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The Impact of Rainfall Fluctuation on the Trophic Status of Maninjau Lake Based on Carlson and Comprehensive Trophic State Index (CTSI)

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Abstract

Maninjau Lake is experiencing increased eutrophication levels, negatively impacting water quality and the balance of its aquatic ecosystems. One of the factors that is thought to play a role in accelerating the process is rainfall fluctuation, which affects nutrient input from the water catchment area. This study aims to analyze the effect of rainfall fluctuation on the trophic status of Maninjau Lake using *the Carlson Trophic State Index* (TSI) and *Comprehensive Trophic State Index* (CTSI) methods. Water sampling was conducted at 10 stations over three periods: September 2022, January 2023, and March 2023, which represented seasonal variations. The parameters measured included chlorophyll-a, total phosphorus (TP), total nitrogen (TN), *chemical oxygen demand* (COD), and Secchi depth according to national standards. Rainfall data were obtained from BMKG stations and correlated with trophic index values. Results showed TSI values ranged from 55–72 and CTSI between 60–75, indicating eutrophic to hypereutrophic conditions. The highest trophic status occurred in periods of high rainfall, with a strong positive correlation between rainfall intensity and nutrient increase (r = 0.999 for TSI; r = 0.989 for CTSI). Rainfall plays a role as the main hydrometeorological driver of trophic dynamics, so adaptive management is needed to mitigate the impact of eutrophication under climate variability.

Keywords: *maninjau lake, rainfall fluctuation, trophic status, eutrophication, comprehensive trophic state index*

Abstrak

Danau Maninjau mengalami peningkatan tingkat eutrofikasi yang berdampak pada penurunan kualitas air dan keseimbangan ekosistem perairan. Salah satu faktor yang diduga berperan dalam mempercepat proses tersebut adalah fluktuasi curah hujan, yang memengaruhi masukan nutrien dari daerah tangkapan air. Penelitian ini bertujuan untuk menganalisis pengaruh fluktuasi curah hujan terhadap status trofik Danau Maninjau menggunakan metode *Carlson Trophic State Index* (TSI) dan *Comprehensive Trophic State Index* (CTSI). Pengambilan sampel air dilakukan di 10 stasiun selama tiga periode—September 2022, Januari 2023, dan Maret 2023—yang mewakili variasi musim. Parameter yang diukur meliputi klorofil a, total fosfor (TP), total nitrogen (TN), *chemical oxygen demand* (COD), dan kedalaman Secchi sesuai standar nasional. Data curah hujan diperoleh dari stasiun BMKG dan dikorelasikan dengan nilai indeks trofik. Hasil menunjukkan nilai TSI berkisar antara 55–72 dan CTSI antara 60–75, yang menunjukkan kondisi eutrofik hingga hipereutrofik. Status trofik tertinggi terjadi pada periode curah hujan tinggi dengan korelasi positif kuat antara intensitas hujan dan peningkatan nutrien (r = 0,999 untuk TSI; r = 0,989 untuk CTSI). Curah hujan berperan sebagai pendorong hidrometeorologis utama dinamika trofik, sehingga diperlukan manajemen adaptif untuk mitigasi dampak eutrofikasi di bawah variabilitas iklim.

Keywords: *danau meninjau, fluktuasi curah hujan, status trofik, eutrofikasi, indeks keadaan trofik komprehensif*

1. Introduction

Maninjau Lake is one of the largest volcanic lakes in West Sumatra, serving as a vital source of water, fisheries, and tourism for the surrounding communities [1]. However, in recent decades, the lake has experienced increasing ecological pressure due to nutrient loading from anthropogenic activities such as floating net cage aquaculture (FNC), domestic waste discharge, and land erosion within its catchment area [2]. The accumulation of these nutrients has triggered eutrophication processes characterized by excessive phytoplankton growth, decreased water transparency, and deterioration of water quality [3]. This condition indicates that Maninjau Lake requires a comprehensive ecological evaluation to understand the dynamics of its trophic development [2].

One of the widely used approaches to assess lake fertility is the Carlson Trophic State Index (TSI), which integrates Secchi depth, chlorophyll-a, and total phosphorus to describe the degree of eutrophication [4]. Although this method provides a quantitative and practical assessment, it often fails to capture the complex interactions and variability typical of tropical volcanic lakes [5]. To overcome this limitation, the Comprehensive Trophic State Index (CTSI) was developed to offer a more holistic evaluation by incorporating weighted parameters and wider ecological variability [6].

Besides anthropogenic pressures, rainfall fluctuation is a crucial hydrometeorological driver influencing nutrient inputs through surface runoff, sediment resuspension, and water mass mixing [7], [8]. High rainfall enhances nutrient transport from the catchment, while dry periods promote nutrient accumulation and internal loading [9]. However, studies that quantitatively link rainfall variability with trophic status using index-based methods remain limited, particularly in tropical volcanic lakes of Indonesia, where distinct rainfall patterns and intensive aquaculture coexist. Previous research has primarily focused on physical and chemical water quality [10], [11], with little emphasis on the integrated effect of hydrometeorological variability on trophic state.

