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# Identifying the Mixing Regime of Lake Taal, Batangas, Philippines: Implications of Lake Mixing and Stratification to Lake Management

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Lake Taal is one of the major lakes in the Philippines which have been supporting several economic sectors for the past five decades. Its exposure to a number of unsustainable practices have resulted in the decline of its water quality. Monitoring activities have been conducted in the lake as early as the year 2000s; however, techniques used in these endeavors are limited. In this study, the vertical profiles of selected physicochemical parameters of Lake Taal including temperature, dissolved oxygen, pH, conductivity, were monitored from February to December 2022. Six sampling points were identified to equally represent its northern and southern basins. Results showed that the lake undergoes complete lake turnover (mixing) during the northeast monsoon, then remains to be stratified for the rest of the year. During its stratified months, dissolved oxygen was only highly concentrated up until 10 m especially during the hot-dry season. In contrast, conductivity showed equal readings between surface and bottom layers with no variation between sampling points and months; a probable indication of the homogeneity of the nutrients of Lake Taal. The application of these techniques, as well as establishing long-term daily monitoring activities, may help in designing a more specific and adaptive lake management program for this important lake ecosystem.

**Keywords;** ecology, fish kill, lake monitoring, tropical limnology, vertical profile

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## Introduction

Lake ecosystems have been identified as sentinels of climate change due to their sensitivity to changes in their environment (Adrian et al., 2009). The Intergovernmental Panel on Climate Change recognized the threats lake ecosystems face today because of the changing climate and various anthropogenic activities (IPCC, 2007). Global estimates of the effects of climate change to freshwater ecosystems however, mostly come from the temperate and boreal regions. Although there has been an increase in long-term and high-frequency monitoring in tropical lake systems, research on their limno-physical characteristics remains inadequate (De Crop & Verschuren, 2019). In the Philippines, these types of studies are underrepresented due to lack of sufficient equipment and its low popularity. Majority of the work focused on monitoring water quality of freshwater systems in the country has been established for the purpose of their economic implications, especially in Lake Taal (Mendoza et al., 2019).

Lake Taal is considered as one of the country's major lakes (Guerrero, 2001). It has been the focus of many research efforts because of its unique morphology – surrounding the active Taal Volcano which bisects the lake into two basins (Ramos, 2002). Lake Taal has become the key source of livelihood of nearby lakeside towns as well as one of the major fish suppliers across Region IV (Bureau of Fisheries and Aquatic Resources, 2019) particularly of the only freshwater member of the genus *Sardinella* (*Sardinella tawilis*) in the world (Froese & Pauly, 2003). According to Papa & Mamaril (2011), aquaculture practice was established in the lake as early as 1975, and by the 1990s, decline in water quality was observed due to unregulated aquaculture practices. Prolonged exposure of the lake to such activities have rendered it too productive even until now, exacerbating its natural trophic condition from oligotrophic (Zafaralla, 1992), to mesotrophic (Perez et al., 2008), and now eutrophic (de Leon et al., 2020). Though water quality monitoring of the lake is conducted by Bureau of Fisheries and Aquatic Resources – Inland Fisheries Research Station (BFAR-IFRS) in the municipalities of Talisay, Laurel and Agoncillo, this was only established as a response to the occurrence of massive and lake-wide

fish kills (BFAR-IFRS). Unfortunately, monitoring activities are only limited to surface waters and as such, the causes and underlying mechanisms of this lake-wide fish kill events have yet to be fully understood. Early data on the causes of fish kills in Lake Taal have been linked to biological causes (i.e., isopod infestation) however, most recent data have shown the role of physicochemical changes in the lake triggering these incidents (Mendoza et al., 2019). These physicochemical changes have been linked to monsoon-driven events, oxygen depletion and sulfur upwelling – factors which relate to lake mixing (turnover), one of the major physical processes lakes undergo (Jankowski et al., 2006). Typically, a complete vertical profile of a lake obtained through the use of a multiparameter sonde is needed to fully realize the mechanisms and patterns behind this occurrence. The limited methodology of water quality monitoring in the lake is therefore insufficient to fully understand the natural processes and conditions of Lake Taal. The first effort to monitor the vertical profile of Lake Taal was done during the FISHTRAT Project (1999-2000), which was able to provide data on the complete mixing of the lake (Perez et al., 2008).

