

Environmental Degradation Analysis of Former Bengawan Solo River Lake Ecosystem

Andi Renata Ade Yudono¹, Suntoro Suntoro², Conrad Danisworo³, & Cahyono Ikhsan⁴

¹Doctoral Program of Environmental Science, Postgraduate School of Universitas Sebelas Maret, Indonesia; ²Department of Soil Sciences, Faculty of Agriculture, Universitas Sebelas Maret, Surakarta, Indonesia; ³Department of Geology, faculty of mineral technology, Universitas Pembangunan Nasional Veteran Yoyakarta, Indonesia; & ⁴Department of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia.

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

Correspondent email:
andiade@student.uns.ac.id

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.

©2024 by the authors Indonesian Journal of Geography

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY NC) license <https://creativecommons.org/licenses/by-nc/4.0/>.

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 (Saber 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 110°48'51.152" E, 7°35'11.056" S to 110°48'51.130" E, 7°37'36.019" S and 110°48'48.646" E, 7°37'24.510" S to 110°49'6.517" E, 7°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 coordinates 110°48'23.655" E, 7°37'39.901" S sampai 110°48'23.651" E, 7°37'58.491" S dan 110°48'13.821" E, 7°37'50.993" S to 110°48'29.424" E, 7°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,

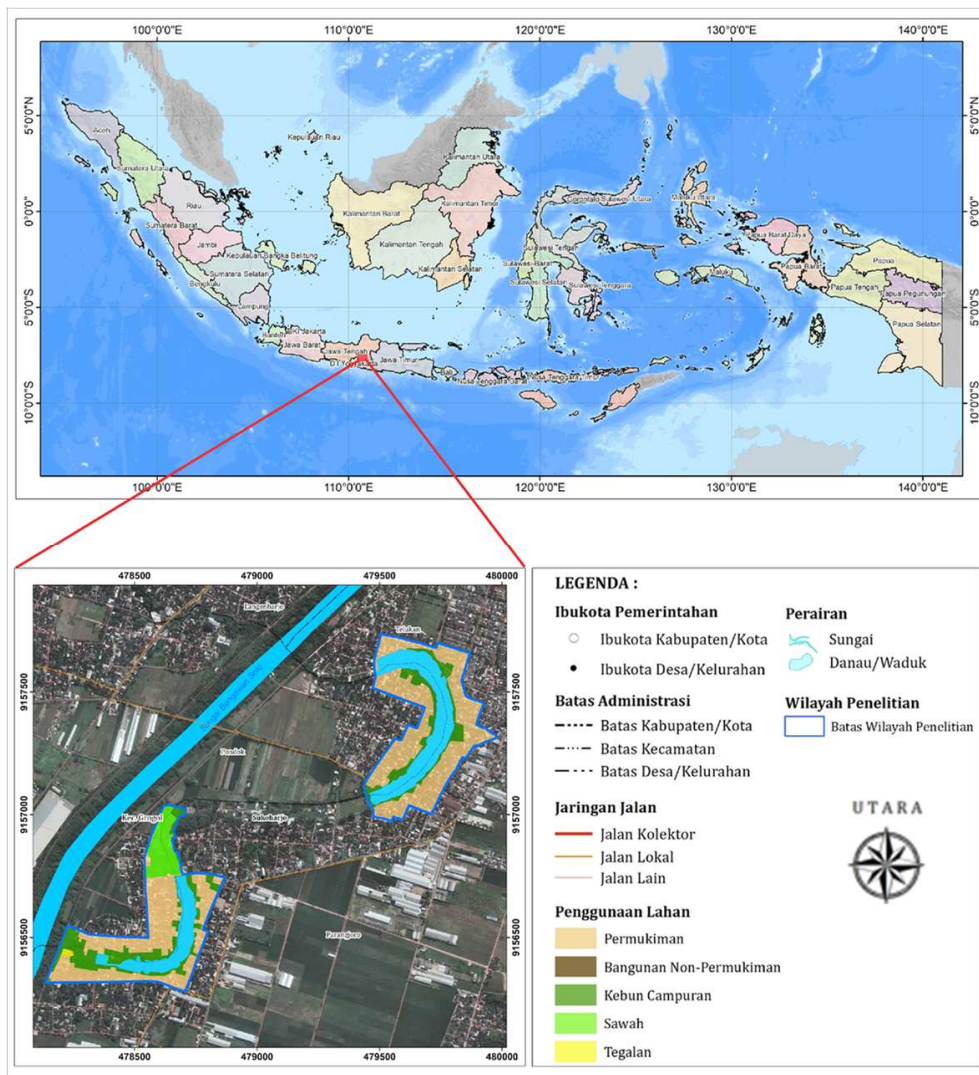


Figure 1. Research Area

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.