Based on this background, this study was conducted to analyze the relationship between rainfall fluctuation and the trophic status of Maninjau Lake using the Carlson TSI and CTSI methods. It is hoped that the results of this study can strengthen the understanding of the influence of hydrometeorological factors on eutrophication dynamics in volcanic tropical lakes and provide a scientific basis for adaptive and sustainable water quality management in Maninjau Lake.

2. Materials and Methods

The study was conducted at Maninjau Lake, Tanjung Raya District, West Sumatra Province, as shown in **Figure 1**. Sampling was carried out for 3 (three) periods, namely September 2022, January 2023, and March 2023 at 10 sampling locations. The description of the sampling point is presented in **Figure 1** and **Table 1**.

Sampling was conducted in September 2022, January 2023, and March 2023 to represent different seasonal conditions. September corresponded to the end of the dry season, January to the peak of the rainy season, and March to the transition toward the dry season. These periods were chosen to capture seasonal variability in hydrological and nutrient dynamics and ensure that they represent ecosystem conditions.

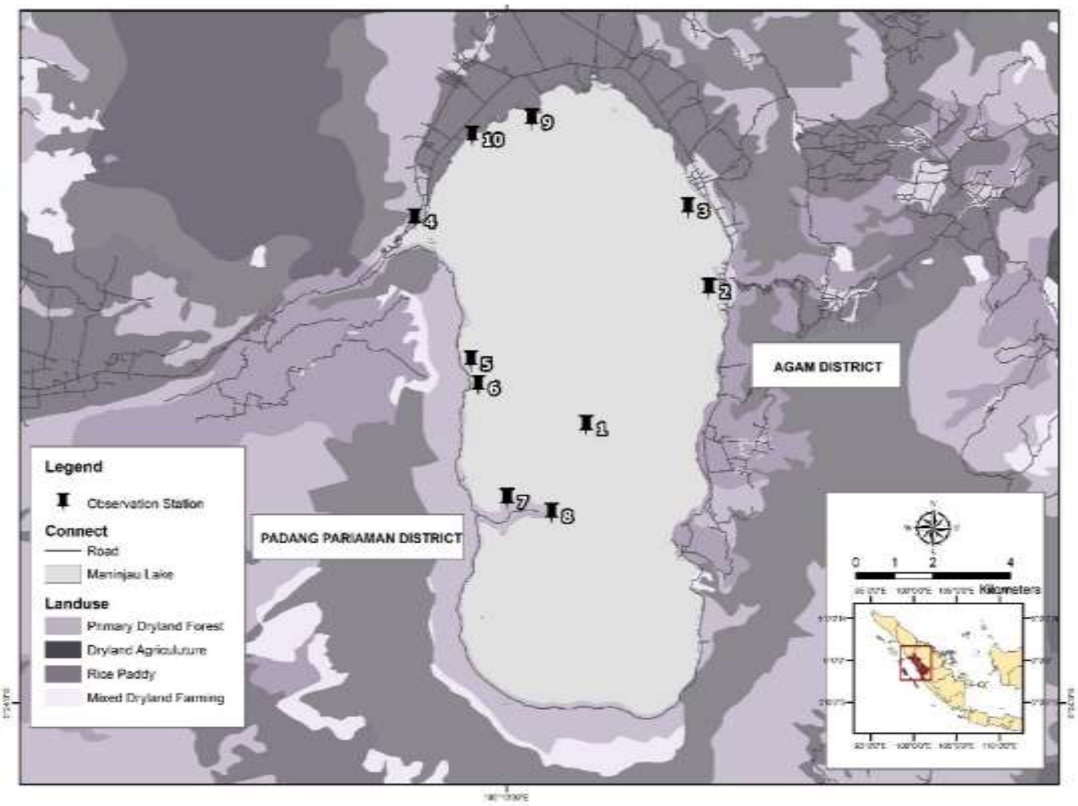

Figure 1. The location of the sampling station is in Maninjau Lake, West Sumatra

Water Sampling

Water sampling refers to the Indonesian National Standard (SNI) 6989-57-2008, utilizing *the composite sampling* method for surface water. Sampling was conducted using a vertical water sampler, and the collected water was then placed in a 500 mL glass bottle. The sample bottle is tightly sealed to prevent contamination from outside air. Furthermore, the sample is preserved according to the procedures established for each test parameter as listed in **Table 2**. All samples are clearly labeled with identity and stored in a cooler during the transportation process to the laboratory.

Rainfall Data

The rainfall data used in this study were obtained from the Meteorology, Climatology, and Geophysics Agency through the Sicincin Climatology Station and Rainfall Observation Stations around the Maninjau Lake catchment area. The analysis was conducted by calculating the average, maximum, and minimum rainfall values and the variation coefficient to assess the local climate instability level. Rainfall patterns were classified into the rainy season (October–March) and the dry season (April–September), in accordance with the climatic characteristics of West Sumatra. Furthermore, rainfall data were correlated with the Trophic State Index (TSI) and Comprehensive Trophic State Index (CTSI) values to identify the relationship between hydrometeorological fluctuations and water fertility levels. This approach allows for a more comprehensive evaluation of the role of rainfall as a natural controlling factor in the eutrophication dynamics of Maninjau Lake.

