ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of Geography Vol 56, No 3 (2024): 417-428
DOI: 10.22146/ijg.979061 website: https://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY

RESEARCH ARTICLE

Environmental Degradation Analysis of Former Bengawan Solo River Lake Ecosystem

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Received: 2024-07-05
Revised: 2024-08-08
Accepted: 2024-10-17
Published: 2024-10-18

Key words: Bengawan Solo Lake Degradation, Erosion, lake water pollution, Lake Shrinkage

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Abstract The ecosystem of the former river section lake in the research area formed by the straightening of the river and located in the Sub-Urban area, faces significant environmental degradation such as pollution, erosion, and water shrinkage that threaten its sustainability. The magnitude of environmental degradation that occurs needs to be studied because it can result in a reduction in clean water and shallowing of the lake. Compared with lakes such as Poyang Lake in China, which has experienced a decline in water quantity and quality due to seasonal fluctuations, climate change and waste, this study offers a similar perspective by highlighting the interaction of natural and human factors, and adds a new dimension related to degradation caused by erosion. This study uses a comprehensive approach, namely by combining image analysis, field measurements using measuring sticks, USV, geodetic GPS, laboratory analysis, and interviews. The results of the study indicate that the lake water quality status ranges from “moderately polluted” to “heavily polluted,” while the groundwater quality varies from “meets quality standards” to “lightly polluted.” The high water quality status is caused by human activities and land conditions, as well as the high rate of erosion around the lake reaching 289.63 tons/ha/year, with an average soil loss of 0.11 tons/year. In addition, the lake in the study area has shrunk by up to 72% due to seasonal fluctuations and climate change. Based on this, effective management is needed to maintain the ecological balance and environmental health of the former river section lake.

1. Introduction

Lake ecosystems play a vital role in conserving biodiversity, regulating hydrological processes, and providing essential resources for communities, such as drinking water, fisheries, and recreational opportunities (Albert et al., 2020; Heino et al., 2020). They also support a variety of flora and fauna, act as natural water storage units, and contribute to local climate regulation (Williams et al., 2019). In addition, lakes offer numerous socio-economic benefits, including tourism, cultural value, and recreation (Dupont et al., 2023). However, lake ecosystems are increasingly threatened by environmental degradation driven by both natural and human factors. Globally, many lakes are experiencing challenges such as pollution, sedimentation caused by soil erosion, and significant reductions in area and volume (Azareh et al., 2021; KemaloAbdulmalik & IsrealZewide, 2021; D’Odorico & Ravi, 2023; Yao et al., 2023).

In the context of the Bengawan Solo River in Indonesia, parts of the river have been transformed into lakes due to river straightening which now face serious environmental challenges such as pollution, erosion, and lake shrinkage. Pollution in lakes generally originates from surface and groundwater degradation, which has adversely affected local livelihoods, especially aquaculture and agriculture (Shah et al., 2020). In addition, sedimentation due to erosion exacerbated by reduced vegetation and inappropriate land use practices has contributed to lake siltation (Jana et al., 2021). These processes not only reduce the water storage capacity of lakes but also damage the physical properties of soils by reducing soil nutrients and moisture (Sobrinho & Barbosa, 2022). Furthermore, lake shrinkage is partly due to climate variability, which accelerates the degradation of lake ecosystems (Yao et al., 2023; Alizadeh et al., 2016).

Although the importance of lake ecosystems is widely recognized, previous studies have shown that climate variability, land degradation, and water pollution are the main contributors to their degradation (Saberi et al., 2023; Schmidt et al., 2020). However, there is still a significant gap in comprehensive studies examining the cumulative impacts of environmental degradation, especially those related to climate variation and human activities. Former riverbed lakes, formed by river truncation, exhibit unique hydrological and ecological characteristics that differ from typical lakes. Comprehensive studies integrating advanced monitoring technologies such as satellite imagery, field measurements, and stakeholder interviews are still limited, making it difficult to develop effective conservation and management strategies.

This paper introduces an innovative approach to understanding lake environmental degradation by utilizing a combination of modern methods, including satellite imagery, Unmanned Surface Vehicles (USV), and geodetic GPS measurements. These advanced techniques provide deeper insights into the dynamics of freshwater ecosystems. In addition, the pollution index methodology is applicable to a wide range of conditions so that it can be adapted to various freshwater ecosystems around the world. This study basically aims to determine the extent of degradation that occurs in former riverbed lake ecosystems. This study can make a significant contribution to the field of environmental engineering, focusing on the cumulative effects of human activities and climate change on aquatic ecosystems.

The novelty of this study lies in its comprehensive multi-method approach, combining USV for bathymetry measurements, satellite imagery for monitoring long-term lake shrinkage, and pollution indices integrated with soil erosion analysis. This approach introduces a new model for assessing environmental impacts quantitatively and sustainably, offering a standardized methodology that can be applied to a wide range of ecosystems worldwide. By focusing on the combined impacts of land-use change and climate variability, this study provides new scientific insights into freshwater ecosystem degradation, with global relevance beyond local case studies. These findings contribute to the growing body of research seeking to develop effective strategies for conserving and managing lake ecosystems in the face of increasing environmental challenges.

2. Methods

a. Research Area/Region.