$$PL_j = \sqrt{\frac{\left(\frac{C_i}{L_{ij}}\right)_M^2 \left(\frac{C_i}{L_{ij}}\right)_R^2}{2}}$$

Information:

PL_j = pollution index for use j,

C_i = concentration of water quality parameters i,

L_{ij} = 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)

$$\text{Soil loss (tons)} = \text{Average soil loss (m)} \times \text{BV (tons/m}^3) \times \text{Plot area (m}^2)$$

ii. Erosion Rate (ton/ha) (Sarminah et al., 2018)

$$\text{Erosion Rate (ton/ha)} = \frac{\text{Land Loss (ton)} \times 10.000 \text{ (m}^2)}{\text{Erosion plot area (m}^2)}$$

iii. Erosion Rate (ton/ha) (Sarminah et al., 2018)

$$\text{Erosion Rate (ton/ha/year)} = \frac{\text{Erosion Rate (ton/ha)} \times \text{Rainfall 1 year (mm)}}{\text{rainfall during the study (mm)}}$$

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

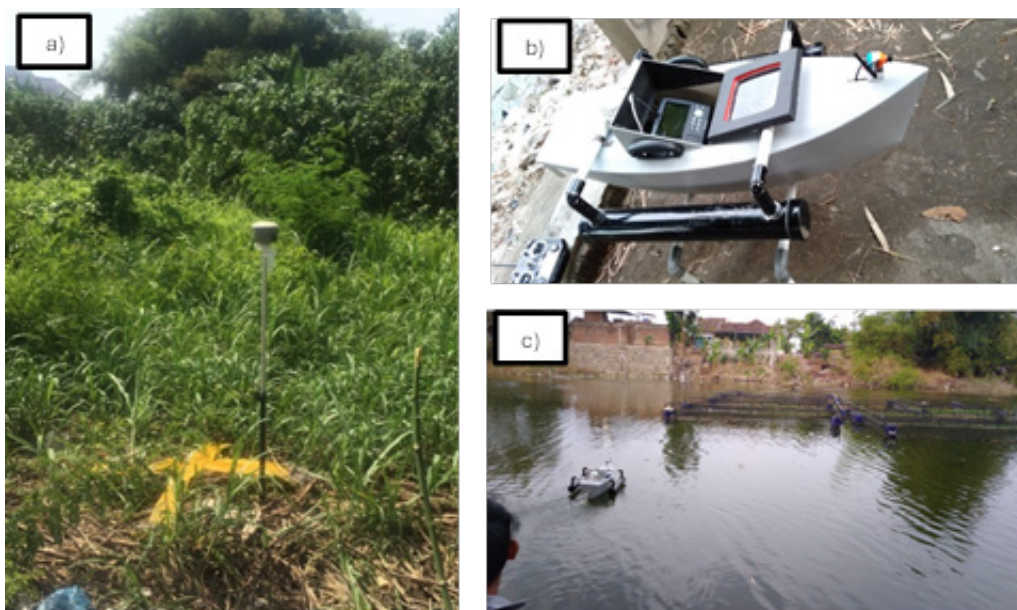


Figure 2. Crosscheck and measurement of underwater topography (bathymetry) using Geodetic GPS and USV in Grogol District, Sukoharjo Regency: (a) Use of Geodetic GPS to measure/record tie points; (b) USV appearance; and (c) Use of USV.

