The University of Tehran Press

Pollution

https://jpoll.ut.ac.ir/

Print ISSN: 2383-451X
Online ISSN: 2383-4501

Multi Sustainability Analysis in the Utilization of Sediments for the Sustainable Conservation of Lake Rawapenning, Central Java, Indonesia

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Article Info

Article type:
Research Article

Article history:
Received: 4 January 2025
Revised: 25 February 2025
Accepted: 28 August 2025

Keywords:
Biodiversity Conservation
Community Involvement in Sediment Use
Pollution
Sediment Management
Water Resource Management

ABSTRACT

Lake Rawapening is one of the 15 lakes prioritized under Presidential Regulation No. 60 of 2021, is experiencing considerable environmental degradation owing to sedimentation, jeopardizing water depth, quality, and ecosystem viability. This study evaluates the sustainability of sediment exploitation in Lake Rawapening, concentrating on ecological, economic, socio-cultural, technological, institutional, and infrastructural aspects. The qualitative survey had 36 participants (18 key informants, 15 primary informants, and 3 supplementary informants) and employed Multi Aspect Sustainability analysis via focus group talks and questionnaires addressing 22 qualities across essential dimensions. The findings indicate that the environmental dimension possesses a sustainability index of 66.67%, with the social dimension exerting the greatest influence at 68.75%, followed by the economic dimension at 56.25%, the legal and institutional dimension at 39.29%, and the infrastructure and technology dimension at 31.25%. This study identifies 11 leverage attributes that significantly influence the sustainability of sediment utilization: socialization and education, occupational safety, product market value, water contamination, data management, infrastructure availability, distribution systems, policy availability, regulatory compliance, legal management extension, and sanction systems.

Cite this article: Akmala Putra, F., Ekowati, T., & Dyah Arianti, F. (2025). Multi Sustainability Analysis in the Utilization of Sediments for the Sustainable Conservation of Lake Rawapenning, Central Java, Indonesia. *Pollution*, 11(4), 1131-1147. https://doi.org/10.22059/poll.2025.388134.2724

DOI: https://doi.org/10.22059/poll.2025.388134.2724

INTRODUCTION

Lake Rawapening in Semarang Regency, Central Java, is a natural lake with an area of 2,670 hectares. Rawapening plays an important role as a flood control, transportation route, and supports culture, economy, sustainable livelihoods, and welfare, as well as being a habitat for flora and fauna (Nugroho, 2024). This lake also serves as a natural reservoir for hydroelectric power generation, irrigation, and tourism (Waskita *et al.,* 2022; Nugroho, 2022; Putra *et al.,* 2025). This lake is the source for 16 rivers that flow into the Tuntang River (Indrayati & Hikmah, 2018). However, in this decade, Lake Rawapening has become one of the 15 lakes prioritized for protection based on Presidential Regulation No. 60 of 2021 (Piranti *et al.,* 2023). Sedimentation is the main challenge which reduces water quality and depth, threatening the ecosystem (Yang *et al*., 2024). This problem is caused by natural factors such as rainfall, topography, and soil type, as well as human activities such as urbanization, agriculture, and deforestation (Singh, 2024; Meshram, 2023; Leppanen *et al.,* 2024; Bussettini & Schmitt, 2022). Excessive sedimentation reduces lake capacity, accelerates the growth of water hyacinth, and causes eutrophication,

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which impacts the waters by making them shallower, losing biodiversity, and decreasing water quality. (Xu & Wu, 2023; Abdiyani *et al.,* 2021; Khumaeroh & Sari, 2024). Lake sediments have high organic matter (61.99%–74.82%), significant phosphorus (2.2%–7.3%), and a pH close to neutral (6.3–7.8) (Piranti *et al.,* 2023; Fariz *et al.,* 2024).

The sediment in Lake Rawapening has potential for utilization because it meets the criteria for water fertility based on phytoplankton abundance and total phosphorus content, which ranges from eutrophic to hypereutrophic, as well as having a clay-textured physical characteristic, thus possessing good water retention capacity (Poikane *et al.,* 2023).

Sedimentation is one of the main causes of lake ecosystem damage, and addressing it has become a top priority in the Lake Rescue Movement (KLH, 2012). To support the effectiveness of this program, an integrated strategy is needed that not only addresses sedimentation but also encourages the sustainable use of sediment. The Multi-Aspect Sustainable Analysis (MSA) approach becomes an effective solution by considering environmental, social, economic, technological, and regulatory aspects in lake sediment management. This research aims to design optimal strategies for managing lake sedimentation, maintaining ecosystem sustainability, and supporting the wise and efficient use of sediment:

1. Analyzing the sustainability status of sediment potential development in Rawapening Lake, Semarang Regency, from the perspectives of ecology, economy, social, technology, and institutions, as well as infrastructure and technology.
2. Analyzing which attributes are sensitive in the sustainability of sediment utilization in Rawapening Lake, Semarang Regency.

MATERIALS & METHODS

This study was conducted at Lake Rawapening, located in Semarang Regency, Central Java Province, Indonesia, from July to October 2024. The research site was deliberately chosen because Lake Rawapening is experiencing significant environmental degradation due to sedimentation, which can endanger water quality, ecosystem sustainability, and reduce depth.

Data collection methods

This research uses primary and secondary data. Primary data were collected through questionnaires with structured questions regarding the characteristics of respondents and their perceptions of lake sustainability based on five dimensions, including open-ended and closed-ended questions. The method used is a qualitative survey with purposive sampling, involving 18 key informants, 15 main informants, and 3 supporting informants. Secondary data were obtained from various sources, such as the Central Statistics Agency (BPS), websites, and research publications (Sugiyono, 2017).

