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Exploring Spatial Dynamics of Water Quality in a Tropical Lake Affected by Aquaculture

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Abstract: Lake Maninjau, like many surface water bodies worldwide, faces significant water pollution challenges due to extensive aquaculture activities, making it an ideal site to study the impact of fish farming on water quality, which has contributed to eutrophication and declining water quality. This study investigates the physicochemical parameters and pollution levels in the lake, aiming to provide insights into its environmental health. In August 2022, a comprehensive sampling campaign was undertaken at nine stations within the upper layers of open water and littoral zones of Lake Maninjau. In situ measurements, including temperature, dissolved oxygen, and pH, were conducted, accompanied by water sample collection for laboratory analysis of trace elements and heavy metals. Our study revealed notable variability in water parameters across different sites, with surface water layers exhibiting the greatest differences. While certain parameters such as temperature and conductivity remain relatively stable, pH levels show a decreasing trend with increasing water depth. Dissolved oxygen levels vary widely, while oxidation–reduction potential indicates water pollution, particularly in littoral zones. Potassium dominance within cations likely suggests anthropogenic influences, notably from aquaculture activities, that may also contribute to nutrient enrichment and heavy metal pollution. Elevated levels of total nitrogen and ammonia underscore the lake's moderate pollution levels, with heavy metals such as mercury exceeding permissible limits, posing risks to aquatic life and human health.

Keywords: water quality; Lake Maninjau; aquaculture; heavy metals; eutrophication; pollution

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1. Introduction

The maintenance of a sustainable and healthy environment hinges on the quality of water available. The survival of aquatic ecosystems, together with the health of both humans and animals that rely on them, are contingent on the water quality. Therefore, water quality is a crucial aspect that cannot be overlooked or taken for granted. Maintaining optimal water quality is crucial for ensuring the well-being and survival of all life forms dependent on aquatic ecosystems. Therefore, the degradation of surface water quality, including deep lakes, is a critical global issue that demands immediate attention.

Natural factors such as hydromorphology and catchment geology play a role in the lake's health; however, human activity has recently been identified as the primary driver of its degradation. Land-use modification, rapid urban development, and industrialization have triggered numerous environmental changes. These changes have caused deterioration of water quality, biodiversity loss, ecological degradation, and consequently diminishing their ecosystem service value [1,2].

Several types of contamination related to human activities are discharged into lakes via surface runoff, atmospheric deposition, leaching processes, etc. [1,3]. The main concern in water management is overload of nutrients and heavy metals [4,5]; however, the issue of plastic debris has been emerging recently [6]. Excessive nutrients, especially nitrogen and phosphorus, may be derived, i.a., with sewage sludge, fertilizers, fish feeding, or released by fish [7,8], triggering algae bloom and, in the worst scenario, oxygen depletion and asphyxiation of fish [3]. Another menacing issue results from the excessive accumulation of heavy metal. Some compounds are essential in small doses; however, numerous metals are toxic and harmful, even in small concentrations [1]. Certain compounds can have toxic effects that not only result in food poisoning and disease but also lead to the death of aquatic organisms. The issue of heavy metal contamination is exacerbated by the fact that these toxins can accumulate in the food chain, posing a long-term threat to the health of animals and humans who consume contaminated fish [9].

One human-related source of environmental pollution is aquaculture. As fish farming expands to meet global food demands, it introduces a range of pollutants that threaten water quality and aquatic life. The discharge of nutrient-rich effluents from fish farms, particularly nitrogen and phosphorus, often leads to eutrophication, promoting harmful algal blooms and depleting oxygen levels in aquatic ecosystems. This is further exacerbated by the accumulation of organic waste, which increases biological oxygen demand, further lowering dissolved oxygen levels. Furthermore, elevated levels of ammonia and suspended solids impair water quality [10,11], while the use of antibiotics and chemicals contributes to broader environmental pollution. Fish farming can also contribute to the accumulation of trace metals [10] in sediments beneath fish cages, with high concentrations of Hg, Zn, Cr, Cu, Pb, and Ni attributed to fish feed, fecal waste, and anti-foulant products used on the farms [12,13].

These metals often originate from contaminated fish feed or fertilizers. In poorly managed systems, heavy metals can accumulate in sediments and water, posing risks to both aquatic organisms and human health through bioaccumulation in fish [10,13]. Obviously, the effects on lakes can vary significantly based on factors such as the lake's volume, the rate of water turnover, the scale of the fish farming, and the type and quantity of waste produced by the farms [11].

The Ministry of Environment and Forestry Republic of Indonesia indicated 15 national priority lakes that are in a critical condition [14]. These lakes have experienced significant ecological deterioration with repercussions for biodiversity, society, and the economy. Several factors were included in the lake's selection processes, i.a., level of environment deterioration and ecological risk, ecosystem services, biodiversity, and level of national importance [15,16]. Considering these indicators, Lake Maninjau has been listed as one such priority ecosystem. The lake is an epicenter of local activity, providing waters for daily needs, food (fish, crustacea), hydropower energy, and being a tourism destination. Moreover, Lake Maninjau holds significant importance for the local community as a center for fish farming, primarily cultivating carp and tilapia in numerous floating cages. The number of these cages has expanded rapidly since 1992 [17]. However, their operation has led to an increased accumulation of organic waste, contributing to elevated levels of nitrogen and phosphorus in the lake, which in turn promotes the growth of phytoplankton blooms.

The high human pressure has led to water quality deterioration of Lake Maninjau, which is heavily eutrophicated and polluted by heavy metals [18–21]. Rapid lake degradation has led to regularly occurring, dramatic, massive fish kills [22]. These situations generate economic losses and endanger biodiversity as many endemic species inhabit the

lake. Moreover, lake ecosystems are never at equilibrium [23,24]; therefore, there is a need to recognize variability of water parameters in time and space.

This research article aims to investigate the water quality of Lake Maninjau, which has been affected by both eutrophication and metal pollution due to the development of fish farming. By analyzing water samples and conducting field surveys, the research aims to evaluate the current state of water quality of the central and southern part of the lake, assess spatial variations in physicochemical parameters, and identify the sources and levels of pollutants.

2. Materials and Methods

2.1. Study Site

Lake Maninjau, a caldera lake, is located in the West Sumatra Province, Republic of Indonesia (Figure 1), at the altitude of 461.4 m a.s.l. [19,20]. The maximum lake depth is 169 m, whereas its width and length equal 7 km and 16 km, respectively [25]. The lake surface covers 9737.5 ha [26,27] with a catchment ca. 13,260 ha [20]. The catchment area is dominated by forest (6951 ha) and dry lands (3606 ha). A significant share of the land use near the lake also has paddy lands (2518 ha), whereas the settlement covers 869 ha [19,28].