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 Pollution

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	
	Well 13	0,63	2,55	0,56	Meets Quality Standards (Good Condition)
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° - 2.9° / 0% - 5% , while PUE 2 and 3 are installed on slopes ranging from 2.9° - 11.3° / 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°-2.9°/0%-5%, PEM 5 installed on slopes 2.9°-11.3°/5%-20% in vegetated (5a) and non-vegetated (5b) areas, and PEM 6 installed on slopes 11.3°-21.8°/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°-21.8°/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°-2,9°/0%-5%)	PEM 2 (2,9°-11,3°/5%- 20%)	PEM 3 (2,9°-11,3°/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°-2,9°/0%-5%)	PEM 5 (2,9°-11,3°/5%- 20%)		PEM 6 (11,3°-21,8°/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

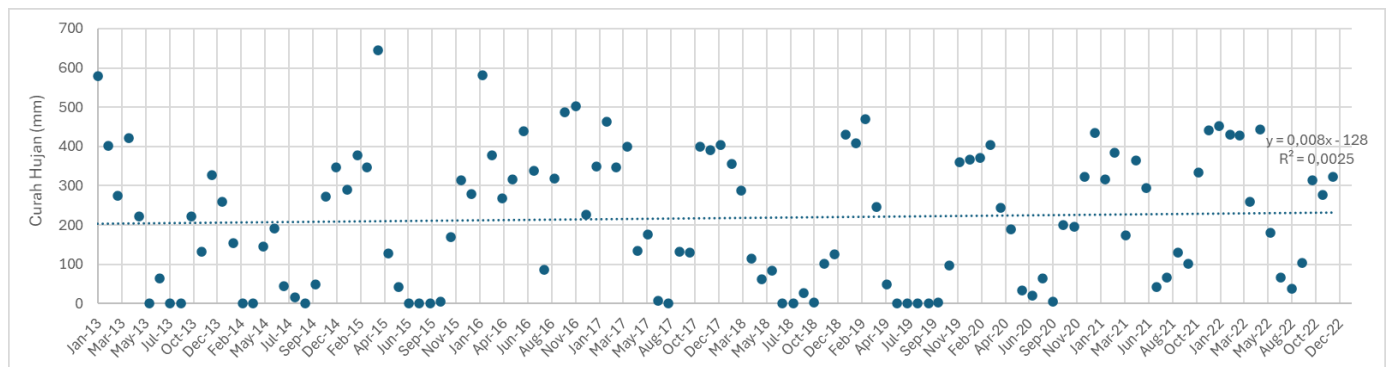


Figure 4. Trendline Graph of Rainfall for the last 10 years (2013-2022).

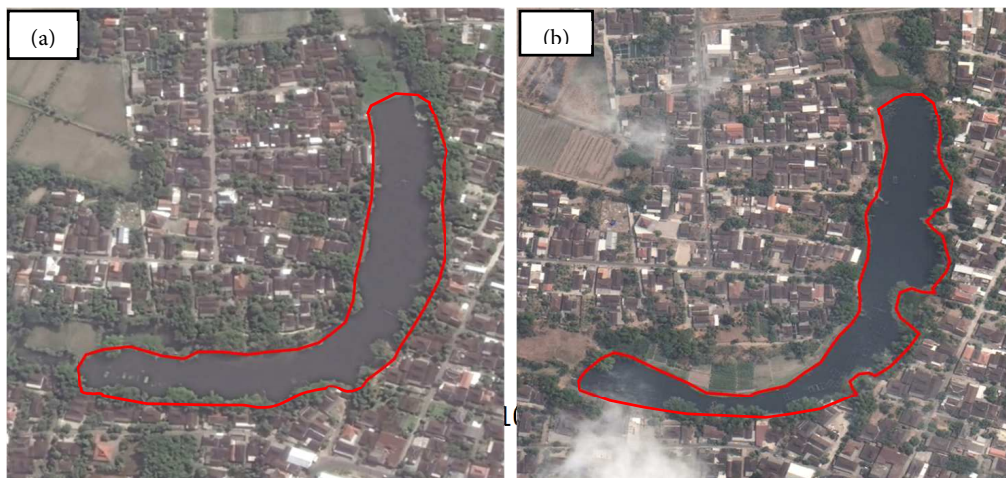


Figure 5 . Appearance of Lake Water Shrinking. (a) SPOT Satellite Image for May 2017; and (b) SPOT Satellite Image for September 2018

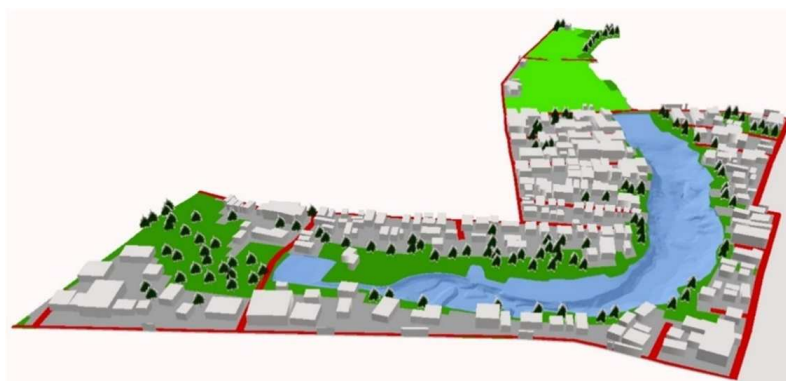


Figure 6. 3D appearance of DPP Lake, the data of which is used to determine the volume of lake water

