ARTICLE

Water Quality Index as a tool for assessing the water quality of the Laguna de Bay from 2020 to 2021

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ABSTRACT

Laguna de Bay (LdB) is a primary freshwater resource that provides multiple ecosystem services. The Laguna Lake Development Authority (LLDA) oversees the periodic monitoring of LdB's water quality. Data collected by the LLDA can be used to assess LdB's status using an easily understandable metric. In this study, Water Quality Index (WQI) was used to assess LdB's quality based on seven parameters (fecal coliform, nitrate, inorganic phosphate, ammonia, biochemical oxygen demand, dissolved oxygen, and pH) measured and recorded by the LLDA from 2020 to 2021. Data from eight major monitoring stations were used to explore how the seven parameters link the stations as well as to compute the WQIs. The lowest WQIs (excellent quality) were obtained using the data representing the end of 2020 for all eight stations, while the highest WQIs (good - poor quality) were obtained for the data measured towards the end of 2021 for Stations I, II, and XVI. Principal Component Analysis (PCA) revealed that the stations had relatively similar environmental influences and overall water quality. Station groupings correspond with the computed WQIs. Stations that had unconventional placements in the biplots (Q3-Q4 of 2021 for Stations I and XVI and Q2 of 2021 for Station V, classified as outliers), correspond to the time points where the lowest water quality was noted. Overall, WQI values are concordant with the water and land use type of the stations. WQI is a useful tool for indicating water quality and is valuable in evaluating LdB and other freshwater resources.

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INTRODUCTION

In the Philippines, freshwater bodies are crucial resources for drinking water and food. These water resources are used for wide-scale development and sustenance of populations, such as aquaculture and agricultural irrigation. An economically important water body within Mega Manila is the Laguna de Bay (LdB). Classified as a Class C inland water, it is suitable for fisheries, agriculture, irrigation, and livestock use (Department of Environment and Natural Resources [DENR] 2016; Santos-Borja and Nepomoceno 2006). LdB is also categorized under Recreational Water Class II, deeming it suitable for boating and other similar activities (DENR 2016). It supports the power generation of plants established in the region, including the Kalayaan Pumped Storage Power Plant (National Grid Corporation of the Philippines 2022). The LdB supplies water for farmland irrigation of coconut plantations, rice paddy fields, and sugarcane fields (Cruz et al. 2012). This provision of water extends to domestic areas through water concessionaires such as the Manila Water Co., Inc. (Cunanan and Salvacion 2016; Israel 2007).

Extensive resource use has led to negative consequences for LdB. Effluents from urban areas continue to contribute to the degradation of the lake's water quality (Macuroy et al. 2019). The lake has been a sink for untreated sewage (Global Environment Facility 2017). Wastewater discharges from industrial companies and residential spaces have polluted it with chemicals and fecal coliforms (Cunanan and Salvacion 2016; Labunska et al. 2011). All of these contributed to the lake's progressive deterioration, with eutrophication and pollution being the most prominent challenges (Cunanan and Salvacion 2016).

To address these problems, LdB's condition is regulated and monitored. The principal regulator of the LdB is the Laguna Lake Development Authority (LLDA). LLDA oversees the development, use, and preservation of the LdB as well as the periodic monitoring and gathering of water quality data. The agency publishes quarterly water quality reports on physical, chemical, and microbial parameters measured from different monitoring stations across the lake. In 2019, these quarterly reports included measurements of fecal coliform, biochemical oxygen demand (BOD), dissolved oxygen (DO), pH, ammonia, nitrate, and inorganic phosphate from nine major monitoring stations and 35 minor monitoring stations. In 2021, six major and one minor monitoring stations were added, with the same measured parameters (Laguna Lake Development Authority [LLDA] 2021). The reports include raw datasets that are large and complicated, making it difficult to generalize meaningful information. This challenge is especially highlighted in unusual circumstances, such as the COVID-19 pandemic, during which the mobility of people and economic activities have been regulated for a considerable amount of time. The government-mandated lockdowns affected the monitoring activities conducted on the lake as well as the factors that dictate, contribute to, or affect the lake's parameters (Lim et al. 2020). For instance, several lakeside businesses and those near water tributaries had to close in 2020 due to the pandemic (Cinco 2020).