Table 1. Description of Sampling Location

No	Sampling Point	Koordinat	Description
1	Middle of the lake	S 0° 21' 37", E 100° 10' 34"	Middle of the lake
2	Pangkal Tanjung	S 0° 21' 37", E 100° 10' 34"	• Nagari Tanjuang Sani Jorong Pangkal Tanjung • Medium FNC area • Medium residential houses
3	Unpopulated area	S 0° 21' 10.757", E 100° 10' 56.610"	• Nagari Tanjuang Sani Jorong Pangkal Tanjung • No residential houses • There is no FNC
4	Antokan	S 0° 17' 34.413", E 100° 8' 56.652"	• Nagari Koto Malintang • Maninjau Lake outlet
5	Batang Kurambik	S 0° 15' 49.967", E 100° 10 11.643	• Nagari Koto Gadang • Maninjau Lake inlet • Agricultural area
6	Hotel	S 0° 17' 59.325", E 100° 13' 25.469"	• Nagari Maninjau • Relatively densely populated areas • Medium FNC
7	Floating Net Cages	S0° 16' 1.216", E 100° 10' 1.788"	• Nagari Bayur • Center FNC • There are several houses • Moderate agricultural area
8	North	S0° 15' 54.124", E 100° 10' 9.376"	• Nagari Bayua Talao area • There is a cluster of houses • Medium FNC • Rare residents
9	Settlement	S 0° 19' 4.321", E 100° 9' 52.047”	• Nagari Tanjung Sani Jorong Tampang river • Densely populated settlements • Many FNC • Medium fishing net
10	Tampang river	S 0° 1842.829", E 100° 9' 56.922"	• Nagari Tanjung Sani Jorong Tampang river • Away from residential areas • Medium FNC

Table 2. Laboratory testing parameters

No	Parameter	Reference	Preservative
1	COD	SNI 6989.73:2009	Analyze immediately or add H2SO4 until pH<2, and refrigerate.
2	Total N	SNI 06.6989.30.2005	Analyze immediately or add H2SO4 until pH<2, and refrigerate.
3	Total P	SNI 06.6989.31.2005	Analyze immediately or add H2SO4 until pH<2, and refrigerate.
4	Chlorophyll-a	Acetone Method Using Spectrophotometer	In a dark place / dark bottle and covered with aluminum foil

Carlson Trophic State Index (TSI)

The Trophic Status Index (TSI) is used to classify the fertility level of lake waters based on the method developed by Carlson (1977) and Simpson (1996). This method uses algal biomass as the primary basis for determining the trophic status of the water. Three parameters used are chlorophyll-a concentration (CHL), clarity depth (Secchi depth/SD), and total phosphorus (TP). These three parameters reflect the physical, chemical, and biological aspects that are interrelated in describing the level of water eutrophication. The TSI value for each parameter is calculated using equations 1-3.

$$TSI(SD) = 60 - 14.41 \ln (SD) \qquad (1)$$
$$TSI(CHL) = 9.81 \ln (CHL) + 30.6 \qquad (2)$$
$$TSI(TP) = 14.42 \ln (TP) + 4.15 \qquad (3)$$

Analysis Comprehensive Trophic State Index (CTSI)

Trophic status analysis was conducted using the CTSI method with chlorophyll-a, brightness, TN, TP and COD parameters, such as equations 1 – 7, spatially and temporally. This CTSI is widely used in the assessment of lake eutrophication in China to determine trophic states as complex responses caused by interactions between various physical, chemical, and biological factors [12]. CTSI is also used to describe the trophic state of lakes based on the trophic status index (TSI), SD, CHL, TP, TN and COD, with equation 4 [6].

$$CTSI = \sum_{j=1}^{m} \left[W_J \ x \ TSI \ (j) \right] \qquad (4)$$

Description:

TSI(j) is the j_{th} Trophic State Index among TSI(CHL), TSI(TN), TSI(TP), TSI(SD), and TSI(COD), calculated by Equations 5 - 9.

m is the number of trophic state indices, and m = 5

Wj is the weight of TSI(j), based on CHL content, and is expressed by Equation (10).

$$TSI\ (CHL) = 10 \text{ x } (2.5 + 1.086 \text{ x } \ln CHL) \qquad (5)$$
$$TSI\ (TP) = 10 \text{ x } (9{,}436 + 1.624 \text{ x } \ln TP) \qquad (6)$$
$$TSI\ (TN) = 10 \text{ x } (5.453 + 1.694 \text{ x } \ln TN) \qquad (7)$$
$$TSI\ (SD) = 10 \text{ x } (5.118 - 1.94 \ln SD) \qquad (8)$$
$$TSI\ (COD) = 10 \text{ x } (0.109 + 2.661 \text{ x } \ln (COD)) \qquad (9)$$
$$Wj = \frac{{r_{ij}}^2}{\sum_{j=1}^{m} {r_{ij}}^2} \qquad (10)$$

Description:

- r_{ij} is the correlation coefficient between the j_{th} index content and CHL concentration. The coefficient values can be 1, 0.84, 0.82, -0.83, and 0.83 for CHL, TP, TN, SD, and COD, respectively.
- CTSI values are on a numerical scale between 0 and 100.
- The trophic status of the lake is classified as Oligotrophic (Oligo) $0 < CTSI \leq 30$
  Mesotrophic (Meso) $30 < CTSI \leq 50$
  Slightly Eutrophic (Slight-Eutro) $50 < CTSI \leq 60$
  Moderately Eutrophic (Mod-Eutro) $60 < CTSI \leq 70$
  Hyper-Eutrophic (Hyper-Eutro) $70 < CTSI \leq 100$.