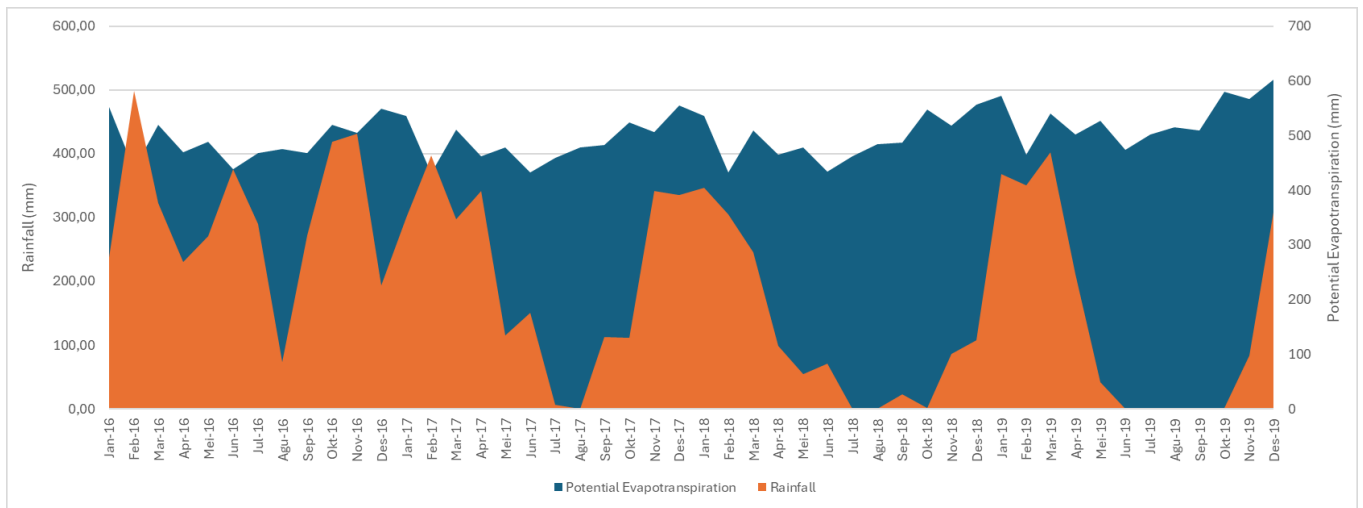


Figure 7. Influence between Rainfall and Potential Evapotranspiration

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 m³ 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.