Environmental changes in the vicinity of LdB and the limited monitoring from 2020 to 2021 provided a unique dataset that is deemed to represent issues and concerns that have implications to its water quality. Elsewhere, Water Quality Indices (WQI) have been used to monitor different types of aquatic systems. In one study, the use of WQI confirmed that the groundwater in Tuticorin, India, was impaired by anthropogenic factors (Selvam et al. 2014). Another study compared the water quality of reservoirs of the Yellow River in China, wherein water samples were analyzed for a period of over six years (Hou et al. 2016). The WQI values calculated ranged from 17.8 to 77.8, suggesting a gradient of water quality across the reservoirs. The use of WQI has proven to be effective in evaluating and classifying the state of surface waters, determining trends in water quality, gauging water pollution, and aiding regulators in decision-making, especially concerning water bodies in temperate regions (Gradilla-Hernández et al. 2020). A prominent feature of WQI is that it allows for the conversion of large numbers of variables into a single value representing water quality, combating the challenge of trying to understand large amounts of unintegrated data (Bhat and Pandit 2014).

Studies on the impact of the COVID-19 pandemic on the quality of select freshwater bodies in Asia have been conducted (Sharma and Gupta, 2022; Chakraborty et al., 2021); however, nothing similar has been done for the LdB. In this study, WQI was used to assess the quality of LdB between 2020 and 2021 by using WQI as a comprehensive and easily understandable metric. WQI values were computed using secondary data on seven parameters, including fecal coliform, nitrate, inorganic phosphate, ammonia, biochemical oxygen demand (BOD), dissolved oxygen (DO), and pH, from 2020 to 2021. We computed WQI values, analyzed temporal and spatial quality trends of the eight major monitoring stations in LdB, and inferred factors contributing to the overall quality of the lake water during the lockdown period. The period between 2020 and 2021 is of special interest since it is when stringent restrictions were applied to prevent the spread of COVID-19 in the Philippines. People's mobility across urban areas surrounding LdB was restricted, as most of the population was mandated to stay at home.

MATERIALS AND METHODS

Study Site and Data Sources

LdB is the largest lake in the country, with an area of 911.7 km^2. It is an economically active waterscape that houses fish pens and cages, supporting fishermen in the provinces of Laguna and Rizal. The lake is divided into four areas, namely West Bay, Central Bay, East Bay, and South Bay. This division is according to the differences in the bathymetry of the bays, sporting a unique urban-rural feature, i.e., the western sectors of LdB are more industrialized while the eastern sectors support agricultural and aquacultural activities (Delos Reyes and Martens 1994). Historical data on routinely reported water quality parameters from 2020 to 2021 were retrieved from the quarterly reports of the LLDA, which are available online. The reports contained monitoring data for the minor and major stations of the LdB. Due to multiple gaps in the data from minor monitoring stations, these data were excluded (Figure 1). Monitoring Stations I, V, XV, and XVI are in the West Bay, which has the largest number of commercial fish pens and cages and is also surrounded by the most densely populated and heavily developed areas (Israel 2007; LLDA 2013). Meanwhile, Monitoring Stations II and XVIII are in the East Bay, which has a population of fishermen operating in smaller fishing areas. In 2013, the East Bay had the highest water quality score among all bays. The Central Bay houses Station XVII, and has been reported to hold the highest percentage of native fish species in catch composition. The South Bay, where Station VIII is located, has the lowest percentage of native species despite being a designated fish sanctuary (LLDA 2013).

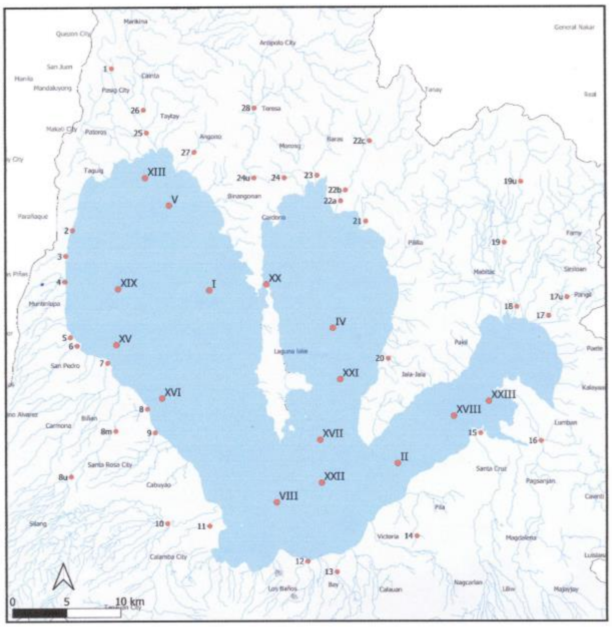

Figure 1: Geographical map of the LdB; Only data for Monitoring Stations I, II, V, VIII, XV, XVI, XVII, and XVIII were analyzed in the current study (map courtesy of LLDA).

