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Integrating RAPFISH-MDS diagnostics into an operational sustainability roadmap for a tropical oxbow lake (Sepunjung, Indonesia)

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Abstract. *Putra RM, Raza'i TS, Sukendi, Budijono, Jhonnerie R, Kurniawan R, Ramdhani EP, Pardi H. 2026. Integrating RAPFISH-MDS diagnostics into an operational sustainability roadmap for a tropical oxbow lake (Sepunjung, Indonesia). Biodiversitas 27 (3): d270308. https://doi.org/10.13057/biodiv/d270308.* Sepunjung Oxbow Lake in Riau Province, Indonesia, is a tropical floodplain lake exposed to increasing ecological and socio-institutional pressures, creating an urgent need for a practical sustainability management framework. This study aimed to develop an operational sustainability roadmap for the lake by integrating biophysical evidence and stakeholder knowledge through Rapid Appraisal for Fisheries with multidimensional scaling (RAPFISH-MDS). Sustainability was assessed across five dimensions using 45 attributes supported by monthly water-quality monitoring from September 2024 to February 2025, fish community observations, field verification, and semi-structured interviews with resource users and relevant stakeholders. The analysis showed that the ecological dimension had the lowest sustainability index (31.8), followed by legal-institutional (43.2), while the economic (52.3), technological (55.9), and socio-cultural (59.0) dimensions were classified as moderately sustainable. Monte Carlo testing confirmed the stability of the ordination results. Sensitivity analysis identified key leverage attributes, and Pareto screening selected 13 priority factors explaining 78.2% of total sensitivity. The most critical intervention areas were aquatic vegetation cover, water quality, riparian forest condition, utilization zoning, community empowerment, monitoring facilities, and fishery product marketing. Based on these findings, a 12-24 month operational roadmap is proposed, focusing on ecological rehabilitation, participatory fisheries control, institutional strengthening, and livelihood improvement. The study demonstrates that multidimensional sustainability diagnostics can be translated into concrete management priorities for tropical oxbow lakes in Indonesia.

Keywords: RAPFISH-MDS, oxbow lake, sustainability, governance, invasive aquatic vegetation

INTRODUCTION

Oxbow lakes are highly productive components of tropical river systems that support aquatic biodiversity and provide essential socio-economic services, including small-scale fisheries and water resources for rural communities (Yaqoob et al. 2021; Rimi et al. 2022; Saha et al. 2022; Hamidy et al. 2023; Kumari et al. 2023). Functioning as spawning and nursery habitats and as nutrient-recycling nodes within inland trophic networks, these floodplain lakes contribute disproportionately to regional food webs and fisheries yields relative to their area (Virgilio et al. 2020; Sarkar et al. 2021; Laiveling et al. 2023). However, their sustainability is increasingly challenged by hydrological disconnection, sedimentation, eutrophication, land-use intensification, and governance gaps, which jointly erode ecological integrity and local livelihoods (Tóth et al. 2020; Subehi et al. 2022; Zhao et al. 2022; Miranda and Dembkowski 2024; Wilke et al. 2024). These pressures are particularly salient in tropical peatland and lowland river settings, where natural acidity and high dissolved organic matter can interact with anthropogenic nutrient loading to produce complex water-quality signals and management trade-offs (Saha et al. 2022; Kumari et al. 2023).

In Indonesia, many oxbow lakes are embedded within rapidly transforming catchments where plantation expansion, settlement growth, and infrastructure development have altered runoff pathways and resource use. In Riau Province, the Sepunjung Oxbow Lake represents a typical tropical oxbow system that continues to support capture fisheries and local water uses, yet faces accelerating multi-sectoral pressures. Prior studies in Sumatra and Riau report that shifts in land use and access regimes can change fish assemblages, intensify fishing pressure, and increase conflict among users, underscoring the need for integrated ecological and institutional responses (Putra et al. 2018; Ningrum et al. 2021; Putra et al. 2023; Tamrin et al. 2025). At the same time, sustainability interventions that focus solely on ecology or solely on governance often fail because leverage points are distributed across multiple dimensions of the socio-ecological system.

Multidimensional sustainability appraisal is therefore required to translate diagnosis into actionable priorities. RAPFISH with multidimensional scaling (RAPFISH-MDS) has been widely used to rapidly assess sustainability status, test robustness, and identify leverage attributes that most strongly influence system performance (Virgilio et al. 2020; Sarkar et al. 2021; Laiveling et al. 2023; Miranda and Dembkowski 2024; Wilke et al. 2024). Yet, many applications stop at reporting index values, with limited operationalization into time-bound actions, monitoring metrics, and responsible institutions, all of which are crucial for management uptake, especially in data-limited tropical inland waters (Tóth et al. 2020; Subehi et al. 2022; Zhao et al. 2022). For Sepunjung, an operational roadmap must integrate biophysical evidence (e.g., water-quality dynamics and fisheries signals) with stakeholder knowledge and local institutional feasibility to ensure that recommended interventions are both ecologically meaningful and implementable.

In addition, management decisions increasingly need to be aligned with national water-quality regulations and local development priorities, while acknowledging site-specific limnological characteristics typical of peat-influenced waters. Embedding such context into an explicit monitoring and evaluation scheme can help avoid over-reliance on perception-based scoring and improve the credibility of proposed interventions for stakeholders and regulators.

This study aims to develop a multidimensional sustainability roadmap for Sepunjung Oxbow Lake by integrating RAPFISH-MDS diagnostics with an operational action framework. Specifically, we (i) assess sustainability status across five dimensions using a transparent 45-attribute protocol, (ii) evaluate result robustness using Monte Carlo simulation, (iii) identify leverage attributes and screen priority intervention points, and (iv) translate these priorities into a 12-24 month roadmap with monitorable indicators and responsible actors. By linking diagnostics to implementable actions, the study provides a practical template for sustainable management of tropical oxbow lakes in Indonesia, particularly within the governance and environmental context of Riau Province (Putra et al. 2018; Sarkar et al. 2021; Tamrin et al. 2021, 2025; Putra et al. 2023).

MATERIALS AND METHODS

Research time and site

The study was conducted from September 2024 to February 2025 at Sepunjung Oxbow Lake, Pelalawan Regency, Riau Province, Indonesia (Figure 1). This horseshoe-type lake covers approximately 6.58 ha, consisting of 3.06 ha of open water and 3.52 ha (53.5%) of surface area dominated by invasive aquatic vegetation. Site selection was based on its geomorphological uniqueness, its hydrological linkage to the Kampar River, and its socio-economic role for small-scale fisheries, particularly for local widows.

