Water quality and weather trends preceding fish kill occurrences in Lake Taal (Luzon Is., Philippines) and recommendations on its long-term monitoring

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Lake Taal is one of the most unique lake ecosystems in the world. The decline in the lake's water quality together with other environmental and human-mediated factors has helped intensify the occurrences of massive fish kills in recent years. Available water quality data collected from areas devoted to aquaculture, were analyzed together with available weather data to determine long-term changes as well as monitor probable water quality and weather trends preceding known fish kill occurrences. There was no observed spatial variability among data from different monitoring sites which means that fewer but more evenly-spaced monitoring stations are recommended for the lake. The lack of important parameters (i.e. primary production, nutrients, plankton and fish) as well as the limited measurement of physicochemical parameters in surface water have hampered a more in-depth analysis of the lake's long-term limnological characteristics. Detected temporal variations in the water quality parameters are attributed to climate and human-induced factors. As to the dataset's usefulness for fish kill monitoring, our analysis revealed trends preceding documented fish kill occurrences - such as increased wind speed and high temperatures one to three days preceding fish kill incidences - may be used as indicators of an impending fish kill. Links between strong wind speed and varying air temperatures to tropical lakes' thermal and oxycline regime was discovered and recommended for further studies. Moreover, continuing lake monitoring is needed to strongly ascertain the cause of fish kill incidences and to ultimately increase the chances of anticipating massive fish kill events.

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INTRODUCTION

Lake Taal is one of the most unique lake ecosystems known to man (Hutchinson 1957) from which the response of lakes with numerous external pressures can be learned from. It is considered to belong to 1% of the world's total number of lakes due to its location and origin since it is a tropical caldera lake with an active volcano island in the middle (Lewis Jr. 2000; Papa and Mamaril Sr. 2011). Since 1975, aquaculture practices have been established in the lake. By the 1990s, unregulated aquaculture practices (i.e. overstocking and accumulation of waste due to uneaten fish feeds) has caused the decline in water quality and the further eutrophication of the lake (Papa and Mamaril Sr. 2011). The increase in nutrient levels from unregulated feeding and the increase of lakeshore inhabitants were defined as the main sources of Lake Taal's eutrophication (Aypa et al. 2008; Papa and Mamaril Sr. 2011; Rosana and Salisi 2000).

Lakes found on tropical regions are more sensitive to increases in nutrient levels and are more responsive to eutrophication than those in the temperate regions (Lewis Jr. 2000). Fish kills in tropical freshwaters are caused by hypoxic conditions, high levels of suspended material in the water column clogging the gills of fish, bacterial disease, low pH, and high concentration of algae (Ochumba 1990; San Diego-McGlone et al. 2008; Townsend et al. 1992; Townsend and Edwards 2003). In nutrient rich systems, fish kills were associated to meteorological factors whenever fish kills occur during unusual warm and calm conditions, or during the hottest months (Glibert et al. 2002; Hoyer et al. 2009). Others are triggered by storms, increased rainfall or induced by wind (Jeppesen et al. 2010). In Philippine lakes, blooms of dinoflagelatte *Prorocentrum minimum*, hypoxia, toxic hydrogen sulfide (H_2S) and ammonia (NH_3) released from the sediments and the rapid increase of aquaculture activities excacerbated by malpractices were the reported causes of fish kills (Jacinto 2011).

Water quality monitoring in Lake Taal was established as a response in the occurrences of massive and lake-wide fish kills. Despite the occurrence of fish kills in Lake Taal, the source and cause of such events and the underlying mechanisms were yet to be elucidated and confirmed.

Available datasets that span several years to decades were digitized and analyzed to describe meteorological and physicochemical patterns. This study provides a good starting point on the use of long-term data to determine trends through changes in environmental conditions which may be linked to fish kill events. In here, we assessed which measured environmental parameters reflect water quality variations in the lake which can be reliably used in a fish kill alarm system in the future. We suppose that fish kills happening in the lake can be detected earlier and fish kill damages would greatly be lessened if patterns on important environmental parameters will be closely monitored. We are also interested on how existing water quality monitoring in Lake Taal can be more effective. We tried to find any variations in the water quality parameters measured between sites to know if the chosen monitoring locations and space amongst them were appropriate. We looked into the documented fish kill events recorded from 2000 to 2011 and its reported causes, and compare it together with the annual water quality trends. Lastly, we tried to look for any consistent patterns in important meteorological parameters ten days before selected fish kill events. Through this study, we hope to help improve lake monitoring protocols and find trends to aid in better management of Lake Taal and mitigate aquaculture disasters (i.e. fish kills).