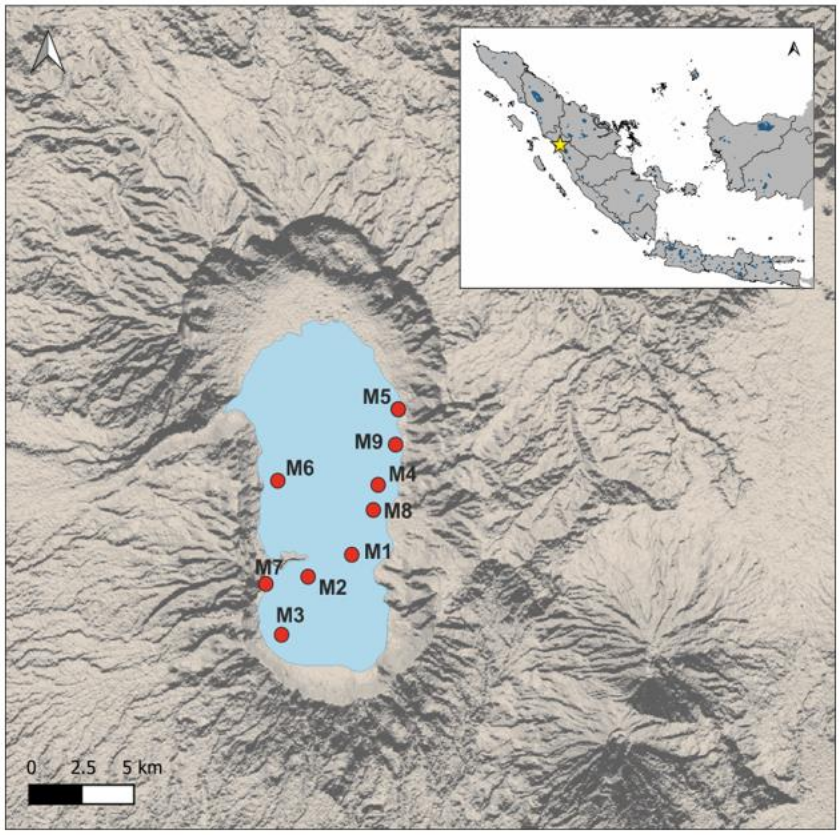


Figure 1. Map showing the locations of water sampling sites (M1–M9) within Lake Maninjau, indicated by red dots. The inset map highlights the position of Lake Maninjau on Sumatera Island, marked with a yellow star.

The study area is characterized by a high amount of annual precipitation (ca. 3100 mm) [27] with two periods of rainfall peaks (April–May, October–November) [28]. The lake is supplied by precipitation, discharges rivers (mostly intermittent), and groundwaters, and has a single outlet located in the north-west coast. In the outlet area, a hydropower plant is situated (Figure 1) with a capacity of 64 MW. Water retention time has been estimated to be 25 years [27].

The lake provides multiple services. Apart from being a hydroenergy source, Lake Maninjau is used for tourism, fisheries, and aquaculture purposes. The latter one is a reason for serious environmental issues. The fish are cultured using floating cages, of which the number has dramatically increased since 1992 (from 64 units to 18,921 units in 2018) [29–32]. This, in turn, has triggered a high input of organic matter into the water, disturbing the ecological balance. The accompanying high flux of nutrients [19] causes the lake ecosystem to suffer from eutrophic/hypereutrophic conditions [33].

2.2. Sampling and Physicochemical Analyses

In August 2022, a sampling campaign was conducted, which included nine sampling stations. Four of the stations were located within the upper layers of open water zone while the remaining five were situated in the littoral zone (as depicted in Figure 1).

At each station, comprehensive in situ measurements were conducted along with the collection of water samples. The field measurements were taken at regular intervals of either 0.5 or 1 m and encompassed the determination of several water quality parameters including water temperature, pH, dissolved oxygen (DO), and total dissolved solids (TDSs), utilizing a water quality checker (Horiba U-10; Horiba Ltd., Kyoto, Japan). Unfortunately, we did not obtain measurements from the stations M5 and M9 due to technical issues.

The water samples were collected using a Van Dorn Bottle Sampler, with samples taken at intervals of 5 m, and filtered through a plankton net with a mesh size of 40 µm. These samples were then stored in plastic bottles and immediately transported to the laboratory of Andalas University (Padang, Sumatra, Indonesia). Main and trace elements in water samples were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES; Universitas Andalas, Padang, Indonesia).

Quality control of the in situ analyses was based on calibration of the equipment and repeated measurements (5 times). The results of replicate measurements were then averaged and used for interpretation and further analysis. Quality of laboratory analysis was controlled by implementing blank samples, repeated measurements (2 times), and by using standards.

2.3. Numerical Analyses

Descriptive statistics were run to initially summarize results of physicochemical measurements. The dataset was normalized by the z-score method. The normality distribution of variables was investigated using the Shapiro–Wilk test. The test displayed a non-normal distribution within the dataset; therefore, the Kendall rank correlation coefficient was utilized to detect multicollinearity between variables. Then, principal component analysis (PCA) using R software (version 4.0.3) [34] was conducted to further explore the dataset. The main goal of PCA implementation was to determine the relationship between variables and infer about the main factors affecting the water chemistry of Lake Maninjau.

3. Results

3.1. Variability in Physicochemical Properties

The physicochemical parameters were analyzed and the results are summarized using descriptive statistics in Table 1, along with vertical profile diagrams displayed in Figures 2–5. The analysis revealed that the physicochemical properties of the lake water were relatively variable, with the greatest differences observed in the surface water layers between study sites. The highest coefficient of variation (CV) above 100% was observed in the case of Co, while high amplitudes of values and, by extension, high CVs, were also observed for DO, Mg, B, and NH_3 (50–100%). In contrast, temperature (CV < 1), conductivity (CV = 3.5), and total dissolved solids (CV = 3.6) were the most stable parameters, with relatively constant values throughout the water column.

Table 1. Descriptive statistics calculated for all measured physicochemical parameters.

Parameter	Unit	Min	Max	Median	75 Percentile	Coeff. Var
Temperature	°C	27.68	29.08	28.21	28.29	0.91
pH	-	5.81	7.61	6.56	6.86	6.61
ORP	mV	70.6	262.25	220.4	243.85	20.52
Conductivity	mS/cm	0.058	0.071	0.066	0.067	3.53
DO	mg/L	0.56	14.83	3.04	3.41	83.38
TDSs	g/L	0.038	0.046	0.043	0.044	3.63
PO_4	mg/L	0.055	0.168	0.079	0.99	31.35
PO_4_P	mg/L	0.017	0.052	0.024	0.305	31.35
NO_3	mg/L	0.729	2.295	1.299	1.856	33.85
NO_3_N	mg/L	0.452	1.424	0.806	1.151	33.85
NH_3	mg/L	0.055	0.401	0.108	0.237	56.34
N_{tot}	mg/L	1.245	2.917	2.023	2.172	24.67
C_{tot}	mg/L	6	20	10	13.5	38.53
TSSs	mg/L	7	31	13	17.5	37.05
Ca	mg/L	0.32	1.65	0.67	1.15	47.59
Mg	mg/L	0.27	1.65	0.53	1.02	63.58
Na	mg/L	0.18	0.82	0.38	0.56	46.19
K	mg/L	1.11	3.45	1.87	2.33	28.5
Ag	mg/L	0.0089	0.0398	0.0176	0.02895	44.75
Al	mg/L	0.0102	0.0312	0.0172	0.01905	24.9
As	mg/L	0.0078	0.0278	0.0152	0.02045	31.16
B	mg/L	0.0065	0.0524	0.0165	0.02515	59.44
Ba	mg/L	0.0037	0.0221	0.0092	0.01585	49.38
Cd	mg/L	0.0078	0.0362	0.0145	0.01875	44.94
Co	mg/L	0.0089	0.189	0.0201	0.0324	120.22
Cr	mg/L	0.011	0.031	0.0152	0.02255	33.95
Cu	mg/L	0.0133	0.0523	0.0187	0.0302	42.96
Fe	mg/L	0.0122	0.0653	0.0319	0.0406	40.27
Hg	mg/L	0.0086	0.0342	0.0132	0.01695	41.27
Mn	mg/L	0.0152	0.0556	0.0287	0.03385	33.98
Ni	mg/L	0.0072	0.0201	0.0121	0.0155	32.88
Pb	mg/L	0.0087	0.0273	0.0145	0.01735	27.89
Se	mg/L	0.0048	0.0328	0.013	0.01615	43.45
Sn	mg/L	0.0078	0.0192	0.0133	0.01665	26.91
Zn	mg/L	0.0156	0.0766	0.0325	0.0543	46.88

Note: Abbreviations: Min—minimum; Max—maximum; 75 Percentile—75th percentile; Coeff. Var—coefficient variation; ORP—oxidation–reduction potential; DO—dissolved oxygen; TDSs—total dissolved solids; N_{tot}—total nitrogen; C_{tot}—total carbon.