3. Result and Discussion

Rainfall Fluctuation Patterns in Maninjau Lake

Analysis of rainfall data during the sampling period showed that there was a relatively straightforward seasonal variation, with the peak of rainfall occurring in Period I (September 2022) and a decrease in Period II (January 2023) to Period III (March 2023), as shown in **Figure 2**.

During the sampling period from September 2022 to March 2023, the highest rainfall was 16.19 mm in September 2022, and the lowest was 9.52 mm in March 2023. According to information from BMKG, the rainy season in Indonesia is expected to begin from September to November 2022 and be followed by the peak of the rainy season in December 2022 and January 2023. High rainfall in Maninjau Lake can have negative impacts, such as fish deaths due to a lack of oxygen. Strong winds accompanied by high rainfall can result in fish deaths due to a lack of oxygen after the reversal of air from the bottom to the lake's surface [13]. This can cause enormous losses for fish farmers around the lake.

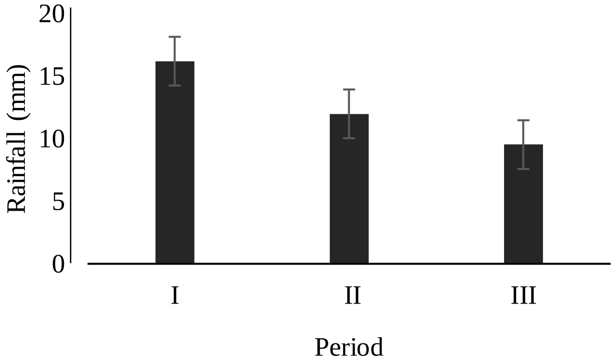

Figure 2. Mean Rainfall

Furthermore, a normality test was conducted on the rainfall parameters to determine whether the data were normally distributed. The results of the rainfall normality test during the sampling period showed that the data were not normally distributed, as indicated by the significant p-value. Value was <0.05, so the decision was made using *the Kruskal-Wallis test.* After the Kruskal-Wallis *test was carried out* during the sampling period, the significance value of rainfall was 0.245 (*p-value>0.05).* Based on the sig value, it can be concluded that rainfall has changed significantly during the sampling period.

Changes in rainfall in Maninjau Lake are closely related to tropical climatic conditions. Compared to previous periods, rainfall in the lake area shows an increasing trend. Fakhrudin et al. reported that the average monthly rainfall in the Maninjau Lake region during 1984–2000 was 299 mm [13]. Meanwhile, Fukushima et al. stated that the period from September to December represents the wet season, while the following months are classified as the dry season [14].

This pattern is consistent with the tropical monsoon climate in West Sumatra, where high rainfall intensity in the western season impacts surface runoff and increased nutrient input to the lake body. In dry seasons, reduced rainfall decreases inflow and causes nutrient concentrations to increase due to evaporation and limited deposition [15].

Trophic Status Based on the Carlson Index (TSI) and the Comprehensive Trophic State Index (CTSI)

The analysis of the trophic status of Maninjau Lake was conducted using the Carlson Trophic State Index (TSI) and the Comprehensive Trophic State Index (CTSI). Both methods were used to assess the level of aquatic fertility spatially and temporally, and identify the influence of rainfall fluctuation on eutrophication dynamics. **Figures 3, 4** and **5** present the trophic status of each index's lake.

In **Figure 3**, the highest TSI SD and CHL values were recorded in period I (September 2022) with average values of 71.62 and 61.17, respectively, indicating eutrophic to hypereutrophic conditions. These conditions coincide with the beginning of the rainy season, where increased rainfall causes surface runoff to carry nutrients from the catchment area to the lake body [16]. The input of external nutrients, particularly phosphorus and nitrogen, enriches the water column and increases the growth of phytoplankton, which is indicated by the high value of chlorophyll-a [17]. In addition, sediment resuspension due to increased water turbulence during the rainy period also contributes to the increase in dissolved phosphate concentrations in the surface layer [18].