References

- Albert, J S., Destouni, G., Duke-Sylvester, S M., Magurran, A E., Oberdorff, T., Reis, R E D., Winemiller, K O., & Ripple, W J. (2020, February 10). Scientists' warning to humanity on the freshwater biodiversity crisis. *Springer Science+Business Media*, 50(1), 85-94. <https://doi.org/10.1007/s13280-020-01318-8>
- Alizadeh, O., Ahmadi-Givi, F., Mirzaei, N., & Ostad, E. (2016, February 2). Climate change and anthropogenic impacts on the rapid shrinkage of Lake Urmia. *Wiley-Blackwell*, 36(13), 4276-4286. <https://doi.org/10.1002/joc.4630>
- Azareh, A., Sardooi, E R., Gholami, H., Mosavi, A., Shahdadi, A., & Barkhori, S. (2021, January 28). Detection and prediction of lake degradation using landscape metrics and remote sensing dataset. *Springer Science+Business Media*, 28(21), 27283-27298. <https://doi.org/10.1007/s11356-021-12522-8>
- Babel, P P. (2014, January 1). Projected Rainfall Erosivity Changes under Future Climate in the Upper Nan Watershed, Thailand. *OMICIS Publishing Group*, 05(10). <https://doi.org/10.4172/2157-7617.1000242>
- Belyakov, E A., & Гарин, Э В. (2018, May 11). Long-term dynamics of flora of karst lakes: Changes and current state. *Oles Honchar Dnipro National University*, 26(2), 160-169. <https://doi.org/10.15421/011825>
- Bogale, A. (2020, November 7). Review, impact of land use/cover change on soil erosion in the Lake Tana Basin, Upper Blue Nile, Ethiopia. *Springer Nature*, 10(12). <https://doi.org/10.1007/s13201-020-01325-w>
- Brazier, R E., Turnbull, L., Wainwright, J., & Bol, R. (2013, March 26). Carbon loss by water erosion in drylands: implications from a study of vegetation change in the south-west USA. *Wiley-Blackwell*, 28(4), 2212-2222. <https://doi.org/10.1002/hyp.9741>
- Chen, X., Zhou, J., & Zhou, H. (2007, July 1). Assessing danger degree of soil erosion in Rikaze prefecture, Tibet. *Springer Science+Business Media*, 12(4), 705-709. <https://doi.org/10.1007/s11859-006-0311-y>
- Costea, A., Bilaşco, Ş., Irimuş, I., Roşca, S., Vescan, I., Fodorean, I., & Sestraş, P. (2022, January 7). Evaluation of the Risk Induced by Soil Erosion on Land Use. Case Study: Guruslău Depression. *Multidisciplinary Digital Publishing Institute*, 14(2), 652-652. <https://doi.org/10.3390/su14020652>
- D'Odorico, P., & Ravi, S. (2023, January 1). Land degradation and environmental change. *Elsevier BV*, 359-367. <https://doi.org/10.1016/b978-0-12-820509-9.00005-8>
- Dupont, A., Botrel, M., Fortin, N., Poisot, T., & Maranger, R. (2023, March 12). A social-ecological geography of southern Canadian Lakes. *Cold Spring Harbor Laboratory*. <https://doi.org/10.1101/2023.03.09.531893>
- El-Gendy, A S., Biswas, N., & Bewtra, J K. (2004, June 1). Growth of Water Hyacinth in Municipal Landfill Leachate with Different pH. *Taylor & Francis*, 25(7), 833-840. <https://doi.org/10.1080/09593330.2004.9619375>
- Fu, Y., Li, G., Zheng, T., Zhao, Y., & Yang, M. (2021, January 1). Impact of rainfall on the distribution of soil aggregate fractions caused by shallow runoff. *Soil and Water Conservation Society*, 76(5), 414-423. <https://doi.org/10.2489/jswc.2021.00154>
- González, H., Lodenius, M., & Otero, M. (1989, December 1). Water hyacinth as indicator of heavy metal pollution in the tropics. *Springer Science+Business Media*, 43(6), 910-914. <https://doi.org/10.1007/bf01702064>
- Haider, A., Roy, A B., Sharma, R., Hegde, V N., & Kumuda, S. (2016, December 1). AquaPredicto — Freshwater quality management system for lakes. *IEEE Region 10 Humanitarian Technology Conference (R10-HTC)*, pp. 1-8. <https://doi.org/10.1109/r10-htc.2016.7906810>