Water temperature exhibited fluctuations of approximately 28 °C (as shown in Table 1), while conductivity was found to be extremely low and did not exceed 100 µS/cm (0.1 mS/cm). There were also noticeable changes in pH levels, ranging from slightly acidic (pH = 5.8) to slightly alkaline (pH = 7.6). The results indicated a decreasing trend in pH along with water depth at the open water sites (Figure 2).

Dissolved oxygen (DO) exhibited variations ranging between approximately 0.56 and 14.83 mg/L, with the highest values recorded at the M2 site between 350 and 950 cm of water depth (Figure 2). Oxidation–reduction potential (ORP) ranged from approximately 70 to 262 mV. Notably, the lowest ORP values were observed at the littoral zone sites and at the open water site M3 (in the upper water layers).

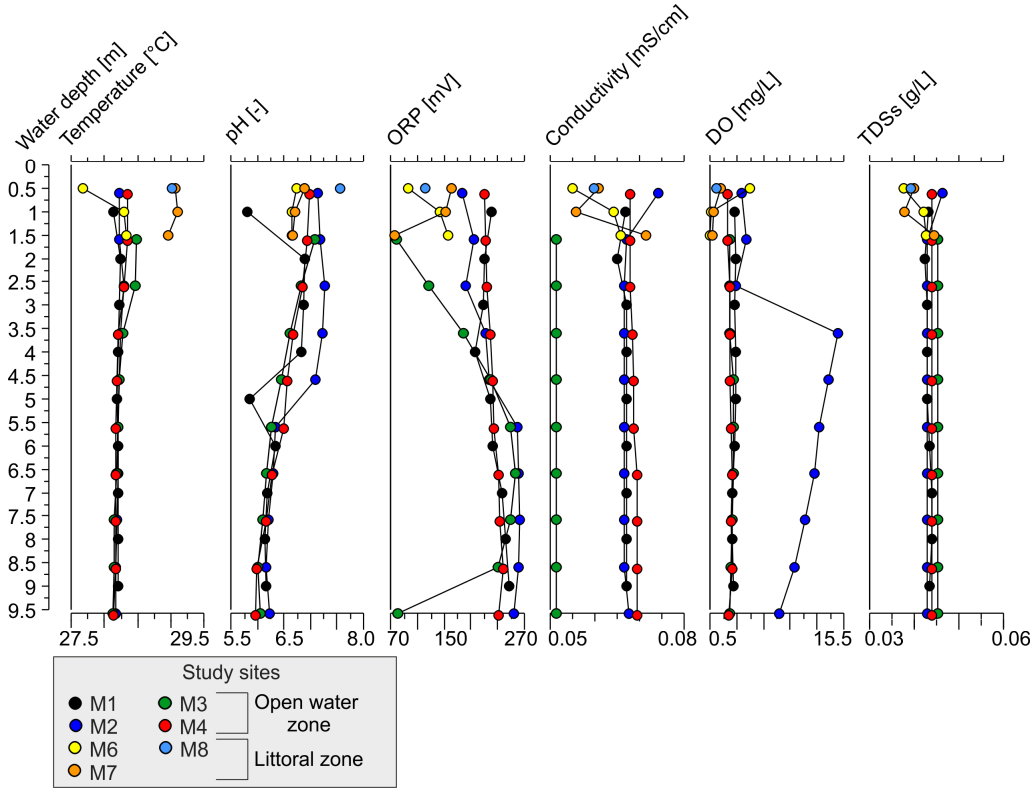


Figure 2. Vertical distribution of the basic water quality parameters (temperature, pH, ORP, conductivity, DO, TDSs) measured in situ during the fieldwork at the sites M1–M4 (open water sites) and M6–M8 (littoral sites). Abbreviations: ORP—oxidation–reduction potential, DO—dissolved oxygen, TDSs—total dissolved solids.

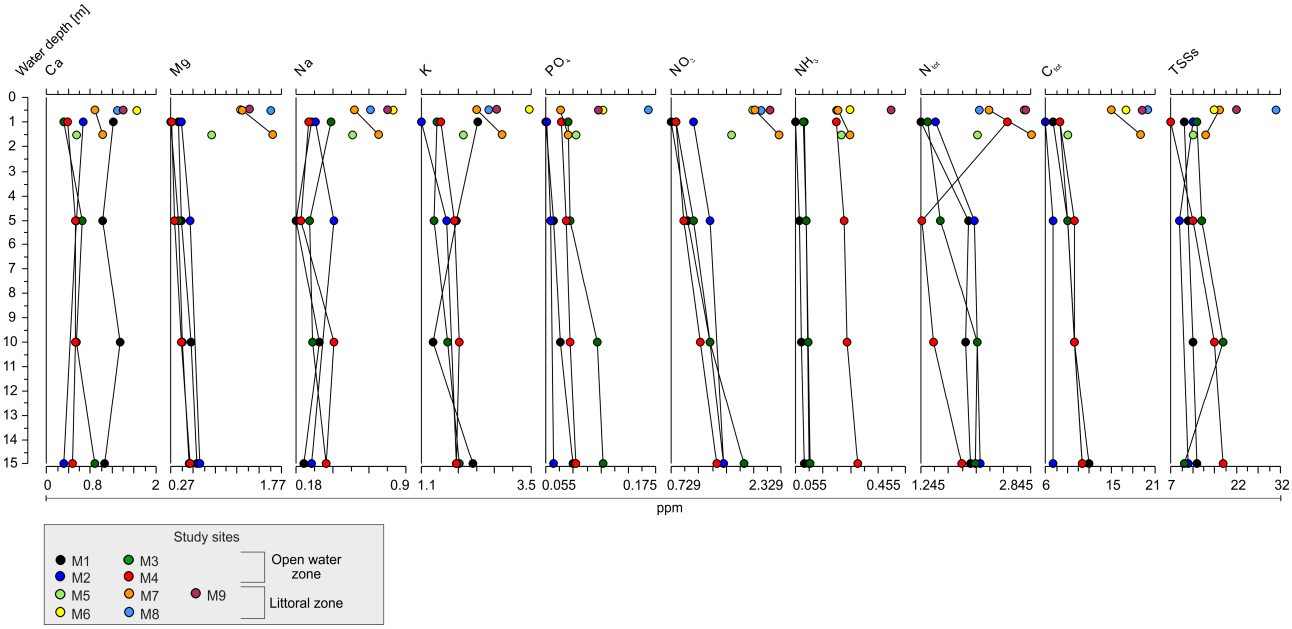


Figure 3. Vertical distribution of the basic cations (Ca, Mg, Na, K), nutrients (PO_4, NO_3, NH_3, N_{tot}, C_{tot}), and total suspended solids (TSSs) determined for Lake Maninjau waters at the stations located in the open water (M1–M4) and littoral zones (M5–M9). Abbreviations: N_{tot}—total nitrogen, C_{tot}—total carbon.