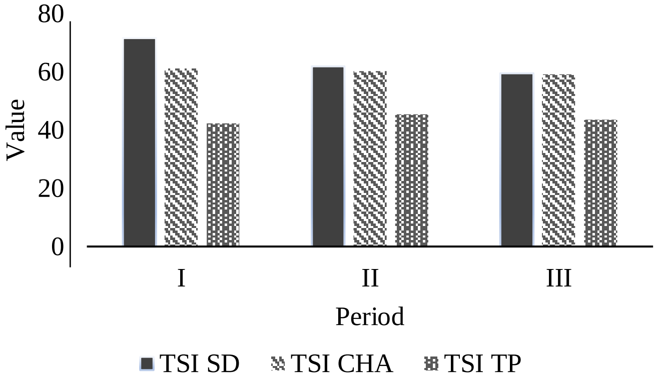

Figure 3. Trophic Status Based on TSI Carlson

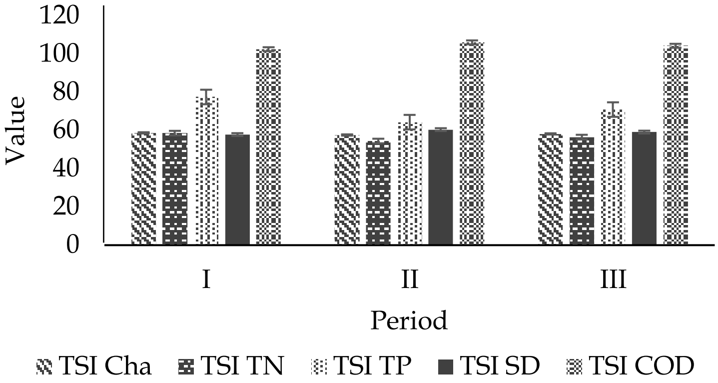

Figure 4. Trophic Status Based on CTSI

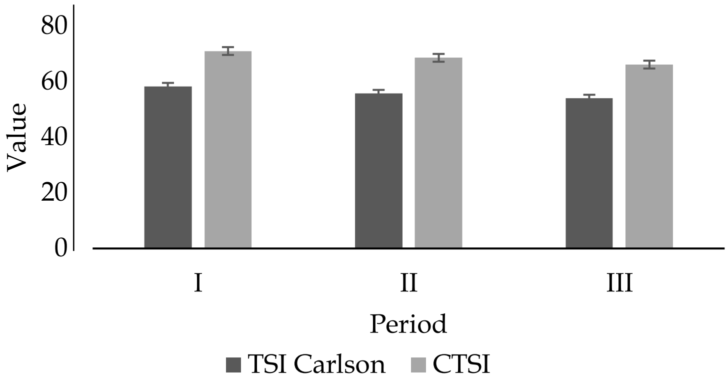

Figure 5. Carlson TSI and CTSI Values in Maninjau Lake

In contrast, the lowest TSI value was obtained in period III (March 2023) with an average of 59.56 for TSI SD and 59.19 for TSI CHL, indicating eutrophic conditions. The decrease in the TSI value in this period is related to the reduction in rainfall intensity towards the end of the rainy season, so the supply of nutrients from the catchment area begins to decrease. In addition, the increased clarity of the water in this period indicates a reduction in turbidity due to reduced runoff and suspended particles.

Overall, the average TSI value between sampling periods was in the eutrophic category with a value of 56.09, which indicates that Maninjau Lake is generally in a high fertility condition. This suggests that the lake water system has experienced chronic nutrient enrichment, so it has high potential for phytoplankton blooming and a decrease in oxygen levels in the lower layer [2][19]. The combination of external inputs from rainfall and internal loads due to floating net cage activities is the main factor that strengthens eutrophication status and reduces the stability of lake ecosystems [7], [20].

In **Figure 4**, the Comprehensive Trophic State Index (CTSI) values show a pattern that aligns with Carlson's TSI, but with relatively higher and stable values between periods. The highest CTSI score was in period I (September 2022) with an average of 67.81, which indicates a hypereutrophic condition. The increase in CTSI values in this period is closely related to the high intensity of rainfall, which leads to increased surface runoff and input of external nutrients from the catchment area. The runoff carries phosphate and nitrogen from agricultural activities, settlements, and feed residues from floating net cages (FCN), further accelerating eutrophication and increasing phytoplankton biomass in the waters.

Meanwhile, the lowest CTSI value occurred in period III (March 2023) with an average of 60.45, which is still included in the eutrophic category. The decrease in the value of CTSI in this period was caused by decreased rainfall and inflows, so nutrient inputs from land were reduced. This condition is followed by an increase in water clarity and a decrease in chlorophyll-a concentration, which indicates reduced primary productivity. Nonetheless, the CTSI values remain high, indicating that the internal nutrient load of the bottom sediment is still large enough to maintain the eutrophic conditions of the lake.

In general, the CTSI results reinforce the findings from the Carlson index that Maninjau Lake consistently had a eutrophic to hypereutrophic trophic status during the study period. The higher CTSI value than the TSI indicates that this comprehensive method is more sensitive to fluctuations in physical, chemical, and biological parameters, and can illustrate the combined influence of rainfall variability and anthropogenic stress on lake fertility. Thus, CTSI provides a more comprehensive picture of the actual level of eutrophication and potential degradation of water quality in Maninjau Lake.

Figure 5 shows the Carlson Trophic State Index (TSI) and the Comprehensive Trophic State Index (CTSI) values during the Maninjau Lake sampling period. In general, both indices showed a relatively consistent pattern with a strong positive correlation ($r = 0.84$; $p < 0.01$), indicating that both depicted similar trends in changes in trophic status. CTSI is generally slightly higher than Carlson's TSI in almost all periods, with differences ranging from 2 to 5 points. This difference reflects the better sensitivity of CTSI in capturing spatial and temporal variations, as this method considers the relative weights between parameters (chlorophyll-a, total phosphorus, and depth of brightness) and the correlation between limnological variables.

