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The Impact of Weather Condition Changes on Vertical Distribution of Sulfides in Lake Maninjau Based on Observation Data

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Abstract: Sulfide is a crucial parameter in volcanic lakes, as its levels and fluctuations in the lake determine the origin of sulfide and the extent of its impact on the lake ecosystem. In stratified lakes, the sulfide produced tends to be retained beneath the oxic layer. The sulfides rise towards the surface as the oxic layer thins triggered by decreased water column thermal stratification. Meanwhile, the strength or weakness of thermal stratification is greatly influenced by weather conditions. Lake Maninjau is a volcanic lake with a relatively high sulfide content. Its vertical distribution in the water column is highly dependent on the stratification of the water column. When stratification disappears, sulfide rises to the surface (locally known as *tubo belerang*) and has a negative impact on surface biota. The objective of this study is to examine the distribution of sulfides in the water column of Lake Maninjau under two different weather conditions. We perform two surveys to measure physicochemical parameters and sulfide concentration on 26–29 November 2022 and 25–26 August 2023 considering the seasonal pattern. We found that air temperatures and sunshine duration combined with precipitation and wind speed drive the thermal stratification of the water column. The lower air temperature, shorter sunshine duration, higher precipitation, and stronger wind speed in the first survey (west monsoon) compared with the second survey (east monsoon) resulted in lower stratification and triggered the elevated sulfide to the surface. In the middle of the lake, the surface sulfide measured during the first survey was 4.16 µg/L. Meanwhile, in the second survey, it was only observed at 1.16 µg/L. The distribution of sulfides within the water column of Lake Maninjau is regulated by the stratification of the water column, a process directly impacted by weather conditions.

Keywords: Lake Maninjau, thermal stratification, Sulfide concentration, air temperature, rainfall

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1. Introduction

Sulfide is a foul-smelling gas that is toxic to aquatic life (Boyd, 2014; Piranti *et al.*, 2018). In active volcanic lakes, sulfide can originate from acidic gases emanating from channels connected to the magma system (Aguilera *et al.*, 2000). However, in dormant volcanic lakes, sulfide arises from sulfate reduction processes and the decomposition of organic matter (Henny, 2009; Dunnette *et al*., 1985). Sulfide in a lake plays a crucial role in the dynamics of nutrients, metals, and dissolved oxygen (DO) in the water column (Jasalesmana *et al*., 2023; Henny & Nomosatryo, 2012). Concerning DO, sulfide can reduce the oxic layer at the lake surface and may even eliminate the oxic layer if the DO content in that layer cannot counterbalance the amount of sulfide (Henny, 2009). This condition poses a threat to aquatic organisms because, in addition to the lack of oxygen for respiration, the existing sulfide becomes toxic to the biota.

Studies on the fluctuations of sulfide concentrations (Wardhani & Sugiarti, 2022; Riki Saputra *et al*., 2017; Sagala & Radiarta, 2012; Handayani *et al*., 2011) and their impact on nutrient dynamics (Henny & Nomosatryo, 2012) in various freshwater in Indonesia have been widely conducted. Similarly, the consequences of sulfide rising to the surface, leading to fish mortality, have been explored. However, there is limited research specifically examining the physical factors that drive the upward movement of sulfide in lakes. This study provides crucial information about the relationship between climatology and sulfide dynamics in the case of Lake Maninjau.

Lake Maninjau is located in Agam Regency, West Sumatra. This lake was formed due to a volcanic eruption around 52000 years ago (Alloway et al., 2004; Pribadi et al., 2007). This lake has several functions: tourism activities, fisheries, aquaculture, and hydroelectric power generation (PLTA). However, deteriorating water quality has caused the tourism sector to become unpopular. The decline in water quality is characterized by frequent eutrophication and the rise of sulfide from the bottom to the surface resulting in the death of fish in Floating Net Cages (FNC). From 1997 to 2019, losses due to fish deaths reached Rp. 212,175,000,000 (Makmur *et al*., 2020).

As a volcanic lake, volcanic activity may contribute to sulfide production in Lake Maninjau. However, a previous study reported that sulfide in Lake Maninjau was produced from the sulfate reduction process by sulfate-reducing bacteria (Henny, 2009). The speed of sulfate reduction to sulfide depends on organic carbon, inorganic carbon, or hydrogen as an electron donor and sulfate as an electron acceptor (Henny, 2009). Therefore, increased organic matter from KJA activity has triggered increased sulfide concentrations in Lake Maninjau (Henny & Nomosatryo, 2012, 2016; Henny, 2009). The resulting sulfide will accumulate in the anoxic base layer. Sulfides can rise to the surface, but when they meet the oxic layer, the sulfides are immediately oxidized back to sulfate, potentially depleting the oxygen in the layer (Dunnette *et al*., 1985).

The distribution of sulfides in the water column is highly dependent on the stratification of the water column, which is directly influenced by weather conditions (Henny, 2009). Stratification inhibits the mixing process between molecules in the hypolimnion and epilimnion layers (Elci, 2016). Consequently, this causes the accumulation of molecules produced in the hypolimnion layer, including sulfide, carbon dioxide, and ammonia (Shi *et al*., 2021; Kusakabe *et al*., 2008). However when strong winds and air temperature decrease, the stratification of the column disappears, causing sulfides and other molecules to rise to the surface (Katsev et al., 2010; Santoso et al., 2018; Fukushima et al., 2017, 2021).

Previous studies of sulfide distribution in the water column of Lake Maninjau have not linked it directly to weather conditions (Henny & Nomosatryo, 2012, 2016; Henny, 2009). Therefore, this study aims to examine the distribution of sulfides in the water column of Lake Maninjau under two different weather conditions: high rainfall intensity and high light intensity.