Data analysis Multi-aspect sustainability analysis

The Exsimpro software, an extension of RAPFISH, conducts MSA analysis. The principle is a rapid assessment through in-depth interviews, observations, and focus group discussions with key stakeholders. The stages of MSA analysis include aggregate status value, aspect value, future conditions, status value ordination, leverage factors, uncertainty error, and policy priority scenarios. Scenarios can be based on status value and leverage factors, with tiered scenarios such as moderate, optimistic, and progressive (Firmansyah, 2022).

Validity and reliability tests

The validity test is used to assess the accuracy of questionnaire-based research instruments in measuring the evaluated indicators. This test determines the validity of each statement in the research instrument based on the calculated r value exceeding the table r value and

a significance value of less than 0.05 (Saragih *et al.,* 2021). Meanwhile, the reliability test measures the consistency of the research instrument in producing the same results in repeated measurements. The instrument is considered reliable if the Cronbach's alpha value exceeds 0.6 (Saragih *et al.,* 2021).

Research Variables and Parameters

Sugiyono (2017) defines a variable as an attribute, characteristic, or value of a person, object, or activity that the researcher specifically modifies for the purpose of the study. The researcher then uses this information to draw conclusions. Indicators can further explain variables, while parameters serve as a process or method for understanding their intricacies. A detailed explanation of the research variables and parameters is provided in the Table 1.

RESULT AND DISCUSSION

General description of Rawa Pening Lake

Lake Rawapening was formed due to the eruption of Mount Suropati, which blocked the flow of the Pening River. With an area of 1,850.10 hectares and a water volume of 48.15 million m^3, this lake plays an important role as a water source for hydroelectric power plants, irrigation, flood control, tourism, and fisheries. Geologically, it was formed during the Holocene to Pleistocene era with volcanic soil from Mount Unggaran and Merbabu. The construction of the dam by the Dutch East Indies (1912–1916) made the Tuntang River the only outlet. This lake also supplies water for industry and drinking water with a flow rate of up to 1,100 liters per second (KLH, 2012).

Besides being used to meet human needs, Lake Rawapening also plays a role in the continuity of other living beings' lives. According to (Nugroho, 2024), it is stated that the fish fauna in Rawapening is recorded to have 26 species, both native and introduced, and has been studied since the 1930s. In addition, according to the Central Java Natural Resources Conservation Center, there were 23 species of birds found in Lake Rawapening in 2018 (There were 13 species of water birds, 5 species of birds protected under Government Regulation Number 7 of 1999 concerning Types of Plants and Wild Animals, and 19 migratory birds).

Table 1. Research Variables and Parameters

No	Variable Aspect Sustainability	Factor	Parameters
11	Social	Conflict Incidents Work Safety Community Role in Sediment Management Socialization and Education	Ordinal Scale
22	Economic	Community Income Towards MSMEs Product Selling Value Labor Absorption Economic Institutions	
43	Environment	Lake Siltation Water Pollution Conservation	
44	Infrastructure and Technology	Technology Mastery Infrastructure Availability Distribution and Transportation System Data and Information Management System	
55	Law and Institutions	Policy Transparency Local Supervisory Institutions Managing Organizations Policy Availability Regulatory Compliance Management Legal Counseling Sanction System	

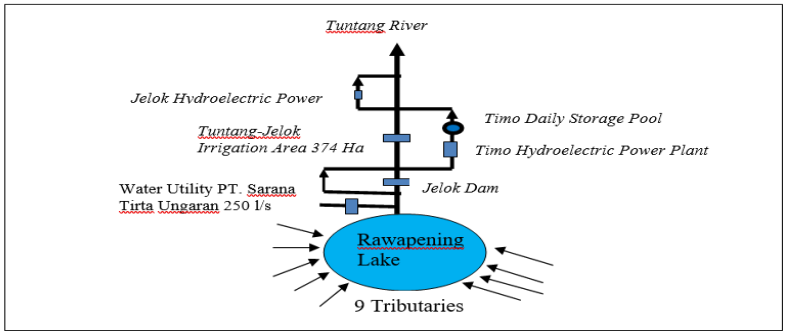

Fig. 1. Scheme of the Rawapening Lake system (BBWS Pemali Juana, 2024)

Table 2. Quality of Lake Rawapening

Parameter	Unit	Concentration Range	Water Quality System Compared to BMA			
			I	II	III	IV
TSS	mg/L	140.9-242.1	Not meet standard limits	Not meet standard limits	meet standard limits	meet standard limits
Total P	mg/L	0.1-0.2	Not meet standard limits	Not meet standard limits	meet standard limits	meet standard limits
COD	mg/L	22.1-29.2	Not meet standard limits	Not meet standard limits	meet standard limits	meet standard limits
BOD	mg/L	3.6-5.0	Not meet standard limits	Not meet standard limits	meet standard limits	meet standard limits
H_2S	mg/L	0.005-0.01	Not meet standard limits	Not meet standard limits	meet standard limits	meet standard limits
Total Coliform	mg/L	5.500-6.800	Not meet standard limits	Not meet standard limits	Not meet standard limits	Not meet standard limits
Pb	mg/L	0.02-0.03	Not meet standard limits	Not meet standard limits	Not meet standard limits	Not meet standard limits
Cd	mg/L	0.01-0.02	Not meet standard limits	Not meet standard limits	Not meet standard limits	Not meet standard limits

Source: Piranti *et al., 2018*

The sources of sedimentation in Lake Rawapening

Various uncontrolled activities affect the ecosystem of Lake Rawapening, especially through pollution from river flows, domestic waste, tourism, agriculture, and fish farming. Organic sediments from the decomposition of water hyacinth, household waste, and fish feed trigger eutrophication, increasing water fertility but harming biodiversity. As a result, the growth of water hyacinth has become increasingly difficult to control due to the high nitrogen and phosphorus content from agricultural waste and leftover fish feed. Since the 1920s, water hyacinth has been a problem, with coverage reaching 65% in 2005, even increasing to 70% during the dry season (Piranti *et al., 2*023; Nugroho, 2024).