The seven water quality parameters were used to produce a multi-component metric describing the water quality of eight major monitoring stations in LdB (see Supplementary Files for computations). Descriptive statistics were performed for each of the parameters, and the results are shown in Table 1. The ranges of each parameter are: fecal coliform (18.000–952.333), nitrate (0.050–0.493), inorganic phosphate (0.038–0.282), ammonia (0.005–0.217), BOD (1.167–3.667), DO (7.033–9.533), and pH (7.967–9.133).

Data Analyses

All major and minor monitoring stations were included in the initial analysis. However, due to gaps in the dataset that represented periods where no data were acquired by the LLDA, the number of monitoring stations was reduced to eight, and none of the minor monitoring stations were included in the final analysis. Data gaps due to failure of data collection were identified and validated as declared by the LLDA through correspondence (Table 2). Multiple imputations by chained equations were done to calculate estimates of parameters during periods where no reported values were extracted from the quality monitoring reports. Imputation was implemented following the assumption that the unavailable data were missing at random (MAR). A predictive mean matching method using the mice package (van Buuren and Groothuis-Oudshoorn 2011) was employed to impute the missing data. The number of imputations was determined using the howManyImputations package following von Hippel's two-stage calculation using a quadratic rule (von Hippel 2018). The data set was analyzed for multivariate normality using the Henze-Zirkler test implemented in the MVN package (Korkmaz et al. 2014). All eight major monitoring stations were included in the WQI computation.

WQI values were computed as described by Hazarika et al. (2020) and Ramakrishnaiah et al. (2009). Seven parameters, i.e., DO, BOD, pH, ammonia, nitrate, inorganic phosphate, and fecal coliform, were used in the computation. These are considered primary parameters for monitoring freshwater and marine water quality (DENR 2016; Santos-Borja and Nepomoceno 2006). Descriptive statistics (i.e., mean, median, minimum, maximum, standard deviation, and coefficient of variation) were computed for each of the parameters. All parameters were evaluated according to how they affected the microbial and overall quality of LdB, resulting in specific parameter weight values. The relative weight of each parameter was calculated using equation (1) (Hazarika et al. 2020; Ramakrishnaiah et al. 2009):

$$w_i = \frac{w_i}{\Sigma w_i} \quad (1)$$

where w_i is the value assigned to each parameter and i=1,…n where n is the total number of parameters. The parameter values assigned based on the previous studies of Babaei Semirom et al. (2011), Ewaid (2017), Gradilla-Hernández et al. (2020), Matthews (2014), Said et al. (2004), Shah (2013), Srivastava and Kumar (2013), and Tomas et al. (2017), as well as on guidelines set by the DENR, are listed in decreasing order based on their relative contribution to the water quality of a freshwater body such as LdB: fecal coliform (5), nitrate (4), ammonia (4), BOD (4), DO (3), PO_4^{3-} (2), and pH (2). A quality rating scale, Q_i, was then computed for each parameter using equation (2) (Hazarika et al. 2020; Ramakrishnaiah et al. 2009):

$$Q_i = \frac{C_i}{S_i} x 100 \quad (2)$$

where C_i is the concentration of a specific parameter (fecal coliform, nitrate, ammonia, BOD, DO, PO_4^{3-}, or pH) in each water sample, and S_i is the established limit or standard. Finally, WQI was computed using equation (3) (Hazarika et al. 2020; Ramakrishnaiah et al. 2009):

$$WQI = \Sigma(W_i Q_i) \quad (3)$$

The water quality indicated by the WQI value may be rated as follows: <50 – excellent; 50–100 – good; 100–200 – poor; 200–300 – very poor; and >300 – unsuitable for drinking (Hazarika et al. 2020; Ramakrishnaiah et al. 2009). The computed WQIs for each station were plotted as a factor of time (24 data points per station for two years, i.e., one WQI value per month).