The study area is in 2 Lake section of the former Bengawan Solo River in the Grogol District, Sukoharjo Regency, Central Java, Indonesia. This area was selected because it contains several lakes formed from old segments of the Bengawan Solo River, which face significant environmental challenges such as pollution, land use, and climate change. The two lakes are situated approximately 800 meters apart, with the following details:

1) Lake 1/DTPP (Telukan, Pondok, and Parangjoro Villages)

   Located at coordinates 110048’51.152” E, 7^{0}35’11.056” S to 110^{0}48’51.130” E, 7^{0}37’36.019” S and 110^{0}48’48.646” E, 7^{0}37’24.510” S to 110^{0}49’6,517” E, 7^{0}37’24,519” S with a research area of 22,68 Ha, and a lake area of 6,255 Ha

2) Lake 2/DPP (Pondok, and Parangjoro Villages)

   Located at coordinates110048’23,655” E, 7^{0}37’39,901” S sampai 110^{0}48’23,651” E, 7^{0}37’58,491” S dan 110^{0}48’13,821” E, 7^{0}37’50,993” S to 110^{0}48’29,424” E, 7^{0}37’50,987” S with a research area of 21,44 Ha, and a lake area of 3,417 Ha.

b. Research Method.

This study uses a systematic approach to understand environmental conditions, evaluate the impacts of degradation,

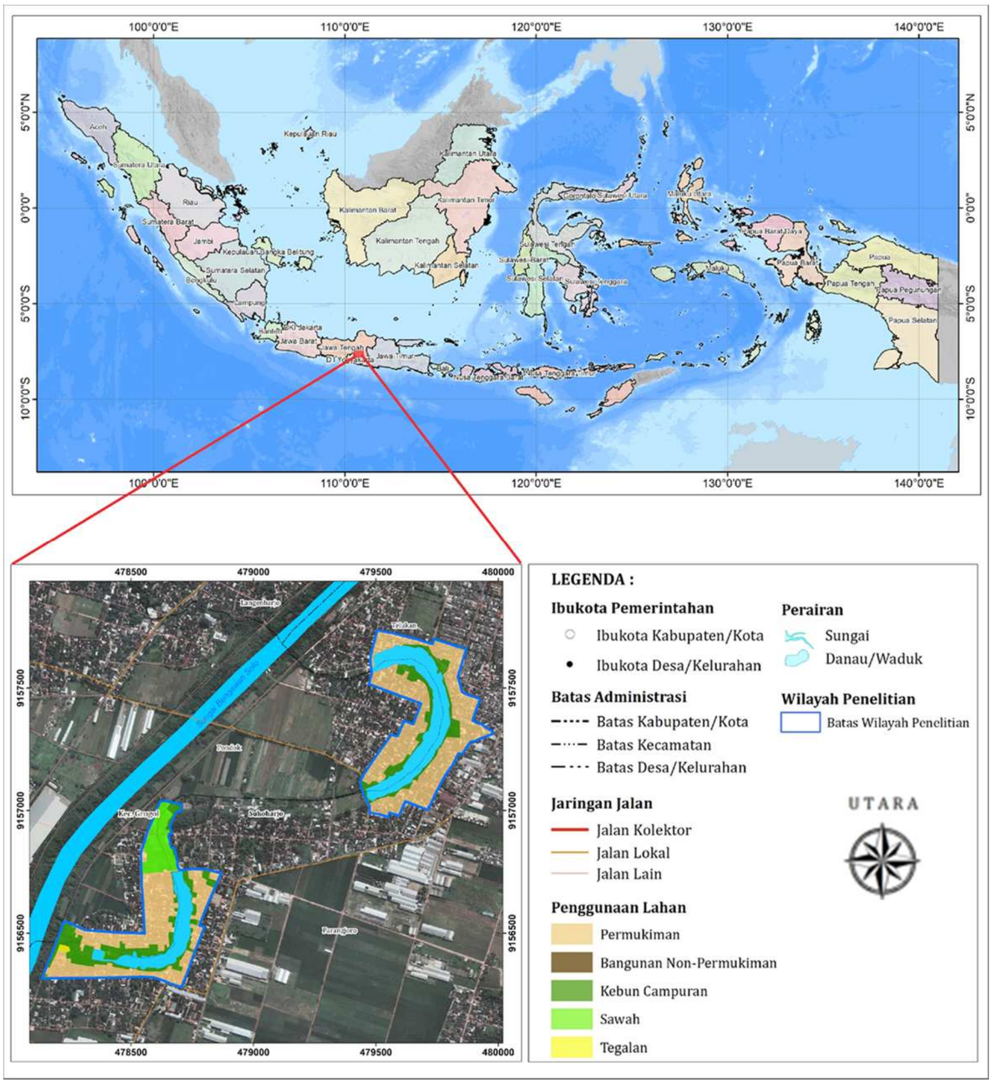

Figure 1. Research Area

and develop a deeper understanding of the factors that influence lake ecosystems. In its implementation, various government regulations and ministerial standards are used as the main references to ensure the quality and validity of the methods used in environmental analysis. Government Regulation No. 22 of 2021 concerning Environmental Protection and Management, and Government Regulation No. 82 of 2001 concerning Water Quality Management and Water Pollution Control, especially regarding Nitrate (NO3-N) and Nitrite (as N), are the main basis for water quality management and environmental protection. This standard is strengthened by the Regulation of the Minister of Environment No. 7 of 2006 which regulates the measurement procedure for standard criteria for soil degradation for biomass production. In addition, this study also refers to the Regulation of the Minister of Health Number 32 of 2017 concerning Environmental Health Standards and Health Requirements, and the Regulation of the Minister of Forestry of the Republic of Indonesia Number 32 of 2009 concerning Environmental Protection and Management, which have been modified according to research needs. Decree of the Minister of Environment No. 115/2003 was also used as an additional guideline to ensure that all aspects of environmental protection were covered.