Quality of Lake Rawapening

The results of a three-month observation by Piranti et al. (2023) showed that eight water quality parameters of Lake Rawapening exceeded the standard limits, including TSS, BOD, COD, orthophosphate, Total Coliform, H_2S, Cd, and Pb. This condition renders the lake water unsuitable for consumption, irrigation, or recreation, potentially posing health risks, disrupting the agricultural sector, and diminishing the attractiveness and economic value of tourism. The quality of Lake Rawapening is presented in Table 2.

Respondent lake sediment management

The respondents in this study are key informants, primary informants, and supporting informants who constitute the sample of this research. The description of the respondents

Table 3. Characteristics of Respondents Based on Gender

Type Gender	Key Informant		Main Informant		Supporting informant	
	--People--	--%--	--People--	--%--	--People--	--%--
Women	7	38.9	2	13.3	0	0
Men	11	61.1	13	86.7	3	100
Total	18	100	15	100	3	100

Table 4. Characteristics of Respondents Based on Type of Institution

Agency	Key Informant		Main Informant		Supporting informant	
	--People--	--%--	--People--	--%--	--People--	--%--
Government Agency	7	38.9	2	13.3	0	0
Educational Institution	4	22.2	0	0	3	100
Research Institution	3	16.7	0	0	0	0
Community Social Affairs Agency	4	22.2	0	0	0	0
Not tied to an institution	0	0	13	86.7	0	0
Total	18	100	15	100	3	100

selected as the research sample is categorized based on their characteristics, namely gender, institution, and educational level.

Based on Table 3, there are 18 key informant respondents, 61.1% were male and 38.9% were female. Meanwhile, out of the 15 main informants, 86.7% were male, and out of the 3 supporting informants, all were male. This data shows the dominance of men in the research, which can affect the perception of credibility. Previous studies have mentioned that the differences in experiences and perspectives between men and women can provide more comprehensive insights, making balanced gender representation important to reduce bias in research (Saranza *et al.,* 2024).

Based on Table 4, there are 18 key informant respondents, 38.9% work in government agencies, 22.2% in educational institutions, 16.7% in research institutions, and 22.2% in social communities. Meanwhile, out of the 15 main informants, 13.3% work in government agencies and 86.7% are not affiliated with any institution. In addition, there are 3 supporting informants from among the students. Institutional representation influences the credibility of research, strengthens the legitimacy of findings, and enhances public trust through balanced and inclusive representation (Gamer, 2024).

Based on Table 5, there are 18 key informant respondents, 16.67% have a high school/ vocational school education, 5.56% have an associate degree, 27.78% have a bachelor's degree, 27.78% have a master's degree, and 22.22% have a doctoral degree. Meanwhile, out of the 15 main informants, 93.3% have a high school/vocational school education and 1 respondent has a associate degree education. The three supporting informants also have a high school/vocational school education. Educational background influences a person's understanding and cognitive abilities in absorbing insights and solving problems. Education also plays a role in shaping the credibility of research findings, ensuring that respondents have an adequate understanding of the research context (Radionova *et al.,* 2024).

Validity and Reliability

The validity test shows that the sustainability analysis instrument is valid with a Pearson correlation value > 0.432 and significance < 0.05 in all dimensions. The reliability test also shows that this instrument is reliable with a Cronbach Alpha value > 0.60, making it suitable for use in research.

Table 5. Characteristics of Respondents Based on Education

Education	Key Informant		Main Informant		Supporting informant	
	--People--	--%--	--People--	--%--	--People--	--%--
High School	3	16.67	14	93.3	3	100
Associate Degree	1	5.56	1	6.7	0	0
Bachelor's Degree	5	27.78	0	0	0	0
Master Degree	5	27.78	0	0	0	0
Doctoral Degree	4	22.22	0	0	0	0
Total	18	100	15	100	3	100

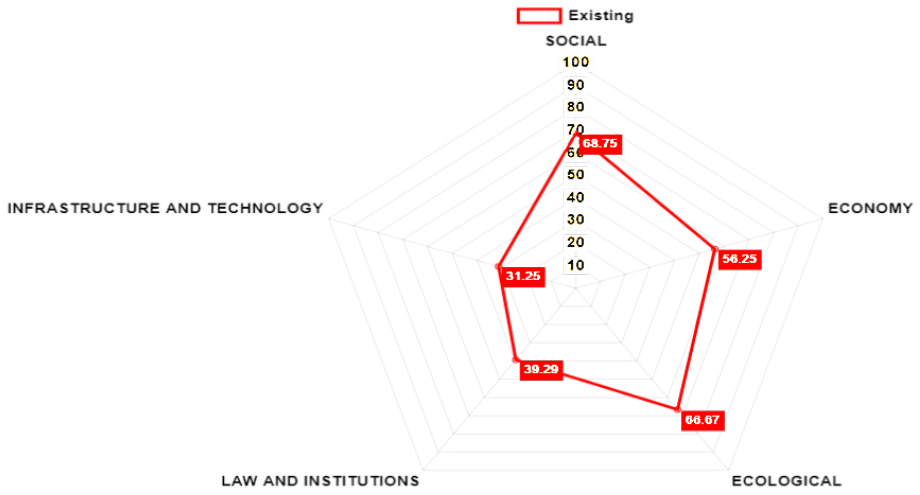

Fig. 2. Graph of the Sustainability Status of Sediment Utilization

Multi-Faceted Sustainability Analysis

The sustainability level of sediment utilization is assessed using the MSA method, with an in-depth analysis of the factors influencing it (Firmansyah, 2022). The proposed hypothesis states that community involvement enhances the sustainability of the sediment utilization system in Rawapening, highlighting key attributes in environmental, social, economic, legal, institutional, technological, and infrastructural aspects.