2. Materials and Methods

2.1. Sampling Location and Sulfide - Analysis

The survey at Lake Maninjau was carried out on 26 – 29 November 2022 and 25 – 26 August 2023 (hereafter we call it "Survey 1" and "Survey 2") at seven (7) sampling points (Figure 1). The selection of these two times will represent weather conditions during rainfall (west monsoon), (November 2022) and high sunlight intensity (east monsoon), (August 2023). Temperature and dissolved oxygen (DO) measurements in survey 1 were conducted using a CTD Rinko Profiler, while survey 2 utilized a ProDO YSI© International. Oxidation-reduction potential (ORP) and pH were measured in both survey 1 and 2 using HORIBA©U-52. Sulfide was measured from water samples taken using a 5 L Niskin Bottle water sampler from a depth of 0.5 m, 2 m, 10 m, 60 m and maximum depth on November 2022 and depth of 0.5 m, 2 m, 10 m, 60 m, and maximum depth on August 2023. The maximum depth varies based on sampling point. Sulfide concentrations were analyzed using the Methylene Blue Method (8131 Method) with the following stages (Manual, 2007): 1. Water samples are taken from a 5 L Niskin Bottle water sampler using a 50 ml syringe and filtered with a 0.45 μm filter. 2. The water sample was quickly transferred to a 10 ml tube to which ZnAc had been added. 3. The water sample is then added to reagents I and II. 4. The sulfide concentration in the sample was then measured using a DR3900 portable spectrophotometer (Manual, 2007).

2.2. Meteorological Data

Air temperature, wind, sun duration (SD), and rainfall on a daily scale were taken from the Padang Panjang Geophysics Station (0° 27' 58.68" S, 100° 22' 46.92" E), which has been published at https://dataonline.bmkg.go.id/data_iklim (Pusat Database-BMKG). Data taken from January 2022 to August 2023. SD is a climatological element used to express solar power exceeding 120 Wm^{-2} (Hamdi, 2014).

2.3. Data Analysis

Relative Thermal Resistance to Mixing (RTRM) is used to assess changes in the stratification strength of the lake water column against weather changes. RTRM is a straightforward approach for quantifying stratification caused by temperature differences (Kunz & Wildman, 2019; Kortmann, 1981). RTRM is calculated with the equation:

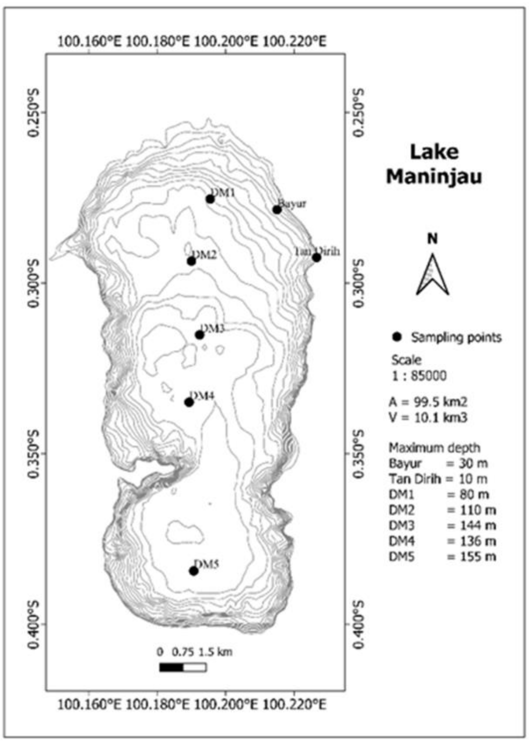
$$RTRM = \frac{\text{density of upper layer} - \text{density of lower layer}}{\text{density at 5°C} - \text{density at 4°C}}$$

....Eq. 1

The water density (ρ_T) of the water layer was calculated from the average temperature (T) of the water layer at each measurement point. Water density is calculated by the equation (Ji, 2017):

$$\rho_T = 999.842594 + 6.793952 \times 10^{-2}T - 9.095290 \times 10^{-3}T^2 + 1.001685 \times 10^{-4}T^3 - 1.120083 \times 10^{-6}T^4 + 6.536332 \times 10^{-9}T^5$$

....Eq. 2



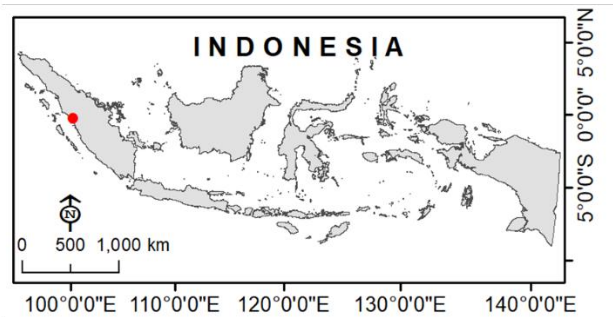


Figure 1. Sampling points at Lake Maninjau. Lake Maninjau located in Sumatra Island, Indonesia (red point).

3. Results and discussion

3.1. Physicochemical Profile of Water Column

The temperature profile of the water column in survey 1 and survey 2 is shown in Figure 2. The temperature profile of the water column in survey 1 relatively looks homogeneous. In contrast, in survey 2 appears stratified, as indicated by the differences in average temperature between the surface and the bottom, with a higher value of 2,2 °C compared to survey 1 is 1.16 °C. Based on the two temperature profiles, the hypolimnion layer of the water column in survey 2 starts from a much deeper depth (29.7 m) compared to survey 1 (1.28 m). The homogeneous temperature profile structure in survey 1 indicates that the Lake Maninjau water column experienced mixing at that time.