Geospatial data were processed using QGIS 3.40 LTR software, projected to the Universal Transverse Mercator (UTM) Zone 47N with the WGS 84 (World Geodetic System 1984) datum (EPSG: 32647). The lake boundaries were delineated through manual on-screen digitizing at a scale of 1:200, using high-resolution Google Satellite imagery as the primary base map, cross-verified with Open Street Map (OSM) for toponymy. Lake area calculations were performed using the geometry function ($area) in the QGIS Field Calculator. Field validation (ground-checking) was conducted using handheld GPS to ensure the accuracy of the digitized boundaries against existing field conditions.

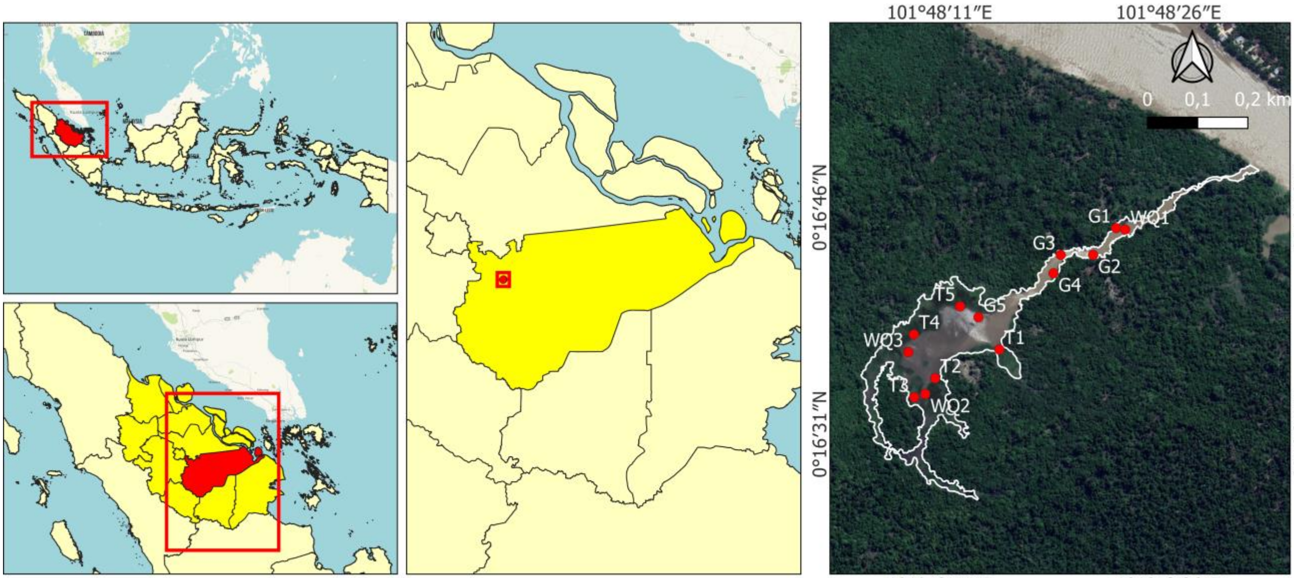

Figure 1. Geographic location and sampling design of Sepunjung Oxbow Lake, Pelalawan, Riau, Indonesia. WQ: Water quality stations; G: Gillnet sampling points; T: Trap (bubu) sampling points

Sampling was distributed across three water quality stations (WQ1, WQ2, WQ3) and ten fishing gear stations, comprising five gillnet sites (G1, G2, G3, G4, G5) and five trap sites (T1, T2, T3, T4, T5) positioned within vegetated areas. Location access and ethical compliance were validated through coordination with village officials and customary leaders to ensure social acceptance (Chukwuka and Adeogun 2023).

Research design and methodological framework

The study adopted an integrated qualitative-quantitative design to evaluate inland lake sustainability across five interrelated dimensions. Qualitative inquiry was used to capture contextual accounts of lake use and stakeholder perceptions, whereas the quantitative component enabled systematic scoring of sustainability attributes. In total, 45 attributes were assessed, comprising ecological (9), economic (9), socio-cultural (10), technological (6), and legal-institutional (11) dimensions. Secondary data included village records, sectoral policies, and relevant scientific literature to support attribute selection and scoring ranges (Putra et al. 2018; Putra et al. 2023). All instruments were pilot-tested to ensure clarity and scoring consistency.

Sampling technique and respondent selection

The social unit of analysis consisted of households and stakeholders directly involved in the use and management of Sepunjung Lake. Respondents were selected purposively based on a minimum of three years of experience and informed consent. To ensure transparency, potential respondents were approached directly through door-to-door visits for local residents and field encounters for fishers. Of the 42 individuals initially invited, 5 declined to participate, resulting in a refusal rate of 11.9%.

The final composition (n=37) comprised 25 women heads of household (widows) who hold the primary communal rights to the lake, and 5 male anglers from outside the area who operate discretely within the lake's boundaries. Additionally, 7 key stakeholders (village officials, customary leaders, and agency representatives) were included to provide institutional perspectives.

Data collection ensured that each respondent scored all dimensions to maintain cross-sectional consistency. To integrate the diverse perspectives of these groups, the scores were aggregated using a combination of the mode (to identify the most frequent consensus) and the arithmetic mean. This dual-analysis approach was chosen to ensure that the dominant perspectives of the primary users (the widows) were captured through the mode, while the mean accounted for the nuanced variations provided by outside fishers and stakeholders. This methodology aligns with stakeholder engagement and adaptive management principles (Chukwuka and Adeogun 2023).

Data collection techniques

Data collection involved complementary qualitative and quantitative procedures. Qualitative data were generated through participatory observation, transect walks, and semi-structured interviews to identify patterns of lake utilization and to elicit sustainability-related perceptions across dimensions. Quantitative data were collected using structured questionnaires administered to score the attributes defined in the assessment framework. These primary data were further complemented by secondary information derived from village records, sectoral policies, and relevant literature (Putra et al. 2018; Putra et al. 2023). All instruments were pilot-tested to ensure clarity and scoring consistency.

Ecological data collection and fish sampling

Water quality monitoring was conducted monthly over a six-month period, from September 2024 to February 2025, at three observation stations (WQ1, WQ2, and WQ3) in Sepunjung Lake, Riau (Figure 1). Measurements were taken at depths of 20-50 cm below the water surface between 09:00 and 11:00 WIB to minimize diel variation effects on temperature and dissolved oxygen. Parameters measured included water depth using an echo sounder (GPSMap 508), transparency with a standard 20 cm Secchi disc, water temperature (°C), and dissolved oxygen (DO, mg/L) using a portable water checker, and pH using a portable pH meter (Taster Pen pH2016). All portable instruments were calibrated prior to each field session using standard buffer solutions (pH 4.0, 7.0, and 10.0).

Water samples of 1 L were collected from each station for nutrient analysis, stored in a cooler box (≈4°C), and transported to the laboratory. Total nitrogen (TN) and total phosphate (TP) were analyzed using a UV/Vis spectrophotometer (BIOBASE BK-UV-1800) following the standard APHA (2017) method, while total suspended solids (TSS) were analyzed using gravimetric methods with 0.45 µm membrane filters. The remaining sample was then dried to constant weight to determine the TSS concentration. Water quality results were evaluated according to the Indonesian Government Regulation No. 22 of 2021 (Appendix VI Class II), which governs the protection of surface water and the conservation of aquatic biota.