- Heino, J., Alahuhta, J., Bini, L M., Cai, Y., Heiskanen, A., Hellsten, S., Kortelainen, P., Kotamäki, N., Tolonen, K., Vihervaara, P., Vilmi, A., & Angeler, D G. (2020, September 1). Lakes in the era of global change: moving beyond single-lake thinking in maintaining biodiversity and ecosystem services. *Wiley*, 96(1), 89-106. <https://doi.org/10.1111/brv.12647>
- Ho, L T., & Goethals, P. (2022, January 1). Imperiled Lake Ecosystems. *Elsevier BV*, 381-388. <https://doi.org/10.1016/b978-0-12-821139-7.00028-3>
- Hrissanthou, V. (2011, September 30). Computation of Lake or Reservoir Sedimentation in Terms of Soil Erosion. *InTech*. <https://doi.org/10.5772/22631>
- Ismail, D., Surya, R A., Yasin, A., & Aba, L. (2023, January 13). Determining River Water Quality Status based on the Pollution Index Method as Control of Environmental Quality: The Laeya River, South Konawe Regency. *European Journal of Development Studies*, 3(1), 29-41. <https://doi.org/10.24018/ejdevelop.2023.3.1.200>
- Jana, S., Mohanty, W K., Gupta, S., & Kumar, P. (2021, October 27). An integrated geomorphological and geophysical study of neotectonic activity: Analysis of heavy siltation in the Chilka Lake of Odisha, India. *Springer Science+Business Media*, 130(4). <https://doi.org/10.1007/s12040-021-01702-2>
- Kamarudin, M K A., Wahab, N A., Juahir, H., Wan, N M F N., Gasim, M B., Toriman, M E., Ata, F M., Ghazali, A., Anuar, A., Abdullah, H., Hussain, N I., Azmee, S H., Saad, M H M., Saupi, M., Islam, M S., & Elfithri, R. (2018, July 25). The Potential Impacts of Anthropogenic and Climate Changes Factors on Surface Water Ecosystem Deterioration at Kenyir Lake, Malaysia. *International Journal of Engineering & Technology*, 7(3.14), 67-74. <https://doi.org/10.14419/ijet.v7i3.14.16864>
- KemaloAbdulmalik, & IsrealZewide (2021, January 1). Effect of Land Degradation on Livelihood. *Asian Journal of Plant Science & Research*, 11(5). <https://doi.org/10.36648/2249-7412.21.11.149-153>
- Kinnell, P I A., & Wood, J. (1992, January 1). Isolating Erosivity and Erodibility Components in Erosion by Rain-Impacted Flow. *American Society of Agricultural and Biological Engineers*, 35(1), 201-205. <https://doi.org/10.13031/2013.28588>
- Li, Q., Lai, G., & Devlin, A T. (2020, November 2). A review on the driving forces of water decline and its impacts on the environment in Poyang Lake, China. *IWA Publishing*, 12(5), 1370-1391. <https://doi.org/10.2166/wcc.2020.216>
- Mandal, D., Patra, S., Sharma, N K., Alam, N M., Jana, C., & Lal, R. (2023, March 19). Impacts of Soil Erosion on Soil Quality and Agricultural Sustainability in the North-Western Himalayan Region of India. *Multidisciplinary Digital Publishing Institute*, 15(6), 5430-5430. <https://doi.org/10.3390/su15065430>
- Mester, T., Benkhard, B., Vasvári, M., Csorba, P., Kiss, E., Balla, D., Fazekas, I., Csépes, E., Barkat, A., & Szabó, G. (2023, April 12). Hydrochemical Assessment of the Kisköre Reservoir (Lake Tisza) and the Impacts of Water Quality on Tourism Development. *Multidisciplinary Digital Publishing Institute*, 15(8), 1514-1514. <https://doi.org/10.3390/w15081514>
- Molinos, J G., Viana, M., Brennan, M., & Donohue, I. (2015, March 10). Importance of Long-Term Cycles for Predicting Water Level Dynamics in Natural Lakes. *Public Library of Science*, 10(3), e0119253-e0119253. <https://doi.org/10.1371/journal.pone.0119253>
- Négyesi, G., Lóki, J., Búró, B., & Szabó, S. (2016, August 1). Effect of soil parameters on the threshold wind velocity and maximum eroded mass in a dry environment. *Springer Science+Business Media*, 9(11). <https://doi.org/10.1007/s12517-016-2626-0>
- Newete, S W., Erasmus, B F., Weiersbye, I., Cho, M A., & Byrne, M J. (2014, January 24). Hyperspectral reflectance features of water