This condition suggests that Carlson's TSI tends to be more influenced by a single fluctuation in one of the parameters, e.g., an increase in chlorophyll-a due to phytoplankton blooming. At the same time, CTSI provides more stable results by taking into account the overall water conditions. This explains why CTSI can represent lake fertility levels more comprehensively, especially in tropical ecosystems such as Maninjau Lake, which experiences high climate variations and nutrient inputs throughout the year.

The increasing pattern of both indices during periods of high rainfall reinforces the indication that hydrometeorological fluctuations are an important factor controlling the trophic dynamics of lakes. During these wet periods, runoff from the catchment area carries phosphate and nitrogen into the lake, accelerating eutrophication. Conversely, lower index values observed in the dry season indicate a decrease in external nutrient inputs, although internal nutrient loading continues to sustain eutrophic conditions within the water column.

These results are consistent with previous studies in other tropical and subtropical lakes. It is reported similar findings in Dianchi Lake, China, where CTSI values were consistently higher than TSI due to the method’s ability to integrate multi-parameter variability and hydrometeorological influences. It is aligned with Chen et al., who stated that comprehensive trophic indices offer improved diagnostic performance for tropical lakes with complex interactions between climatic drivers and anthropogenic inputs [22].

Overall, the results of this comparison confirm that CTSI has superior diagnostic capability in representing actual trophic conditions and long-term eutrophication trends in Maninjau Lake. Therefore, the simultaneous use of both indices is highly recommended, as they complement each other: TSI directly indicates biological productivity, while CTSI describes the integrated limnological balance of the aquatic system. These findings strengthen the argument for adopting a multi-index approach in the sustainable monitoring and managing lake water quality, particularly in tropical regions with high rainfall variability such as Maninjau Lake.

The Relationship Between Rainfall and Trophic Status

The relationship between rainfall fluctuation and trophic status variation in Maninjau Lake was analyzed to determine how much hydrometeorological factors influence aquatic fertility. The pattern of this relationship is illustrated in **Figure 6**, which shows the correlation between rainfall variation and the Trophic State Index (TSI) and Comprehensive Trophic State Index (CTSI) values across observation periods.

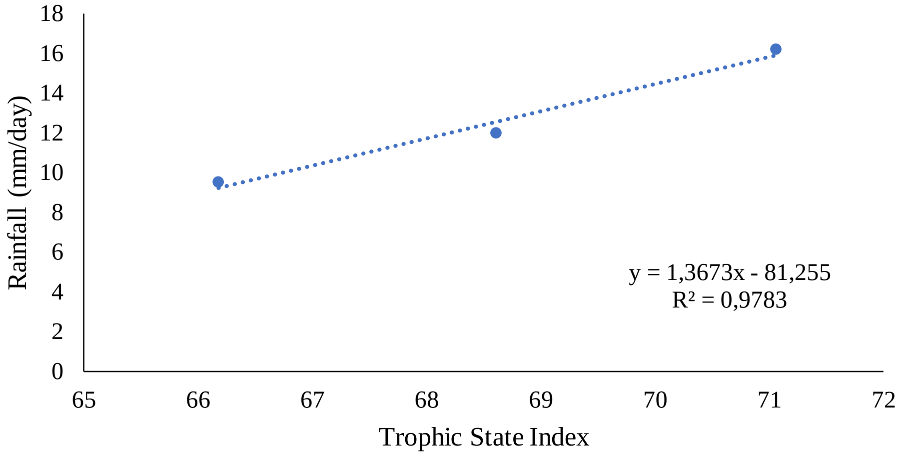

Figure 6. Rainfall and CTSI Influences

The results of the correlation analysis showed a very high positive relationship between rainfall and the Carlson Trophic State Index (TSI) and Comprehensive Trophic State Index (CTSI) values, respectively, of r = 0.999 and r = 0.989. This relationship suggests increased rainfall intensity is associated with high trophic levels due to increased external nutrient loads. In periods of high rainfall, runoff from catchment areas carries phosphorus, nitrogen, and organic matter derived from anthropogenic activities such as floating net cages, settlements, and agriculture around lakes [2], [23]. The process enriches the water column and stimulates the growth of phytoplankton, which is reflected in the increased concentration of chlorophyll-a as well as trophic index values [24], [25]. In addition, high rainfall accompanied by water turbulence triggers sediment resuspension and releases bound phosphates from the lake floor, thereby strengthening the eutrophication process [15], [26].

In periods of low rainfall, such as in March 2023, the external nutrient supply from the catchment area decreases, so the TSI and CTSI values decrease. However, eutrophic conditions still occur due to the release of internal nutrients from sediments. This pattern suggests that Maninjau Lake is highly responsive to hydrometeorological variability, with rainfall as a natural regulator of fluctuations in trophic status. The results align with Chen et al. (2021) and Zhang et al. (2024), who reported that rainfall variability significantly affects trophic status through runoff and nutrient dispersion from the catchment area. Similar conditions were also observed in Lake Dianchi, China, where CTSI values increased with the intensity of seasonal rainfall [12]. Thus, the interaction between climatic factors and anthropogenic pressures is the primary controller of eutrophication processes in tropical volcanic lake ecosystems.