The assessment of water quality included the analysis of transparency, depth, temperature, pH, dissolved oxygen (DO), total nitrogen (TN), total phosphate (TP), and total suspended solids (TSS). Depth was considered as a habitat and morphometric descriptor, rather than a variable for compliance with water quality standards. Water transparency was not evaluated in a binary manner (pass/fail), as low transparency in peat-affected waters can be attributed to naturally occurring dissolved humic substances. Additionally, pH was not used to reduce the score, given that pH criteria are explicitly acknowledged as not applicable to peat water. This approach reflects the true conditions of the oxbow lake system located in the peat swamp region of Riau Province.

Table 1. Sustainability status categories of Sepunjung Lake management. Source: Pitcher and Preikshot (2001)

Index value	Category
0.00 - 25.00	Poor (not sustainable)
25.01 - 50.00	Less (less sustainable)
50.01 - 75.00	Sufficient (quite sustainable)
75.01 - 100.00	Good (sustainable)

Fish community data were collected monthly from September 2024 to February 2025 at ten gear stations representing habitat heterogeneity in Sepunjung Lake: five gillnet sites in open-water zones (G1-G5) and five trap sites positioned within vegetated littoral areas (T1-T5) (Figure 1). To account for the lake's substantial macrophyte coverage (53.5%), a multi-gear protocol used traditional gears common to local fishers: (i) five units of monofilament gillnets (75 m length, 2 m depth) with multiple mesh sizes (1.0, 2.0, and 3.0 inches) set in open water, and (ii) five units of wooden-framed traps (40 × 30 × 60 cm, 1.0-2.0 inch mesh) baited with palm oil seeds and placed within vegetated habitats. To capture both diurnal and nocturnal assemblages, gears were retrieved twice daily at 05:00-06:00 and 17:00-18:00 WIB, maintaining a standardized 12-hour soaking interval. Sampling effort was standardized as Catch Per Unit Effort (CPUE), and the twice-daily retrievals were pooled into a 24-hour sampling unit for calculation of Shannon-Wiener diversity (H′) and Simpson dominance (D) indices following Odum (1971).

Taxonomic identification was performed personally by the first author, an ichthyologist at the Faculty of Fisheries, Universitas Riau, Indonesia, ensuring high-quality data control (QA/QC). Identification was conducted at the Aquatic Biology Laboratory, referencing the authoritative taxonomic keys of (Kottelat et al. 1993; Haryono et al. 2024). All specimens were meticulously examined for diagnostic morphological features, and representative voucher specimens were preserved in 10% formalin for further verification. This rigorous protocol ensured that the ecological attributes used in the RAPFISH-MDS analysis were based on accurate species richness and abundance data, fulfilling the requirements for multidimensional sustainability modeling.

Aquatic vegetation cover and riparian forest area, which were used as ecological attributes in the sustainability assessment, were delineated through manual digitization in QGIS 3.40 LTR using high-resolution satellite imagery accessed via the QuickMapServices plugin. Historical imagery in Google Earth Pro was used to evaluate changes in open-water extent across multiple acquisition dates (10 August 2010, 12 December 2015, 25 December 2018, and 10 August 2020). Polygons were refined in QGIS using topology checks, and land-water classes (water vs non-water, including aquatic vegetation) were analyzed using spatial overlay. The mapped outputs were cross-checked during field surveys to ensure consistency with current lake conditions.

Data analysis

The sustainability of Sepunjung Lake was evaluated using Multidimensional Scaling (MDS) via RAP-Oxbow, a modified rapid assessment tool based on the RAPFISH framework (Pitcher and Preikshot 2001; Kavanagh and Pitcher 2004; Tesfamichael D, Pitcher TJ. 2006). This approach integrated five dimensions: ecological, economic, socio-cultural, technological, and legal-institutional. Attributes for each dimension were selected based on their relevance to Indonesian oxbow-lake contexts and policy sensitivity (Putra et al. 2018, 2023). Each attribute was scored on an ordinal scale with attribute-specific anchors (commonly 0-4, 0-3, 0-2, or 0-1); scores were then normalized to a 0-100 index to classify sustainability status categories (Table 1). To maintain comparable weighting across attributes with different ranges, scores were standardized prior to the RAPFISH-MDS analysis.

The MDS ordination utilized the ALSCAL algorithm in a two-dimensional space. Model robustness was validated through a Monte Carlo simulation with 100 iterations using an automated random seed to introduce stochastic variation (Atufa et al. 2023). Model fit was confirmed using Stress values (≤ 0.25) and Squared Correlation ($R^2 \geq 0.80$). To identify key management drivers, leverage analysis was performed by calculating the Root Mean Square (RMS) of ordination changes, where attributes with the highest RMS values were prioritized as strategic leverage points (Kavanagh and Pitcher 2004).

Data integrity was maintained by applying a mean substitution method for missing values (not exceeding 5% of the dataset). Furthermore, the results were integrated with adaptive management principles through stakeholder consultations to ensure that the proposed actions, such as invasive species control and zoning, align with local wisdom and institutional capacity (Saha et al. 2022; Putra et al. 2023).

RESULTS AND DISCUSSION

Ecological dimension

Field observations and interviews identified nine ecological attributes. Fish diversity was high (H′ = 3.7748; D = 0.1369), indicating a diverse community with low dominance. No protected species were recorded, and water quality met standards for fisheries and irrigation. However, utilization zoning has not yet been established. Aquatic vegetation covered 53.5% of the lake surface and was classified as poor, while riparian forest areas have declined due to conversion to plantations. Forest protection efforts remain conditional and inconsistent. Annual flooding occurs during the rainy season, and aesthetic value was moderate, supporting recreational fishing, culinary activities, and cultural functions.

Table 2. Summary of water quality characteristics of Lake Sepunjung from September 2024 to February 2025

Parameter (unit)	Observed range	Class 2 standard
Water transparency (m)	0.37-1.07	≥4.0
Water depth (m)	4.40-6.70	-
Water temperature (°C)	27-30	Dev. +/-3°C
pH	4.6-5.8	6-9*
Dissolved oxygen (mg/L)	4.03-5.88	≥ 4.0
Total nitrogen (mg/L)	0.088-0.208	≤ 0.75
Total phosphate (mg/L)	0.010-0.016	≤ 0.03
Total suspended solids (mg/L)	35-44	≤ 50

In addition to this ecological analysis, water quality monitoring was conducted from September 2024 to February 2025 at three sampling stations in Sepunjung Lake. The results are summarized in Table 2. Most core parameters relevant to aquatic biota protection (dissolved oxygen, total nitrogen, total phosphate, and total suspended solids) were within the Class 2 criteria during the monitoring period; water transparency and pH were outside the Class 2 benchmarks and are discussed in the context of peat-influenced oxbow lakes.