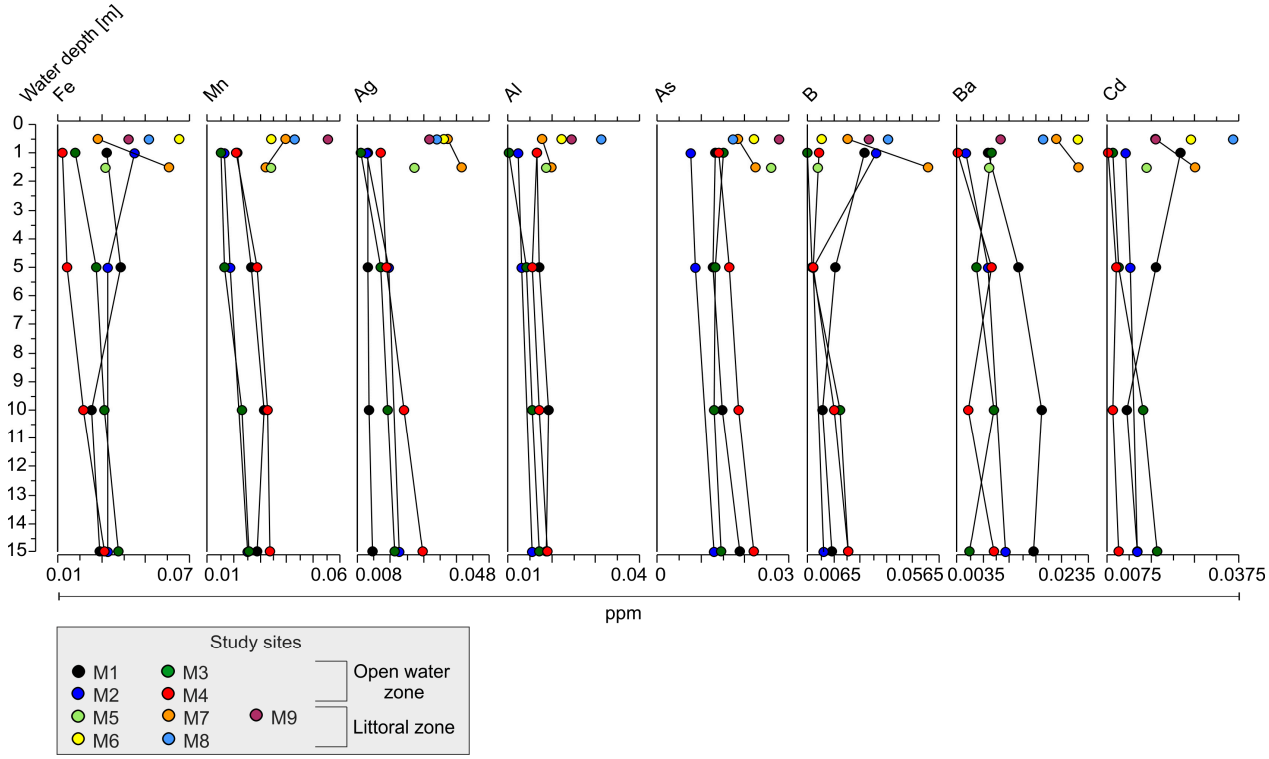


Figure 4. Vertical distribution of the trace elements (Fe, Mn, Ag, Al, As, B, Ba, Cd) determined for Lake Maninjau waters at the stations located in the open water (M1–M4) and littoral zones (M5–M9).

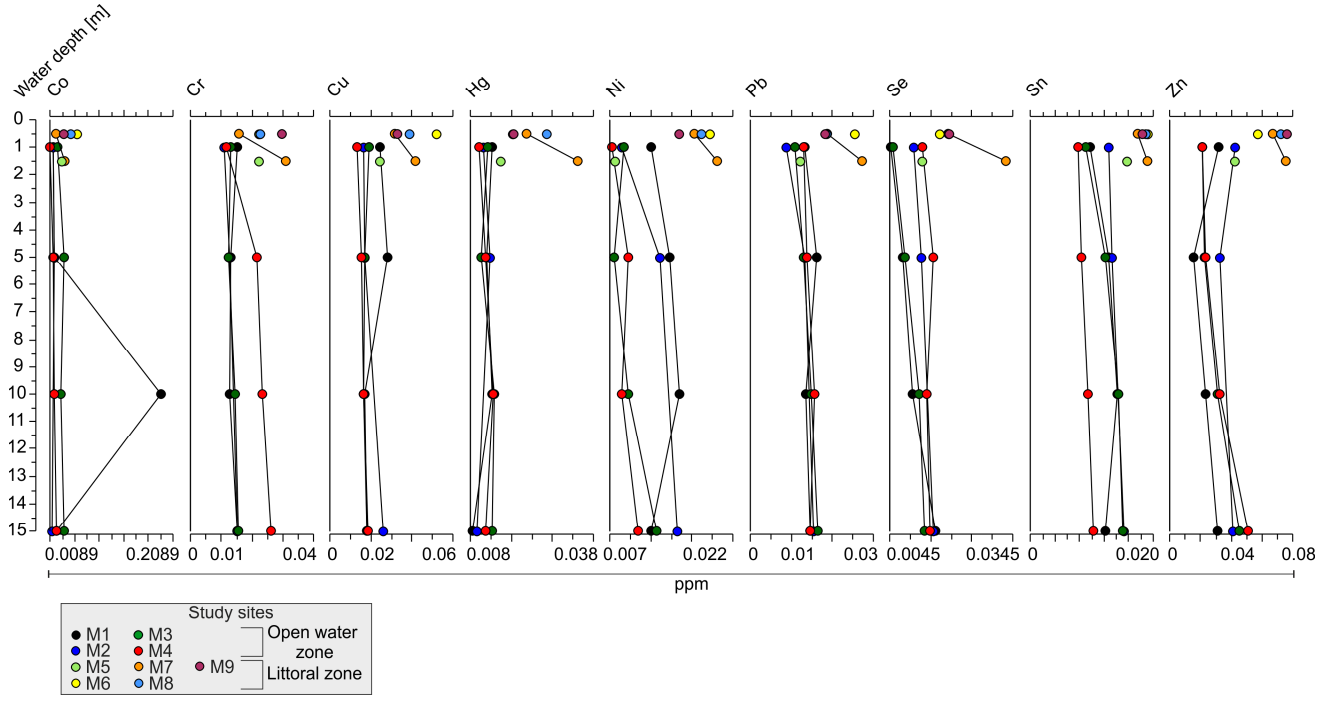


Figure 5. Vertical distribution of the trace elements (Co, Cr, Cu, Hg, Ni, Pb, Se, Sn, Zn) determined for Lake Maninjau waters at the stations located in the open water (M1–M4) and littoral zones (M5–M9).

3.2. Main Cation Content

The findings of our study revealed that Lake Maninjau has low basic cation content (as shown in Table 1), with potassium being the dominant cation at all study sites. The concentration of potassium ranged from 1.11 to 3.45 mg/L, while calcium played a secondary role, with a few exceptions in favor of magnesium at M4 (15 m), M5, M7, and M8 stations (Figure 3). Station M1 had the highest levels of Ca and K within the open water sites. It is worth noting that the littoral sites generally exhibited higher content of basic cations compared to the open water zone. However, there was no visible trend in the content along the water depth.