MATERIALS AND METHODS

Study Area

This paper focuses on Lake Taal, formerly Lake Bombon (Figure 1) (13°55'-14°05'N, 120°55'-121°105'E; Altitude: 2.5 m a.s.l.), a caldera lake located in the province of Batangas, island of Luzon (Papa and Briones 2017; Papa and Zafaralla 2011). Lake Taal covers an area of 268 km^2, have a maximum depth of 198 m, and is the third largest and second deepest lake in the country (Papa and Zafaralla 2011). The lake originated from series of volcanic and geological processes (Ramos 2002) and home to unique and endemic freshwater species such as the endangered freshwater sardine, *Sardinella tawilis* (Santos et al. 2018) and freshwater snake, *Hydrophis semperi* (Garcia et al. 2014).

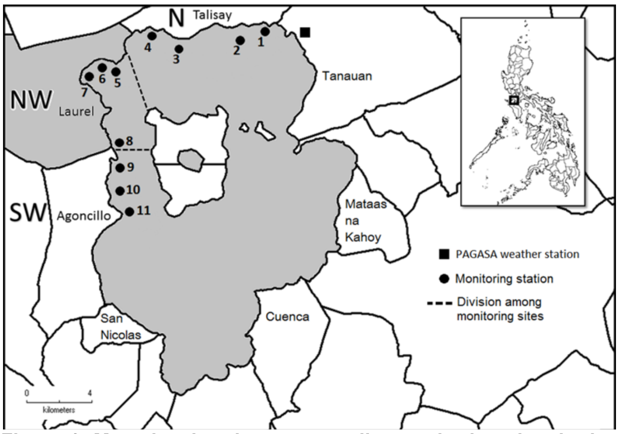

Figure 1: Map showing the water quality monitoring sites in the aquaculture area and the location of the PAGASA-Ambulong weather station in Lake Taal, Philippines

Water quality and weather data

The water quality data and fish kill records used in this study were from the monthly monitoring program of the Bureau of Fisheries and Aquatic Resources – Inland Fisheries Research Station (BFAR-IFRS), from which most of the monitoring sites are identified as high-risk areas of fish kills consequently being frequently monitored (Appendix I). The monitoring efforts of BFAR-IFRS has been one if not the only available long-term data in Philippine lakes. Challenges were faced while consistent monitoring was attempted, such as breakdown of instruments, lack of specialized chemicals for analyses and inclement weather which posed additional risks during field monitoring. These resulted to limited data, which, if carefully treated could still provide important information. For a limited natural resource, such as lakes, monitoring of important water quality parameters, even from surface water that have been gathered for a significant amount of time can facilitate important tests of ecological principles, and capture significant events and cumulative effects of stressors (Dodds et al. 2012; Whitehead et al. 2009). Furthermore, utilizing long-term ecological datasets were acknowledged to be necessary in setting management goals and developing appropriate plans for effective monitoring, encouraging discovery insights that applies to a much larger geographic area, and is of immediate use to managers, researchers and the public (Hunt et al. 2009; Webb et al. 2009). We digitalized 9 water quality data, such as water temperature, water transparency, water hardness, pH, dissolved oxygen, hydrogen sulfide (H_2S), ammonia (NH_3), nitrite (NO_2) and carbon dioxide (CO_2) from the years 2000 to 2011, measured from 0.1 m depth of the lake. These were years when the BFAR-IFRS started to routinely monitor water quality in fish cage areas of Lake Taal to address the problems resulting to fish kills (i.e. declining water quality). The BFAR-IFRS used various test kits (i.e. Hach and Merck) to measure CO_2, NH_3, NO_2, H_2S and water hardness, Secchi disk to measure water transparency, Winkler method for dissolved oxygen and a multiparameter probe for pH and water temperature. Prior to analyses, we carefully inspected and retained the available long-term data from sites where consistent and more frequent monitoring were done. From these, we tried to detect spatial and temporal (i.e. monthly and annual) variations in the water quality parameters and only presented significant results. Estimated number of aquaculture cages, cost of damage (in US dollars) and records of fish kills and its potential causes from the same time period (i.e., 2000-2011) retrieved from the BFAR-IFRS were analyzed. Data from 2005 and 2011 which are important periods in the lake as the previous was the time when under-regulated aquaculture practices were obviously rampant while the latter was the period after mandating a management plan of decreasing the number of fish cages in the lake, were compared.