- hyacinth growing under feeding stresses of *Neochetina* spp. and different heavy metal pollutants. *Taylor & Francis*, 35(3), 799-817. <https://doi.org/10.1080/01431161.2013.873145>
- Osman, K T. (2013, September 5). Physical Deterioration of Soil. *Springer Nature*, 45-67. https://doi.org/10.1007/978-94-007-7590-9_2
- Rahmadi, D., Machdar, I., & Syaubari, S. (2023, January 2). ANALYSIS OF WATER QUALITY AND QUALITY STATUS IN ACEH RIVERS BASED ON ENVIRONMENTAL POLLUTION INDEX. *Syah Kuala University*, 17(2), 171-181. <https://doi.org/10.23955/rkl.v17i2.28865>
- Saberi, B., Rahimi, D., & Dastjerdi, J K. (2023, March 15). Impact of Environmental Degradation and Climate Change on Water Quality in North Karoun Basin (Iran). *Research Square (United States)*. <https://doi.org/10.21203/rs.3.rs-2676255/v1>
- Sarminah, S., Kristianto, D., & Syafrudin, M. (2018, February 13). Analisis Tingkat Bahaya Erosi Pada Kawasan Reklamasi Tambang Batu Bara Pt Jembaran Muarabara Kalimantan Timur. *Ulin: Jurnal Hutan Tropis*, 1(2). <https://doi.org/10.32522/ujht.v1i2.793>
- Schindewolf, M., Bornkamp, C., Werner, M V., & Schmidt, J. (2015, December 9). *Simulation of Reservoir Siltation with a Process-based Soil Loss and Deposition Model*. pp. 51-57. <https://doi.org/10.5772/61576>
- Schmidt, M., Gonda, R., & Transiskus, S F. (2020, March 28). Environmental degradation at Lake Urmia (Iran): exploring the causes and their impacts on rural livelihoods. *Springer Science+Business Media*, 86(5), 2149-2163. <https://doi.org/10.1007/s10708-020-10180-w>
- Shah, H A., Sheraz, M., Khan, A U., Khan, F A., Shah, L A., Khan, J., Khan, A W., & Khan, Z. (2020, June 1). Surface and Groundwater Pollution: The Invisible, Creeping Threat to Human Health. *De Gruyter Open*, 16(1), 157-169. <https://doi.org/10.2478/cee-2020-0016>
- Singh, R P. (2023, January 1). Impact of Climate and Land Use Land Cover Changes on Soil Erosion. *Springer Nature (Netherlands)*, 415-441. https://doi.org/10.1007/978-981-19-8665-9_14
- Sobrinho, J F., & Barbosa, F E L. (2022, June 15). Soil Losses in Agricultural Area Of The Semi-Arid. *Universidade Federal do Ceará*, 21(1), 1-13. <https://doi.org/10.4215/rm2022.e21020>
- Sujarwo, M W., Indarto, I., & Mandala, M. (2020, June 9). Pemodelan Erosi dan Sedimentasi di DAS Bajulmati : Aplikasi Soil dan Water Assesment Tool (SWAT). *Diponegoro University*, 18(2), 220-230. <https://doi.org/10.14710/jil.18.2.220-230>
- Suprianingsih, N W., Adnyana, I W S., & Diara, I W. (2023, May 25). Prediksi Erosi Dan Perencanaan Konservasi Tanah Dan Air di Daerah Aliran Sungai Pakerisan Provinsi Bali. *Udayana University*, 17(1), 69-69. <https://doi.org/10.24843/ejes.2023.v17.i01.p06>
- Tserendorj, U., Tuulaikhuu, B., Chananbaatar, A., Moonkhor, K., Sharavjams, O., Purevee, A., Purev, T., Naranbat, D., Danzan, T., Myangan, O., & Naranbat, D. (2022, November 15). Impact of overgrazing and climate change on the lake ecosystem in arid region. , 15(36), 9-20. <https://doi.org/10.5564/mjas.v15i36.1360>
- Tutuarima, C T., Talakua, S M., & Osok, R M. (2021, June 30). Penilaian Degradasi Lahan dan Dampak Sedimentasi terhadap Perencanaan Bangungan Air di Daerah Aliran Sungai Wai Ruhu, Kota Ambon. *Jurnal Budidaya Pertanian*, 17(1), 43-51. <https://doi.org/10.30598/jbdp.2021.17.1.43>
- Wang, G., Guodong, C., Shen, Y., & Ju, Q. (2003, January 1). Influence of land cover changes on the physical and chemical properties of alpine meadow soil. *Springer Nature*, 48(2), 118-124. <https://doi.org/10.1007/bf03037014>
- Wijitkosum, S. (2012, March 31). Impacts of land use changes on soil erosion in Pa Deng sub-district, adjacent area of Kaeng Krachan National Park, Thailand. *Soil and Water Research*, 7(1), 10-17. <https://doi.org/10.17221/32/2011-swr>
- Williams, S E., Hobday, A., Falconi, L., Hero, J., Holbrook, N J., Capon, S J., Bond, N., Ling, S D., & Hughes, L. (2019, November 20). Research priorities for natural ecosystems in a changing global climate. *Wiley-Blackwell*, 26(2), 410-416. <https://doi.org/10.1111/gcb.14856>
- Woolway, R I., Kraemer, B M., Lenters, J D., Merchant, C J., O'Reilly, C M., & Sharma, S. (2020, July 14). Global lake responses to climate change. *Nature Portfolio*, 1(8), 388-403. <https://doi.org/10.1038/s43017-020-0067-5>
- Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J., Wada, Y., & Bergé-Nguyen, M. (2023, May 19). Satellites reveal widespread decline in global lake water storage. *American Association for the Advancement of Science*, 380(6646), 743-749. <https://doi.org/10.1126/science.abo2812>
- Yudono, A R A., Sungkowo, A., & Gomareuzzaman, M. (2020, June 10). Analisis Dampak Erosi Terhadap Kapasitas Sungai Mati Di Kecamatan Tawang Sari Dan Kecamatan Sukoharjo. *Jurnal Mineral, Energi, dan Lingkungan*, 4(1), 61-72. <https://doi.org/10.31315/jmel.v4i1.3190>
- Zhang, C., Kong, X., Xue, B., Zhao, C., McGowan, S., Qi, L., Zhang, K., & Shen, J. (2023, April 1). Double-edged effects of anthropogenic activities on lake ecological dynamics in northern China: Evidence from palaeolimnology and ecosystem modelling. *Wiley-Blackwell*, 68(6), 940-955. <https://doi.org/10.1111/fwb.14077>
- Zhang, Y., Qin, B., Zhu, G., Song, C., Deng, J., Xue, B., Gong, Z., Wang, X., Wu, J., Shi, K., Gu, X., & Zhang, G. (2022, October 1). Importance and main ecological and environmental problems of lakes in China. *Science China Press*, 67(30), 3503-3519. <https://doi.org/10.1360/tb-2022-0178>
- Zhao, Z., & Shi, P. (2023, May 15). *Vegetation patterns affect soil aggregate loss during water erosion*. <https://doi.org/10.5194/egusphere-egu23-1955>