Fluctuations in Nitrogen Compound and Phosphate Concentrations

The total nitrogen (TN) content in the water of our sampling locations ranged from approximately 1.245 to 2.917 mg/L, with a median value of around 2 mg/L. The dominant form of nitrogen found in the water was nitrates (NO_3), with concentrations varying between 0.729 (0.452 mg/L NO_3_N) and 2.295 mg/L (1.424 mg/L NO_3_N). Meanwhile, ammonia content was observed to be present in a range of 0.055 to 0.401 mg/L. Furthermore, our analysis also showed that the concentration range of total carbon in the water was between 6 and 20 mg/L, while the phosphate concentration ranged from 0.055 (0.017 mg/L PO_4_P) to 0.168 mg/L (0.052 mg/L PO_4_P). Slightly higher values of nutrients were noted for deeper water layers at the open water sites and in the littoral zone.

3.3. Trace Element Variability

Median metal concentrations decreased in the following order: Co, Sn, Zn, Fe, Mn, Cu, Ag, Al, B, Cr, As, Pb, Cd, Hg, Se, Ni, and Ba. The highest values of most of these elements were determined at the littoral stations. Between open water sites, the total content of analyzed heavy metals mostly did not differ significantly; however, elevated content of B was found at sites M1 and M2 (upper water levels). The littoral sites definitely showcased notable distinctions compared to the open water sites, as depicted by the higher concentrations of various trace elements (Figures 4 and 5).

3.4. Comparison with Water Quality Standards

The concentrations of trace elements were subjected to scrutiny through comparison with established thresholds provided by the World Health Organization [35] and Indonesian Governmental Regulations [36] as outlined in Table 2. The Indonesian Governmental Regulations (IGRs) provide guidelines regarding requirements of water quality for various purposes. According to the IGRs, waters are grouped into four classes: I—good quality waters that are readily suitable for sources of drinking purposes with minimal treatment; II—waters exhibiting relatively low levels of pollution, rendering them suitable for a range of activities such as fish farming (aquaculture), agricultural utilization, and recreational pursuits; III—waters characterized by moderate pollution levels that necessitate substantial treatment to meet the standards for drinking water usage. However, these waters remain suitable for purposes such as irrigation, industrial applications, and non-contact recreational activities; IV—waters exhibiting a high degree of pollution, rendering them unsuitable for direct human utilization and necessitating comprehensive treatment or remediation for any intended purpose. These waters are often impacted by industrial discharge, sewage, or other substantial sources of pollution.

The majority of the elements examined were observed to conform to the prescribed limits set by the authoritative bodies. However, it was ascertained that concentrations of Hg surpassed the threshold outlined by both the WHO and IGRs at all sites tested. Additionally, results of Cd analyses indicated concentrations that exceeded the recommended values set by the WHO and were found to exceed the guidelines of the IGRs for all four classes at several measurement points (Table 2). It is noteworthy to consider the concentrations of Se and Zn, as they exceed the standards set by the WHO and IGRs. In accordance with the IGRs, the waters of Maninjau surpass the permissible limit of Zn even for water class III.

Table 2. Basic statistics calculated for trace elements juxtaposed with the guidelines of the World Health Organization (WHO) for drinking water and water classification according to the Indonesian Governmental Regulations (IGRs).

Parameter	Unit	Min	Max	Median	WHO	Water Class (Indonesian Governmental Regulations)			
						Class I	Class II	Class III	Class IV
Ag	mg/L	0.0089	0.0398	0.0176	0.1	-	-	-	-
Al	mg/L	0.0102	0.0312	0.0172	-	-	-	-	-
As	mg/L	0.0078	0.0278	0.0152	0.01	0.05	0.05	0.05	0.1
B	mg/L	0.0065	0.0524	0.0165	2.4	1	1	1	1
Ba	mg/L	0.0037	0.0221	0.0092	1.3	1	-	-	-
Cd	mg/L	0.0078	0.0362	0.0145	0.003	0.01	0.01	0.01	0.01
Co	mg/L	0.0089	0.189	0.0201	-	0.2	0.2	0.2	0.2
Cr	mg/L	0.011	0.031	0.0152	0.03	-	-	-	-
Cu	mg/L	0.0133	0.0523	0.0187	2	0.02	0.02	0.02	0.2
Fe	mg/L	0.0122	0.0653	0.0319	-	0.3	-	-	-
Hg	mg/L	0.0086	0.0342	0.0132	0.006	0	0	0	0.01
Mn	mg/L	0.0152	0.0556	0.0287	0.08	0.4	0.4	0.5	1
Ni	mg/L	0.0072	0.0201	0.0121	0.07	0.05	0.05	0.05	0.1
Pb	mg/L	0.0087	0.0273	0.0145	0.01 *	0.03	0.03	0.03	0.5
Se	mg/L	0.0048	0.0328	0.013	0.04	0.01	0.05	0.05	0.05
Sn	mg/L	0.0078	0.0192	0.0133	0.02	-	-	-	-
Zn	mg/L	0.0156	0.0766	0.0325	-	0.05	0.05	0.05	2

3.5. Numerical Analysis

Prior to PCA, the Kendall rank correlation was run to exclude variables exhibiting high correlation (>0.7 or <−0.7). The analysis results revealed the presence of high correlation among the following element pairs: DO-NH_3, NH_3-Se, C_{tot}-Pb, Ag-Se, Ba-Pb, Mg-Sn, Mg-Ni, conductivity-TDSs, Ba-Ni, and NO_3-Mg (SM1; figure displays only statistically significant correlations with p-value ≤ 0.05). Consequently, in order to mitigate the effects of multicollinearity, a decision was made to include only one element from each correlated pair in the PCA. In our study, one PC axis was extracted as a significant explanatory variable using the "elbow" point method (Figure 6a). The absolute percentage of variance was 56.5%. (Figure 6). As shown in Figure 6, $C_{tot,}$ TSSs and all metals were strongly positively correlated with PC1, and had the highest quality of representation, whereas ORP negatively correlated with PC1 at a significant level.

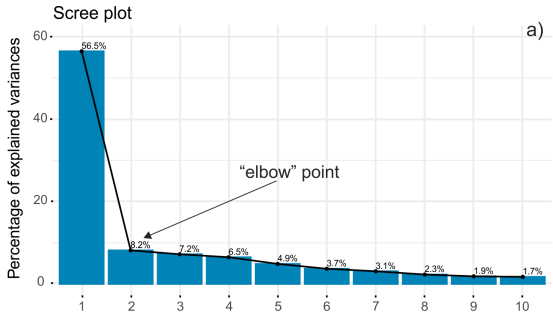


Figure 6. *Cont.*

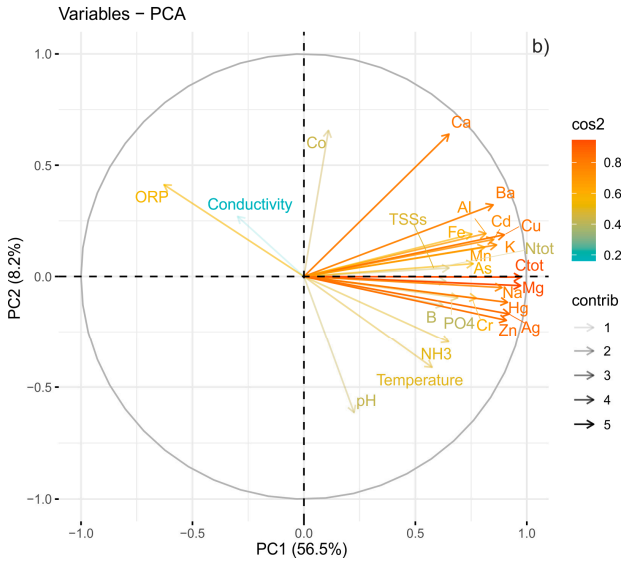


Figure 6. Results of Principal Component Analysis of water samples collected up to a depth of 10 m: (**a**) scree plot of percentage explained variance, (**b**) PCA based on correlation matrix Axes 1 and 2. Abbreviations: cos2—the quality of the representation (high values indicates a good representation of the species on the principal component), contrib—the contributions (in percentage) of the variables to the PC, ORP—oxidation–reduction potential, TDSs—total dissolved solids, N_{tot}—total nitrogen, C_{tot}—total carbon.