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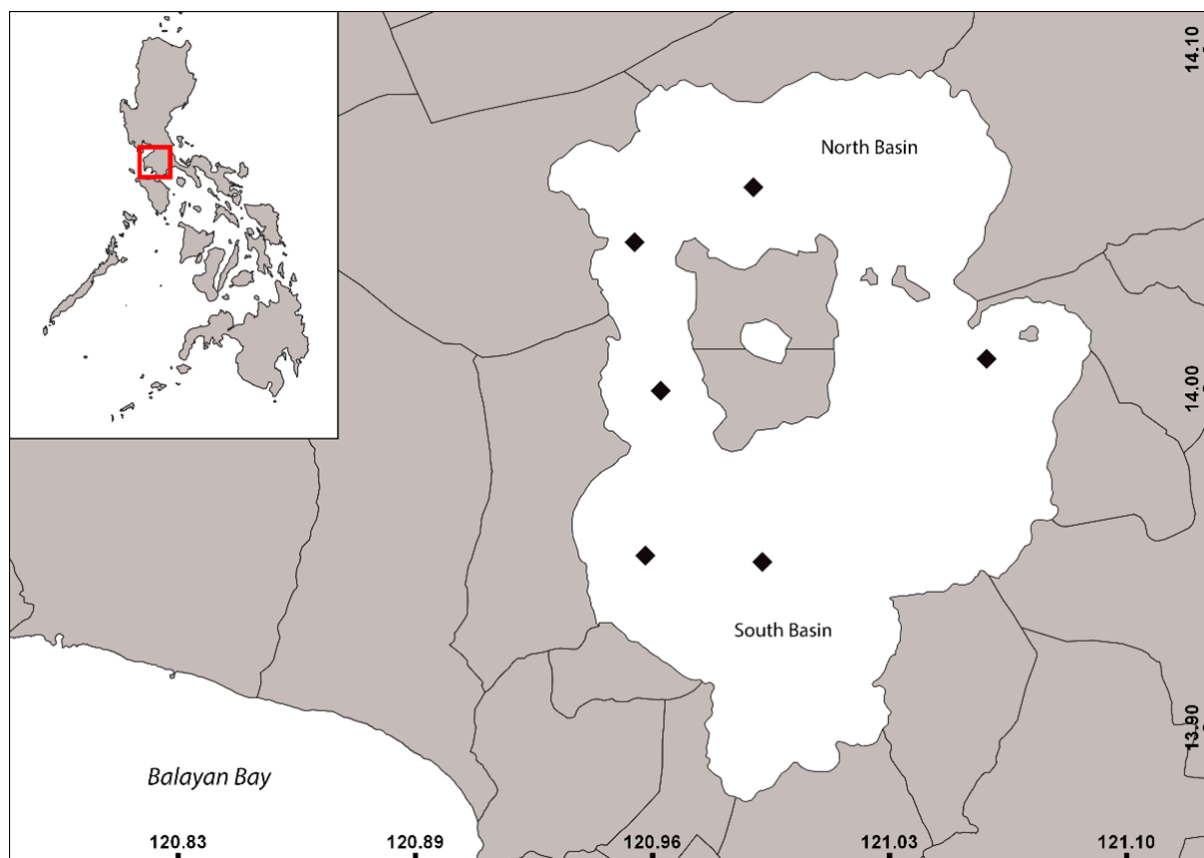
Lake mixing or turnover is one of the fundamental physical processes lakes undergo. During this period, water density between the surface (epilimnion) and bottom (hypolimnion) layers of lakes equalizes and allows for the transport of nutrients and gases from surface to bottom, and vice versa (Zhang et al., 2014). Lakes can be classified based on the pattern of their mixing regimes. The north basin of Lake Taal was observed to naturally undergo complete mixing once a year during the month of February (Perez et al., 2008), identifying it as a monomictic type of lake. During the rest of the year, Lake Taal was observed to be stratified, bottom waters are much denser and appearance of the thermocline was noted. However, this study greatly underrecognizes the lake as it has only been conducted in the north basin of Lake Taal. Stratification is the condition of lakes where surface and bottom layers are separated through the formation of a middle layer (metalimnion) and the thermocline – the barrier which prevents the movement of nutrients and gases from both layers (Zhang et al., 2014). These two natural physical processes have a huge effect on the overall ecological processes of lakes such as phytoplankton blooms during nutrient upwelling and anoxia-driven mass mortality during turnovers (Janowski et al., 2006). Complete mixing of the north basin of Lake Taal have been shown to be driven by monsoon events (Perez et al., 2008), coinciding with the data from BFAR-IFRS which reported the occurrence of massive fish kill following such changes (Mendoza et al., 2019). Due to the complete overturn of the water column – locally

known as “*duong*”, stored hydrogen sulfide (and possibly other gases) accumulating near the sediments gets released to the upper layers and eventually the atmosphere (Sanchez et al., 2019). Although standardized methodologies have long been established in lake assessment and monitoring, these techniques are yet to be applied in the Philippine setting. Understanding the limno-physical processes and uncovering the trend that drive catastrophic events such as lake-wide and massive fish kills may help mitigate such economically devastating occurrences (Mendoza et al., 2019).

## Methodology

### Study Site

Lake Taal (13°55'-14°05' N, 120°55'-121°105' E; altitude: 2.5 masl) is the third largest lake in the Philippines with a total surface area of 268.0 km<sup>2</sup> (Perez et al., 2008). It is volcanic in origin which lies within a caldera, and situated in the middle is the Taal Volcano – one of the smallest and most active volcanoes in the world (Perez et al., 2008). Bathymetry of the lake showed the existence of two basins bisected by the volcano island, identified as its northern and southern basins (Figure 1). Between the two, the northern basin is described to be shallower with a maximum depth of 100 m, while the latter, where the deepest point of the lake can be found, reaches a maximum depth of ~198.00 m (Cuenca, southern basin) (Perez et al., 2008; de Leon et al., 2020). Surrounding the lake are mountainous ranges, with high peaks at its northwestern edge, the Tagaytay Ridge, and southeastern portion, Macolod Ridge. The total catchment area of the lake is about 682.8 km<sup>2</sup>, with 37 small stream inflows – some of which are seasonal, and only one outlet at the Pansipit River, located at the southwestern side of the lake, draining it to the Balayan Bay of the West Philippine Sea (Perez et al., 2008; Mendoza et al., 2015). Climate in Lake Taal is characterized as Type I with two distinct seasons: dry season from November to May, and wet season during the rest of the year. The dry season is further divided into cool-dry (November to February) and hot-dry season from March to May (Philippine Atmospheric, Geophysical and Astronomical Services Administration [PAGASA], 2014).