Associations between the parameters used for WQI computation were determined using Principal Component Analysis (PCA) employed through the factoextra package (Kassambara and Mundt 2020). Eight data points per parameter that correspond to Q1, Q2, Q3, and Q4 for the years 2020 and 2021 were used for the exploratory data analysis. Non-Parametric Comparison of Multivariate Samples was also conducted to test for statistical differences across all stations using the quarterly physico-chemical parameter data (see Supplementary Files). The non-parametric comparison was performed using the nonpartest function of the npmv package (Burchett et al. 2017) with the permreps argument set to 1000. In order to identify which stations significantly differ for a given physico-chemical parameter, a post hoc analysis was performed using the dunn.test package (Dinno 2017) with p values adjusted following the Benjamini-Hochberg correction in order to minimize false discovery rates. All data analyses and visualizations were conducted in RStudio (2022.07.2).

Table 1: Descriptive statistics for selected water quality parameters.

Parameter	Unit	Mean	Median	Minimum	Maximum	Standard Deviation	Coefficient of Variation
Fecal coliform (FC)	**MPN/100 mL**	98.578	56.167	18.000	952.333	156.013	1.583
Nitrate (N)	**mg/L**	0.143	0.130	0.050	0.493	0.089	0.621
Inorganic phosphate (PO_4^{3-})	**mg/L**	0.081	0.063	0.038	0.282	0.047	0.584
Ammonia (A)	**mg/L**	0.046	0.035	0.005	0.217	0.045	0.984
Biochemical oxygen demand (BOD)	**mg/L**	2.563	2.333	1.167	3.667	0.573	0.224
Dissolved oxygen (DO)	**mg/L**	7.802	7.700	7.033	9.533	0.502	0.064
pH	**-**	8.376	8.367	7.967	9.133	0.251	0.030

Table 2: Cases of failure of data collection in several monitoring stations.

Quarter, Year	Station(s) Affected	Parameter(s)	Reason	Remarks
Q1 2020	XIII, XIX-XXIII	All	*new stations	
	1-6, 8-19 (Minor)	All	COVID-19 pandemic	
	7 (Biñan River)	All	Inaccessibility (*water hyacinth)	
	20 (Jala-jala River)	All	Dry sampling site	
Q2 2020	Alle	All	COVID-19 pandemic	
	XIII, XIX-XXIII	All	*new stations	
Q3 2020	All minor	All	COVID-19 pandemic	
	I-XVIII	All	COVID-19 pandemic	
	XIII, XIX-XXIII	All	*new stations	
Q4 2020	I-XVIII	FC, BOD	Power interruption caused by typhoon Ulysses in November	missing one data point
	XIII, XIX-XXIII	All	*new stations	
Q1 2021	5 (Tunasan River-Downstream)	All	Ongoing construction at the bridge	
	9 (Cabuyao River)	All	Inaccessibility (*water hyacinth)	
	All minor excl. 5, 9, 20-28	All	ECQ in Metro Manila and provinces of Rizal, Laguna, Cavite, and Bulacan	
	All	NO3	Unavailability of chemical reagents	
Q2 2021	All minor	All	ECQ/MECQ	
	I-XXIII	BOD, DO, pH, Pi, NO3	ECQ/MECQ	missing one data point
	All major	Ammonia		
Q3 2021	XVII (Fish Sanctuary–Central Bay)	BOD, DO, pH, Pi	Strong winds and big waves	
	All minor excl. 25	All excl. BOD	ECQ/MECQ	missing two data points
	25 (Manggahan Floodway–Taytay)	All	Inaccessibility (*water hyacinth)	
Q4 2021	2 (Bagumbayan River–Taguig)	All	Dry sampling site	missing one data point
	7 (Biñan River)	All	Inaccessibility (*water hyacinth)	missing two data points
	27 (Angono River)	All	Inaccessibility (*water hyacinth)	missing one data point