Based on Fig. 2. it is stated that the research results from the sustainability analysis of sediment utilization in Lake Rawapening show that the social index value is higher than that of law and institutions, infrastructure and technology, economy, and environment. This is due to the various benefits of sediment utilization for the community. The utilization of sediment plays a role in supporting agricultural activities; sediment can enhance plant growth and yield, thereby increasing the socio-economic benefits for farmers (Talukdar *et al.,* 2021). Additionally, sediment management practices can create jobs and additional income for local residents, thereby enhancing social welfare (Talukdar *et al.,* 2021). The social benefits derived from sediment utilization often exceed the direct economic benefits, as these benefits encompass broader societal impacts, including improved livelihoods and social cohesion (Braga *et al.,* 2023).

Social Dimension

The social dimension in the utilization of sediment from Lake Rawapening reflects support or obstacles to the sustainability of its management. Five main attributes that influence this dimension include conflicts of interest in sediment utilization, workplace safety through procedures, and the active role of the community in monitoring and decision-making. In addition, socialization and education play a crucial role in raising awareness about effective

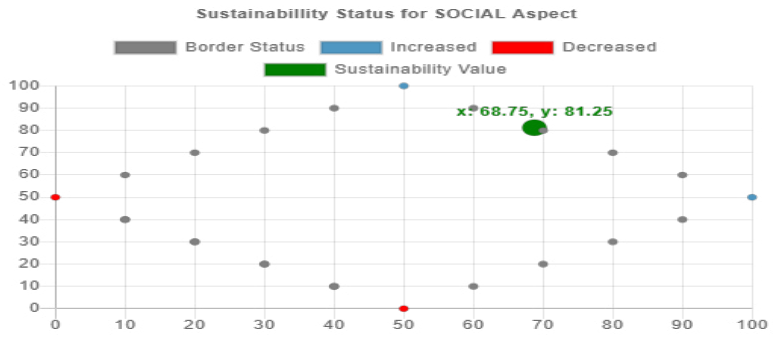

Fig. 3. Status of Social Aspect Sustainability

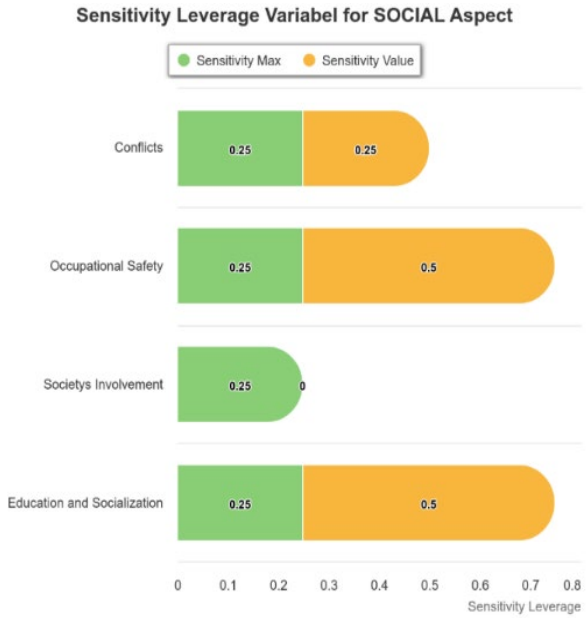

Fig. 4. Leverage Sensitivity of Social Aspects

and sustainable sediment management. Leverage analysis is used to identify the potential social benefits of sediment utilization by evaluating various scenarios and their impacts, as well as demonstrating the contribution of the social dimension to the sustainability of sediment management. The leverage analysis of the social dimension is presented in Fig. 4.

Based on Fig. 4. Socialization, education, and workplace safety in sediment utilization are the most sensitive indicators in the social aspect with a sensitivity value of 0.5. Training is necessary to prevent accidents and ensure the safe and sustainable use of sediment. The implementation of safety protocols reduces risks for workers and ensures compliance with health regulations. Socialization aims to enhance the understanding of the community, workers, and stakeholders regarding best practices in sediment management and its impact on the environment and health. Education through training equips individuals with skills that support better practices and enhance community engagement (Nugroho, 2024).

The occurrence of Conflict in sediment utilization has a sensitivity index of 0.25, caused by unclear or overlapping policies, such as Presidential Regulation No. 60 of 2021 and Government Regulation No. 37 of 2010, which restrict the use of sediment from public water sources. In addition, the presence of toxic substances such as heavy metals raises concerns regarding safety in agriculture and other applications. Studies show that strict regulations, such as those in Lake

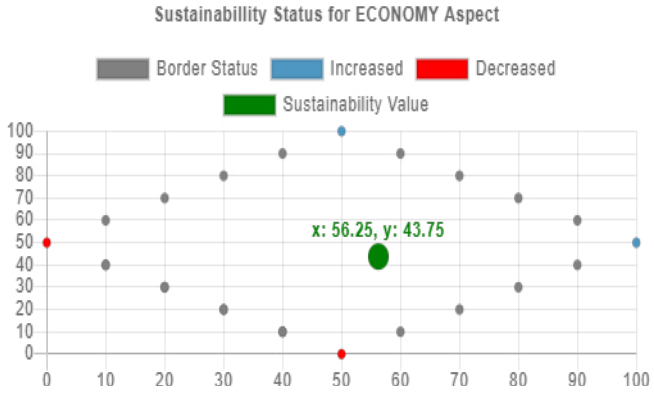

Fig. 5. Status of Economic Sustainability Aspect

Nasser and Southern California, limit innovation in sediment management. A comprehensive approach is needed to address conflicts, ensure fair distribution of benefits, and minimize threats to sustainability (Hennings, 2021).