**Figure 1.** Map of the Study Site

**Note.** Sampling points are identified equally representing the northern- and southern sub-basins of Lake Taal

### Data collection and analysis

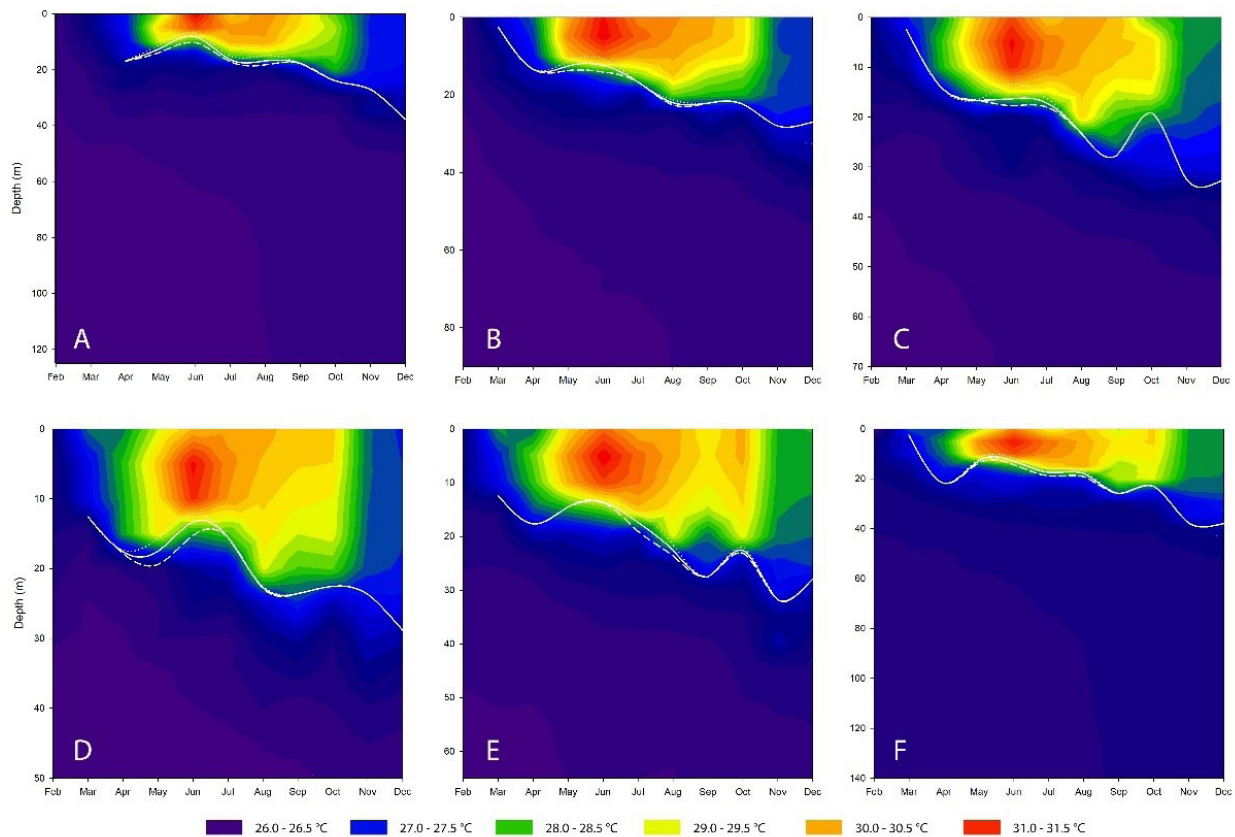
Six sampling points were identified to equally represent the northern and southern basins of Lake Taal. These points were based on Papa et al. (2011) and fall within the municipalities of Talisay ( $14^{\circ} 3' 33.8''$  N,  $120^{\circ} 59' 41.2''$  E), Laurel ( $14^{\circ} 2' 35.4''$  N,  $120^{\circ} 57' 34.9''$  E) and Agoncillo ( $13^{\circ} 59' 57.7''$  N,  $120^{\circ} 58' 2.7''$  E) for the northern basin. On the other hand, the municipalities of San Nicolas ( $13^{\circ} 57' 2.8''$  N,  $120^{\circ} 57' 46.4''$  E), Cuenca ( $13^{\circ} 56' 56''$  N,  $120^{\circ} 59' 50.79''$  E) and Balete ( $14^{\circ} 0' 31.6''$  N,  $121^{\circ} 3' 49.1''$  E) represent the southern basin (Figure 1). Monthly vertical profiles (surface to lake bottom, 1.0 m intervals) of different physicochemical parameters i.e., temperature, dissolved oxygen, pH, and conductivity, were collected from each sampling point using a multiparameter sonde (EXO2, YSI Inc., Yellow Spring, OH, USA) from February to December 2022. Data collection was done every 7AM starting at Cuenca then completed by 9AM at Balete. The multiparameter sonde was secured to a make-shift metal cage and a rope ( $\varnothing = 6.0$  in;  $l = 220.0$  m) to ensure the free-fall drop until the lake bottom. Template loaded to the sonde was designed to collect data every 0.5 sec and collection was done twice – obtaining four replicates. No data collection

was conducted on January 2022 due to intermittent weather, and no pH reading was collected on the month of July due to technical problems encountered during the sampling period. Replicates were then cleaned and averaged, and data visualization was done using SigmaPlot version 11 (Systat Software, Inc., San Jose, CA, USA). Metalimnion and thermocline depths were computed using the rLakeAnalyzer package (Winslow et al. 2019) of R studio version 1.2.5033 (Rstudio Team, Boston, MA, USA) software.

### Results

Monthly assessment of the water temperature vertical profile of Lake Taal showed that it is completely mixed during the month of February and March, but remains to be stratified for the rest of the year. Formation of the thermocline was first observed in the month of March except for the site in Balete, which had its first thermocline appearance in April 2022 (Figure 2A). Metalimnion thickness appeared to be inconsistent throughout the sampling period ranging from 0–4.2 m, with the thickest encountered between the months of May to July 2022.