Data on air temperature and wind speed from PAGASA weather station during a ten-day period before and after the date of reported monsoon-driven fish kill was used to analyze temperature fluctuations and wind speed changes. Incomplete data sets were not used for the analysis. The daily weather data were from the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA) – Ambulong station located at the northeast side of the lake (Figure 1).

Water quality and weather data trends

The Kolmogorov-Smirnov Test (KS Test) was first performed to determine the normality of each water quality parameters. Furthermore, the temporal and spatial variability between the stations in each of the parameters was tested via the Kruskal-Wallis (KW) with post-hoc Tukey-Kramer Test (TK test). Considering the substantial differences in the variance of the different water quality and weather parameters, separate principal component analysis (PCA) was done. Through PCA, we look on what water quality and weather parameters greatly drives changes in the lake. PCA is one of the important tools to determine underlying relationships between water quality parameters, trace stressors and clustering of monitoring stations with same characteristics (Barakat et al. 2016). Boxplots were generated to investigate seasonal and annual patterns in the water quality parameters that can be related to fish kill occurrences. Patterns of air and water temperature fluctuations and wind speed change with 10 days preceding and following the eight cases of fish kill events, which was reported to have monsoon-driven causes, was observed.

RESULTS AND DISCUSSION

Water quality variations

Among the water quality parameters, only dissolved oxygen and water transparency exhibit spatial heterogeneity. Dissolved oxygen values were significantly different at stations 1 and 11 ($p<0.001$, KW post-hoc TK test). Stations 1 and 11 also had higher median DO values (7.65 mg L^{-1} and 7.025 mg L^{-1} respectively) compared to other stations with 6.6±0.42 mg L^{-1} median value range. Water transparency presented significantly higher value between site 11 and the rest of the sites ($p<0.001$, KW post-hoc TK test) with median value of 3.0±0.71 m. These sites (1 and 11) are stations that have proximity to the open water areas, which may have affected the values recorded. Previously, open water areas were reported to have different characteristics from the fish cage areas, such as having deeper depths and higher Secchi disc transparency readings (White et al. 2007). The reduced visibility in fish cage areas was attributed to the increased production of phytoplankton resulting from the high amounts of nutrients because of overfeeding in fish cages. Papa & Mamaril (2011) presented some water quality parameters that were noted to have higher values in the fish cage areas of Lake Taal than in the open water (i.e. nutrient levels and microbial activity). The same study noted lower values of dissolved oxygen and water transparency in the fish cage areas.

Only pH (Figure 2A), water temperature (Figure 2B) and water transparency (Figure 2C) showed apparent seasonal patterns. Months of April to October had greater pH and water temperature values according to performed statistical analysis (KS test, p-values < 0.05). While water transparency readings were statistically low (KS test, p-value < 0.05) during May to October. Seasonality of water quality parameters influence the distribution of aquatic organisms which regulates the structure and function of freshwater ecosystems (Lacoul and Freedman 2006; Li et al. 2017).