This study applied a quantitative and multidimensional approach through a case study of two lakes formed from the straightening of the Bengawan Solo River. Data were collected through field observations including measurements of water quality, soil loss, and lake depth using Unmanned Surface Vehicles (USV); secondary data collection such as climate information and historical lake data through satellite imagery analysis; laboratory testing of water and soil parameters; and interviews with local stakeholders related to the management of the existing lake ecosystem. In addition, the analysis carried out included analysis of pollution (water quality status), erosion, and lake shrinkage (water quality status), erosion, and lake shrinkage.

1) Water Pollution

   Water pollution is related to water quality and is determined by measuring/testing using digital tools and laboratory equipment, both in surface water (lakes) and groundwater. Measurement/testing of the parameters for surface water quality (lake) in the laboratory includes TDS, TSS, COD, BOD, Phosphate, Nitrate, Cadmium, Chromium VI, Copper, Lead, Fluoride, Nitrite, Chloride, H2S, Detergents, Phenol, and Total Coliform. Surface water quality testing uses Lake Quality Standards in Government Regulation No. 22 of 2021 concerning Environmental Protection and Management combined with Government Regulation No. 82 of 2001 concerning Water Quality Management and Control of Water Pollution for Nitrate (NO3-N) and Nitrite (as N). While measurement/testing of parameters for surface water quality with digital tools only involves DO as per Lake Quality Standards stated in Government Regulation No. 22 of 2021 regarding Environmental Protection and Management. Groundwater quality testing at the laboratory covers Odor Taste Color Turbidity Iron Detergents Fluoride Hardness as CaCO3 Manganese Nitrate Nitrite pH Total Coliform. Groundwater quality testing uses Standard Ministerial Regulations Number 32/2017 Concerning the Standard of Environmental Health and Health Requirements.

   The status of water quality is assessed utilizing the Pollution Index technique, which is applicable to a sole water quality examination sample. This method provides a comprehensive and simplified representation of the complex water quality data (Ismail et al., 2023) (Rahmadi et al., 2023). The Pollution Index is employed to evaluate the comparative degree of pollution in relation to the authorized water quality criteria. The pollution index method is based on Decree of the Minister of Environment No. 115/2003, using the equation below.

$$PLj = \sqrt{\frac{(\frac{C_1}{L_{1j}})^2_M \, (\frac{C_i}{L_{ij}})^2_R}{2}}$$

   Information:
   PLj = pollution index for use j,
   Ci = concentration of water quality parameters i,
   Lij = concentration of water quality parameter i listed in water designation standard j,
   M = maximum,
   R = average.

2) Erosion

   The magnitude of erosion is indicated by calculating the erosion rate analyzed using the dipstick erosion method on certain land units that follow the Regulation of the Minister of Environment No. 7 of 2006 concerning Procedures for Measuring Standard Criteria for Soil Damage for Biomass Production, with slight adjustments according to field conditions in the study area. Calculation of the erosion rate using the dipstick method begins with measuring soil loss and conducting laboratory tests to determine the soil volume weight, which is then used to determine the erosion rate. The equations can be seen below.

   i. Land Loss (ton) (Sarminah et al., 2018)
      Soil loss (tons) = Average soil loss (m) x BV (tons/m3) x Plot area (m2)
   ii. Erosion Rate (ton/ha) (Sarminah et al., 2018)
      Erosion Rate (ton/ha) =
      Land Loss (ton) x $\frac{10.000\ (m^2)}{Erosion\ plot\ area\ (m^2)}$
   iii. Erosion Rate (ton/ha) (Sarminah et al., 2018)
      Erosion Rate (ton/ha/year) =
      Erosion Rate (ton/ha) x $\frac{Rainfall\ 1\ year\ (mm)}{rainfall\ during\ the\ study\ (mm)}$

   The erosion rate is then classified according to the Erosion Hazard Level based on the Regulation of the Minister of Forestry of the Republic of Indonesia Number 32 of 2009 concerning Environmental Protection and Management with its amendments. Understanding the level of erosion hazard is very important because it can identify areas at risk of erosion (Chen et al., 2007). The Classification of Erosion Hazard Levels can be seen in table 1.