**Figure 2.** Contour Plots of the Vertical Profile of Water Temperature(°C)

**Note.** Readings of the six sampling sites from February to December 2022: (A) Balete, (B) Talisay, (C) Laurel, (D) Agoncillo, (E) San Nicolas, (F) Cuenca, showing thermocline depth (solid white line) and the top and bottom depths of the metalimnion (dashed white lines).

Average water temperature from all sampling points during its mixed months ranged from 26.56–26.96 °C with no distinction between surface and bottom waters due to the absence of the thermocline. On the other hand, the appearance of thermocline in March in all sampling points, April for Balete, presented a clear transition of water temperature above and below the thermocline. Table 1 summarizes the water temperature difference between the surface and bottom waters of all sites considering the thermocline depth of each month.

**Table 1.** Mean Water Temperature Parameters of Surface and Bottom Waters of All Sampling Points

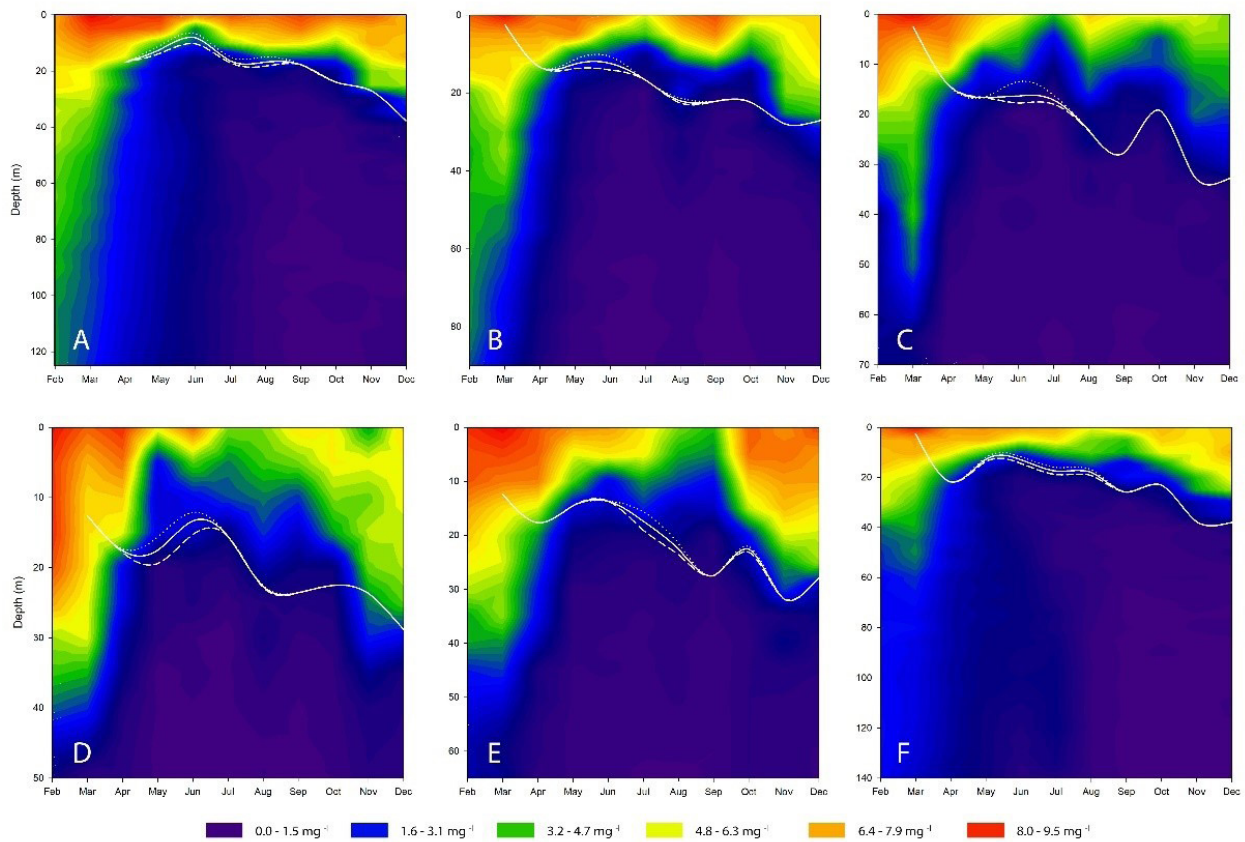
		Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<i>Balete</i>	TD	–	17.04	12.47	8.24	16.48	16.94	17.82	24.06	27.08	37.83
	T <sub>s</sub>	–	28.10	29.40	30.70	30.50	30.39	29.93	29.49	28.29	28.04
	T <sub>b</sub>	–	26.67	26.66	26.73	26.95	26.68	26.73	26.85	26.80	26.72
	SD	–	1.01	1.94	2.81	2.51	2.62	2.26	1.87	1.05	0.93
<i>Talisay</i>	TD	2.50	13.43	12.57	12.45	16.70	22.03	22.16	22.42	28.03	27.01
	T <sub>s</sub>	27.83	28.48	30.25	31.09	30.50	30.06	29.77	29.54	28.37	28.28
	T <sub>b</sub>	26.71	26.90	26.80	26.87	26.92	26.72	26.79	26.79	26.89	26.93
	SD	0.79	1.12	2.44	2.98	2.53	2.36	2.11	1.94	1.05	0.95
<i>Laurel</i>	TD	2.50	14.13	16.65	16.35	17.19	23.20	27.72	19.17	32.44	32.81
	T <sub>s</sub>	28.17	28.68	29.82	30.74	30.18	30.15	29.59	29.50	28.45	28.35
	T <sub>b</sub>	26.80	27.07	26.79	26.83	26.85	26.93	26.86	27.04	26.86	26.90
	SD	0.96	1.14	2.14	2.76	2.35	2.28	1.93	1.73	1.12	1.03
<i>Agoncillo</i>	TD	12.61	17.59	17.51	13.35	15.55	22.66	23.57	22.54	23.68	28.81
	T <sub>s</sub>	28.28	28.91	29.87	30.86	30.09	30.02	29.75	29.76	28.58	28.36
	T <sub>b</sub>	26.78	26.77	26.85	27.25	27.04	27.16	27.29	27.13	27.41	27.16
	SD	1.06	1.51	2.14	2.56	2.16	2.02	1.74	1.86	0.83	0.85
<i>San Nicolas</i>	TD	12.41	17.68	14.53	13.69	17.42	22.53	27.50	22.57	31.84	27.90
	T <sub>s</sub>	28.22	28.69	29.68	30.81	30.22	29.85	29.16	29.87	28.49	28.55
	T <sub>b</sub>	26.71	26.75	26.81	27.07	26.86	26.80	26.79	26.92	26.98	27.01
	SD	1.07	1.37	2.03	2.64	2.38	2.16	1.68	2.09	1.07	1.09
<i>Cuenca</i>	TD	2.50	21.81	12.80	12.97	17.45	17.90	25.91	23.06	37.70	37.98
	T <sub>s</sub>	28.10	28.16	29.91	30.82	30.07	30.08	29.26	29.69	28.27	28.24
	T <sub>b</sub>	26.68	26.61	26.74	26.77	26.70	26.72	26.66	26.74	26.71	26.73
	SD	1.00	1.10	2.24	2.86	2.39	2.37	1.84	2.09	1.10	1.07