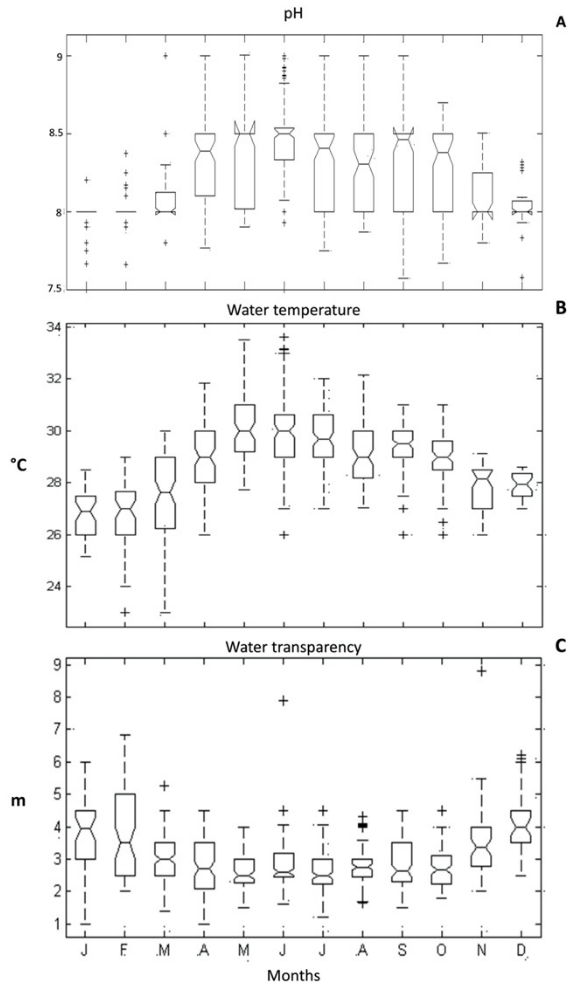

Figure 2: Boxplot of monthly pH, water temperature and water transparency from 2000 to 2012

The PCA results were explained in Table 1, which presents the total percent variances for each principal components (PCs) and the eigenvalues of each parameters to the PCs. The high contribution of pH to the first PC revealed its importance in the water quality monitoring. Although pH is not a parameter used as a main basis for water quality assessment as compared to temperature, DO, TP, EC, etc., significant findings on pH is still observed in some surface water quality studies. Discriminant

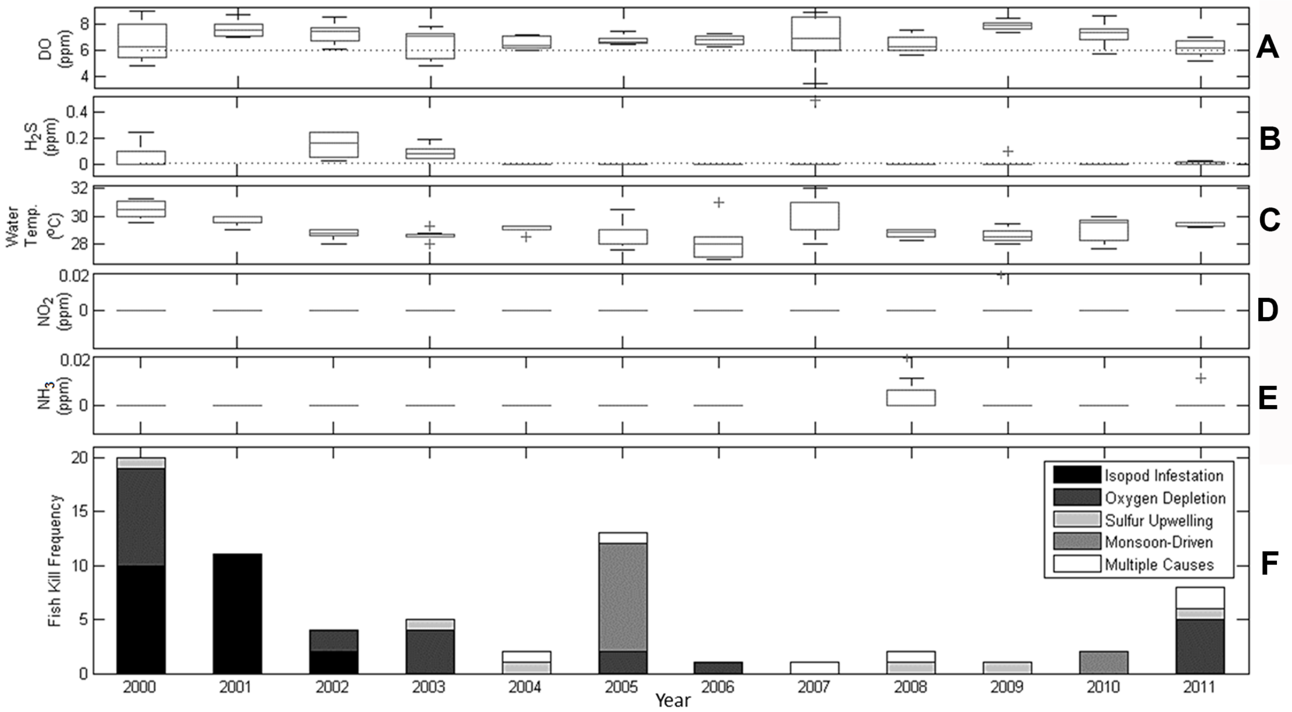

Figure 3: Boxplot of water quality parameters in Lake Taal (A-E), threshold values for fish exposure represented by grey dotted line (A-B) and yearly occurrences of fish kill in Lake Taal with reported causes (F) from 2000 to 2011 (BFAR-IFRS water quality monitoring updates and quarterly fish kill report 2000-2011)