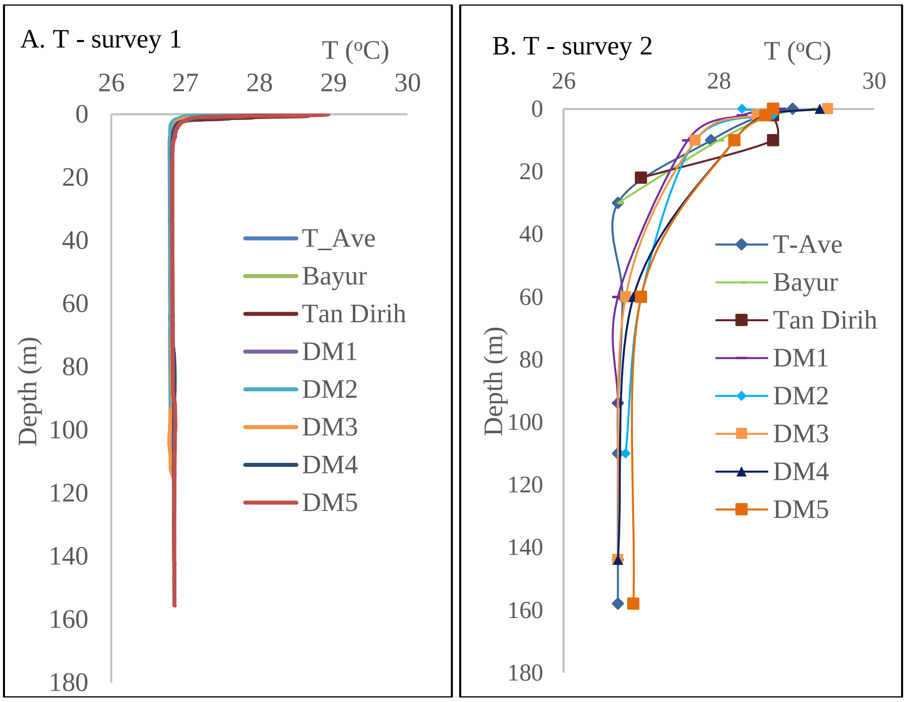


Figure 2. Water column temperature profile in (A) Survey 1 and (B) Survey 2. T-ave is the average temperature of the water column from each station.

The dissolved oxygen (DO) profile also indicates mixing conditions in the water column during survey 1. In survey 1, the water column's DO profile exhibits homogeneity from the surface to the bottom, with an average surface DO concentration of 0.74 mg/L, and its structure is similar to the temperature profile. Conversely, in the second observation, the water column displayed a high DO content, with an average surface DO concentration of 7.64 mg/L. The anoxic layer in the first observation, which was entirely in every layer of the water column, shifted to a depth of 10 in the second observation. This condition can be caused by the production of oxygen from the photosynthesis process by phytoplankton taking place optimally and sulfide as an oxygen reducer remaining in the bottom layer so that it does not reduce the oxygen content at the surface.

Fluctuations in the ups and downs of oxygen levels in the surface layer of Lake Maninjau can occur within a short time (up to an hour scale). In fact (Santoso & Triwisesa, 2020) stated that DO deficiency in Lake Maninjau could occur at any time, significantly if the loading of organic matter from KJA activities increases. However, in long-time observations, the anoxic layer of Lake Maninjau's water column tends to approach the surface (Subehi *et al.*, 2021; Fukushima *et al.*, 2017).

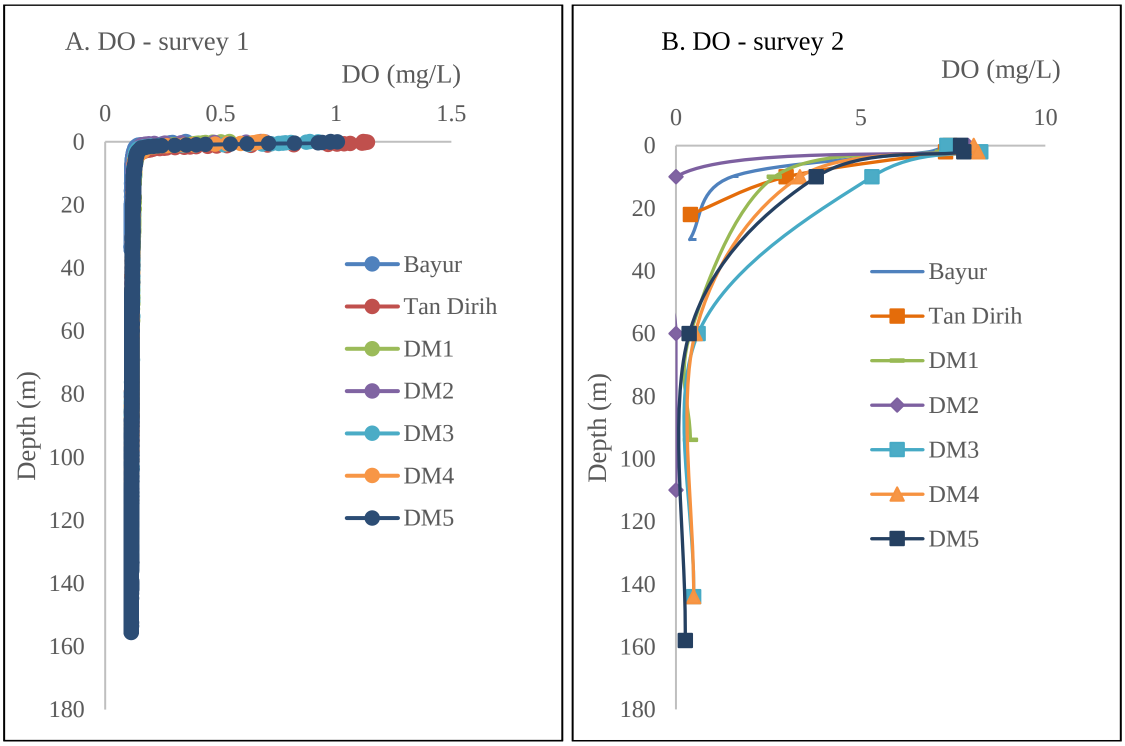


Figure 3. DO profile of the Maninjau Lake water column A) Survey 1 and B) Survey 2. DO water column in survey 1 appears to be homogeneous from the surface to the bottom with a low level. This differs from the water column in survey 2, which has a high DO concentration in the epilimnion layer.