3) Lake Water Depletion

   The reduction in lake water volume over a specific time, often attributed to climate change, is referred to as lake

Table 1. Erosion Hazard Level Classification

Soil Solum Thickness (cm)	Erosion Class				
	I	II	III	IV	V
	Erosion (ton/Ha/year)				
	< 15	15 - 60	60 - 180	180 - 480	> 480
There is no land/soil			S 0		
Deep (> 90)	VL I	L II	M III	H IV	VH V
Medium (60 – 90)	L II	M III	H IV	VH V	VH V
Shallow (30 – 60)	M III	H IV	VH V	VH V	VH V
Very shallow (< 30)	H IV	VH V	VH V	VH V	VH V

Source: Regulation of the Minister of Forestry of the Republic of Indonesia Number 32 of 2009 on Environmental Protection and Management with modification.

Information:
S 0 = Safe, VL I = Very Light, L II = Light, M III = Medium, H IV = Heavy, VH V = Very Heavy

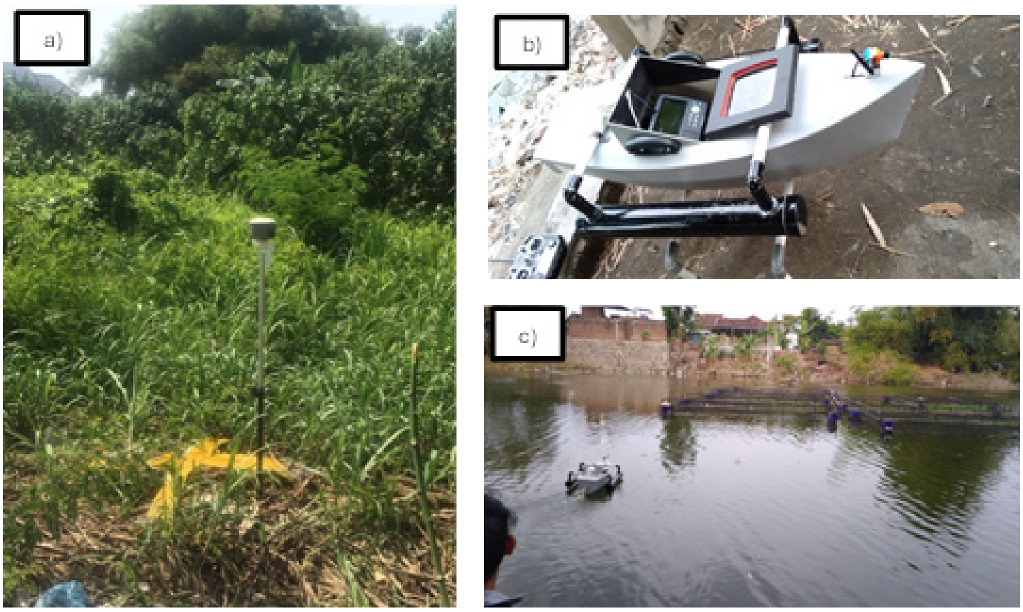

Figure 2. Crosscheck and measurement of underwater topography (bathymetry) using Geodetic GPS and USV in Grogol District, Sukoharjo Regency: (a) Use of Geodetic GPS to measure/record tie points; (b) USV appearance; and (c) Use of USV.

water recession. The magnitude of lake water recession is calculated based on field data, which is then integrated with satellite imagery to analyze the changes in lake area and extent. The satellite imagery selection encompasses two distinct conditions: one depicting extreme recession over a 10-year period, and the other reflecting the current state. To determine the lake's capacity and volume, the depth of the lake and its surrounding area is measured using an Unmanned Surface Vehicle and Geodetic GPS (Figure 2). Additionally, the extent of the recession is classified according to the percentage of water loss (0% = extremely safe – 100% = extremely vulnerable).

3. Result and Discussion

a. Water Polution

Analysis using the Pollution Index Method showed that the surface water quality of Lake DTPP falls under the "Heavily Polluted" classification, with several parameters exceeding the quality standards, such as Total Phosphate, Sulfur as H2S, Detergents, Phenols, and Total Coliforms. Meanwhile, Lake DPP is classified as "Moderately Polluted," with some parameters exceeding the standards, including Chemical Oxygen Demand, Biological Oxygen Demand, Total Phosphate, Sulfur as H2S, Detergents, Phenols, and Total Coliforms.

Furthermore, the groundwater quality of Lake DTPP is classified as "Meeting the Quality Standards," although some parameters, such as Detergents, Manganese, Nitrite, and Nitrate, exceeded the standards. Additionally, there was one parameter, Total Coliforms, that exceeded the standards in all wells but was not included in the Pollution Index analysis due to being uncountable. The groundwater quality of Lake DPP is classified as "Lightly Polluted," with some parameters, such as Detergents, Manganese, and Nitrate, exceeding the standards. Like Lake DTPP, there was one parameter, Total Coliforms, that exceeded the standards in all wells but was not included in the Pollution Index analysis due to being uncountable. The chart illustrating the water quality condition of the surface and groundwater in both lakes can be seen in table 2.

The high surface water quality status classified as moderately to heavily polluted is attributed to the presence

Table 2. Pollution Index Class Level

LOCATION		water quality status			
Average		Maksimum	PLj	Category	
1. Lake 1 (DTPP)					
a. Surface water		1,97	8,77	13,42	Heavy Polluted
b. Subsurface water	Well 10	0,99	2,42	0,7	Meets Quality Standards (Good Condition)
	Well 13	0,63	2,55	0,56	
2. Lake 2 (DPP)					
a. Surface water		1,45	7,37	5,41	Moderately Polluted
b. Subsurface water	Well 2	0,95	4,35	2,04	Light Polluted
	Well 8	0,41	1.47	1,12	

Source: secondary data processing, 2023.