The community plays an important role in the utilization of sediment related to social, economic, and environmental aspects. Sediment management reflects human activities that influence the dynamics of aquatic ecosystems. The optimization of river sediments for agriculture can enhance productivity and socio-economic benefits. In addition, the reuse of dredged materials supports a circular economy by turning waste into valuable resources. An interdisciplinary approach is necessary to address changes in sediment flow due to human activities for sustainable development and environmental management. (Talukdar *et al.,* 2021).

Community participation in the utilization of sediment can enhance agricultural practices and well-being, especially in rural areas. The use of sediment as soil fertilizer enriches nutrients, supports sustainable agriculture, and increases crop yields and food security. Moreover, the ecological use of sediments can help maintain water quality and support irrigation and household needs (Braga *et al., 2*023).

Economic Dimension

The economic dimension reflects the welfare and financial stability of an individual, group, or society as a whole around Lake Rawapening. The potential of sediment can provide financial benefits and support the welfare of the local community. Lake sediments can be utilized as organic fertilizers, creating business opportunities, increasing income, and generating jobs. The understanding of the economic dimension within the framework of sustainable regional development is translated into four attributes that operationally can collectively describe the conditions from the economic dimension perspective.

Leverage analysis is used to identify the potential economic benefits generated from sediment utilization. This analysis illustrates various scenarios and potential economic impacts, as well as demonstrating how the economy significantly contributes to the sustainability of sediment utilization. The leverage analysis of the economic dimension is presented in Fig. 6.

Based on Fig. 6. the utilization of lake sediments has high economic potential, especially with a product selling price reaching 95.000/M³ with a sensitivity of 0.75, indicating its impact on economic sustainability. However, the low selling price of raw sediment reduces market interest, especially from fertilizer producers and mushroom farmers. Processing sediment into construction materials such as paving blocks can increase added value and profit. In addition, sediment is also beneficial for improving the quality of agricultural land and crop yields.

In addition to direct economic value, sediment utilization contributes to job creation with

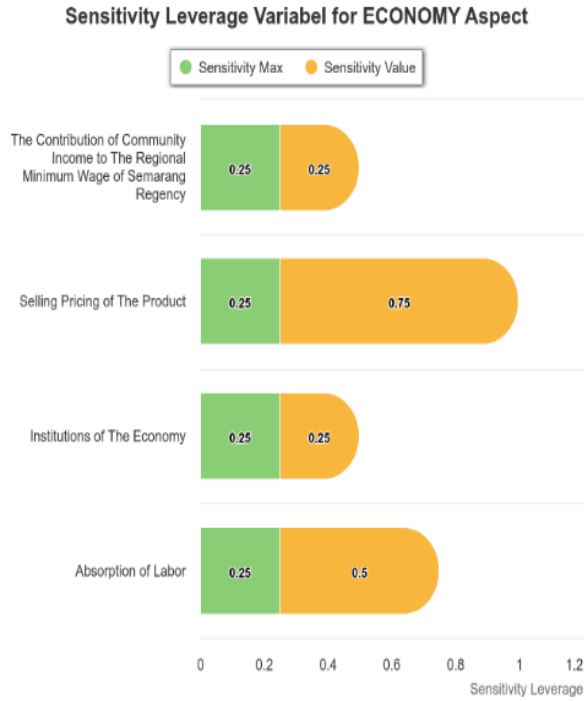

Fig. 6. Leverage Sensitivity of Economic Aspects

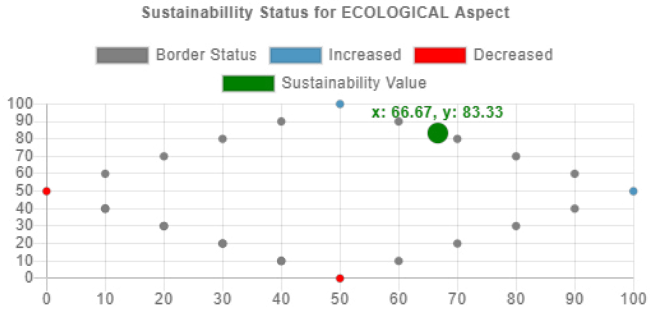

Fig. 7. Status of Environmental Aspect Sustainability

a sensitivity of 0.50, covering the sectors of machine operation, logistics, and agriculture. Reclamation and ecosystem restoration projects also absorb labor in the environmental sector and have the potential to boost the tourism sector around the lake. However, the contribution of income from sediment utilization to the minimum wage of the community in Semarang Regency has a lower sensitivity (0.25), indicating that the direct impact on community income is still limited.

The income from the utilization of sediment in Lake Rawapening is only IDR 2.558.500, slightly below the minimum wage of Semarang Regency. (IDR 2.582.287). The low income is caused by the suboptimal processing of sediment into value-added products, unlike studies that show that lake sediment can provide significant economic benefits to the surrounding community. (Braga *et al., 2*023). The nutrient content of sediments allows their use as fertilizers, increasing crop yields and farmers' incomes by up to 48% for crops such as corn and cabbage (Braga *et al., 2*023). In addition to direct economic benefits, the utilization of sediments reduces fertilizer costs by up to 30% and supports sustainable land management, enhancing food security and environmental health. (Susanto *et al., 2*024).