RESULTS AND DISCUSSION

Results

Computed WQI values and overall water quality trends

Monthly WQI values throughout 2020 and 2021 for each of the eight major monitoring stations are shown in Table 3. Based on the rating scale by Hazarika et al. (2020) and Ramakrishnaiah et al. (2009), low water quality is indicated by numerically high WQI values (Iticescu et al. 2019; Kizar 2018). The lowest WQI values were seen at the end of 2020 (Q4), the least being 33.7556. In contrast, the highest WQI values were seen at the end of 2021 (Q4), with the highest value at 197.9782. The highest and lowest values are relative to all WQI values obtained from the eight monitoring stations across the study period. Between Q1 and Q2 of 2020, it can be noted that there were WQI increases, indicating borderline good to poor conditions for Stations I, V, XV, XVI, and XVII (Figures 4a and 4b). On the other hand, in Q4 of 2020, the WQI values of all stations ranged between 33.7556 and 56.6645, indicating excellent to good overall quality. The year 2021 had higher computed WQI values for most stations (Figures 4a and 4b). Only Station XVII had an increase in the computed WQI value for the first quarter of 2021. Stations V and XV showed particularly high WQI values for Q3 of 2021. Stations I, II, and XVI had particularly high WQI values for Q4 of 2021 (Figures 4a and 4b).

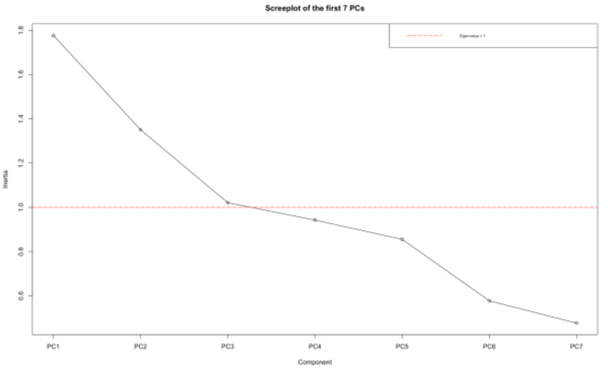

Figure 2: Screeplot of the extracted principal components.

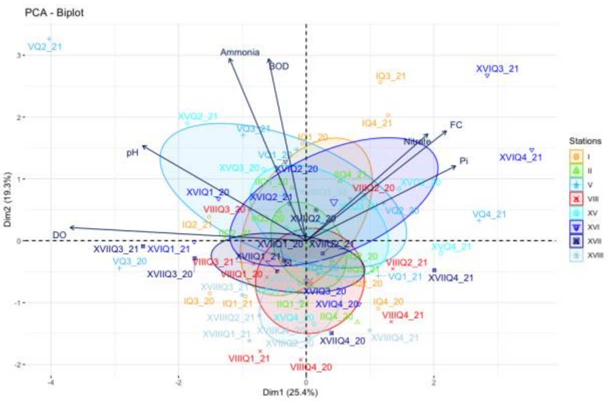

Figure 3: PCA Biplot showing the relationship of the analyzed physico-chemical parameters and the monitoring stations.

Physico-chemical parameters and associations among monitoring stations

Seven principal components (PC1–PC7) were extracted, which account for variance in the data (Table 4). Considering the first two PCs, inorganic phosphate, fecal coliform, nitrate, BOD, and ammonia all have positive factor loadings, suggesting that they all contribute to the variations in the data (Table 5). All of these variables are required minimum parameters for water quality monitoring in the guidelines set by the DENR.

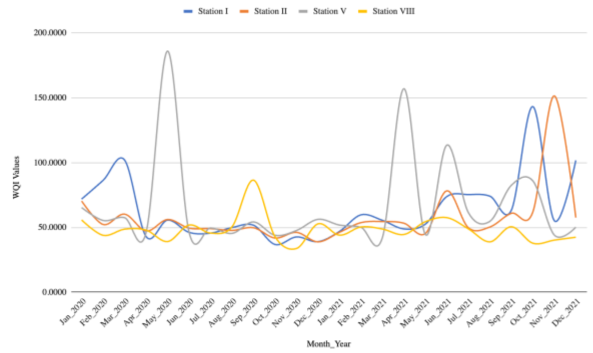

Figure 4a: Historical changes in the computed WQI values for Stations I, II, V, and VIII.