Table 2 summarizes the water quality characteristics of Sepunjung Lake from September 2024 to February 2025. The monitoring results show that several core parameters relevant to aquatic biota protection were within the Class 2 criteria, including dissolved oxygen (4.03-5.88 mg/L), total nitrogen (0.088-0.208 mg/L), total phosphate (0.010-0.016 mg/L), and total suspended solids (35-44 mg/L). Water transparency remained low (0.37-1.07 m) relative to the Class 2 benchmark and should be interpreted cautiously in peat-associated oxbow lake systems, where dissolved humic substances can naturally reduce light penetration. The lake water was also acidic (pH 4.6-5.8), reflecting peatland influence; therefore, regulatory comparisons for pH should be presented as a benchmark reference rather than as a strict compliance statement for this ecological setting.

The ecological sustainability index was 31.8%, classified as less sustainable. Monte Carlo validation produced a value of 33.3 (difference = 1.8), with low stress (0.14), high explanatory power ($R^2 = 0.94$), and minimal error (RMS < 2%). Sensitivity analysis identified four dominant leverage attributes: aquatic vegetation cover, water quality, riparian forest area, and utilization zoning (Figure 2.A-B).

Economic dimension

Assessment of nine economic attributes indicates easy physical access to fishing grounds (approximately 5-10 minutes by motorized boat) combined with weak regulatory enforcement. Household dependence on fisheries is very high (>80%), and fishing activities are predominantly part-time and largely undertaken by women using gillnets. Capital availability is low because most women fishers are widows. Average monthly income ranges from IDR 3.1-3.3 million. Marketing channels remain limited to local collectors, while local labor use is high (25 widows depend entirely on fishing). Although recreational, culinary, and cultural tourism potential exists, infrastructure and supporting facilities are minimal.

This profile reflects a livelihood system highly dependent on fisheries with unrealized diversification potential through ecotourism and value-added marketing. The economic sustainability index reached 52.3% (moderately sustainable), with Monte Carlo validation of 51.7 (difference = 0.6), stress of 0.14, $R^2 = 0.95$, and RMS < 2% (Figure 3.A). Sensitivity analysis identified four key leverage attributes: fishery product marketing (RMS = 5.2), utilization of local labor (RMS = 4.4), tourism potential (RMS = 3.3), and capital availability (RMS = 3.2) (Figure 3.B).

Socio-cultural dimension

Ten socio-cultural attributes indicate strong community participation involving customary leaders and village authorities. Fisher solidarity is maintained through communal activities, and conflict potential is low due to mediation by religious and customary institutions. Local wisdom remains active in problem-solving, and community relations are open and democratic. However, alternative livelihood options are limited, empowerment programs have been minimal over the last three years, education levels remain predominantly primary to lower secondary, and environmental knowledge is largely derived from sporadic extension activities. Social facilities remain basic.

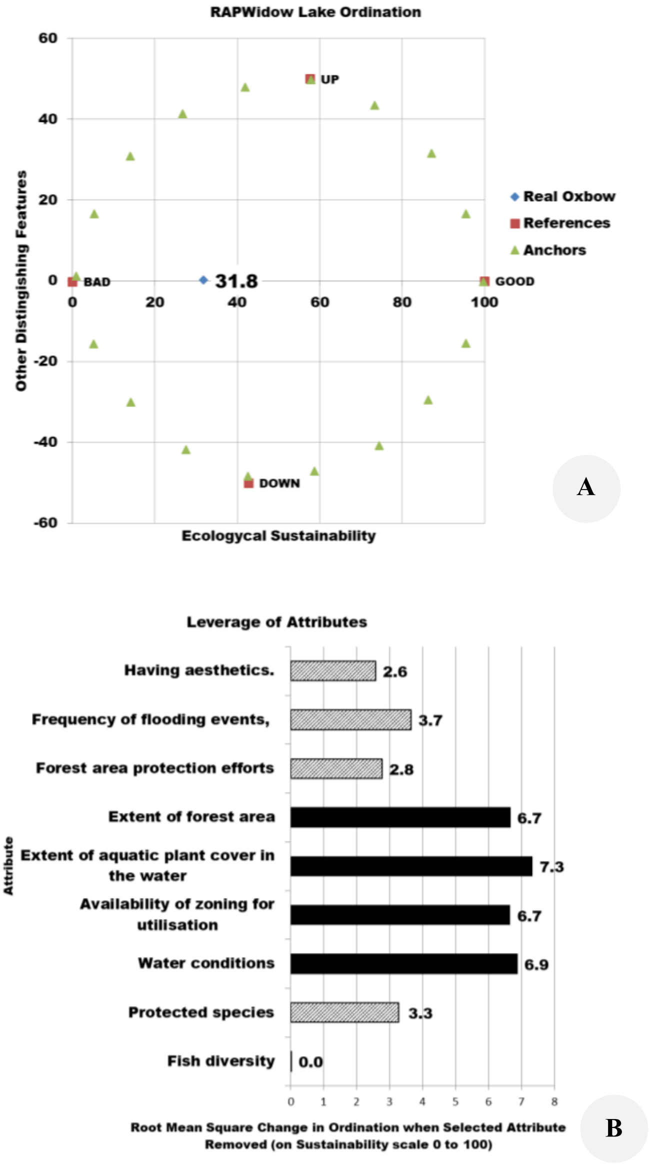

Figure 2. A. Ecological sustainability index of Sepunjung Lake, B. Leverage analysis of ecological attributes

This configuration reflects high social capital but limited empowerment capacity and human resource development. The socio-cultural sustainability index reached 59.0% (moderately sustainable), validated by Monte Carlo analysis (57.5; difference = 1.5), with stress of 0.14 and R^2 = 0.94 (Figure 5.A). Key leverage attributes were community empowerment (RMS = 7.6), local wisdom and knowledge (RMS = 5.3), conflict potential (RMS = 5.1), education level (RMS = 5.0), fisher solidarity (RMS = 4.4), and environmental knowledge (RMS = 4.1) (Figure 4.B).

Technological dimension

Six technological attributes indicate that fishing gears are predominantly passive (gillnets, traps, and lines) with moderate selectivity and limited habitat impact. Prohibited fishing gear was not observed. However, monitoring facilities are absent, and extension services occur only sporadically through university outreach programs. Fishing practices thus exhibit low to moderate ecological risk, but institutional support for monitoring and capacity building remains weak.

The technological sustainability index was 55.9% (moderately sustainable), validated by Monte Carlo results of 55.1 (difference = 0.8), stress of 0.15, and R^2 = 0.94 (Figure 5.A). The two strongest leverage attributes (Figure 5.B) were prohibition of illegal fishing gear (RMS = 8.4) and availability of monitoring infrastructure (RMS = 7.4).