Although the results of this study show a strong relationship between rainfall fluctuations and trophic dynamics, some limitations need to be noted. Temporal coverage that covers only three periods in a single hydrological cycle does not fully represent long-term extreme climate variations. At the same time, spatial heterogeneity between zones (inlets, cage areas, and pelagic regions) can affect the accuracy of trophic index assessments. In addition, the accuracy of the analysis of chlorophyll-a, total phosphorus, and total nitrogen parameters is highly dependent on preservation methods and laboratory procedures. Pseudo-equilibrium assumptions in the TSI and CTSI methods can also cause bias in tropical volcanic lakes with dynamic hydrological regimes. Therefore, further research is recommended using higher monitoring frequencies, in situ sensors, and hydrodynamics–biogeochemical modelling approaches to improve predictive understanding of the interaction between rainfall and nutrient dynamics in Maninjau Lake.

4. Conclusion

This study demonstrates that Maninjau Lake is in a eutrophic to hypereutrophic condition, based on Carlson’s Trophic State Index (TSI) and the Comprehensive Trophic State Index (CTSI), with values ranging from 55 to 72 and 60 to 75, respectively. The highest trophic levels were observed during intense rainfall, indicating that rainfall fluctuation significantly regulates nutrient dynamics through surface runoff and sediment resuspension. Increased precipitation enhances external nutrient loading, while reduced rainfall decreases inflow but allows internal sediment release to sustain eutrophic conditions. The comparison of both indices shows that CTSI provides more stable and representative results than Carlson’s TSI, as it incorporates parameter weighting and captures hydrometeorological variability more effectively.

Rainfall is the primary natural regulator influencing trophic dynamics in tropical volcanic lakes such as Maninjau.

However, this study is limited by its short temporal coverage and the lack of continuous hydrological data, which may not capture the full extent of interannual variability. Future research should incorporate long-term monitoring, higher-frequency sampling, and hydrodynamic–biogeochemical modeling to quantify the uncertainties and predict trophic responses under changing climate scenarios.

5. Acknowledgments

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6. References

[1] T. R. Soeprobowati *et al.*, “Riparian Vegetation of Maninjau Lake, West Sumatra, Indonesia: a Study of Biodiversity and Above-Ground Carbon Stock,” *Int. J. Conserv. Sci.*, vol. 16, no. 2, hal. 1065–1086, 2025.

[2] P. S. Komala *et al.*, “Spatio-temporal Changes of Water Quality Based on Water Quality Index Method in Tropical Lake of Indonesia,” *Water. Air. Soil Pollut.*, vol. 234, no. 9, Sep 2023, doi: 10.1007/s11270-023-06599-9.

[3] C. B. De Maisonneuve *et al.*, “Bathymetric survey of lakes Maninjau and Diatas (West Sumatra), and lake Kerinci (Jambi),” *J. Phys. Conf. Ser.*, vol. 1185, no. 1, 2019, doi: 10.1088/1742-6596/1185/1/012001.

[4] M. Karpowicz, N. Kuczyńska-Kippen, Ł. Sługocki, R. Czerniawski, E. Bogacka-Kapusta, dan J. Ejsmont-Karabin, “Trophic status index discrepancies as a tool for improving lake management: insights from 160 Polish lakes,” *Sci. Total Environ.*, vol. 981, hal. 179581, 2025, doi: https://doi.org/10.1016/j.scitotenv.2025.179581.

[5] L. Lyu *et al.*, “Estimation of the lake trophic state index (TSI) using hyperspectral remote sensing in Northeast China,” *Opt. Express*, vol. 30, hal. 10329–10345, 2022, doi: 10.1364/OE.453404.

[6] C. Tang *et al.*, “Planktonic indicators of trophic states for a shallow lake (Baiyangdian Lake, China),” *Limnologica*, vol. 78, no. December 2018, hal. 125712, 2019, doi: 10.1016/j.limno.2019.125712.

[7] P. S. Komala, Z. Zulkarnaini, R. I. Kurniati, dan M. Fauzi, “The effect of anthropogenic activities on the spatial distribution of total nitrogen and total phosphate in Lake Maninjau,” *J. Water L. Dev.*, no. 60, hal. 71–78, 2024, doi: 10.24425/jwld.2024.149109.

[8] C.-Y. Shou, Y. Tian, B. Zhou, X.-J. Fu, Y.-J. Zhu, dan F.-J. Yue, “The Effect of Rainfall on Aquatic Nitrogen and Phosphorus in a Semi-Humid Area Catchment, Northern China,” *Int. J. Environ. Res. Public Health*, vol. 19, hal. 10962, 2022, doi: 10.3390/ijerph191710962.

[9] D. B. da Silva, V. R. Bellotto, J. D. S. B. Barbosa, dan T. B. Lima, “Spatiotemporal variation on water quality and trophic state of a tropical urban reservoir: A case study of the lake paranoá-DF, Brazil,” *Water (Switzerland)*, vol. 13, no. 22, 2021, doi: 10.3390/w13223314.