Table 1: Percentage of total variance associated with the 3 first principal components (PCs) of water quality (A) and local climate (B). The contribution of each parameter to the formation of each PC were as follows

A	Water Quality		
	PC1	PC2	PC3
Variance (%)	29.47	23.10	19.74
NH_3	0.41	0.34	-0.27
CO_2	-0.04	0.49	0.28
DO	-0.22	0.18	0.41
H_2S	0.45	0.40	0.17
Nitrite	0.11	0.47	-0.45
pH	0.47	-0.31	-0.04
Hardness	0.12	0.09	0.61
Water T°C	0.38	-0.35	0.02
Transparency	-0.42	0.11	-0.28

B	Meteorological Data		
	PC1	PC2	PC3
Variance (%)	52.74	31.20	16.05
Air T°C	0.50	0.73	-0.46
Precipitation	0.53	-0.68	-0.50
Wind Speed	0.68	-0.01	0.73

analysis of water quality parameters (WQP) by Shrestha & Kazama (2007) included pH as an important parameter in determining spatial variances. Mentioned previous work had found pH to be significantly different when comparing highly polluted sites from less polluted ones. Implications of low pH levels in lakes, specifically within 5.8 to 6, were reported to severely affect the growth and reproduction of aquatic organisms (Kelly et al. 1984).

Hydrogen sulfide was formed when soluble sulfides were hydrolyzed in water and decreases with increasing pH. In freshwaters, it is usually derived from natural sources (anaerobic bacterial activity) and industrial processes (i.e. input of organic materials) (Capone and Kiene 1988; Rasmussen 1974; WHO 1996). While NH_3 is known to be naturally occurring, it turned to be one possible contaminant and possible toxicant in Lake Taal (Hallare et al. 2009) probably due to the unconsumed fish feeds. CO_2 and NO_2, may also be linked to the volcanic nature and man-made factors as these parameters were usually from fluxes of organic matter in the sediments of lakes (Nielsen et al. 2004). The occurrence of these major contributors to the variability of the PCs may have been caused by volcanic activity and intensive aquaculture in the lake, making pH, H_2S, NH_3, CO_2 and NO_2, both naturally occurring and anthropogenically contributed.

For mostly large temperate lakes, wind speed is one of the important drivers that can influence a lake's response to change (Read and Rose 2013). We also noticed the importance of wind as a driver of change in Lake Taal (Table 1). Strong winds affected water currents, transport of dissolved substances, and mixing of the water column took place, which are important events for the aquatic ecosystems (Shilo et al. 2007). However, wind speed is greatly affected by climate change, which have been observed to be increasing 5% per decade (Desai et al. 2009), leading to an increase in the speed of the surface water current, thus indirectly affecting biogeochemical processes in the lake.

Aquaculture and fish kills in Lake Taal

The municipality of Agoncillo had the highest number of fish cages with a total of 5,357 in the year 2005 followed by Talisay and Laurel, with 2,834 and 1,501 fish cages, respectively. Fish kill occurrences in the abovementioned municipalities varied between 2005 and 2011. Talisay had the largest cost of damage reaching $599,000.00. It was followed by Laurel and Agoncillo with damage cost of $583,000.00 and $16,000.00 respectively (Table 2). From 2005 to 2011, there was a significant reduction in the number of aquaculture fish cages except in San Nicolas. Despite this, there was still an increase in the financial cost of fish kills. This may be due to intended increase of fish stocks in the fish cages, in the hope of gaining more harvest by the fish cage operators.

The threshold values for fishery water class II, tourist zones and recreational water class I for DO was set at 6.0 ppm (DENR 2016). Several years (i.e. 2000, 2003, 2007, 2008 and 2011) exhibited values less than 6.0 ppm. H_2S threshold value for fish exposure was fixed at 0.02 ppm. There were noticeable annual values exceeding the threshold for H_2S for years 2000, 2002 and 2003 (Figure 3B). Water temperature did not show any pronounced annual pattern (Figure 3C). NO_2 and NH_3 had constant median values from 2000 to 2011 (Figure 3E-F). Threshold values of fish exposure for these water quality parameters were 0.1 and 0.02 ppm respectively.