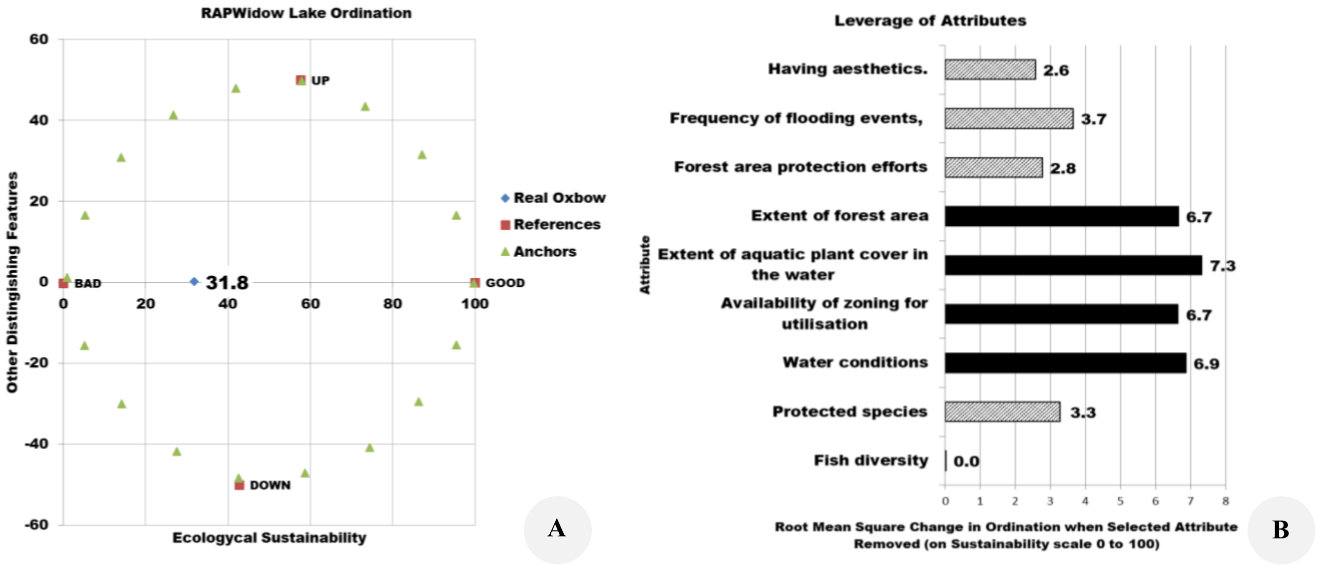

Figure 2. A. Ecological sustainability index of Sepunjung Lake, B. Leverage analysis of ecological attributes

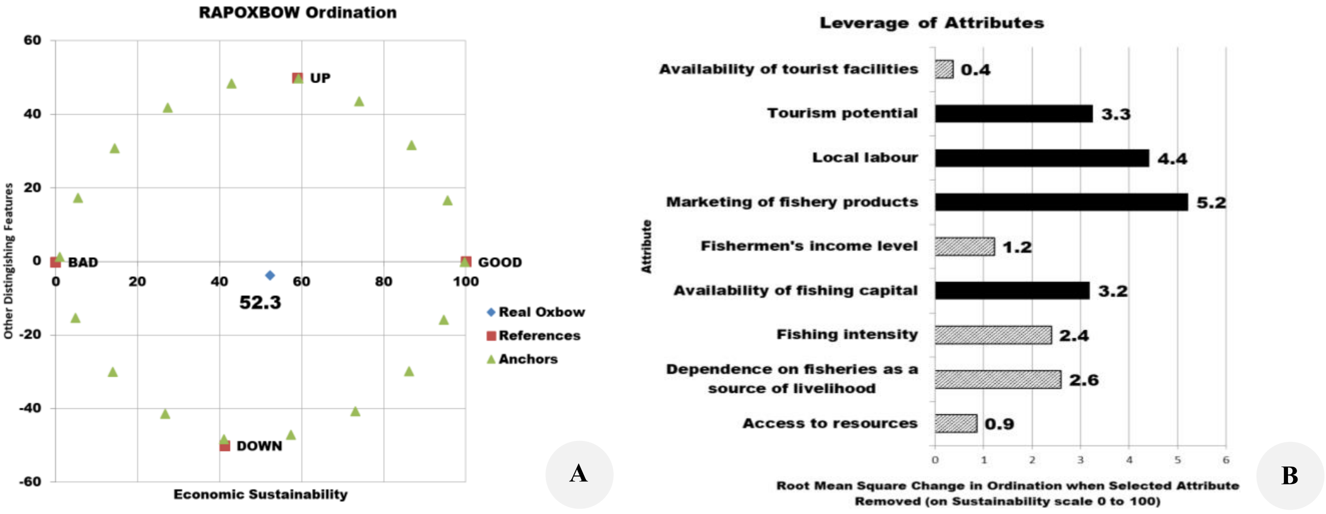

Figure 3. A. Economic sustainability index of Sepunjung Lake, B. Leverage analysis of economic attributes

Legal-institutional dimension

Eleven legal-institutional attributes reveal strong social legitimacy but weak governance structures. Lake access is easy, ownership rests with village authorities, and use is dominated by local residents, particularly widows. Traditional fishing spot auctions persist but lack conservation orientation. No formal management organization exists, coordination remains informal, enforcement of rules is inconsistent, environmental law education is absent, and sanctions are limited to verbal warnings. The legal-institutional sustainability index reached 43.2% (less sustainable), validated by Monte Carlo analysis (43.5; difference = 0.3), with stress of 0.14 and R^2 = 0.95 (Figure 6.A). Key leverage attributes (Figure 6.B) were the presence of community-based management organizations (RMS = 3.7), environmental law education (RMS = 3.2), resource ownership clarity (RMS = 2.6), and sanction enforcement (RMS = 2.3).

Leverage and determining factors

Cross-dimensional leverage analysis identified 20 sensitive attributes. Applying the Pareto principle to RMS rankings, thirteen determining factors were retained because they cumulatively explained 78.2% of total sensitivity variance, whereas each remaining attribute contributed less than 4% individually. This cut-off ensures analytical parsimony while preserving the dominant drivers of sustainability dynamics (Table 3). These thirteen attributes therefore provide a robust bridge between sustainability diagnosis and operational management planning.