**Note.** Data is from March to December 2022, taking into consideration thermocline depth (TD; m).

TS – surface temperature (°C); TB – bottom temperature (°C); SD – standard deviation.

(–): no distinction made due to the mixed state of the sampling point.

From all the sampling points, peak difference between the surface and bottom water temperature was observed during the month of June (Table 1). A pattern of deepening of the thermocline was also observed following the change of seasons; with its shallowest during the month of March at 2.50 m and its deepest by November and December at ~23.00–38.00 m.

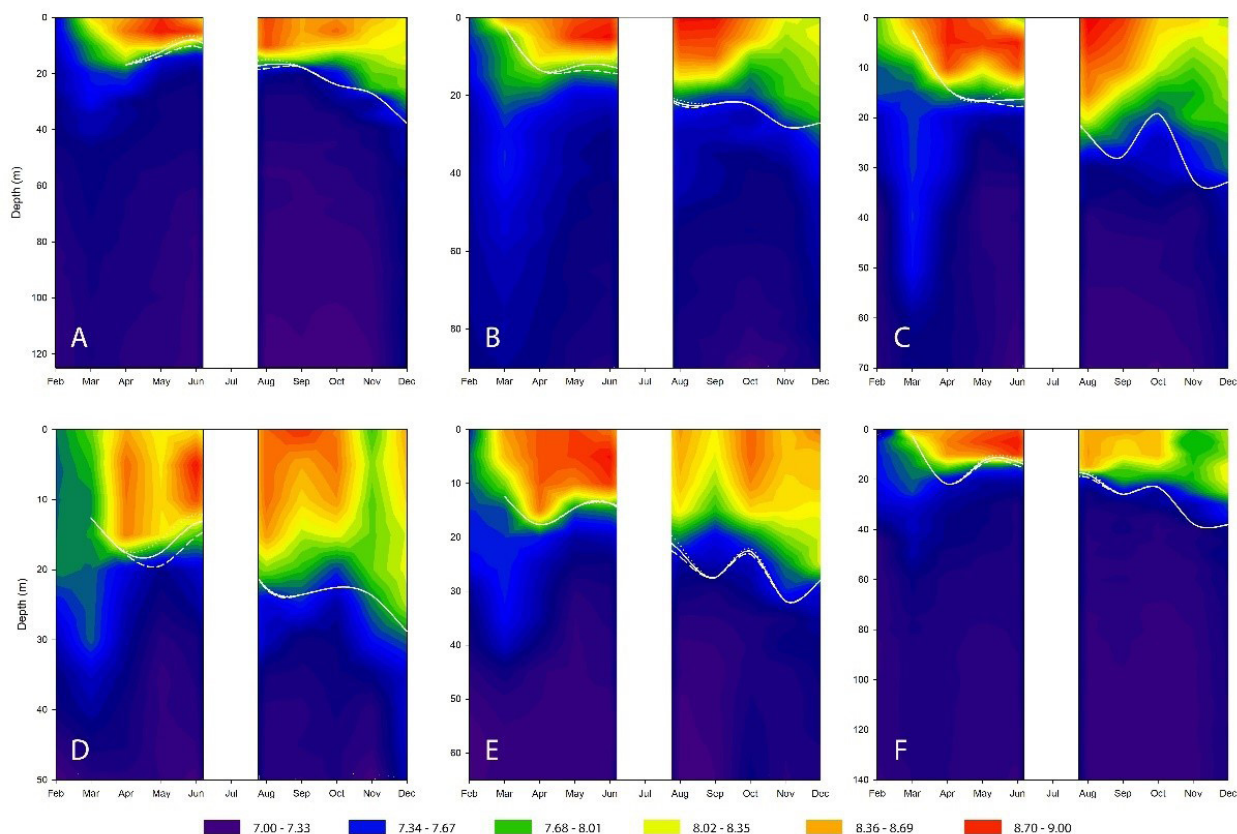


**Figure 3.** Contour Plots of the Vertical Profile of Dissolved Oxygen Concentrations ( $\text{mg}^{-1}$ )

**Note.** Readings of the six sampling sites from February to December 2022: (A) Balete, (B) Talisay, (C) Laurel, (D) Agoncillo, (E) San Nicolas, (F) Cuenca, showing thermocline depth (solid white line) and the top and bottom depths of the metalimnion (dashed white lines).