Economic institutions, despite having low sensitivity (0.25), still play a crucial role in

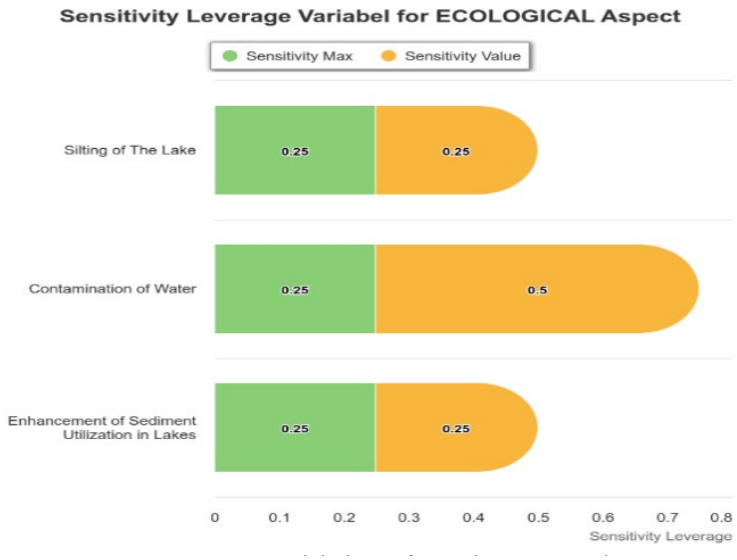

Fig. 8. Leverage Sensitivity of Environmental Aspects

supporting sediment utilization through regulation and cross-sector collaboration, including the roles of the government, environmental agencies, and communities. Institutional support includes environmental impact monitoring, funding, and infrastructure that help prevent pollution risks and maximize economic benefits sustainably. (Susanto *et al., 2*024).

Environmental Dimension

The environmental dimension reflects the factors that influence human understanding and interaction with the ecosystem. The environment is viewed as a dynamic system influenced by various interconnected aspects. In the context of sustainable sediment utilization, the environmental dimension is translated into three main attributes that describe its ecological condition. Leverage analysis is used to identify the environmental benefits of sediment utilization, evaluate various scenarios and the resulting ecological impacts, and demonstrate the role of the environment in supporting the sustainability of sediment utilization. The leverage analysis of the environmental dimension is presented in Fig. 8.

Based on Fig. 8. sensitivity data shows that water pollution in lakes has the greatest impact on the ecosystem with a sensitivity value of 0.5. The increase in pollution poses a significant threat to water quality and the ecosystem due to factors such as habitat degradation, invasive species, and chemicals from industry and agriculture. (Singh, 2024). Invasive aquatic plants also worsen water quality by reducing oxygen levels and increasing the risk of flooding. (Huang *et al., 2*022).

Lake ecosystem management requires strategies focused on pollution reduction and eutrophication control through waste management, water quality monitoring, and environmental education (Huang *et al., 2*022). The utilization of sediments can reduce sedimentation and support land rehabilitation. (Yang *et al.,* 2024). Additional strategies such as tree planting and erosion control are necessary to maintain ecological balance and water quality. (Yang *et al.,* 2024).

Sedimentation and sediment utilization have a lower sensitivity (0.25), indicating a moderate yet still significant impact. Sedimentation reduces lake capacity and risks disrupting power plant operations and water supply. (BBWS Pemali Juana, 2024). It also affects biodiversity and fish resources, as seen in Dongting Lake. (Huang *et al., 2*022).

The utilization of sediments can help address the impacts of siltation, support the efficiency

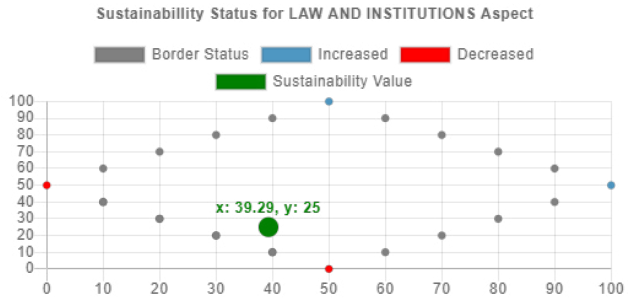

Fig. 9. Sustainability Status for Legal and Institutional Aspects

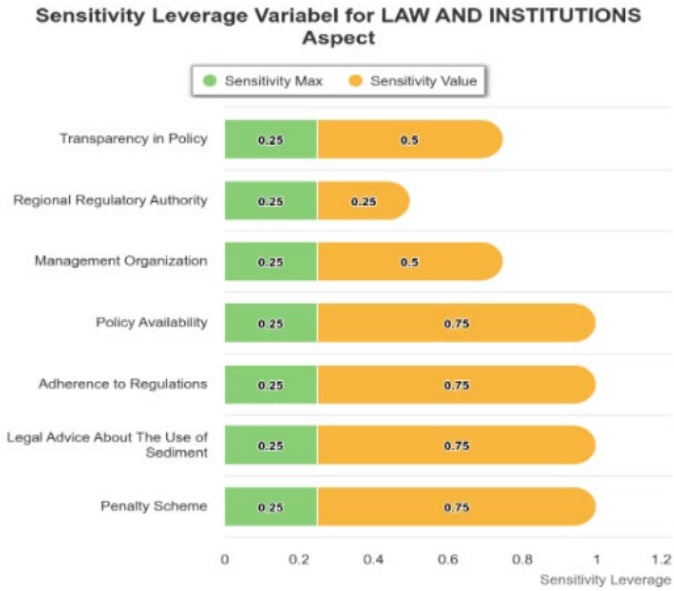

Fig. 10. Leverage Sensitivity of Legal and Institutional Aspects

of water systems, and contribute to land rehabilitation as well as the local economy. It also helps manage waste and reduce heavy metals in the environment, with the potential to support sustainable development through water absorption and pollution control in urban areas. (Cai *et al., 2*021; Huang *et al., 2*022).

Legal and Institutional Dimension

The legal and institutional dimensions in sediment utilization emphasize the importance of clear regulations and competent authorities to oversee and enforce the law. This aims to ensure that sediment utilization occurs sustainably without harming the environment, preventing conflicts, and maintaining ecosystem balance. The synergy between strong regulations and effective institutions is key to creating fair and sustainable sediment governance. Understanding of these legal and institutional aspects is translated into seven attributes that describe its operational conditions. Leverage analysis is used to identify the legal and institutional benefits of sediment utilization by evaluating scenarios and the impacts of regulations and institutions. Through this approach, the effectiveness of policies and institutional support can be optimized to maximize benefits and minimize risks in sediment management. The leverage analysis of the legal and institutional dimensions is presented in Fig. 10.