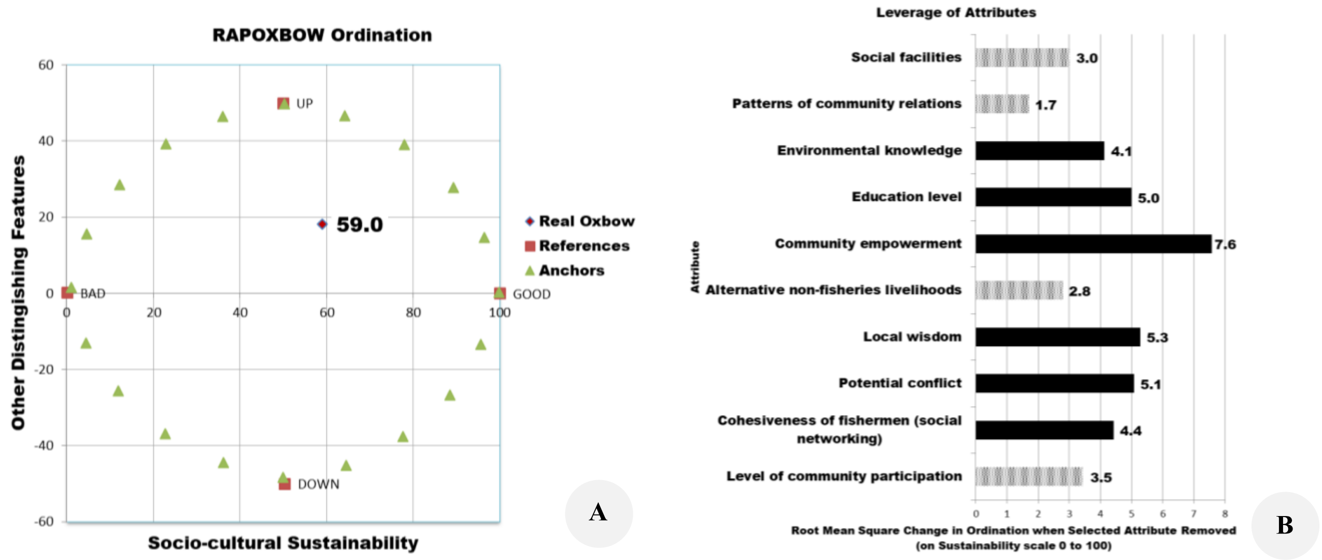

Figure 4. A. Socio-cultural sustainability index of Sepunjung Lake, B. Leverage analysis of socio-cultural attributes

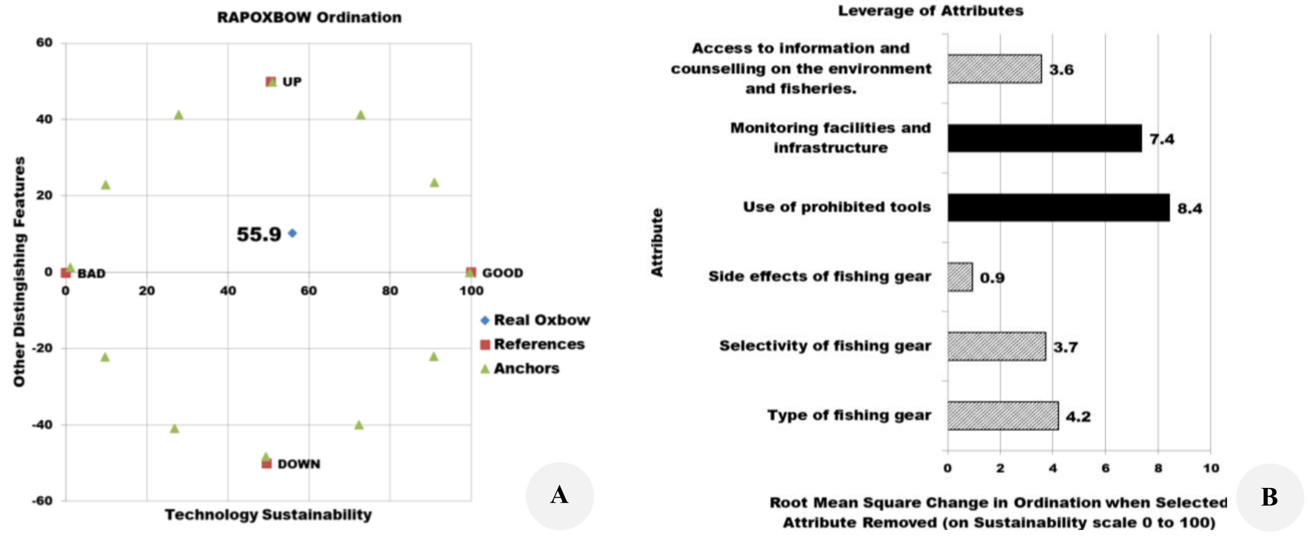

Figure 5. A. Technological sustainability index of Sepunjung Lake, B. Leverage analysis of technological attributes

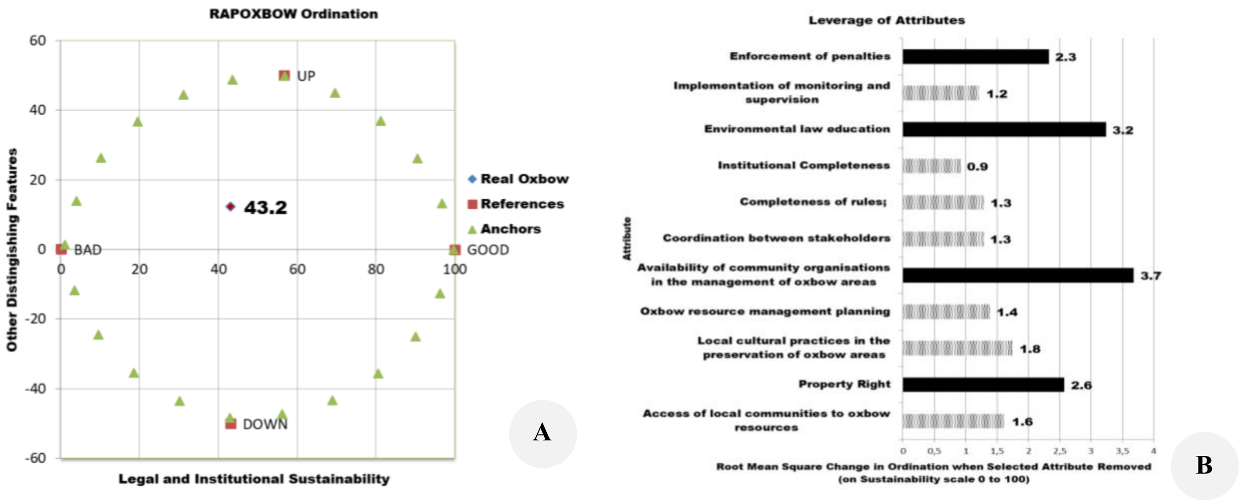

Figure 6. A. Legal-institutional sustainability index, B. Leverage analysis of legal-institutional attributes

The determining factors comprise: use of illegal fishing gear, community empowerment, monitoring facilities and infrastructure, aquatic vegetation cover, water quality, riparian forest area, availability of utilization zoning, local wisdom and knowledge, fishery product marketing, conflict potential, education level, local labor, and fisher solidarity.