The first year of monitoring (year 2000) recorded the highest fish kill frequency (21 incidences). Among those recorded incidents, 11 were caused by isopod infestation, 9 by O_2 depletion and 1 by sulfur upwelling. Fish kill events that happened on the early part of the decade were mainly attributed to some biotic factors such as isopod infestation. On the later years, fish kill occurrences were attributed to the anomalies in the physico-chemical parameters such as oxygen (i.e. year 2002, 2003, 2005 and 2011), H_2S (year 2003) and in nitrogen compounds such as NO_2 (year 2008). While monsoon-driven fish kills were also reported in year 2005 and 2010. Fish kill events were either preceded by days with high wind speed or high air temperature. Higher wind speeds were observed before

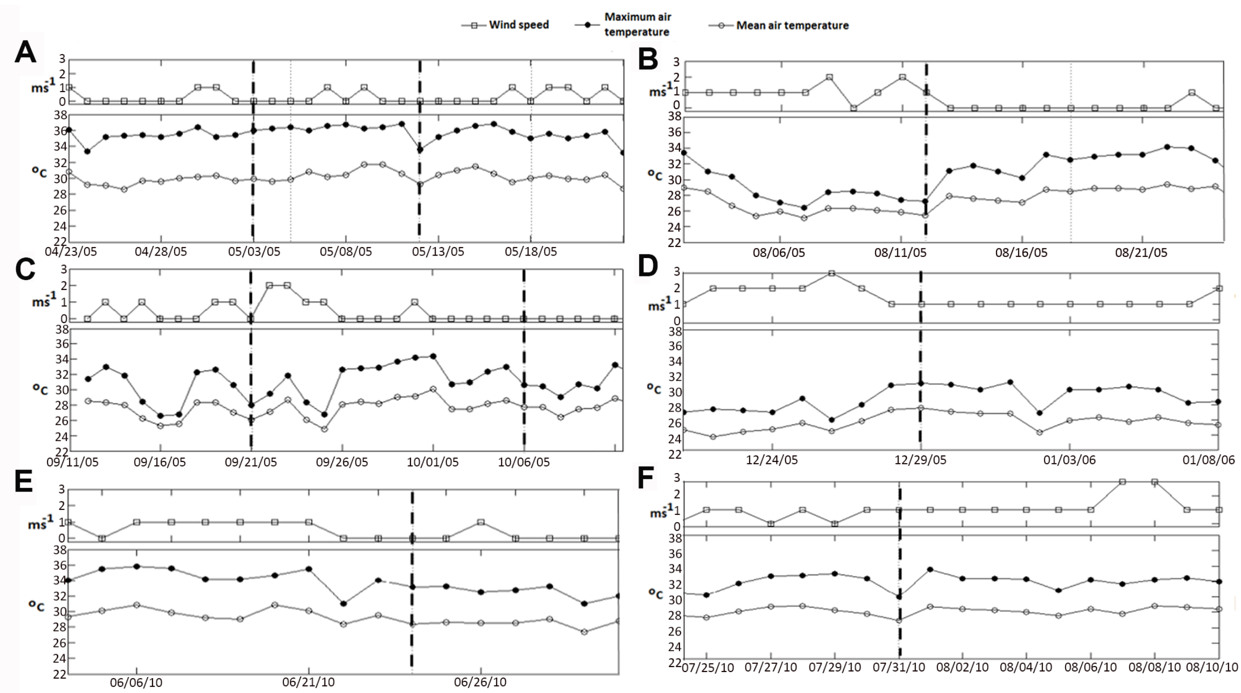

Figure 4: Wind speed, maximum air temperature, minimum air temperature and monsoon-driven fish kills (broken lines) for the periods spreading from April 23, 2005 to May 28, 2005 (A), from August 2 to August 24, 2005 (B), from Sep. 11 to Oct. 16, 2005 (C), December 21 to January 8, 2006 (D), June 14 – 30, 2010 (E), and July 25 to August 10, 2010 (F) where fish kill caused by monsoon-driven events were reported by BFAR-IFRS

Table 2: Approximate number of aquaculture fish cages, fish kill frequency and cost of fish kill damage in Lake Taal during 2005 and 2011. Data are from Department of Agriculture-Bureau of Fisheries and Aquatic Resources - Inland Fisheries Research Station (DA-BFAR-IFRS).