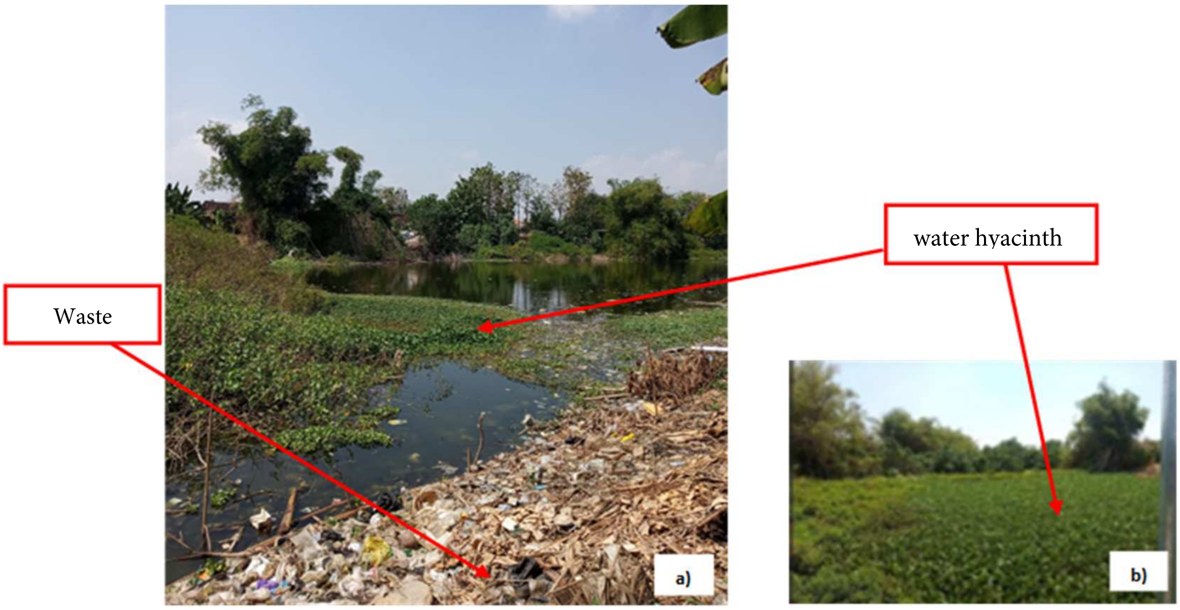

Figure 3. (a) illustrates the existence of refuse and water lily in the DPP lake ecosystem, whereas (b) portrays the occurrence of water lily in the DTPP lake ecosystem

of pollutant sources in the surrounding areas of the lake, such as domestic waste. The elevated concentrations of contaminants in the lake are likewise signified by the existence of water hyacinth flora, which act as a bioindicator of elevated metal contamination (Newete et al., 2014) (González et al., 1989) and can also reveal acidity levels (El-Gendy et al., 2004).

These findings are consistent with global trends in freshwater ecosystem degradation driven by human activities and climate change (Albert et al., 2020; Kamarudin et al., 2018). A comparable study in other regions, such as the severe pollution in Lake Taihu, China, reported contamination caused by runoff from intensive agricultural areas and domestic waste discharge from urban regions, leading to eutrophication and increased levels of heavy metals and nutrients in the water (Zhang et al., 2022).

The presence of household waste and agricultural runoff around these lakes serves as the primary source of pollution. This pattern is commonly observed in many freshwater systems worldwide, particularly those near densely populated or intensively farmed areas, as documented by Shah et al. (2020) and Jana et al. (2021) in their studies, which highlight how unmanaged waste contributes to water quality degradation, adversely affecting aquatic life and local human populations.

b. Erosion

In determining the locations for soil loss measurement and soil sampling, the parameters influencing erosion were found to be relatively consistent across the study area. As such, the primary criterion used to select the measurement and sampling points was the slope gradient.

1) Lake 1/DTPP (Telukan, Pondok, and Parangjoro Villages)

In the DTPP Lake in Sukoharjo Regency, erosion measurement plots were established at 3 locations consisting of PUE 1 installed in an area with a slope of 0^0-2.9^0/0%-5%, while PUE 2 and 3 are installed on slopes ranging from 2.9^0-11.3^0/5%-20% at different locations. Based on the measurement and analysis results, the erosion rate values for each plot range from 227.67 tons/ha/year to 360.76 tons/ha/year. The highest erosion rate is found in erosion plot 3 with an average erosion of 360.76 tons/ha/year and an average soil loss of 0.14 tons per year. Conversely, the lowest erosion value is found in erosion plot 1 with an average of 227.67 tons/ha/year and a soil loss average of 0.09 tons. Among all the erosion plots, the average erosion rate obtained is 289.63 tons/ha/year with an average soil loss of 0.11 tons. The results can be seen in table 3.