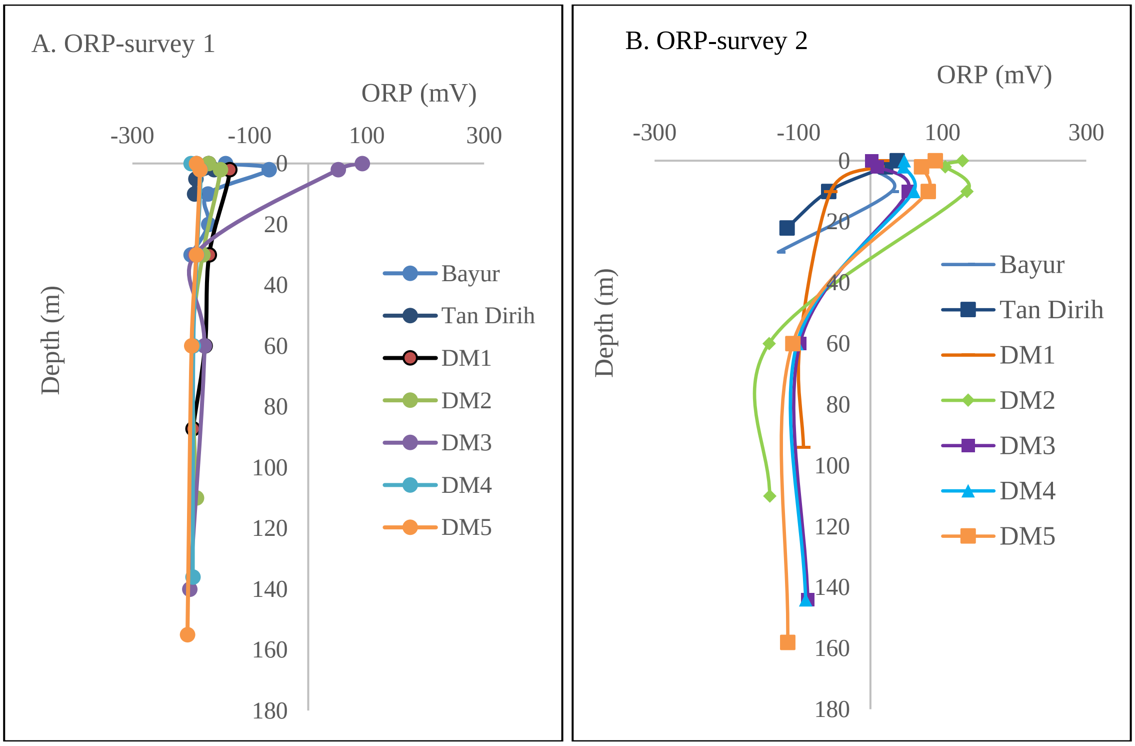


Figure 4. ORP profile of Lake Maninjau water column in (A) survey 1, (B) survey 2.

The significant difference in DO levels in the water column between the first and second survey periods indicates two different redox conditions. This can be seen from the ORP profile in the water column. Figure 4. A shows the ORP of the water column in the first survey period, which is generally negative from the surface to the bottom. In the second survey, the average ORP is negative from a water depth of 10 m (Fig. 4.B). A negative ORP indicates that much oxygen is used for the reduction process, so the oxygen content in the water column decreases drastically. Based on Figure 4.A it can be explained that each layer of the water column in the first survey period is in a reduced state, while the water column in the second survey is in a reduced state starting at a depth of 10 m.

3.2. Sulfide Distribution in Water Column

The physicochemical characteristics of the lake, as demonstrated by the temperature, dissolved oxygen (DO), and oxidation-reduction potential (ORP) profiles in each survey, have an impact on the sulfide profile in the water column. The homogeneity in temperature and DO throughout the water column in survey 1 indicates the absence of stratification, facilitating the movement of various molecules and gases, including sulfides, from the bottom to the surface. Figure 5 displays the distribution of sulfide in the water column of Lake Maninjau during survey 1 and survey 2. Based on Figure 5. A, sulfide in survey 1 is found at the surface with a concentration of 4.16 µg/L, suggesting that sulfides can rapidly rise to the surface due to the absence of thermal stratification. The sulfide concentration in the lake exceeded the class III water quality (for aquaculture) standard set at 2.0 µg/L (Piranti *et al.*, 2018). In contrast, as depicted by the sulfide profile in survey 2 (Figure 5.B), the average sulfide concentration on the surface is only 1.16 µg/L. However, the sulfide concentration in the lower layers is higher compared to the findings from survey 1. By comparing the sulfide concentration at a depth of 60 m, it can be seen that the sulfide in the survey 2 is on average 6 times greater than the sulfide in survey 1.

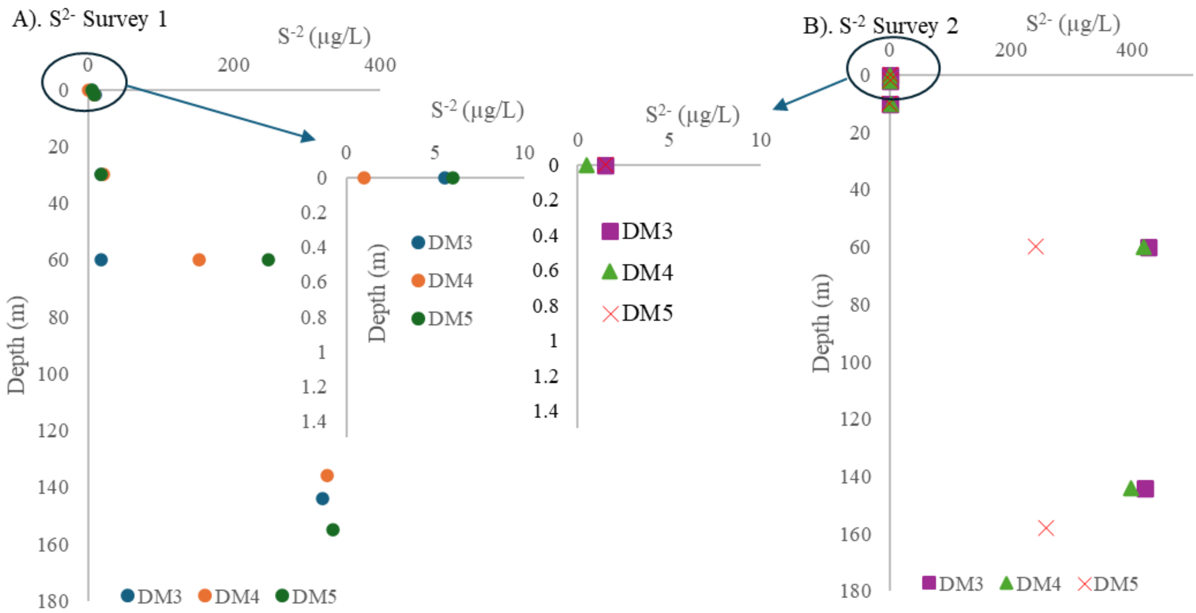


Figure 5. Distribution of sulfide in the water column of Lake Maninjau in (A) survey 1 and (B) survey 2. Small graphs provide snapshot of sulfide levels at the surface.