Dissolved oxygen (DO) concentration followed the mixing and stratification of the lake, with the mixed months supplying DO to greater depth, surface to near-bottom, than strongly stratified months such as May to July. DO concentration during the mixed months had average readings of 3.63–4.72  $\text{mg/L}$  ( $\text{SD} = 1.60$ ) however, this was only observed in Balete and Talisay (Figure 3A-B). The remaining sites still showed anoxic conditions ( $< 2.00 \text{ mg/L}$ ; Nurnberg, 2004) in the deeper layers of the lake even during the mixed months (Figure 3C-F). The presence of the thermocline during the stratified months clearly demarcates the surface from bottom waters, with DO greatly concentrated at the top layers of the lake. During strongly stratified months (April–July), DO is only well-supplied to the upper layers of the lake at a

maximum depth of 10.00 m (Figure 3). Summary of the DO concentration obtained during the stratified months of the sampling period is shown in Table 2. Vertical profiles of the pH readings similarly followed the mixing and stratification pattern of the lake (Figure 4). However, the mixed months (February and March for Balete, and only February for the rest of the sampling points) did not exhibit much change from the general trend of only the surface waters presenting basic pH readings. Except for Agoncillo, the shallowest sampling point (max depth = ~50.00 m), where a basic pH reading near the bottom was recorded (~30.00 m) (Figure 4). pH readings obtained from the study site during the stratified months of the sampling period is likewise summarized in Table 2.



**Figure 4.** Contour Plots of the Vertical Profile of pH

**Note.** Readings of the six sampling sites from February to December 2022: (A) Balete, (B) Talisay, (C) Laurel, (D) Agoncillo, (E) San Nicolas, (F) Cuenca, showing thermocline depth (solid white line) and the top and bottom depths of the metalimnion (dashed white lines).

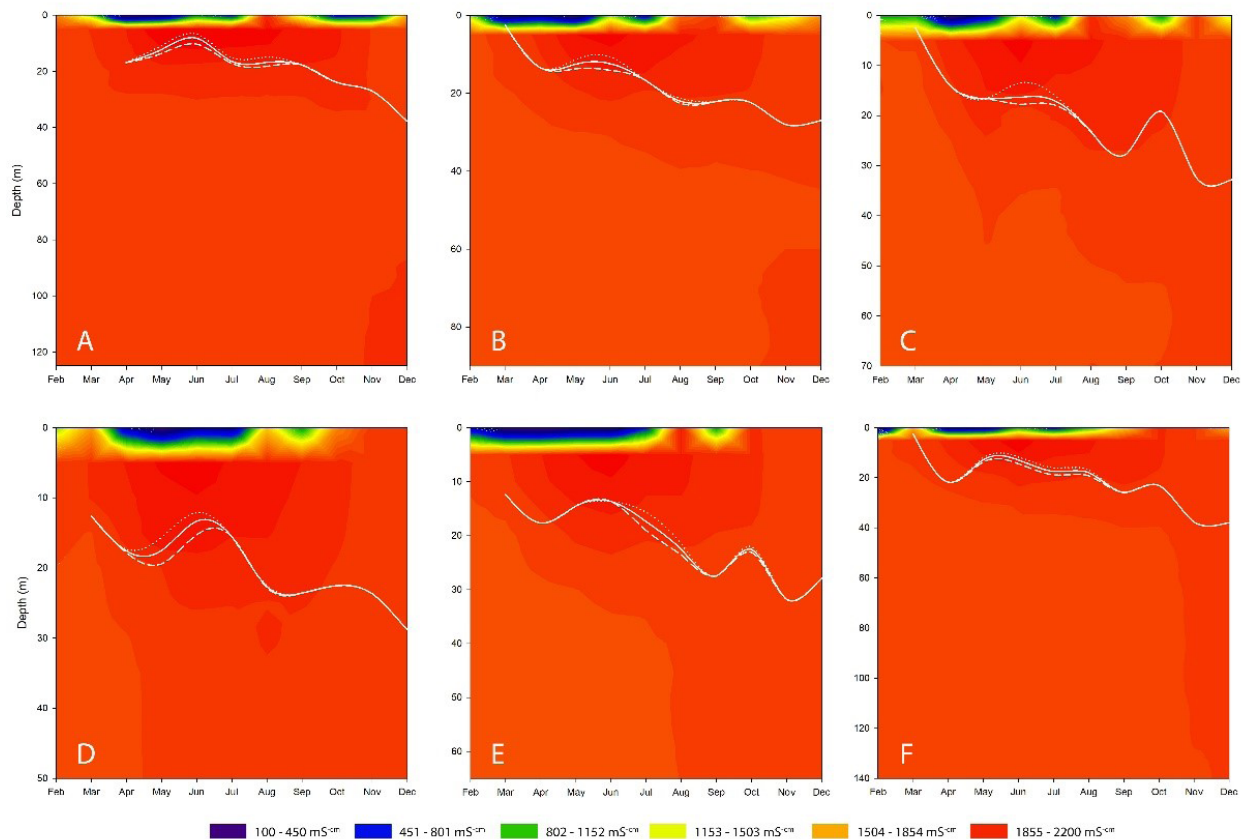


**Table 2.** Mean, Standard Deviation, and Range of Dissolved Oxygen and pH Readings of Surface and Bottom Waters of All Sampling Points