2) Lake 2/DPP (Pondok, and Parangjoro Villages)

In one plot of land (Plot Erosion Measurement) in Lake 1/DPP in Sukoharjo Regency, there are 4 locations consisting of PEM 4 installed on areas with slopes 0^0-2.9^0/0%-5%, PEM 5 installed on slopes 2.9^0-11.3^0/5%-20% in vegetated (5a) and non-vegetated (5b) areas, and PEM 6 installed on slopes 11.3^0-21.8^0/20%-40%. Based on the measurement and analysis results, it was found that the erosion rate in each plot ranged from 145.18 tons/ha/year to 454.02 tons/ha/year. The highest erosion rate was recorded in plot number 6 with an average erosion of 454.02 tons/ha/year, resulting in an average soil loss of 0.17 tons. The lowest erosion value is found in erosion plot 5b with an average value of 145.18 tons/ha/year, and an average soil loss of 0.06 tons, where the PEM location is in a vegetated (grassy) area. Among all the erosion plots, the average erosion value obtained is 287.56 tons/ha/year with an average soil loss of 0.11 tons. The results can be seen in table 4.

Based on the magnitude of erosion values and soil depth in the study area, it was found that almost the entire area around the lake falls under the moderate erosion hazard category, except for PEM 6, which falls under the severe erosion hazard category with an erosion value of 189.07 tons/ha/year at a soil depth of > 90 cm due to a moderately steep slope of 11.3^0-21.8^0/20%-40%. The table of erosion hazard levels for each erosion measurement plot in Lake DTPP and Lake DPP is presented in Table 5.

Based on the magnitude of erosion and soil depth in the research area, it was found that almost the entire area surrounding the lakes falls under a moderate erosion hazard level, except for PEM 6, which is classified as a severe erosion hazard with an erosion rate of 189.07 tons/ha/year at a soil depth of > 90 cm due to a relatively steep slope of 11.30-21.80/20%-40%. This can directly or indirectly lead to siltation, which may reduce the lake's storage capacity (Yudono et al., 2020).

The high erosion rates and levels of erosion risk are fundamentally associated with rainfall patterns, as indicated by prior research (Fu et al., 2021). However, other parameters such as soil type and characteristics also influence the magnitudes of erosion, playing a crucial role in determining soil erodibility (Négyesi et al., 2016). Based on historical rainfall analysis, it was found that increasing trends in precipitation are likely to correlate with elevated erosion rates (Kinnell & Wood, 1992), if other influential parameters remain constant (Babel, 2014). Moreover, the noted patterns in precipitation over the previous decade are illustrated in figure 4

Table 3 Erosion Rates in DTPP Lake

MEASUREMENT	Plot Erosion Measurement			Average
	PEM 1 (0^0-$2,9^0$/0%-5%)	PEM 2 ($2,9^0$-$11,3^0$/5%- 20%)	PEM 3 ($2,9^0$-$11,3^0$/5%- 20%)	
Land Loss (Ton)	0,09	0,11	0,14	0,11
Erosion Rate (Ton/Ha)	43,53	53,62	68,97	55,37
Erosion Rate (Ton/Ha/ year)	227,67	280,47	360,76	289,63

Source: secondary data processing, 2023.

Table 4 Erosion Rate in Lake DPP

MEASUREMENT	Plot Erosion Measurement				Average
	PEM 4 (0^0-$2,9^0$/0%-5%)	PEM 5 ($2,9^0$-$11,3^0$/5%- 20%)		PEM 6 ($11,3^0$-$21,8^0$/20%-40%)	
		Non-Vegetation (PEM 5a)	Vegetation (PEM 5b)		
Land Loss (Ton)	0,09	0,12	0,06	0,17	0,11
Erosion Rate (Ton/Ha)	46,68	58,67	27,76	86,80	54,98
Erosion Rate (Ton/Ha/year)	244,17	306,86	145,18	454,02	287,56

Source: secondary data processing, 2023.

Table 5. Erosion hazard levels for each erosion measurement plot in Lake DTPP and Lake DPP

Parameter	PEM 1	PEM 2	PEM 3	PEM 4	PEM 5a	PEM 5b	PEM 6
Erosion (Ton/Ha/Tahun)	94.809	116.794	150,23	101.68	127.79	60.46	189.07
Soil Depth (cm)	>90	>90	>90	>90	>90	>90	>90
Erosion Class	Medium	Medium	Medium	Medium	Medium	Medium	Heavy

Source: secondary data processing, 2023.

These rates are comparable to those observed in regions with similar topographic patterns and land use, such as Lake Tana in Ethiopia, which faces severe erosion challenges due to the conversion of forest land to agricultural use. This erosion exacerbates sedimentation in the lake, reducing water storage capacity and impacting the overall aquatic ecosystem (Bogale, 2020).