The elevated sulfide levels in the lower layer during survey 2 indicate that the temperature stratification of the water column during this survey restricted the upward movement of sulfide from the bottom layer to the surface. Simultaneously, the process of sulfate reduction to sulfide by sulfate-reducing bacteria persisted in the bottom layer, leading to the accumulation of sulfide in these lower layers. This is shown by the sulfide concentration in bottom layer during survey 2 was higher than in survey 1. In contrast, the lower sulfide concentrations in the lower layer during survey 1 resulted from the upward movement of sulfide to the surface as thermal stratification disappeared. Consequently, the dynamics of water column stratification play a crucial role in controlling the distribution of sulfides in Lake Maninjau's water column.

3.3. The Effect of Weather on the Sulfide Distribution

The lake's physical factor most significantly influenced by meteorological parameters is temperature. The temperature of the lake water column will be strongly stratified when the lake absorbs a large amount of heat energy from the atmosphere. When the stratification of the water column is strong, the lake water column will be stable from the mixing process, either through diffusion or convection (Read *et al.*, 2011).

Figure 6 shows the air temperature taken from the Padang Panjang BMKG station in 2022 and 2023. Visually, it can be seen that the air temperature in November 2022 is slightly lower than the air temperature in August 2023 with average temperatures of 22.43 and 22.94 °C, respectively. Even though the air temperature did not differ significantly, the rainfall between the two observation periods differed significantly. The average daily rainfall in the first observation was 21.34 mm, while in the second observation, it was 12.46 mm (Figure 7). Liu et al. (2020) reported that rain can reduce the lake's surface temperature; therefore, the decrease in lake surface temperature in survey 1 was more drastic than in survey 2. This will cause a temperature difference between the surface layer (which is usually warmer), and the bottom layer (which is cooler) becomes smaller, and even the temperature of the water column becomes homogeneous.

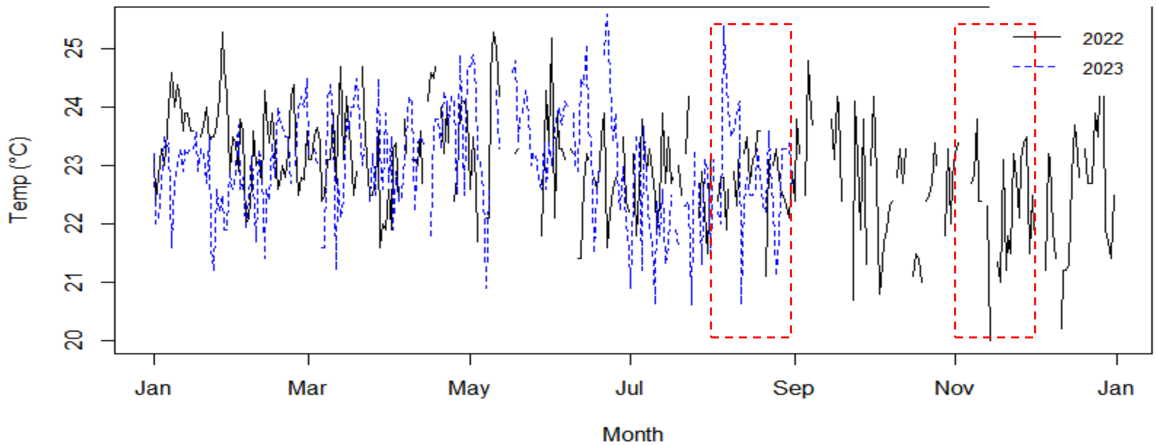


Figure 6. The average air temperature in 2022 and 2023. The black line shows the average air temperature in 2022, and the dotted blue line shows the average air temperature in 2023. The air temperature in 2023 can be found on the website https://dataonline. bmkg.go.id/data_iklim is only available until August.

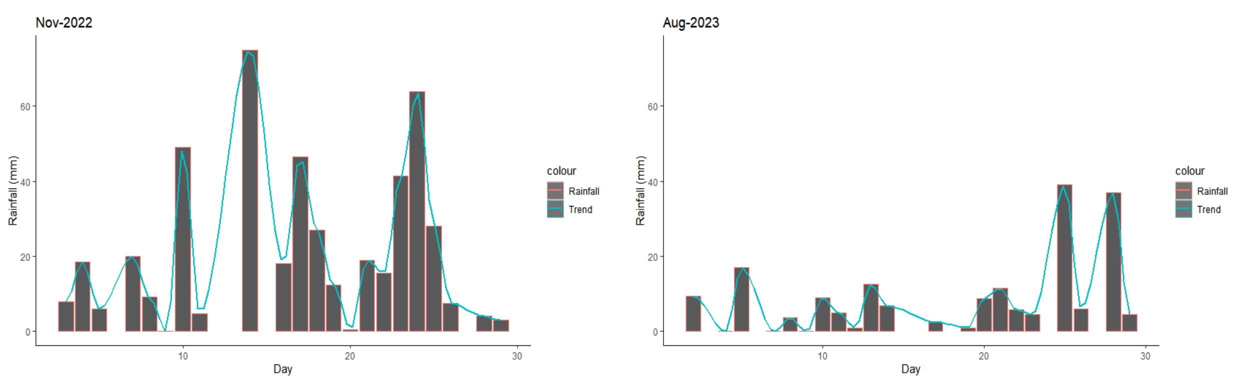


Figure 7. Daily rainfall in November 2022 (left) and August 2023 (right). In general, the average rainfall in November 2022 is higher than August 2023.