Municipality	No. of aquaculture fish cage units		No. of Fish kill incidents		Cost of fish kill damage	
	2005	2011	2005	2011	2005	2011
Talisay	2834	2000	3	3	$ 599,000	$ 2,372,000
Laurel	1501	1360	3	1	$ 583,000	$1,455,000
Agoncillo	5357	1500	3	2	$ 16,000	$ 1,525,000
San Nicolas	0	1000	2	2	$ 9,000	$ 1,525,000
Cuenca	0	20	0	1	$ 0	$ 14,000
Mataas na Kahoy	0	120	1	1	$ 386,000	$ 57,000
Tanauan	0	0	0	1	$ 0	$ 207,000

the recorded fish kill incidents in May, August and December 2005, and June 2010 (Figure 4A, 4B, 3D and 4E). Furthermore, fish kill incidents were preceded by several days of prolonged high air temperatures (i.e. May 12, 2005 in Figure 4A; September 21; October 6, 2005 in Figure 4C; and July 31, 2010 in Figure 4F).

Upon comparison with aquaculture production values from the years 2005 and 2011, higher production for the two main aquaculture species - milkfish (*Chanos chanos*) and tilapia (*Oreochromis niloticus*) were recorded in 2011 (Bureau of Fisheries and Aquatic Resources 2006; 2012). This means that the decrease in the number of fish cages did not translate to a reduction of aquaculture productivity. This result also confirms the work of Vista et al. (2006) who reported the continuation of under-regulated aquaculture practices prevalent in Lake Taal. These practices may lead to nutrient pollution from excessive feeding as well as overstocking of individual cages. It was obvious that fish cage operators do not follow the recommended 30,000 to 50,000 stocking density per cage.

Fish kills linked to biological, water quality variations or monsoon-driven events

The three Principal Component (PC) explained 29.5 and 23.1, and 19.7% of the total variance, respectively (Table 1). The first PC (PC1) is positively related to NH_3, H_2S, pH, and water temperature, and negatively related to water transparency. The second component (PC2) is positively related to CO_2, nitrite and H_2S. It is on the other hand negatively related to water temperature and pH. The water hardness and DO were weakly represented on PC1 and PC2 but were well represented on PC3. The PCA on weather parameters revealed two Principal Component explaining more than 80% of the total variance. The first PC ($PC1_w$) is positively related to wind speed, precipitation and air temperature. The second PC ($PC2_w$) is positively related to air temperature but negatively related to precipitation and wind speed (Table 1).

According to BFAR-IFRS fish kill reports, causes of fish kills in Lake Taal were isopod (*Corallana grandiventra*) infestation, O_2 depletion, sulfur upwelling, and monsoon-driven phenomena. Sometimes, it is a combination of the events that cause fish kills in the lake. Some water quality parameters are linked to fish kill occurrences including DO, H_2S, water temperature, NO_2 and NH_3 (Figure 2). Sudden changes in DO (i.e. high variability at the annual scale, Figure 2a) were related to fish kill occurrences in the lake (Figure 2F) during the years 2000, 2003 and 2011 with DO values lower than 6.0 ppm. High organic load, traced back to excess feeds and fish wastes from the fish cages in the lake (Hallare et al. 2009), occurred when recorded H_2S concentrations were higher than 0.002 ppm (i.e. in 2000, 2002 and 2003, Figure 2B). The same was true for NO_2 (Figure 2D) and NH_3 (Figure 2E) when records show that their values are greater than 0.1 ppm and 0.02 ppm, respectively. Coincidentally, massive fish kills occur where aquaculture is intensive, where exceeding in the required carrying capacity of fish pens were practiced which resulted into producing organic material from unused fish feeds and waste products decomposing in the water column and sediments (Jacinto 2011).

While monsoon-driven fish kill incidents in 2005 and 2010 (Figure 3F) were attributed to changing wind patterns, the sudden shift in water temperature due to heavy rainfall after a period of high temperature may have also caused overturns, thereby moving anoxic water and organic load from the sediments to the surface. Unfortunately, analysis of annual mean temperature data does not reveal any apparent trend relating it to the number of fish kill occurrences attributed to monsoon-driven events (Figure 3C and 3F). However, the daily temperature fluctuations preceding fish kill events suggest a relationship between the two (Figure 4). Differences between temperature and wind speed values during the day of the fish kill and the days preceding it was noticeable. Fish kill happened after consecutive days of strong winds were recorded (Figure 4A, 4B, 4D and 4E). Likewise, prolonged high temperature values were also recorded before a fish kill event (Figure 4A, 4C and 4F). Changes in air temperature and wind speed is closely related to lake thermal variables such as water temperature, stratification and its length (Magee and Wu 2017). Long-term monitoring data was used to show fish kills caused by lake mixing when anoxic water column moves upward (Henny and Nomosatryo 2016). We suspect that lake mixing in Lake Taal was driven by sudden change in air temperature and wind speed cause. Consequently, oxygen depleted water column, and release of toxic nutrients (i.e. phosphates and sulfide) from the sediments after lake mixing cause fish kills. Further analyses of water quality data prior to future fish kill events will allow for a better characterization of such relationship. As such, analyzing the available long-term data in Lake Taal may be used to look for trends that can help creating a better understanding of current limnological conditions in the lake and help in crafting better lake conservation measures that utilize scientific data.