	Dissolved Oxygen (mg <sup>l</sup> )				pH			
	Surface		Bottom		Surface		Bottom	
	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max	Mean (SD)	Min-Max
<i>Balete</i>	5.45 (1.44)	2.49 – 7.59	0.96 (0.86)	0.11 – 4.80	8.64 (0.20)	8.19 – 9.04	7.93 (0.09)	7.81 – 8.32
<i>Talisay</i>	4.66 (1.79)	0.93 – 7.82	1.10 (1.45)	0.11 – 6.31	8.60 (0.26)	8.16 – 9.02	7.91 (0.17)	7.60 – 8.68
<i>Laurel</i>	3.66 (1.80)	0.83 – 8.30	1.04 (1.58)	0.12 – 6.93	8.47 (0.25)	8.03 – 8.92	7.84 (0.21)	7.63 – 8.85
<i>Agoncillo</i>	3.78 (1.31)	1.22 – 6.41	1.12 (1.16)	0.23 – 4.85	8.52 (0.17)	8.13 – 8.85	7.91 (0.15)	7.69 – 8.34
<i>San Nicolas</i>	5.08 (2.01)	0.73 – 8.35	1.08 (1.29)	0.14 – 5.87	8.65 (0.23)	8.06 – 9.01	7.93 (0.13)	7.78 – 8.34
<i>Cuenca</i>	5.17 (1.72)	1.55 – 8.80	1.19 (1.22)	0.11 – 7.03	8.60 (0.26)	8.04 – 9.04	7.91 (0.11)	7.80 – 8.54

**Note.** Data is from March to December 2022, taking into consideration thermocline depth.

Contrary to the other parameters, the vertical profile of conductivity (mS/cm) showed no distinct pattern between sampling point and months (Figure 5). Vertical profiles of conductivity presented a consistently high reading starting just below the surface with mean conductivity readings of 1924.47 mS/cm.



**Figure 4.** Contour Plots of the Vertical Profile of Conductivity Levels (mS-cm)

**Note.** Readings of the six sampling sites from February to December 2022: (A) Balete, (B) Talisay, (C) Laurel, (D) Agoncillo, (E) San Nicolas, (F) Cuenca, showing thermocline depth (solid white line) and the top and bottom depths of the metalimnion (dashed white lines).

## Discussion

Despite Lake Taal being one of the major lakes in the Philippines, and is considered to be one of the most well-studied lake ecosystems in the country (Ramos, 2002; Perez et al., 2008; Papa & Mamaril, 2011; Papa & Zafaralla, 2011; Papa et al., 2011; Papa et al., 2012; Garcia et al., 2014; Mendoza et al., 2015; Mendoza et al., 2019), not much is known to its limno-physical characteristics. The FISHTREAT research project was the first to attempt to uncover the mixing and stratification pattern of the north basin of Lake Taal with monthly monitoring of the vertical profiles of water temperature, dissolved oxygen, pH, and chlorophyll-a conducted from July 1999 – August 2000 (Perez et al., 2008). Its north basin, similar to some of the seven maar lakes of San Pablo, Laguna (Aguilar et al., 2023), was observed to undergo complete lake mixing during the northeast monsoon, then remains to be stratified for the rest of the year (Perez et al., 2008). This single mixing event for the entire year classifies the lake as warm-monomictic based from Lewis (1983). The results of this study expanded this previously known

information, showing that both basins of Lake Taal are capable of undergoing complete mixing despite the huge difference in their maximum depths. According to Lewis (1983), altitude and lake depth are two of the factors to influence lake mixing dynamics, with most deep lakes within the tropical latitudes falling into the warm-monomictic classification. Previous studies which classified mixing regimes of Philippine lakes are limited to the works of Lewis (1973) and Aguilar et al. (2023), with the former identifying Lake Lanao, one of the world's ancient lakes, as warm-monomictic, and the latter classifying San Pablo's seven maar lakes into warm-polymictic (Palakpakin), warm-monomictic (Sampaloc, Mohicap, Bunot, Yambo), and meromictic (Pandin, Calibato) lakes.

Average surface water temperature of Lake Taal during the months the lake undergoes stratification was at 29.28 °C, then began to drop at an average of 26.67 °C during the turn of the season. This trend is likewise observed with the decreasing differences between the surface and bottom water temperatures, especially from the months

of October to December (SD; Table 1). This water temperature homogenization process can be an indication of Lake Taal's transition to mixing. Unfortunately, no data was collected during the supposed peak month of mixing (Jan) due to the weather. This trend (Apr-Dec, stratified; Jan-Mar, mixed) however, has been similarly observed from other Philippine monomictic lakes (Lewis, 1973; Aguilar et al., 2023). During these mixing events, water density decreases allowing effective transport of nutrients from enriched surface waters to the bottom layers (Tilzer & Goldman, 1978; Caliro et al., 2008). This observation was made with all parameters measured in Lake Taal, especially with DO, exhibiting high concentrations even at near bottom depths (Figure 3). Similarly, transport of toxic gasses and decaying matter to the upper layers is also made possible, which have been shown to cause depletion of DO and decline in pH levels (Caliro et al., 2008). These drops in DO and pH levels were associated with the release of hydrogen sulfide (H<sub>2</sub>S) – a common gas for lakes with volcanic origins, which have been shown to be a causative agent for fish kill events (Caliro et al., 2008). In Lake Taal, sulfur upwelling has been similarly identified as a direct cause of massive fish kills (Mendoza et al., 2019; Philippine News Agency, 2019; The Philippine Star, 2014). In early August 2022, depleting DO levels were reported to cause a massive fish kill event, affecting the town of Agoncillo (Manila Bulletin, 2022). Although the exact date was not captured during the monthly monitoring, there was an observable decrease in DO levels starting July 2022, especially for the sites in Talisay, Laurel, Agoncillo, and San Nicolas (Figure 3). Based on the data, sulfur-upwelling may not have been the direct cause of this event, since there was no observed drop in the pH levels even in the deeper layers of the lake (Figure 4). This necessitates the continuous monitoring of the entire vertical profile of Lake Taal, especially of DO, pH, and H<sub>2</sub>S levels, at a shorter interval properly pinpoint the causes of these economically devastating events. Establishing this more effective monitoring program may allow for a more accurate management system that may be used as a predictive tool in alerting fisherfolks of possible fish kill events.