Apart from rainfall and air temperature, wind, and solar radiation significantly influence the regulation of water column stratification (Santoso *et al.*, 2018). Figure 8 illustrates the maximum wind speed and sunshine duration (SD) in November 2022 and August 2023. While the average wind speed in November 2022 (v = 3.80 m/s) is not markedly different from that in August 2023 (v = 3.90 m/s), the figure reveals that the wind speed during survey 1 was higher than in survey 2. Conversely, the sunshine duration in November 2022 (1.07 hours) was lower than in August 2023 (SD = 4.41 hours). Therefore, the combination of high rainfall, low air temperature, high wind speed, and low sunshine duration during survey 1 led to a weakening of water column stratification, while the opposite occurred in survey 2.

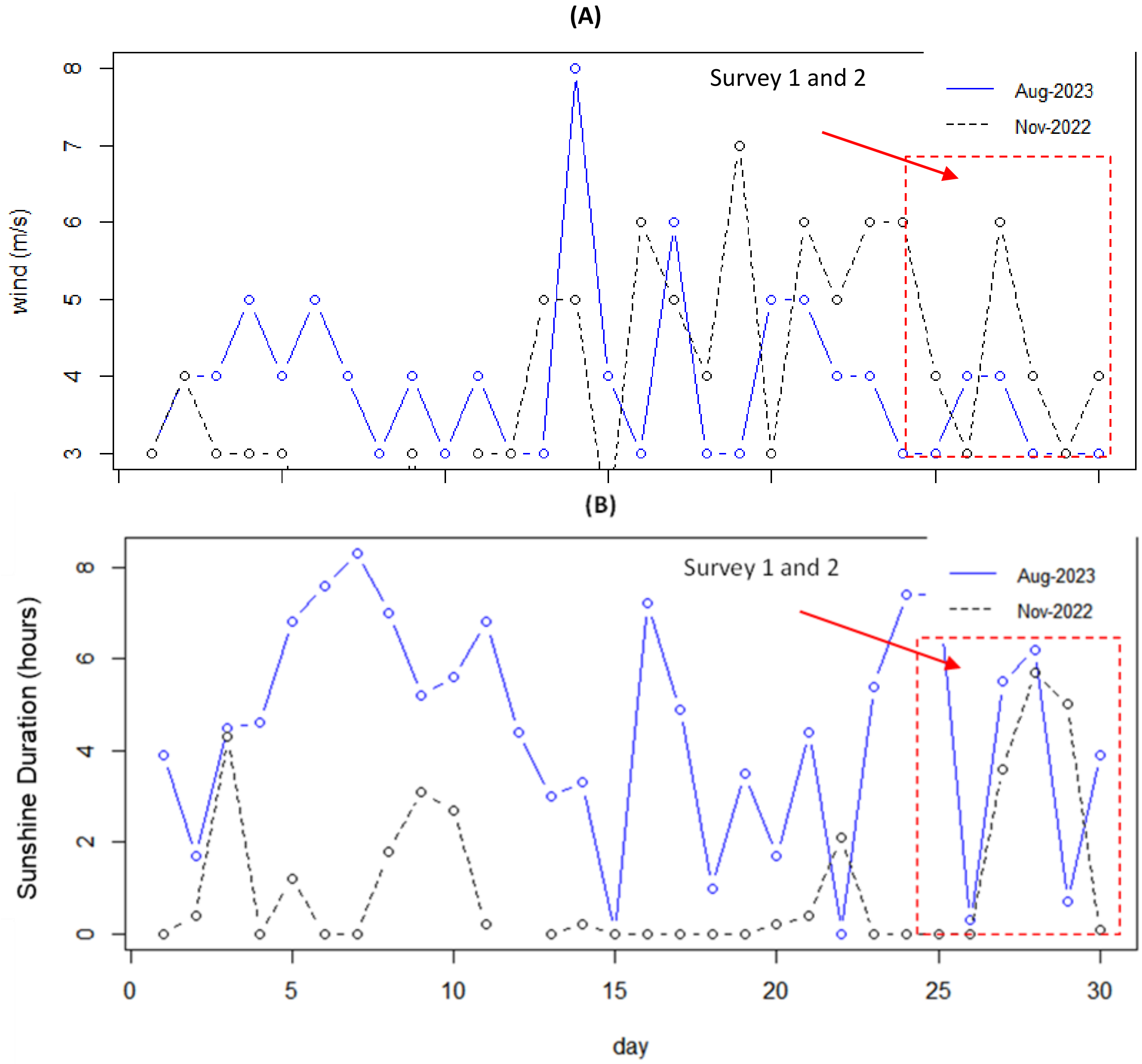


Figure 8. Comparison of (A) Maximum wind speed and (B) sunshine duration in November 2022 and August 2023

The differences in meteorological parameters between the first and second observations impact the stratification of the water column and, at the same time, impact the distribution of sulfides in Lake Maninjau. The sulfide detection on the surface in survey 1 was caused by weakening stratification forces in the water column due to low air temperatures and high rainfall. This condition can be seen from the RTRM profile of the water column in survey 1 (Figure 8.A). Based on Figure 9. A, the RTRM value for the total water column in survey 1 was 36.39, while the RTRM for each water layer varied between -0.16 – 5.60. The water column RTRM in survey 1 was lower than survey 2, which had a total RTRM of 77.50, with the

RTRM of each layer varying in the range -0.13 – 13.59 (Figure 9 B).

The RTRM in survey 1, which is lower than that in survey 2, indicates that the water column in survey 1 experienced mixing, while the water column in survey 2 appeared relatively more stable Visually it can also be seen that the RTRM in survey 1 is zero in almost every layer. Only the water column at a depth of 0 - 1.2 m has an RTRM of more than 1. Because the depth of RTRM > 0 is deeper than the depth of the hypolimnion (29.7 m), as a result, the epilimnion and hypolimnion layers in survey 2 did not undergo mixing. The depth of 32 m to the bottom can be expressed as a mixed hypolimnion layer, where reduction reactions occur, with zero DO content and high sulfides.