Based on Fig. 10. the legal and institutional aspects in the utilization of sediment are greatly influenced by policies, regulatory compliance, legal socialization, and the sanction system, which have high sensitivity (0.75). Effective regulations play a role in maintaining sediment quality

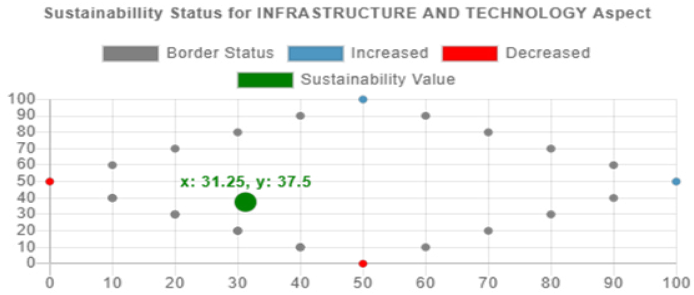

Fig. 11. Sustainability Status for Infrastructure and Technology Aspects

and preventing pollution, although challenges such as economic impacts and policy barriers remain. Various international policies have been implemented to manage sediment sustainably, such as the EU Water Framework Directive and the Louisiana Sediment Management Plan (Bussettini & Schmitt, 2022; Leppanen *et al., 2*024).

Compliance with regulations is important in sediment management and requires toxicity testing standards to assess environmental risks. A strong sanctions system is also necessary to address sediment pollution, while automation technology can enhance efficiency and compliance with environmental standards. Legal assistance in sediment management highlights the importance of dam owners' responsibility and policy transparency to ensure sustainable practices (Bussettini & Schmitt, 2022; Leppanen *et al., 2*024)

Organizational management in sediment utilization requires coordination among various parties, especially in facing challenges such as rising sea levels and environmental impacts. However, local regulatory agencies have a lower influence (0.25) compared to other factors, although they still play a role in enforcing sediment quality standards and environmental protection at the regional level (Bussettini & Schmitt, 2022; Leppanen *et al., 2*024).

Infrastructure and Technology Dimension

The dimensions of infrastructure and technology in sediment utilization emphasize the importance of physical facilities and technical innovations to support effective and sustainable sediment management. Adequate infrastructure, such as processing facilities and transportation systems, ensures the safe and efficient extraction and distribution of sediment. Technology plays a role in increasing efficiency through advanced monitoring and environmentally friendly processing methods. The four main attributes in this dimension are technological mastery, infrastructure availability, distribution and transportation systems, and data and information management. Leverage analysis is used to identify the potential of infrastructure and technology from sediment utilization, evaluate various scenarios and their impacts, and reveal how the implementation of infrastructure and technology solutions can enhance the efficiency and sustainability of sediment management. The analysis of the legal and institutional dimensions of leverage is presented in Fig. 12.

Based on Fig. 12. the leverage sensitivity graph for infrastructure and technology aspects, there are four main variables analyzed. The availability of infrastructure, distribution and transportation systems, as well as data management and organization systems, show high sensitivity with a value of 0.75. This indicates that these variables are highly sensitive and have a significant impact on the success of infrastructure and technology aspects. Changes in these variables can significantly affect the operational effectiveness and sustainability of technology and infrastructure.

The availability of sediment utilization infrastructure is very important for the management and recycling of sediment waste in urban environments. Dredged sediment has the potential

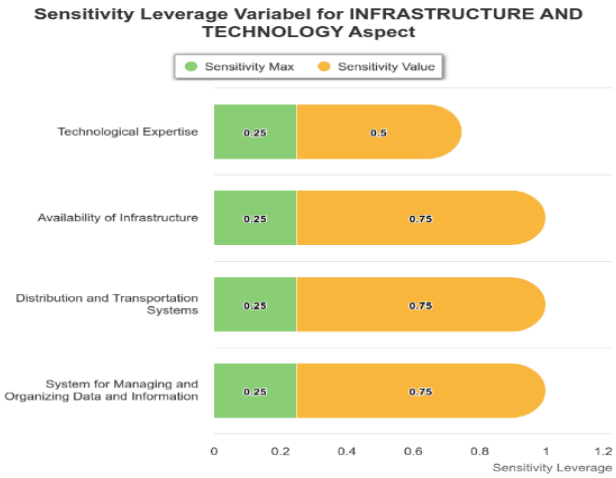

Fig. 12. Leverage Sensitivity of Infrastructure and Technology Aspects Illustration

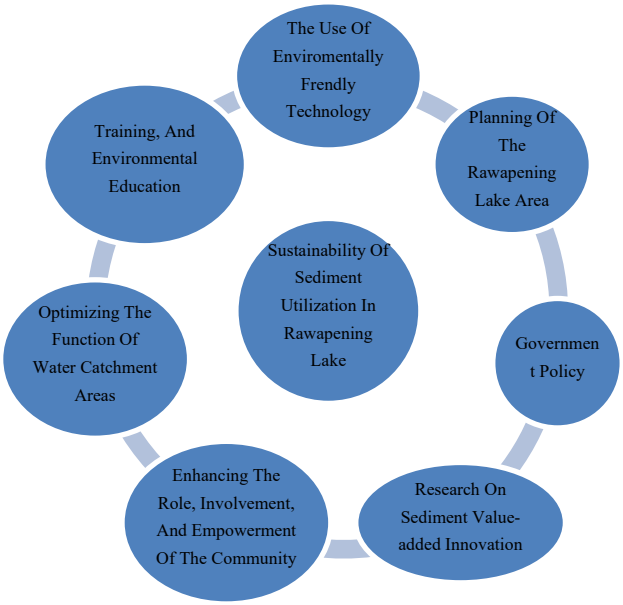

Fig. 13. Development of Sediment Utilization in Rawapening Lake

to be utilized in infrastructure development, land reclamation, and agriculture by improving soil quality and water conservation. However, regulatory constraints and the need for testing hinder widespread implementation. Innovations such as more effective drainage designs can also support environmentally friendly infrastructure. Although the opportunities are great, the existing challenges need to be addressed to maximize the benefits in sustainable urban development (Braga *et al., 2*023).