Table 3 synthesizes the cross-dimensional determining factors based on RMS sensitivity and Pareto filtering. Four ecological attributes aquatic vegetation cover, water quality, riparian forest area, and availability of utilization zoning fall within the highest RMS cluster and together with nine attributes from other dimensions form the core management priorities for Sepunjung Lake.

The three highest-ranked attributes use of illegal fishing gear, community empowerment, and monitoring facilities and infrastructure reflect an integrated management logic of prevent damage, build capacity, and ensure compliance. Ecological factors account for a large proportion of total variance, confirming the central role of biophysical connectivity and spatial governance. At the same time, socio-economic and cultural factors (local wisdom, marketing, education, labor, and solidarity) indicate that sustainability cannot be achieved through ecological restoration alone but requires co-optimization of livelihoods and conservation outcomes.

Based on the cross-dimensional RMS ranking, the final sequence of determining factors used consistently in the abstract, strategy, and conclusion sections is as follows: (i) use of illegal fishing gear, (ii) community empowerment, (iii) monitoring facilities and infrastructure, (iv) aquatic vegetation cover, (v) water quality, (vi) riparian forest area, (vii) availability of utilization zoning, (viii) local wisdom and knowledge, (ix) fishery product marketing, (x) conflict potential, (xi) education level, (xii) local labor, and (viii) fisher solidarity. This prioritization framework provides a transparent and evidence-based foundation for translating ordination outputs into integrated management strategies.

Strategies and management roadmap

Drawing on sustainability index values, cross-dimensional leverage attributes, and supporting literature, four integrated strategies were formulated to address multidimensional sustainability challenges in Sepunjung Lake. These strategies translate ordination results (Figures 2-6) and leverage factors (Table 3) into operational management pathways (Table 4). The first strategy strengthens participatory enforcement and surveillance to prevent the use of illegal fishing gear and reinforce compliance with sustainable fishing practices. Community-based monitoring and enforcement systems have been shown to increase fisher compliance and promote biodiversity recovery (Etiegni et al. 2020; Orina et al. 2024).

The second strategy emphasizes ecological restoration through invasive aquatic vegetation control, water quality improvement, riparian forest rehabilitation, and adaptive utilization zoning. Such approaches increase ecological carrying capacity and reduce eutrophication risks when implemented through evidence-based and adaptive management frameworks (Pitcher and Preikshot 2001; Ma et al. 2024). The third strategy promotes inclusive socio-economic empowerment, particularly for women fishers, by enhancing value addition, improving market access, and strengthening solidarity-based local economic systems. Women's participation in economic institutions has been shown to reinforce governance capacity and socio-ecological resilience (Njue and Odek 2025).

The fourth strategy focuses on institutional strengthening and legal literacy through the establishment of local management organizations, clarification of ownership regimes and rules of use, improved coordination among stakeholders, and consistent enforcement mechanisms. Synergy between regulatory frameworks and community empowerment has proven effective in sustaining compliance in decentralized water governance contexts (Martin 2023; Wan Omar et al. 2024). The operational action route (Table 4) prioritizes interventions according to the thirteen determining factors and links each strategy to measurable performance indicators and relevant SDG targets. Performance indicators are designed for a 12-24 month implementation horizon to support adaptive evaluation and policy learning.

Table 3. Cross-dimensional leverage attributes of Sepunjung Lake based on RMS values

Attribute	Dimension	RMS	Cumulative %	Priority
Use of prohibited gear	Technological	8.4	8.2	Primary
Community empowerment	Socio-cultural	7.6	15.6	Primary
Monitoring facilities and infrastructure	Technological	7.4	22.8	Primary
Extent of aquatic plant cover in the water	Ecological	7.3	29.9	Primary
Water condition (compliance)	Ecological	6.9	36.6	Primary
Extent of forest area	Ecological	6.7	43.1	Primary
Availability of zoning for utilization	Ecological	6.7	49.6	Primary
Local wisdom	Socio-cultural	5.3	54.8	Primary
Marketing of fishery products	Economic	5.2	59.9	Primary
Potential conflict	Socio-cultural	5.1	64.8	Primary
Education level	Socio-cultural	5.0	69.7	Primary
Local labor	Economic	4.4	74.0	Primary
Cohesiveness of fishermen (social networking)	Socio-cultural	4.4	78.2	Primary
Environmental knowledge	Socio-cultural	4.1	82.2	Secondary
Availability of community organizations in the management of oxbow areas	Legal-institutional	3.7	85.8	Secondary
Tourism potential	Economic	3.3	89.0	Secondary
Availability of fishing capital	Economic	3.2	92.1	Secondary
Environmental law education	Legal-institutional	3.2	95.3	Secondary
Property right	Legal-institutional	2.6	97.8	Secondary
Enforcement of penalties	Legal-institutional	2.3	100.0	Secondary

Table 4. Strategic roadmap for Sepunjung Lake management: Feasibility and Action Plan

Strategy	Key action plan	Baseline and leverage link	Responsibility and resources	Performance indicators (12-24 months)
Strengthening participatory surveillance	Form community-based surveillance; scheduled patrols; graduated sanctions.	Baseline: No formal monitoring.Leverage: Prohibited gear and supervision facilities.	Village Gov and Customary Leaders.Budget: Village Funds for boat fuel and signage.	Recorded incidents of illegal gear (violations logged in patrol logbooks and verified community reports) reduced by 80% relative to the 2024 baseline; ≥12 patrols/year.
Ecological restoration and spatial management	Control invasive vegetation; riparian reforestation; Village Regulation on zoning.	Baseline: 53.5% plant cover. Leverage: Vegetation cover, water quality, and zoning.	Youth organization and Widows' Collective. Equipment: Village-owned tools for manual harvesting.	Invasive cover <30 %; Zoning map ratified via village regulation; ≥ 4 monitoring events/year.
Inclusive socio-economic empowerment	Training on fish processing; eco-labeling; community ecotourism.: Marketing	Baseline: Marketing limited to collectors. Leverage: Marketing, local labor, and solidarity.	Women's Group and village-owned enterprises Support: Small-scale enterprise grants.	Women fishers' income increased by ≥25%; ≥ 2 labeled products.
Institutional strengthening and legal literacy	Establish Management Unit; Legal education on fishery laws	Baseline: Informal ad-hoc coordination. Leverage: Community organization and legal education.	District Fishery Office and Village Gov. Facilitator: University/NGO partners.	Active Management Org; ≥ 2 legal training sessions/year.