The lower RTRM in survey 1, compared to survey 2, indicates that water column stratification is strongly influenced by weather conditions. The low RTRM of the water column in survey 1 facilitated the rise of sulfide to the surface. On the other hand, the high RTRM water column in survey 2 prevents sulfide from rising to the surface as a result it accumulates in the hypolimnion layer, as shown in Figure 5 B.

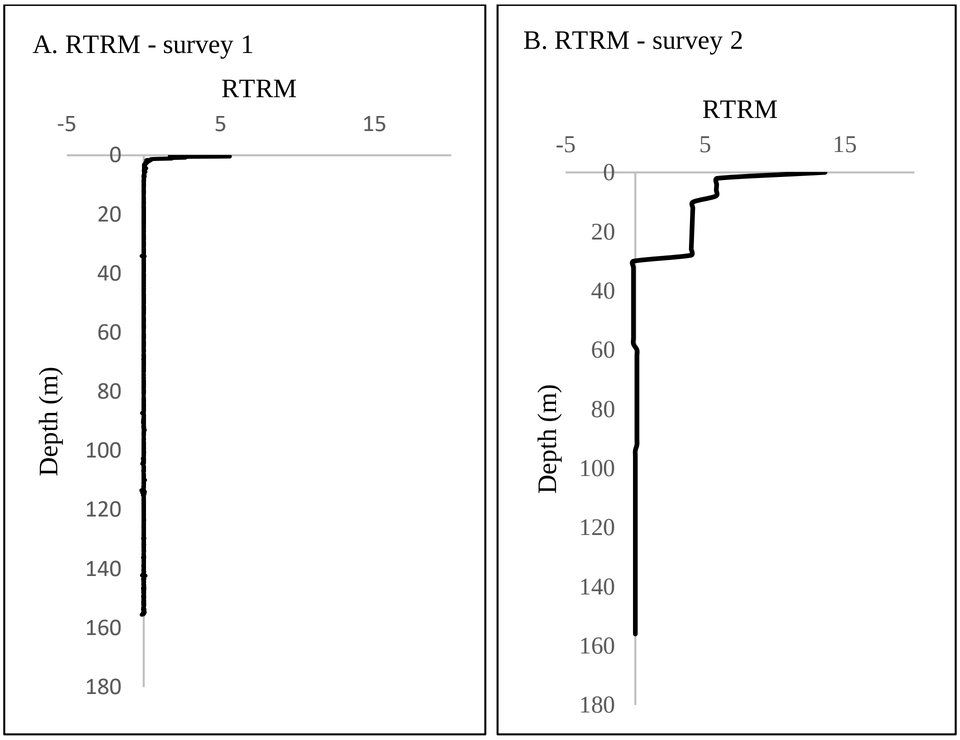


Figure 9. Relative thermal resistance to mixing (RTRM) of water column in Survey 1 and Survey 2

4. Conclusion

This research highlights the importance of characterizing climatological parameters (patterns and magnitudes) as driving factors for the changes in the thermal stratification of a lake. The alteration of thermal stratification due to weather changes has implications for the distribution of sulfide in the water column. The combination of high rainfall and wind speed, along with low sunshine duration and air temperature in survey 1, led to the disappearance of water column stratification, resulting in the upward movement of sulfides to the surface. Conversely, when the air temperature and sunshine duration are high, and the rainfall and wind speed are low, the water stratification will be strong, resulting sulfides remaining in the hypolimnion layer and continuing to increase. This research can be applied to similar lakes and serve as a basis for the development of early warning systems to prevent fish kill event caused by the rise of sulfide to the surface.

Data availability statement

All data used in this study are primary and secondary data. The secondary data is climatological data, which can be accessed openly on the website Pusat Data-BMKG

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Conflict of interests

All authors declare that there are no conflicts of interest in this study.

Author's Contribution

MRP was the team leader of the project. **MRP** and **TJ** developed the idea for this manuscript. **MRP**, **MA** and **CH** provided substantial intellectual contributions to the manuscript. **TJ**, **SN**, and **ASA** contributed on survey and data preparation. All co-authors reviewed and consented to the final version of the document.

References

Aguilera E, Chiodini G, Cioni R, Guidi M, Marini L, Raco B. 2000. Water chemistry of Lake Quilotoa (Ecuador) and assessment of natural hazards. *Journal of Volcanology and Geothermal Research* 97: 271–285. DOI: 10.1016/S0377-0273(99)00168-7

Alloway B V., Pribadi A, Westgate JA, Bird M, Fifield LK, Hogg A, Smith I. 2004. Correspondence between glass-FT and 14C ages of silicic pyroclastic flow deposits sourced from Maninjau caldera, west-central Sumatra. *Earth and Planetary Science Letters* 227: 121–133. DOI: 10.1016/j.epsl.2004.08.014

Boyd C. 2014. Hydrogen Sulfide Toxic, But Manageable. *Global Aquaculture Advocate* 17: 34–36

Dunnette D, Chynoweth D, Mancy K. 1985. The Source of Hydrogen Sulfide in Anoxic Sediment. *Water* 19: 875–884

Elci S. 2016. Effects of thermal stratification and mixing on reservoir water quality. DOI: 10.1007/s10201-008-0240-x

Fukushima T, Matsushita B, Subehi L, Setiawan F, Wibowo H. 2017. Will hypolimnetic waters become anoxic in all deep tropical lakes? *Scientific Reports* 7: 1–8. DOI: 10.1038/srep45320

Fukushima T, Setiawan F, Subehi L, Fakhrudin M, Triwisesa E, Dianto A, Matsushita B. 2021. Convection of waters in Lakes Maninjau and Singkarak, tropical oligomictic lakes. *Limnology*. DOI: 10.1007/s10201-021-00686-8

Hamdi S. 2014. Mengenal Lama Penyinaran Matahari Sebagai Salah Satu Parameter Klimatologi. *Berita Dirgantara* 15: 7–15. DOI: 10.20885/unisia.vol28.iss56.art12