Water quality monitoring recommendations and future research opportunities

The comparison of monitoring sites shows that less, but well-spaced stations are needed as well as the inclusion of sites that are not yet included in the monitoring. Addition of sampling sites in the open water areas, and biological parameters, phytoplankton, chlorophyll a, zooplankton, other ecological parameters and potential toxic contaminants based on anthropogenic activities such as total phosphates, nitrates and run off patterns should be included in the monitoring. Nevertheless, measured water quality parameters by the BFAR-IFRS should be consistently monitored. Stricter monitoring of prescribed stocking densities in the fish cages should be implemented. The inclusion of water quality parameters measured from samples collected from greater depths should also be considered to come up with a vertical profile of selected parameters, as surface water measurements do not necessarily reflect values representative of the entire water column. This may help understand the dynamics of mixing patterns which may be correlated to other observed parameters or analyzed to reveal long-term trends. If possible, future monitoring should also focus on land-use patterns and identification of other human activities around Lake Taal.

Measurement of vertical profiles of conductivity, temperature, pH and DO for selected sites representing the open water and fish cage areas is also recommended. These will complement the existing monitoring scheme (Freed and Slimak 1978) and can lead to a better long-term assessment of the lake's limnological characteristics. Several European lakes (i.e. Annecy, Bourget, Constance and Geneva) (Jacquet, Domaizon, and Anneville 2014; Odermatt et al. 2008) and other Asian lakes (i.e. Biwa and Manchar) (Kazi et al. 2009; Okamura 2008) with routine monitoring programs are examples of more efficient monitoring systems wherein lesser number of sites is sampled but more parameters are included in the monitoring. These examples of water quality monitoring procedures were developed from science-based studies. With our recommendations above, we are hoping to contribute to the achievement of a similar monitoring in Lake Taal.

CONCLUSION

Analysis of long-term monitoring data still lacks for Philippine lakes, where up to now most of what we know about lakes' responses to changes in the environment are based on temperate or subtropical models. This study will help build a larger knowledge-base on how tropical lakes with the same characteristics, respond to anthropogenic and natural stressors. Despite some limitations in the utilization of the available data sets, our analyses show the potential application of further studies on the responses of Lake Taal to human-induced or even climate-influenced changes. This is the first time that long-term limnological data on Lake Taal has been put together for a more in-depth analysis of its limnological characteristics and its responses to current conditions brought about by intensive aquaculture.

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CONTRIBUTION OF INDIVIDUAL AUTHORS

MU Mendoza and RDS Papa conceptualized the study and wrote the main parts of the manuscript. MU Mendoza, RDS Papa, G Dur, S Souissi, O Anneville, MD Santos and MTM Mutia performed data analyses and contributed to the manuscript. L Villanueva, M Ite, M Rosana and N Kawit collected the water quality parameters and performed preliminary analyses on the datasets used in this study.

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APPENDIX

Appendix 1: Water quality monitoring sites in the aquaculture fish cage area of Lake Taal with their corresponding coordinates

Location	Site	Coordinates
North (N)	1	14°04'58.4904", 121°02'59.3808"
	2	14°04'50.9232", 121°02'21.0264"
	3	14°04'38.9388", 121°00'06.3216"
	4	14°04'44.0472", 120°58'08.9220"
Northwest (NW)	5	14°03'57.2904", 120°57'21.9528"
	6	14°04'09.2784", 120°56'46.1112"
	7	14°03'40.5072", 120°56'25.0980"
	8	14°01'27.4152", 120°57'28.1340"
Southwest (SW)	9	14°00'43.0452", 120°57'26.8956"
	10	14°00'02.2716", 120°57'24.4260"
	11	13°59'25.0944", 120°57'28.1340"