The targets in Table 4 are realistic for three reasons. First, implementation capacity is supported by strong fisher solidarity and the active role of local widows who have a direct economic stake in lake health. Second, the costs of primary actions (e. g., vegetation harvesting and patrols) are relatively low and can be incorporated into the Annual Village Budget. Third, key social risks are identifiable: resistance from external anglers to new zoning rules is anticipated and will be addressed through inclusive socialization and clear entry-point signage. Monitoring is scheduled quarterly so seasonal variation in water quality and fishing intensity can be captured, enabling adaptive adjustments.

Discussion

Ecological constraints at Sepunjung Lake highlight a challenge common to tropical oxbow lakes: maintaining habitat complexity while preventing the acceleration of eutrophication, which is influenced by factors such as aquatic vegetation cover, water quality, riparian forest extent, and utilization zoning. These findings are consistent with previous studies. Aquatic vegetation enhances habitat complexity and nutrient uptake; however, excessive growth reduces light penetration, lowers dissolved oxygen, and can trigger fish mortality while disrupting transport and economic activities (Zhang et al. 2021; Kiyemba et al. 2023). Similar patterns have been documented in tropical oxbow lakes of the Amazon, where invasive species constitute a major threat to ecosystem functioning (Virgilio et al. 2020). Water quality degradation is largely driven by nutrient runoff from agriculture and plantations and is amplified by seasonal hydrological variability, underscoring the need for upstream nutrient control (Zambory et al. 2019; Qiu et al. 2023).

Hydrological connectivity stabilizes nutrient dynamics and reduces eutrophication pressure; restoring river-oxbow connectivity contributes to biodiversity recovery (Napiórkowski and Napiórkowska 2017). Riparian forests act as buffers by filtering pollutants, regulating sedimentation, and supporting ecosystem stability. Their decline accelerates erosion and nutrient loading, degrading habitat integrity (Huang et al. 2018; Güntzel et al. 2020; Ahmed 2024). Tropical studies consistently demonstrate positive relationships between forest cover, species richness, and ecosystem resilience, including climate change mitigation benefits (Carlson Mazur et al. 2022; Muthoka et al. 2024; Azuero-Pedraza et al. 2024). The absence of zoning weakens the balance between conservation and utilization. Zoning is a central management instrument within RAPFISH-based frameworks for integrating ecological objectives with community economic needs (Pitcher and Preikshot 2001).

Factors influencing community economic growth, such as the direct marketing of fishery products by local communities or collecting traders, the utilization of local labor (including widows) which contributes to community welfare, the tourism potential based on conservation, and the availability of capital, are leverage points that align with existing evidence. Smart marketing strategies, including eco-labeling, direct sales, and improved product accessibility, have the potential to expand market reach and strengthen sustainable fisheries practices (Bolognini et al. 2023). Formal market access increases income and compliance, while certification enhances consumer trust (Carlson and Palmer 2016; Namotemo et al. 2021). Promoting local species and responsible fishing narratives strengthens product identity in regional markets trust (Rahayu and Saragih 2022).

Utilization of local labor, particularly women, improves household welfare and strengthens community engagement in lake governance trust (Kamaludin et al. 2020). Participatory ecotourism contributes to conservation and environmental awareness when designed inclusively and with cultural sensitivity trust (Sharip et al. 2018; Guo et al. 2019; Saadi et al. 2023). Public involvement in tourism planning enhances social cohesion and long-term sustainability of small destinations such as oxbow lakes (Zhan 2024).

The socio-cultural fabric of Sepunjung Lake, characterized by strong solidarity and customary leadership, represents an invaluable asset for adaptive management. Initiatives that empower the community, rooted in local values, can help reduce resource conflicts and enhance collective decision-making. These results support previous findings that empowerment grounded in local values strengthens adaptive capacity and reduces conflicts over resource access (Nyakeya et al. 2020). However, the generally low education levels, which are largely limited to primary school education, may hinder compliance with more complex fishing regulation. To overcome this, it is necessary to pay attention to public education. Education improves decision-making and compliance with fishing regulations (Shalehin et al. 2022). Furthermore, integrating traditional ecological knowledge with scientific approaches enhances policy acceptance and governance effectiveness (de Oliveira et al. 2018; Glaser et al. 2019). Finally, environmental education generates long-term conservation benefits, particularly for women and youth (Abobi et al. 2021; Kiruba-Sankar et al. 2021; Atufa et al. 2023).

Sensitive factors in the Technological Dimension include the prohibition of illegal fishing gear and the availability of monitoring infrastructure. Although illegal gear was not observed, this attribute reflects regulatory preparedness rather than current violations. The RAPFISH sensitivity analysis measures the system's vulnerability to governance weakening; thus, reduced enforcement capacity would substantially lower sustainability scores. This attribute serves as a preventive governance indicator rather than evidence of ongoing non-compliance.

Consistent with the literature, enforcing bans on destructive gear is critical for preventing habitat degradation and biodiversity loss (Babcsányi et al. 2020). Monitoring systems facilitate early threat detection, while community-based monitoring enhances data quality, ownership, and compliance (Olokotum et al. 2020; Trella and Wołos 2021).

The existence of community-based management organizations, environmental legal education, clarity of resource ownership, and enforcement of sanctions are sensitive factors within the legal-institutional dimension. These findings reinforce the evidence that local organizations are essential for mediating conservation-livelihood trade-offs and enabling adaptive governance (Taufieq et al. 2023; Lega et al. 2024). Environmental legal education enhances participation and compliance (Ahmad and Balisany 2023; Su et al. 2023), while unclear ownership regimes increase the risk of exploitation without formal rules and legitimate sanctions (Palfrey et al. 2021). Strengthening institutions, clarifying rights, and implementing proportional sanctions are therefore critical prerequisites for sustainable participatory governance.

In conclusion, this study confirms that the sustainability of Sepunjung Lake is currently at a critical threshold, characterized by significant disparities across dimensions. The ecological (31.8%) and legal-institutional (43.2%) dimensions are the weakest links, classified as "less sustainable" due to advanced eutrophication and the absence of formal governance. In contrast, the economic, technological, and socio-cultural dimensions maintain a "moderate" status, largely supported by robust social capital and the customary role of local widows as primary resource managers. The primary scientific novelty of this research lies in its operational roadmap, which translates multidimensional scaling (MDS) diagnoses into targeted interventions at the village level. By focusing on thirteen cross-dimensional leverage points, with particular emphasis on preventing the use of illegal fishing gear and formalizing utilization zoning, this study bridges the gap between technical sustainability indices and local institutional practice. Another distinctive feature of this roadmap is its gender-inclusive perspective, which positions women-headed households as key actors in both conservation and the solidarity-based economy. For future implementation, the success of this management scheme should be validated through long-term performance indicators, including the reduction of invasive vegetation cover to below 30%, the formal ratification of a Village Regulation on spatial zoning, and measurable increases in the income of local women fishers. These follow-up studies, combined with hydrological connectivity modeling, will be essential to ensure that the management of Sepunjung Lake remains adaptive and effectively contributes to the achievement of SDG 6 and SDG 15 at the site scale.

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