The high erosion rates worsen sedimentation, subsequently reducing the lake's water storage capacity and increasing the risk of flooding. This aligns with the findings of Fu et al. (2021), who demonstrated that increased erosion due to land use changes can lead to significant sediment deposits in water bodies

c. Lake Shrinkage

At DPP Lake, an investigation was conducted utilizing SPOT satellite imagery to assess the lake's area and the depth measurements (bathymetry) taken over the past decade. The findings revealed a volumetric decrease of 55,503.87 m3 (72%) in 2017 and 2018, indicating a substantial reduction in volume and a state of high susceptibility. Conversely, DTPP Lake has not exhibited any significant volume reduction over the same 10-year period according to the analysis of SPOT satellite imagery. The distinctions between DPP Lake in 2017 and 2018 are illustrated in the accompanying figure 5. The substantial shrinkage can be attributed to high evapotranspiration rates exceeding precipitation levels. This trend may also be exacerbated by the effects of climate change, which can

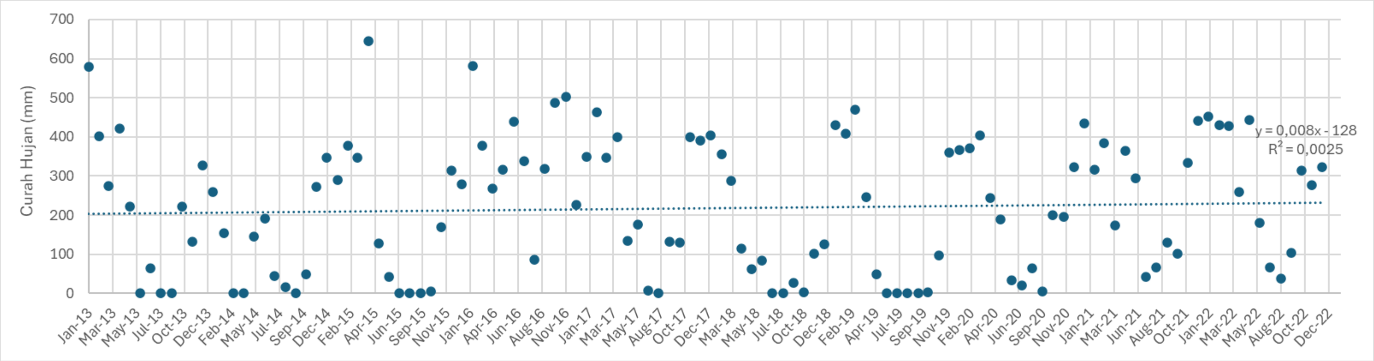

Figure 4. Trendline Graph of Rainfall for the last 10 years (2013-2022).

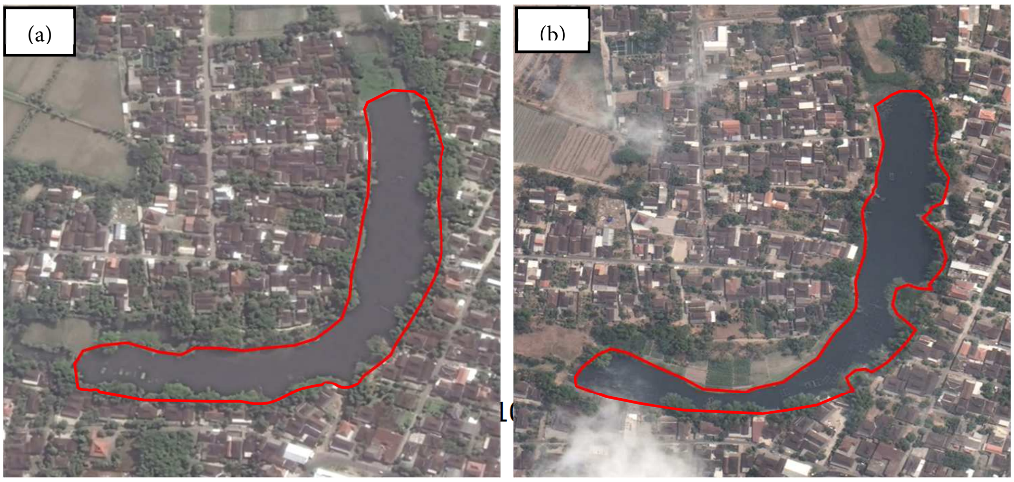

Figure 5 . Appearance of Lake Water Shrinking. (a) SPOT Satellite Image for May 2017; and (b) SPOT Satellite Image for September 2018

Figure 6. 3D appearance of DPP Lake, the data of which is used to determine the volume of lake water