Regulation

- Government of the Republic of Indonesia. 2021. Government Regulation Number 22 of 2021 concerning Environmental Protection. Ministry of Environment: Jakarta.
- Government of the Republic of Indonesia. 2001. Government Regulation Number 82 of 2001 concerning Water Quality Management and Water Pollution Control. Ministry of Environment: Jakarta.
- Government of the Republic of Indonesia. 2021. Government Regulation Number 22 of 2021 concerning Environmental Protection and Management. Ministry of Environment: Jakarta.
- Government of the Republic of Indonesia. 2017. Regulation of the Minister of Environment Number: 32 of 2017 concerning Environmental Health Standards and Health Requirements. Ministry of Environment: Jakarta.
- Government of the Republic of Indonesia. 2006. Regulation of the Minister of Environment Number: 7 of 2006 concerning Procedures for Measuring Standard Criteria for Land Damage for Biomass Production. Ministry of Environment: Jakarta.
- Government of the Republic of Indonesia. 2009. Regulation of the Minister of Forestry of the Republic of Indonesia Number 32 of 2009 concerning Environmental Protection and Management with its amendments. Ministry of Forestry: Jakarta.
- Government of the Republic of Indonesia. 2003. Decree of the Minister of Environment No. 115 of 2003 concerning Guidelines for Determining Water Quality Status. Ministry of Forestry: Jakarta.

STATEMENT OF ORIGINALITY AND CONFLICT OF INTEREST DECLARATION

Title of the manuscript: Analysis of Environmental Degradation in Lake Ecosystems: Case Study of Lake Section of the Former Bengawan Solo River in Grogol District, Sukoharjo Regency

Authors: Andi Renata Ade Yudono

As the corresponding author I certify that this manuscript is original, and its publication does not infringe any copyright.

As the corresponding author I declare that the manuscript has not been previously published, in whole or in part in any other journal or scientific publishing company. Also the manuscript does not participate in any other publishing process. I also declare there is no conflict of interest.

As the corresponding author I declare that all persons listed hereafter were committed in the creation of the paper and were informed about their participation.

10 Agustus, 2024



Andi Renata Ade Yudono

**This statement must be uploaded as a supplementary files while submitting your manuscript.*

Three Suggestions Reviewers

1. Prof. Dr. Sunarto M.S.; rm.sunarto@staff.uns.ac.id;
Universitas Sebelas Maret
2. Dr. Ir. Eko Teguh Paripurno, M.T.; paripurno@upnyk.ac.id; Universitas Pembangunan Nasional “Veteran Yogyakarta
3. Prof Dr. Ir. Sari Bahagiarti K., M.Sc.; saribk@upnyk.ac.id;
Universitas Pembangunan Nasional “Veteran Yogyakarta