4. Discussion

Water pollution is an issue affecting surface water bodies globally, and Lake Maninjau is no exception. The primary problem is the high level of both organic and inorganic pollutants. The pollutants, such as nutrients and heavy metals, have severe impacts on the aquatic ecosystem, and, therefore, many studies of chemical composition in Lake Maninjau have already been conducted [18,19,22,26,37,38]. Our data revealed that the problem of water quality is still pressing and manifested by several indices.

Waters of Lake Maninjau at all studied sites were characterized by extremely low conductivity, with the domination of potassium within the base cations. Conductivity was strongly positively correlated with TDSs. This is primarily because the main components of TDSs, including dissolved salts, and ions, are also significant contributors to the overall water conductivity. As the concentration of dissolved solids and ions rises, there is a concurrent increase in both conductivity and TDS values, establishing a positive correlation between these two parameters. However, such a trend is not always present and usually is found in natural waters [39].

Most Indonesian lakes are characterized by low EC with a decreasing trend along with water depth [40]. However, EC values noted within this study were extremely low and were rather stable until 950 cm of water depth. The previous research of Lukman et al. [26] revealed almost two times higher EC, and encompassed fourfold measurements at different months (June, September, December in 2013, and March 2014). These months differed in the rainfall amount, with the highest value noted in December 2013 and lowest in June 2013 [41]. However, the discrepancies between studies may result from the rainfall anomaly that appeared in 2022 exceeding the 30-year average precipitation amount [42]. It means the rainy season appeared earlier, and rainfall intensification was especially noticed since the third week of August. This period converged with our field trip, which suggested a dilution effect of waters and needed to be kept in mind. On the other hand, catching data about physicochemical conditions of Lake Maninjau at the time of early rainy season (or just before) seems to be crucial in the context of the reappearing of massive fish kills. It was pointed out by Prof. Syandri that these dramatic events are likely related to the

deterioration of weather conditions and heavy rains [43]; therefore, such data may provide valuable information about early signals of ongoing massive fish kills.

Calcium ions, usually dominating in the inland freshwater ecosystem [1], played a secondary role in Lake Maninjau. Herein, the dominant cation was potassium, which usually is the least abundant [44]. There are several sources of potassium in Lake Maninjau, including natural (weathering of K-bearing minerals) and anthropogenic. However, these sources may also contribute to, i.a., calcium content. Therefore, we rather exclude natural factors as a driver of K domination. Several activities within anthropogenic potential forces need to be listed, like aquaculture, wastewater disposal, and agricultural runoff. These sources, unfortunately, may also provide additional Ca^{2+}, thus it is not possible to settle which one is the most important potassium provider in Lake Maninjau waters at this stage of the research. We just may suppose that aquaculture is the prevailing factor considering the scale of the fish farming in the lake. However, it needs to be highlighted that surface runoff also has an influence on water quality in Lake Maninjau [45].

Temperature noted did not differ significantly, oscillating around 28 °C and coinciding with some previous findings [18,22,26]. However, sometimes extremes with water temperature above 30 °C have been reported [38]. According to our data, no vertical thermal stratification appeared, but this may result from limits of this research (measurements only up to 10 m) or the date of the fieldwork. Fakhrudin et al. [38] noticed weak thermal stratification with a temperature gradient between surface water and 30 m depth of only 1 °C on average. On the other hand, they revealed a high dynamic of temperature in the uppermost surface water layer (between 0 and 2 m water depth). We did not notice such a pattern, but our research was conducted in August whereas Fakhrudin et al. [38] analyzed data gathered between January and May 2018. They also revealed that the stratification index (SI) indicated that the southern basin is more susceptible to water column mixing. Moreover, the depth of thermocline occurring in Lake Maninjau varies significantly from 6–8 m to 20 m water depth depending on the weather conditions [37]. Therefore, it is assumed that the waters at the time of our field campaign were relatively well mixed.

Measurements of temperature are important as it acts as a limiting factor of oxygen content [1]. Despite a relatively stable temperature in the water column, our data revealed a wide range of dissolved oxygen content from very well oxygenated (up to 14.8 mg/L O_2) to hypoxic conditions (<2 mg/L O_2). Values as low as 0.56 mg/L O_2 were observed at the littoral site near the floating cage. This suggests that the lowest O_2 content reported was likely related to higher biological activity and higher content of organic matter, and thus its decomposition. This is likely triggered by extra input of allochthonous organic matter, i.a., from the surface runoff. Additionally, it was proved by [18] that more than 50% of total organic matter input in Lake Maninjau comes from floating net cages. Therefore, we may expect lower oxygen content at the littoral sites, especially those situated near cages. Interestingly, all previous studies revealed good oxygen conditions for surface waters, with values mostly above 4 mg/L O_2 [18,19,22,37,38], and lower values were usually observed below 3–5 m depth [37,38]. Furthermore, the elevated levels of DO documented in this study could be attributed to high photosynthetic activity. According to Henny and Nomosatryo [46], the presence of certain indicators, such as dissolved oxygen exceeding 9 mg/L, Secchi depth less than 3 m, and pH higher than 9, may serve as an early warning signal for potential critical conditions in Lake Maninjau. All data, however, displayed a wide range of variability for this parameter and may be a signal of further deteriorating water quality conditions. Our finding indicates the importance of very complex, well-designed long-term monitoring.

Furthermore, low content of DO was related to the surface water layer, which is in contradiction to previous findings [37,38] and the generally observed trend. Especially interesting results are those obtained for the planktonic site, M2, where we noticed a sudden increase in dissolved oxygen at the depth 350 cm. This unusual situation could be related to the water temperature drop, as lower temperature affects oxygen solubility [47]. Such an event, however, likely appears at lakes with distinct temperature boundaries between

water layers, whereas herein, the temperature gradient is negligibly small. Another forcing factor could be activity of deep-dwelling photosynthetic organisms.

Higher levels of dissolved oxygen contribute to a more oxidizing environment, leading to higher ORP values. In well-aerated water, where DO concentrations are high, the potential for oxidation reactions increases. Therefore, the consequence of lower DO at the littoral sites is lower ORP levels [48]. This supports the aforementioned assumption about higher allochthonous matter input, including organic pollutants. This requires more electron acceptors for decomposition, resulting in lower ORP [49]. Therefore, ORP is a good indicator of water pollution and it is broadly accepted that healthy water has values between 300 and 500 mV [50]. ORP values reported for Lake Maninjau confirm water pollution, of which the level varies spatially. Furthermore, vertical variability in ORP was observed at the open water stations, with heightened values detected in deeper water layers at most of the open water sites, except for station M2. Additionally, there were no substantial alterations in DO levels, accompanied by lower pH values. Decreasing pH with depth may limit oxygen solubility in the water, as lower pH reduces water's ability to bind oxygen. Meanwhile, intensive activity of photosynthetic organisms increases ORP through oxygen production. In such a scenario, despite stable levels of dissolved oxygen, an increase in ORP may be observed because oxygen production by photosynthetic organisms outweighs its solubility in water, leading to more oxidizing conditions. This intricate interaction between pH, DO, and ORP can lead to different patterns and trends in different parts of the lake, depending on local conditions and biological and chemical processes.