Technology mastery has a moderate sensitivity (0.50), so although it is important, its impact is not as significant as other variables. Therefore, the focus needs to be directed towards the development of adequate infrastructure, effective distribution and transportation systems, as well as efficient data management. Mastery of technology in sediment utilization involves the integration of innovative methods to process and recycle contaminated sediment, which is essential for environmental sustainability.

Advancements in zero-emission sediment processing technology and the 4Rs enable the

separation of sediment into useful materials for construction and landscaping. Additionally, the utilization of iron-containing sediments can reduce pollution while simultaneously creating new raw materials. Ex-situ remediation technologies, such as sediment washing and biological treatment, also support the sustainable management of heavy metal contamination, strengthening ecological recovery and resource utilization (Xu & Wu, 2023).

Current Government Policies at Rawa Pening Lake

The current government policy in rehabilitating Rawa Pening Lake often lacks focus on strengthening policy strategies because each change in government leadership frequently leads to shifts in work programs and does not continue existing work programs. Additionally, there are often overlapping regulations that result in a lack of exclusivity in management mandates, policy management, and management effectiveness (Tintingon *et al., 2*023). This is in line with what was expressed by an academic from Diponegoro University during an interview, stating that:

"Currently, the existing policies in sediment management at Rawa Pening Lake lack clarity and exclusivity in their mandates, which can hinder the effectiveness of efforts to rehabilitate Rawa Pening Lake. Rawa Pening Lake is currently in a crisis status due to the accumulation of sediment in the lake and is now one of the 15 lakes prioritized based on Presidential Regulation No. 60 of 2021 due to high environmental degradation." Integrated policy strategies require extensive consultation and a multi-sector team to develop robust policies.- Prof Naning

The lack of clarity and exclusivity in the mandate can hinder policy effectiveness, requiring extensive consultations and a multi-sector team to develop robust management policies (Tintingon *et al., 2*023). Integrated policy strategies for lake rehabilitation emphasize a multifaceted approach that combines ecological, social, and governance elements to address the complex challenges faced by lake ecosystems. Global assessments highlight the importance of engaging various stakeholders and cross-sector collaboration as crucial factors for the success of lake restoration, noting that nutrient enrichment, climate change, and species in the lake need to be addressed through comprehensive strategies (Poikane *et al., 2*024). The success of the Alte Donau restoration in Austria illustrates the effectiveness of a holistic management approach that includes both internal and external actions, such as nutrient reduction, biomanipulation, and technical interventions to restore and maintain water quality (Poikane *et al., 2*024). Additionally, sustainable planning and green infrastructure strategies are crucial for long-term lake restoration, as they integrate natural systems into urban planning to support ecological resilience (Poikane *et al., 2*024).

The Impact of Government Policies in the Future on Rawa Pening Lake

If the current policies are not adjusted regarding clarity and exclusivity in the mandate, they may hinder the effectiveness of lake management policies (Tintingon *et al.,* 2023). In the future, Lake Rawapening will face ecological challenges that threaten the sustainability of the lake and will continue to experience degradation. This is in line with previous research (Sanjaliwala & Bhargava, 2021) which found that the governance of Gundalav Lake in India is often hindered by a disconnect between policy implementation and community involvement, jeopardizing the sustainability of the lake's ecosystem and potentially increasing the lake's pollution levels.

Globally, lakes are influenced by human activities, necessitating integrated restoration efforts and preventive measures to maintain ecological balance. Sediment management policies must be improved with clearer regulations, multi-stakeholder involvement, public participation, and a comprehensive approach to achieve sustainable lake management (Kalmah *et al., 2*022; Tintingon *et al., 2*023; Meshram *et al., 2*023).

Government policies regarding lakes in the future will be influenced by environmental governance, climate change adaptation, and integrated management strategies. Good policies

can drive economic and ecological development through inter-agency collaboration (Meshram *et al.,* 2023). Climate change adds challenges, such as in Bhandara District, which proposes inter-lake connections for water management and food security. A study in Lake Balaton emphasizes the importance of expert-based policies and public participation, while research in France highlights the need for innovative approaches in predicting the impact of land use changes on lake eutrophication (Meshram *et al.,* 2023).

CONCLUSION

The utilization of sediment has a very large potential in various aspects of life, ranging from the economy, environment, social, to technology. This is evidenced by the research results at Lake Rawapening, therefore:

1. The environmental dimension sustainability index reached 66.67%, indicating a positive contribution to sustainability growth. The social dimension has the highest influence (68.75%), followed by the economic dimension (56.25%), legal and institutional (39.29%), and infrastructure and technology (31.25%).

2. This study identifies 11 attributes that influence the sustainability of sediment utilization. The environmental dimension includes water pollution, the social dimension encompasses socialization, education, and occupational safety, while the economic dimension focuses on price. In the legal and institutional dimension, the factors at play are the availability of policies, legal compliance, legal counseling, and the sanction system. Meanwhile, the technology and infrastructure dimension includes data management, infrastructure availability, and distribution systems.

GRANT SUPPORT DETAILS

Many thanks to Faculty of Animal Science and Agriculture, Diponegoro University and the National Research and Innovation Agency for research funding assistance.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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