[10] P. S. Komala, S. Silvia, dan S. Windi, “Phytoplankton Dynamics and Its Relation to Physicochemical Parameters in the Dry Season of Maninjau Lake , West Sumatra , Indonesia,” *J. Ecol. Eng.*, vol. 24, no. 9, hal. 218–231, 2023.

[11] A. Sunaryani, “Determination of Water Quality Status and Trophic Classification of Lake Maninjau,” *J. Teknol. Lingkung.*, vol. 24, no. 1, hal. 21–27, 2023.

[12] Q. Chen, J. Zhao, Q. Gao, H. X. Liu, dan X. M. Han, “Trophic state footprint index model and its application to Dianchi Lake, China,” *Ecol. Indic.*, vol. 132, no. August, hal. 108317, 2021, doi: 10.1016/j.ecolind.2021.108317.

[13] M. Fakhrudin, H. Wibowo, L. Subehi, dan I. Ridwansyah, “Karakterisasi Hidrologi Danau Maninjau Sumbar,” *Pros. Semin. Nas. Limnol.*, no. April 2018, hal. 65–75, 2002.

[14] T. Fukushima *et al.*, “Convection of waters in Lakes Maninjau and Singkarak, tropical oligomictic lakes,” *Limnology*, vol. 23, no. 2, hal. 375–383, 2022, doi: 10.1007/s10201-021-00686-8.

[15] L. Mwadzingeni, R. Mugandani, dan P. Mafongoya, “Risks of Climate Change on Future Water Supply in Smallholder Irrigation Schemes in Zimbabwe,” *Water (Switzerland)*, vol. 14, no. 11, hal. 1–20, 2022, doi: 10.3390/w14111682.

[16] D. Naderian *et al.*, “Environmental controls on the conversion of nutrients to chlorophyll in lakes,” *Water Res.*, vol. 274, hal. 123094, Apr 2025, doi: 10.1016/j.watres.2025.123094.

[17] E. Dindar, “Assessment of pollution status using Water Quality Index (WQI) and hydrochemical

ındicators in the Gemlik Gulf, Marmara Sea, Türkiye: a spatial and temporal perspective.," *Environ. Sci. Pollut. Res. Int.*, vol. 32, no. 24, hal. 14860–14890, Mei 2025, doi: 10.1007/s11356-025-36560-8.

[18] G. Carper dan R. Bachmann, "Wind Resuspension of Sediments in a Prairie Lake," *Can. J. Fish. Aquat. Sci.*, vol. 41, hal. 1763–1767, 2011, doi: 10.1139/f84-217.

[19] Sulastri, C. Henny, dan S. Nomosatryo, "Phytoplankton diversity and trophic status of Lake Maninjau, West Sumatra, Indonesia," *Pros. Semin. Nas. Masy. Biodivsersotas Indones.*, vol. 5, no. 2, hal. 242–250, 2019, doi: 10.13057/psnmbi/m050217.

[20] Y. Qi *et al.*, "Research on the Analysis of and Countermeasures for the Eutrophication of Water Bodies: Waihu Reservoir as a Case Study," *Processes*, vol. 12, no. 4, 2024, doi: 10.3390/pr12040796.

[21] Q. Chen *et al.*, "No-linear dynamics of lake ecosystem in responding to changes of nutrient regimes and climate factors: Case study on Dianchi and Erhai lakes, China," *Sci. Total Environ.*, vol. 781, hal. 146761, 2021, doi: 10.1016/j.scitotenv.2021.146761.

[22] Q. Chen, M. Huang, dan X. Tang, "Eutrophication assessment of seasonal urban lakes in China Yangtze River Basin using Landsat 8-derived Forel-Ule index: A six-year (2013–2018) observation," *Sci. Total Environ.*, vol. 745, hal. 135392, 2020, doi: https://doi.org/10.1016/j.scitotenv.2019.135392.

[23] M. A. Salsabil, A. Rinanti, dan M. F. Fachrul, "Analysis of water quality in Maninjau Lake, West Sumatera, Indonesia using phytoplankton," *MATEC Web Conf.*, vol. 197, hal. 1–4, 2018, doi: 10.1051/matecconf/201819713007.

[24] Yu *et al.*, "Effects of nitrogen and phosphorus on chlorophyll a in lakes of China: A meta-analysis," *Environ. Res. Lett.*, vol. 17, no. 7, 2022, doi: 10.1088/1748-9326/ac7d64.

[25] D. L. Baho, S. Drakare, R. K. Johnson, dan D. G. Angeler, "Phytoplankton size- and abundance-based resilience assessments reveal nutrient rather than water level effects," *Sci. Total Environ.*, vol. 746, hal. 141110, 2020, doi: 10.1016/j.scitotenv.2020.141110.

[26] G. A. H. Sallam dan E. A. Elsayed, "Estimating the impact of air temperature and relative humidity change on the water quality of Lake Manzala, Egypt," *J. Nat. Resour. Dev.*, hal. 76–87, 2015, doi: 10.5027/jnrd.v5i0.11.