The important pollutant directly affecting, i.a., oxygen levels, is TSSs [50]. Surprisingly, obtained values within this study suggest relatively clear waters [50] with tendency, as expected, to more suspended solids in the littoral zone. In the past, TSSs usually were below 20 mg/L. Herein, we found a locally higher content of TSSs, as high as 31 mg/L. Despite that fact, reported values still allow the assignment of Lake Maninjau waters to class I or II in terms of TSSs. However, data from 2018 [51] revealed that the concentration of TSSs may achieve as high a level as 850 mg/L, suggesting the susceptibility of the lake to this type of pollution. Previous research has revealed the relationship between TSSs in Lake Maninjau and rainfall events along with surface runoff [45]. It is plausible that the intensity of these processes contributes significantly to discrepancies observed in the content of this environment variable.

Aquaculture as a contamination source is usually discussed in terms of macronutrients like nitrogen and phosphorus as the main ingredients (e.g., [52]). Lukman et al. [26] discovered that there were no substantial spatial differences in the water quality of Lake Maninjau; however, they observed slightly higher content of TN and NH_4 along with oxygen depletion at the sites near the floating cages. This may be an effect of the input of additional nutrients to the ecosystem from fish feces and excretion. Previous studies displayed values in the following ranges: 0.15–0.36 mg/L for NO_3_N, 0.23–0.47 mg/L for PO_4_P [22], 0.142–0.351 mg/L for NH_3, and 0.656–1.476 mg/L for N_{tot} [26]. Our data significantly deviated from previous findings, exhibiting especially notably higher values of total nitrogen (N_{tot}) with a minimum content that remained consistently above 1.2 mg/L. The observed concentrations of N_{tot} are deemed elevated, suggesting a moderate degree of water pollution and the potential for progressive nutrient enrichment. Whereas moderate nutrient enrichment has the potential to enhance biodiversity and promote increased fish production, exceeding the nutrient threshold leads to environmental degradation.

Lake Maninjau receives nitrogen from multiple sources, contributing to the overall nitrogen load. In addition to the natural input of nitrogen through the decay of organic matter, Lake Maninjau receives additional nutrient inputs from various anthropogenic sources. These include atmospheric deposition, agricultural runoff, domestic sewage, and wastewater, as well as aquaculture and fish farming activities. For instance, the widespread practice of rice cultivation in the surrounding areas involves the use of fertilizers and pesticides, which can introduce nutrients and chemicals into the lake ecosystem. However, aquaculture most likely has the highest contribution to the nitrogen flux. According to

estimates made in 2015, the organic waste generated from fish culture activities in Lake Maninjau was projected to reach a substantial range of 10–30 tons per day [26]. Since that period, there has been a notable surge in the number of floating cages in Lake Maninjau, as indicated by data from the Badan Pusat Statistik Kabupaten Agam for the years 2015, 2016, 2017, and 2018 [29–32]. This expansion in fish farming operations has correspondingly led to a proportional increase in the generation of organic waste in the lake. Hence, our findings are of significant concern and indicate that, despite the implementation of the Save Maninjau Program, the water quality of Lake Maninjau is experiencing a gradual decline. This indicates a further significant potential for organic waste accumulation originating from the fish farming sector and the necessity for more robust countermeasures to be promptly implemented.

Among the commonly encountered heavy metal pollutants, mercury, cadmium, and copper are the most prevalent [53]. This observation appears to hold true for Lake Maninjau as well, indicating the presence of these particular heavy metals at high levels in its waters. According to our data, the major pollutant is Hg, of which content exceeds the allowable level of all water classes [36], and it is higher than in another Sumatran waterbody, Lake Singkarak, where aquaculture activity is significantly lower (Table S1).

Mercury enters the environment through both natural and anthropogenic sources via wet and dry deposition. The primary natural source is geological activity, while key human-driven contributors include mining, fossil fuel combustion, and waste disposal. In some cases, mercury pollution may also arise from point sources due to localized contamination [54]. Additionally, the source of elevated concentration of heavy metals may be wastewater and excreta which sometimes have been added as a form of nutrient source, a practice still common in some Asian countries [55].

In the case of Lake Maninjau, fertilizers potentially used in aquaculture and agriculture may be a source of metals. Phosphate fertilizers, for example, are widely known to contain heavy metals such as Cd, Hg, and Pb, which can enter the lake either directly or through surface runoff, contributing to the pollution of the ecosystem [56]. Apart from potential natural sources of Hg, as the catchment area comprises volcanic rock and soils, a previous study highlighted that anthropogenic activities are key contributors to the lake's contamination [57].

In a prior study conducted by Komala et al. [57], it was observed that the Hg content in waters at floating cage locations in Lake Maninjau may be even ten times greater than those levels reported herein. This generates a huge ecological risk, especially considering the bioaccumulation potential of heavy metals. Komala et al. [57] revealed that the mercury content in one of the endemic fish species (*Rasbora argyrotaenia*) of Lake Maninjau surpasses the permissible levels. Luckily, the aforementioned research discovered that the mercury levels in the species of fish *Oreochromis niloticus* cultivated in floating cages remained well within acceptable limits.

The situation is profound and should be constantly monitored. Mercury has low solubility and can be accumulated in significant amounts in lake sediments which may be released into the water under favorable conditions. Additionally, benthic organisms may transfer some elements to the higher trophic levels. As the sediments act as the sink, a likely analogous situation is expected in the case of other heavy metals. As an example, the presence of elevated concentrations of Cd and Cu in the waters of Lake Maninjau also can be attributed to aquaculture practices. The levels of these elements surpassed the permissible thresholds set by the IGRs for all water classes at several investigated locations, and their concentrations are significantly higher than those in Lake Singkarak (Table S1). Previous studies also reported similar findings [21,57]. Both cobalt and copper, in appropriate doses, can bring benefits; however, elevated exposure causes adverse effects on humans and other organisms [53]. Additionally, it has been observed that there are localized areas within the lake where the concentrations of Zn and Se are significantly higher. This indicates the presence of elevated levels of these metals in specific regions. Furthermore, a study conducted by Komala et al. in 2021 [21] and 2022 [57] revealed that contamination by lead

(Pb) was detected not only in the water but also in the fish population in the northern part of the lake.

Our research, along with that conducted by Komala et al. [21,57], revealed significant problems, especially related to Hg content. The aforementioned study focused on the north and central part, and our data partly fill the gap in knowledge about heavy metal pollution in the south part of the lake. The higher levels of heavy metals reported by Komala et al. [21,57] likely resulted from higher human pressure on the north shore (higher density of settlements) and/or a potential dilution effect due to exceptional weather conditions during our field trip. While one might assume that large, deep lakes are more resistant to contamination, the available data indicate a different reality. The discussed data reveal that pollution is prevalent across the entirety of the lake. These findings emphasize the urgent need for immediate action. It is evident that the lake, despite its size and depth, is not immune to the harmful impacts of pollution. Therefore, swift and decisive measures must be taken to mitigate the contamination and prevent further degradation of the lake's ecosystem. The significance of taking immediate action becomes even more apparent when considering the scientific evidence. Research by Xie et al. [13] reveals that the concentration of heavy metal contamination remains persistently high in the sediments even after the removal of floating cages, indicating a prolonged presence of contaminants.

