressure is a primary driver of freshwater biodiversity loss and service decline globally (Reid et al., 2019).

The attribute of the community's level of dependence on the lake ranks second in the leverage analysis (4.51%), reflecting the complexity of socio-ecological relationships in the Lake Batur area. Villages such as Kedisan and Abang Songan show a very high level of dependence, where most community livelihoods depend directly on lake resources through fishing, lake tourism, and agriculture that utilizes lake water. This creates a sustainability paradox where the communities most dependent on the lake contribute to its degradation through intensive resource use practices and anthropogenic pressures, a phenomenon consistent with the concept of the "tragedy of the commons" proposed by Hardin (1968). This pattern of high dependence leading to environmental degradation is frequently observed in common-pool resource systems across the globe (Ostrom, 2009). These dynamics highlight the critical importance of formal and informal institutions in mediating between dependence and sustainable use (Partelow, 2018).

The number of poor families shows a leverage value of 4.26%, indicating the role of poverty as a reinforcing factor in socio-ecological dynamics. Poverty creates a cycle of degradation where economic pressures drive short-term exploitation of lake resources without considering long-term sustainability. Villages with high poverty rates tend to rely on extractive survival strategies for lake resources, and research shows that economic growth, poverty, income inequality, and environmental damage influence each other (Pribadi & Kartiasih, 2020). In the context of Lake Batur, poor families tend to depend on intensive fishing activities, the use of riparian land for agriculture, and suboptimal waste management practices due to limited access to infrastructure and technology. This pattern aligns with the poverty-environment nexus, where a lack of assets restricts access to sustainable technologies and enforces reliance on immediate, often degrading, natural resource use (Barbier & Hochard, 2018).

The reliability of these social dimension findings is reinforced by Monte Carlo analysis, which showed a distribution of units that tends to be dense and not spread out, indicating no significant disturbances related to the social dimension (Fauzi, 2019). The application of such robustness tests is essential for ensuring that policy recommendations derived from sustainability assessments are credible and actionable (Polasky et al., 2019).

Interpretation of Economic Sustainability

The extreme heterogeneity in economic sustainability scores (ranging from 22.60 to 65.68) points to profound disparities in economic development and infrastructure among the villages. The prominence of the number of MSMEs as the most sensitive attribute (leverage value 9.27%) highlights their role as engines of local economic resilience. The existence of adequate MSMEs enables the absorption of local labor, increases people's purchasing power, and develops the economic value chain, reducing dependence on the primary sector (fisheries and agriculture) which is prone to fluctuations. This aligns with findings that diversified local economies are more resilient to environmental and market shocks in rural areas (Scoones, 2009). The availability of MSMEs also functions as economic resilience by providing alternative livelihoods when the dominant/primary sector experiences fluctuations.

The number of cooperatives ranks second in the leverage analysis with a value of 8.79%, indicating their important role in the local economy of the villages around Lake Batur. Cooperatives should serve as a bridge connecting small communities with large markets; however, field findings reveal they are not yet functioning optimally as expected. Interview results show that KJA farmers and fishermen do not utilize cooperatives for marketing their fishery products, but instead sell directly to middlemen. This condition proves that cooperatives have a very important role that is currently unfulfilled, as existing savings and loan cooperatives only provide basic financial services without facilitating crucial functions such as crop aggregation, collective price negotiation, or market access. As a result, farmers and fishermen lack market price information and must accept prices determined by middlemen, undermining their bargaining power and profit margins. Overcoming these institutional gaps is critical, as studies show that well-designed farmer organizations can significantly improve market integration and incomes for small-scale producers (Trebbin, 2014).

The number of lodgings as the third sensitive attribute (8.61%) reflects the strategic role of the tourism sector in the economy of the Lake Batur region. The data shows a direct correlation between lodging numbers and economic sustainability indices, with villages having the most lodgings—Kedisan (65.68), Songan B (61.19), and Batur Tengah (58.41)—also showing the highest economic scores. Conversely, villages with limited lodging facilities, such as Terunyan (22.60) and Abang Songan (33.33), show low economic indices, confirming the causal relationship between tourism infrastructure and village economic welfare. The tourism sector creates multiplicative effects beyond accommodation, generating chain benefits for supporting MSMEs such as restaurants, handicrafts, and transportation services. However, the benefits of tourism can be spatially uneven, often bypassing remote or culturally distinct communities, which reinforces existing inequalities (Lapeyre, 2010). The integration of these three sensitive attributes forms a synergy model where MSMEs provide products and services, cooperatives act as facilitators of capital and marketing, while lodging creates demand and a market for local products.