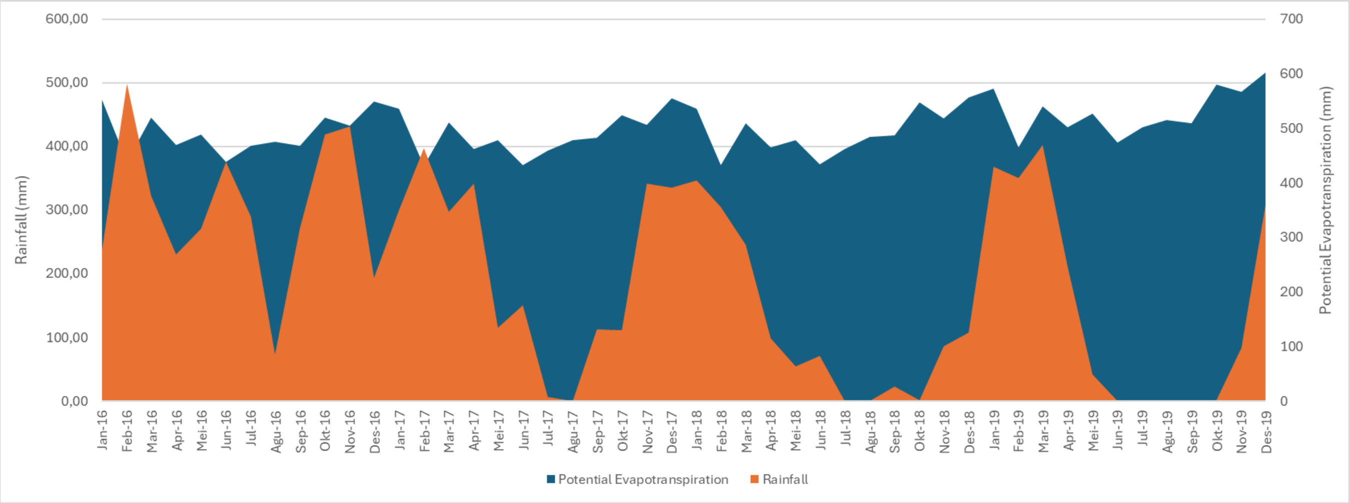

Figure 7. Influence between Rainfall and Potential Evapotranspiration

prolong dry seasons and shorten wet seasons (Tutuarima et al., 2021) (Sujarwo et al., 2020) (Suprianingsih et al., 2023), ultimately contributing to the lake's diminishing water levels. The following is a 3D view of the DPP lake and a visual representation of the lake's shrinkage and a graph depicting the relationship between rainfall and potential evapotranspiration can be seen in figure 6 and figure 7.

Lake DPP has shrunk by 72% between 2017 and 2018, primarily due to changes in rainfall patterns and evapotranspiration rates driven by climate change. Similar findings have been reported in studies of Lake Poyang in Tiongkok, where water volume reduction was caused by the impacts of climate change, including altered rainfall patterns and unsustainable water management practices. This decline affects the ecosystems and communities dependent on the lake (Li et al., 2020). In regions such as those under study and Lake Poyang, Woolway et al. (2020) emphasized the role of climate change in altering the hydrological cycle, leading to the depletion of freshwater resources. The interaction between human activities and climate variability exacerbates this issue, necessitating urgent intervention strategies for sustainable conservation and management.

4. Conclusion

This research provides in-depth insights into the environmental conditions of the lake ecosystem that was once part of the Bengawan Solo River in Sukoharjo Regency. The results are anticipated to be employed by municipal authorities to devise more efficient strategies for overseeing the lake ecosystem, by local populations to boost ecological consciousness, and by scholars for additional investigation on analogous topics in different areas.

The study results indicate that the water quality status of Lake DTPP falls under the "Heavily Polluted" classification, while the groundwater surrounding Lake DTPP is classified as "Meeting Quality Standards." Meanwhile, the water quality status of Lake DPP is categorized as "Moderately Polluted," and the groundwater around Lake DPP is classified as "Lightly Polluted." The elevated levels of contamination are ascribed to the existence of household refuse and farming operations in the surroundings of the lakes.

The soil erosion levels around Lake DTPP and DPP are extremely high, with average erosion rates of 289.63 tons/ha/year and 287.56 tons/ha/year, respectively, and an average soil loss of 0.11 tons. This significant erosion contributes to the siltation of the lakes, increasing the risk of flooding due to reduced lake capacity. The soil degradation is mainly induced by unregulated land-use modifications and the decrease of soil-retaining vegetation.

The shrinkage of Lake DPP, which reached 55,503.87 m^3 or 72% from 2017 to 2018, is attributed to a decrease in rainfall due to climate change, which has prolonged the dry season and shortened the wet season. This has impacted the continuity of the lake's water supply, threatening the sustainability of the ecosystem.

The study of the lake ecosystem, which was once part of the Bengawan Solo River, is in line with global findings on freshwater degradation. Environmental degradation characterized by pollution, erosion, and shrinking of the lake has mirrored the problems faced by similar lake ecosystems around the world. Immediate action through improved waste management, reforestation, and climate change adaptation is essential to mitigate further degradation and ensure the sustainability of this ecosystem. The study highlights the urgent need for effective conservation and environmental management practices to safeguard the future of the lake ecosystem. Key recommendations include vegetation rehabilitation, improved waste management, and adoption of strategies to address the impacts of climate change. Successful implementation of these measures requires collaborative efforts between government agencies, local communities, and relevant stakeholders to maintain the quality and availability of water in the DPP and DTPP Lakes and to secure the long-term viability of this vital freshwater ecosystem.

Acknowledgement

The writers wish to express their gratitude to all parties who have offered assistance and contributions to this investigation. The writer's special appreciation is extended to Professor Suntoro, Professor Danisworo, and Dr. Cahyono, for their invaluable supervision and counsel throughout the research process. Furthermore, gratitude is also owed to the writer to Mr. Head of Village and Mr. Head of Dukuh Desa Pondok, Prangjoro, and Telukan who supported the writer in finalizing this manuscript.

The writer also acknowledges the insightful feedback of evaluators who have enhanced the caliber of this manuscript. Lastly, appreciation is extended to family and companions for their unwavering moral encouragement.

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