Lake Maninjau is located in close proximity to both active volcanoes (Marapi, Singgalang, Tandikat) and a strike-slip fault. The lake lies close to highly active Mount Marapi. This stratovolcano has experienced numerous of short-lived and small eruptions [58], with the most recent major activity occurring in 2023. Mount Marapi often releases ash and pyroclastic material to effusive lava flow and it is likely that some material may be transported for long distances. Products of its activity indicate a range of compositions from basaltic to andesitic reach in silica, aluminum, and iron [59]. The sediments within the lake contain elements such as Fe, Ca, K, and others [58], which, given suitable conditions, have the potential to leach into the water column. Moreover, the surrounding rocks primarily comprise calc-alkaline andesite and high-K rhyolite [60], serving as an additional source of these elements. Obviously, volcanic products can serve as additional sources of trace elements. For instance, pyroclastic materials from the eruption of Mount Talang, approximately 150 km from Lake Maninjau, contain elements such as Pb, As, and Br. While the concentrations of these elements in the volcanic ash were slightly higher than those found in agricultural soils, they were significantly lower than in sludge. However, repeated volcanic eruptions can lead to the accumulation of these elements in the catchment area [61]. As the rocks undergo weathering and the soil erodes, they release various minerals and trace elements. When heavy rainfall or runoff occurs, the intensified erosion acts as a catalyst, increasing the transport of these substances into the lake. This influx results in fluctuations in the concentrations of minerals and trace elements within the lake water, contributing to its dynamic chemistry.

Moreover, Lake Maninjau lies just 15 km from the Sumatran Fault and is situated in an area marked by significant volcanic activity, making the region rich in geothermal phenomena. Therefore, hydrothermal vents could influence Lake Maninjau in several ways. Characteristics of these vents include the presence of both vapor-dominated and water-dominated geothermal resources. Thermal springs in Sumatra can reach temperatures between 60 °C and over 100 °C [62]. If similar vents are present near or within Lake Maninjau, they could introduce warm water into the lake. Additionally, the discharge of hydrothermal fluids into the lake would not only contribute to the elevated water temperatures but also play a significant role in altering the lake's chemical composition. Vents emit various fluids, notably including gases such as hydrogen sulfide, which can profoundly affect the chemistry of the water. The geothermal waters of Sumatra geothermal system are usually neutral chloride or bicarbonate types [62]. Some systems exhibit a notable concentration of acid sulfate–chloride or chloride–sulfate waters, particularly around the volcanic slopes, whereas neutral NaCl waters tend to be present in outflows located in the foothill areas [63].

Hydrothermal fluids may affect water pH, dissolved oxygen, and trace element content [64]. For instance, hydrothermal inputs lead to pH lowering. This, in turn, may affect metal solubility. Solubility of most metals increase inversely proportional to pH [65,66], which may partially explain higher concentration of some elements (Ca, Fe, Cd, B) at greater depth. However, the specific behavior depends on the presence of other ions, mineralogy, and redox conditions.

In order to effectively address the challenge posed by heavy metal and other contaminants, it is crucial to identify their sources. Determining the origin of these contaminants is essential for developing appropriate mitigation strategies and implementing targeted measures. The sources of heavy metals in Lake Maninjau can be natural or anthropogenic. For instance, volcanic activity in this region or weathering of rocks may release metals into the waterbody. However, considering the PCA results indicating one source of elements as predominant, we assume that anthropogenic activities are responsible for shaping water chemistry of Lake Maninjau. These data suggest that both main nutrients and metals have the same source and are coupled. Therefore, we suppose the enrichment in elements is related to higher input of organic matter from floating cage activities. This is consistent with other studies that have shown that floating cage aquaculture can lead to nutrient enrichment and degradation of water quality, primarily through organic matter inputs and feed waste.

Given the well-established connection between floating cage aquaculture and nutrient enrichment in tropical lakes, it is essential to implement targeted policy interventions to mitigate these environmental impacts. Regulatory frameworks should prioritize limiting nutrient discharge from aquaculture operations, optimizing feed use, and encouraging sustainable practices that reduce environmental harm. Additionally, establishing regular monitoring programs to track water quality is crucial for maintaining the long-term ecological health of lake ecosystems. Future research could also investigate alternative systems, such as integrated multi-trophic aquaculture [67], which has demonstrated potential for reducing environmental impacts by combining species that occupy different trophic levels, creating a more balanced ecological interaction. Engaging stakeholders in the development of sustainable aquaculture practices, while drawing on global best practice, is another important step in shaping effective pollution control measures.

Several management strategies have recently been proposed to address the water quality issues at Lake Maninjau, where pollution from fish cage aquaculture has become a growing concern. These strategies include reducing the number of fish cages, implementing surface water clean-up operations, and employing bioremediation techniques. Additional measures, such as dredging to remove accumulated sediments, modifying hydropower infrastructure to better regulate water flow, and promoting alternative livelihoods to lessen local communities' dependence on aquaculture, have also been suggested [17]. The goal of these combined efforts is to restore the lake's ecological balance while fostering sustainable economic development.

However, not all proposed interventions have been effectively implemented, due to a range of institutional, social, and economic challenges. One significant issue stems from conflicting interpretations of property rights between local communities and lake managers. Furthermore, discrepancies between government regulations and customary laws undermine local governance, leading to weak enforcement of policies and limiting the success of initiatives like cage reduction. This disconnect also hampers cooperative support for pollution control programs. Inadequate communication between lake management authorities and the local population exacerbates mistrust and reduces local participation in environmental interventions, such as reducing fish cage numbers.

Economic dependence on aquaculture is another barrier, as many farmers view it as an indispensable source of income. Despite recurrent environmental degradation and financial setbacks, aquaculture is still perceived as a profitable venture, making it difficult for farmers to shift toward alternative livelihoods, as proposed by initiatives like Save Maninjau [17]. These complex, interrelated issues emphasize the need for more comprehensive

approaches that integrate ecological sustainability with social, economic, and institutional considerations. Without addressing these underlying challenges, efforts like fish cage reduction may face significant obstacles in achieving their desired outcomes.

5. Conclusions

The examination of the physicochemical parameters of the lake water together with nutrient and trace element analysis yielded several significant findings:

- Conductivity, total dissolved solids, and temperature exhibited relatively stable values throughout the water column. The observed stability in the water parameters can be attributed to the mixing of the lake waters under distinctive weather conditions and the limitations of the sampling strategy;
- Lake Maninjau waters were characterized by extremely low conductivity, likely as an effect of dilution related to the exceptionally early coming of the rainy period;
- Notable changes in pH levels were detected, ranging from slightly acidic to slightly alkaline, with a decreasing trend along with increasing water depth at the open water sites;
- The littoral sites, especially those near floating cages, exhibit lower dissolved oxygen levels, likely due to organic matter decomposition and enhanced biological activity, including oxygen consumption by fish;
- There is variability in the concentration of nutrients, including total nitrogen, nitrates, ammonia, total carbon, and phosphate. Deeper water layers and the littoral zone tend to exhibit slightly higher values of these nutrients;
- The recorded levels of N_{tot} indicate a moderate level of water contamination;
- Certain heavy metals, including Hg and Cd, surpass the recommended thresholds established by the World Health Organization and Indonesian Governmental Regulations.

Our findings and previous research provide insight into the diverse and complex characteristics of Lake Maninjau waters, highlighting the need for further investigation to identify the underlying factors influencing the observed variations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16213079/s1, SM1: Results of correlation analysis (Kendall tau method) displaying correlation coefficients statistically significant. Table S1: Unpublished data on major heavy metals in surface waters of Lake Singkarak from the 2022 campaign: consistent methodology with the present study.

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