Handayani CIM, Arthana IW, Merit IN. 2011. Identifikasi Sumber Pencemar dan Tingkat Pencemaran Air di Danau Batur Kabupaten Bangli. *Ecotrophic* 6: 37–43

Henny C. 2009. Dynamics of Biogeochemisrty of Sulfur in Lake Maninjau. *Limnotek* XVI: 74–87

Henny C, Nomosatryo S. 2012. Sulfide Dynamics in Lake Maninjau: The Implication on Phosphate Release in the Hypolimnion. *Limnotek : perairan darat tropis di Indonesia* 19: 102–112

Henny C, Nomosatryo S. 2016. Changes in water quality and trophic status associated with cage aquaculture in Lake Maninjau, Indonesia. *IOP Conference Series: Earth and Environmental Science* 31. DOI: 10.1088/1755-1315/31/1/012027

Jasalesmana T, Putri MR, Abdurrachman M. 2023. Water Quality Assessment of Lake Maninjau After the Mass Fish Kill Event. *IOP Conf. Series: Earth and Environmental Science*

Ji ZG. 2017. *Hydrodynamics and water quality: Modeling rivers, lakes, and estuaries*. *Hydrodynamics and Water Quality: Modeling Rivers, Lakes, and Estuaries*. DOI: 10.1002/9781119371946

Katsev S, Crowe SA, Mucci A, Sundby B, Nomosatryo S, Douglas Haffner G, Fowle DA. 2010. Mixing and its effects on biogeochemistry in the persistently stratified, deep, tropical Lake Matano, Indonesia. *Limnology and Oceanography* 55: 763–776. DOI: 10.4319/lo.2009.55.2.0763

Kortmann RW. 1981. RTRM. *LakeLine. Ecosystem Consulting Services, Inc.* 7–10

Kunz K, Wildman R. 2019. Effects of Solar Radiation and Air Temp on Thermal Stratification of Lakes. 0–3

Kusakabe M, Ohba T, Issa, Yoshida Y, Satake H, Ohizumi T, Evans WC, Tanyileke G, Kling GW. 2008. Evolution of CO2 in lakes Monoun and Nyos, Cameroon, before and during controlled degassing. *Geochemical Journal* 42: 93–118. DOI: 10.2343/geochemj.42.93

Liu M, Zhang Y, Shi K, Zhang Y, Zhou Y, Zhu M, Zhu G, Wu Z, Liu M. 2020. Effects of rainfall on thermal stratification and dissolved oxygen in a deep drinking water reservoir. *Hydrological Processes* 34: 3387–3399. DOI: 10.1002/hyp.13826

Makmur S, Muthmainnah D, Subagdja. 2020. Fishery activities and environmental condition of Maninjau Lake, West Sumatra. *IOP Conference Series: Earth and Environmental Science* 564. DOI: 10.1088/1755-1315/564/1/012025

Manual. 2007. *DR 2800 Spectrophotometer*.

Piranti AS, Rahayu DRUS, Waluyo G. 2018. Evaluasi Status Mutu Air Danau Rawapening. *Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan (Journal of Natural Resources and Environmental Management)* 8: 151–160. DOI: 10.29244/jpsl.8.2.151-160

Pribadi A, Mulyadi E, Indyo P. 2007. Mekanisme erupsi ignimbrit Kaldera Maninjau , Sumatera Barat. *Jurnal Geologi Indonesia* 2: 31–41

Pusat Data -BMKG. (n.d.). *Pusat Database – BMKG. DataOnline https://dataonline.bmkg.go.id/data_iklim*. (last acessed on 30 August 2023)

Read JS, Hamilton DP, Jones ID, Muraoka K, Winslow LA, Kroiss R, Wu CH, Gaiser E. 2011. Derivation of lake mixing and stratification indices from high-resolution lake buoy data. *Environmental Modelling and Software* 26: 1325–1336. DOI: 10.1016/j.envsoft.2011.05.006

Riki Saputra IWR, Restu IW, Ayu Pratiwi M. 2017. Analisis Kualitas Air Danau Sebagai Dasar Perbaikan Manajemen Budidaya Perikanan Di Danau Buyan Kabupaten Buleleng, Provinsi Bali. *ECOTROPHIC : Jurnal Ilmu Lingkungan (Journal of Environmental Science)* 11: 1. DOI: 10.24843/ejes.2017.v11.i01.p01

Sagala S, Radiarta IN. 2012. Vertical-Horizontal Water Quality Profiles of Batur Lake, Bangli District, Bali Supporting Sustainable Lake Management. *Indonesian Aquaculture Journal* 7: 157. DOI: 10.15578/iaj.7.2.2012.157-169

Santoso AB, Triwisesa E. 2020. Ecosystem Metabolism and Oxygen Deficit in Lake Maninjau: Insight From High-Frequency Measurement. *Limnotek : perairan darat tropis di Indonesia* 27: 93–102. DOI: 10.14203/limnotek.v27i2.306

Santoso AB, Triwisesa E, Fakhrudin M, Harsono E, Rustini HA. 2018. What do we know about Indonesian tropical lakes? Insights from high frequency measurement. *IOP Conference Series: Earth and Environmental Science* 118: 0–5. DOI: 10.1088/1755-1315/118/1/012024

Shi J, Wang L, Yang Y, Huang T. 2021. Effects of seasonal thermal stratification on ammonia nitrogen transformation in a source water reservoir. *Processes* 9: 1–12. DOI: 10.3390/pr9122218

Subehi L, Ridwansyah I, Fukushima T. 2021. Dissolved Oxygen Profiles and Its Problems at Lake Maninjau, West Sumatra – Indonesia. *Indonesian Journal of Limnology* 1. DOI: 10.51264/inajl.v1i1.3

Wardhani E, Sugiarti ZA. 2022. Depth Profiles of Dissolved Oxygen (DO) and Hydrogen Sulfide (H2S) Concentration in a Tropical Freshwater Reservoir. *Jurnal Presipitasi : Media Komunikasi dan Pengembangan Teknik Lingkungan* 19: 316–329. DOI: 10.14710/presipitasi.v19i2.316-329