The Monte Carlo analysis for the economic dimension shows the distribution of units clustering at the initial point of MDS ordination, which can be interpreted as minimal error and mistakes in the economic dimension (Fauzi, 2019), confirming the reliability of these economic findings. The validity of such sustainability assessments is enhanced by robust sensitivity analyses, which ensure findings are not artifacts of data uncertainty (Saisana et al., 2005).

Integrated Multidimensional Implications

The analysis reveals a clear hierarchy of sustainability challenges across the Lake Batur region, with the economic dimension exhibiting the greatest disparity among villages. This pronounced heterogeneity suggests that access to economic resources and infrastructure is the most unevenly distributed pillar of sustainability, creating a fundamental barrier to regional equilibrium. In contrast, the social and ecological dimensions demonstrate more moderate variation, indicating that while pressures exist, they are somewhat more consistently managed or experienced across the different communities.

The comparative analysis of villages yields two critical archetypes. Batur Tengah emerges as a model of integrated sustainability, demonstrating that balanced development across all three dimensions is achievable. Its consistent performance suggests the presence of effective local governance, diversified livelihoods, and infrastructure that mitigates trade-offs between ecological, social, and economic goals. Conversely, the profile of Terunyan presents a compelling paradox, revealing a condition of social resilience amidst socio-ecological collapse. This finding is critical, as it demonstrates that strong social cohesion and community structures can persist even under severe ecological and economic stress. Such a scenario aligns with the concept of "poverty traps," where communities are locked in a stable state of low welfare due to reinforcing feedbacks between resource depletion and limited economic options (Barrett & Swallow, 2006). However, this social sustainability is likely fragile, as the deteriorating ecological base and profound economic marginalization ultimately threaten the long-term viability of the community itself, a dynamic consistent with theories on the limits of social resilience in the face of entrenched resource depletion (Adger, 2000).

The aggregate visualization provided by the sustainability kite diagram offers a powerful summary of the systemic challenges in Lake Batur management. The distinctly "concave" or narrowed shape on the economic side is a visual confirmation that economic vulnerabilities represent the weakest link in the region's overall sustainability. This pattern directly corroborates the leverage analysis, which identified factors like the number of MSMEs and functional cooperatives as highly sensitive. The fuller shapes on the ecological and social sides of the kite indicate that, on average, these dimensions are in a more stable—though not optimal—state.

This multidimensional assessment underscores the necessity for a differentiated and targeted management strategy. A one-size-fits-all approach would be ineffective given the stark contrasts between villages like Batur Tengah and Terunyan. The findings compellingly argue that interventions must be strategically prioritized to strengthen the economic dimension across the region, focusing on enhancing local entrepreneurship, improving market access, and developing tourism in an equitable manner. Ultimately, achieving the integrated sustainability of Lake Batur as a national priority site and UNESCO Global Geopark depends on management policies that are as multidimensional and nuanced as the system they aim to protect.

Conclusion

The assessment of the sustainability status of Lake Batur using Rapfish MDS focuses on the ecological, social, and economic conditions of the villages that are directly connected to Lake Batur. The results of the analysis show significant variations in sustainability status between villages and dimensions, ranging from unsustainable to moderately sustainable. Batur Tengah is the only village that consistently achieves a moderately sustainable status in all three dimensions. Meanwhile, Terunyan shows the most critical condition with an unsustainable status in the economic dimension. In the ecological dimension, the attributes sensitive to sustainability are flood frequency, waste transportation frequency, and the number of fish cages. Population density, the number of poor families, and the community's level of dependence on the lake emerged as sensitive attributes in the social dimension. Meanwhile, in the economic dimension, the number of MSMEs, the number of cooperatives, and the number of lodgings were the results of the leverage analysis. These findings indicate the need for a differentiated management approach that integrates multidimensional interventions with a focus on strengthening sensitive attributes to achieve the sustainable management of Lake Batur as a national priority lake and part of the UNESCO Global Geopark. This necessitates polycentric governance systems that can tailor actions to local contexts while coordinating at the landscape level to address lake-wide pressures (Morrison et al., 2019).

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

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