The appearance of the thermocline – the distinction between warmer mixed surface waters and cool deep waters, by March (April for Balete) coincides with the hot-dry season of the region (PAGASA, 2014). This thermal stratification is an important control on the in-lake vertical transport of dissolved and particulate matter (Robertson and Imberger, 1994; Aeschbach-Hertig et al., 2007). During lake

stratification, there is a great difference in the water density of surface and bottom waters (Read et al., 2011), acting as a barrier for the transport of nutrients. In Lake Taal, this is effectively exhibited by the DO levels during the hot-dry season. In all sampling points, DO appears to be only highly concentrated up until 10 m (Figure 3), even with the deepening of the thermocline. Beyond 10 m, Lake Taal was observed to exhibit anoxic conditions (< 2.00 mg/L; Nurnberg, 2004) that is detrimental for higher-order organisms e.g., fish. Tropical lakes were reported to be more prone to depleting oxygen levels especially in the deep waters (Lewis, 2002), stricter guidelines for nutrient loadings must therefore be established. This information is particularly important for aquaculture practitioners, as this could facilitate a more appropriate design of fish cages (maximum cage depth of 10 m) and aquaculture practices (limiting nutrient loading e.g., avoiding excess fish feeds), taking high consideration of Lake Taal's capacity to support these activities.

Similar to DO concentrations, pH levels follow the stratification and mixing pattern of Lake Taal with waters above the thermocline exhibiting basic readings compared with the neutral bottom waters (Figure 4). The monthly monitoring activities conducted in this study did not capture any decline in pH levels that could be indicative of the release of H<sub>2</sub>S from the bottom layers. The pH and H<sub>2</sub>S is similarly monitored by BFAR-IFRS, although only at surface layers. For 2022, there were no reports of sulfur-upwelling in Lake Taal. However, proper monitoring practice – such as daily monitoring of the vertical profile of an identified point in Lake Taal is necessary for a more effective lake management system. Contrary to the other parameters measured, conductivity levels appeared to be similar across all sampling points and months (Figure 5). This observation might be an indication of the homogeneity of the waters of the lake.

Since the 1970s, aquaculture practice has been present in Lake Taal and unregulated aquaculture has begun as early as the 1990s (Papa & Mamaril, 2011). It was only in the early 2000s that reduction of fish cages was conducted in Lake Taal to try and mitigate its decreasing water quality (Aypa et al., 2008; Taal Volcano Protected Landscape – Protected Area Development and Management (TVPL-PAMB), 2011). Unfortunately, this prolonged exposure to such unsustainable practices have already resulted in the decline of its water quality, and with Lake Taal's long retention period (45 years; Perez et al., 2008), it would take another decade of stricter implementation of policies for proper lake

management to see its results.

## Conclusion

Aquaculture is one of the major contributions of Region IV to the national economy, and Lake Taal is one of the major sites used by the aquaculture industry. Aside from this, other economically important activities are also being supported by the lake e.g., tourism, navigation, etc. Therefore, proper lake monitoring schemes must be put in place to safeguard this ecosystem. Various monitoring activities are being conducted in the lake by national agencies; however, proper methodologies must be put in practice in order to make more accurate decision-making with regards to its protection and conservation. Based on our results, the pattern of the lake's mixing regime was uncovered, wherein it was observed that both basins undergo complete mixing at specific months of the year, coinciding with the changing of seasons. In addition, based on monthly monitoring of its vertical profile, dissolved oxygen in particular, was observed to be only limited up to 10 m all throughout Lake Taal – which could be useful information for fisherfolks utilizing fish cage farming.

## Recommendation

Long-term monitoring of the entire water column is necessary to design a more appropriate management system for Lake Taal. Monitoring the vertical profiles of selected physicochemical parameters e.g., water temperature, dissolved oxygen, pH, H<sub>2</sub>S, etc., at a shorter time interval using automated data collection through sondes could be one of the major undertakings that may be undertaken by its major stakeholders. With the knowledge that the lake is already homogenous at present, we can efficiently identify specific sites that would serve as monitoring stations to represent the northern and southern basins of Lake Taal. Lastly, with the identification of the lake's thermal mixing regime, we can effectively predict the months when the lake is expected to undergo complete turnover that could potentially circumvent economically-damaging fish kill events.

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## Declaration of conflict of interest

Upon submission of the manuscript, the author/s, including the corresponding author, declare no conflict of interest with any of the members of the Editorial Board of the NRCP Research Journal, whether financial, professional, or personal.

## Ethics statement

The research did not involve human and/or animal subjects, bioprospecting, confidential data, or business/marketing practices. Each author certifies that this material or similar material has not been and was not submitted to or published in any other publication before its appearance in the NRCP Research Journal. Each author also agrees that this paper is currently not under consideration in any other journals elsewhere in the world upon submission to NRCP journal. Lastly, each author hereby validates his/her consent regarding the submission and publication (in its final form) of such manuscript bearing his/her full name.

## Authorship contributions

Each author has confirmed their participation and contribution to the work, including the concept, design, analysis, writing, and/or manuscript revision. Furthermore, all authors take full public responsibility for the manuscript's content.

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