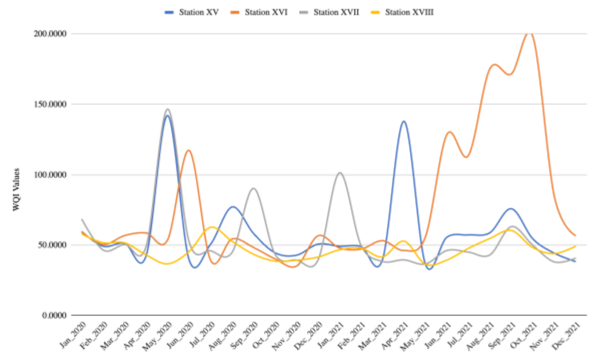

Figure 4b: Historical changes in the computed WQI values for Stations XV, XVI, XVII, and XVIII.

Individual PCAs of the parameters are closely similar to the results of PC1 and PC2 with respect to the clustering of the parameters (Table 5 and Figure 3). Overall, the influence of the parameters that are strongly correlated with the first and second principal components is sufficient to account for the variation observed in the data (Figure 2). Inorganic phosphate correlates most strongly with PC1. Inorganic phosphate, fecal coliform, and nitrate varied together during the study period, i.e., an increase in inorganic phosphate indicates increases in both fecal coliform and nitrate. For PC2, the variables that most strongly correlate are ammonia and BOD, with loadings of 0.564 and 0.563, respectively. In summary, PCA has shown a high correlation between inorganic phosphate, fecal coliform, and nitrate. These parameters are the most significant contributors to PC1, as indicated by their positive loadings. Ammonia is the most important contributor to PC2 and is correlated with BOD, fecal coliform, and nitrate (factor loadings of 0.300 or greater) (Figure 5).

As seen in Figure 3, most data points representing all quarters per major monitoring station are clustered together, indicating the consistent effect of the physico-chemical parameters on the overall status of each station during the study period. Except for fecal coliform measurements for Stations XVI and XVII, results of testing for significant differences using the quarterly data on physico-chemical parameters revealed that all monitoring stations generally had the same qualities from 2020 to 2021 (corrected $p > 0.05$ for all variables). Outliers, namely Q3 and Q4 of 2021 for Stations I and XVI and Q2 of 2021 for Station V, correspond to the time points when lowest water quality was noted based on WQIs.

Table 3: WQI values of eight major monitoring stations from 2020-2021.

Month_Year	Station I	Station II	Station V	Station VIII	Station XV	Station XVI	Station XVII	Station XVIII
Jan_2020	71.8730	70.3312	65.3000	55.7617	59.7581	59.4115	68.6556	57.9058
Feb_2020	86.3044	52.2494	55.3458	43.9077	49.2480	50.4952	46.5417	51.7151
Mar_2020	101.9077	60.2480	57.5268	48.6772	51.4105	56.8522	50.5647	51.6911
Apr_2020	42.9375	47.2004	46.1252	47.9550	42.4401	58.7252	49.0210	43.0996
May_2020	55.6730	56.1129	185.8633	39.0948	142.0288	53.7611	146.5685	36.7282
Jun_2020	46.1647	49.4274	46.3532	51.8456	39.6099	117.2794	52.3831	45.4800
Jul_2020	45.5893	49.0869	49.6036	45.6313	50.6778	39.3520	46.0542	62.7341
Aug_2020	49.8893	47.6804	45.3865	50.5063	77.1591	54.4417	44.8417	52.7647
Sep_2020	51.7230	49.7708	54.2343	86.4579	58.3119	48.4028	90.3383	43.5619
Oct_2020	36.8532	41.7938	43.9230	42.8921	44.5911	40.3091	43.5748	38.6925
Nov_2020	42.6966	46.2210	47.6192	33.7556	42.8921	35.1573	39.4806	39.3133
Dec_2020	39.0169	38.8615	56.2526	52.7740	50.7782	56.6645	39.3698	41.5421
Jan_2021	46.8962	46.2522	51.7950	44.0306	49.2188	48.0063	101.4407	46.7012
Feb_2021	59.7212	53.7058	50.0885	50.3643	49.0845	47.1935	49.9863	47.8379
Mar_2021	55.4597	54.5341	42.1841	48.7726	39.6228	53.2252	38.5032	41.6865
Apr_2021	48.8258	53.2633	156.8891	44.5476	137.9216	46.1958	39.5972	52.8925
May_2021	52.5300	45.3157	44.5236	54.4254	36.5073	55.8754	36.6282	36.4323
Jun_2021	73.8716	78.2234	113.4752	57.5625	55.7054	128.5446	46.2762	39.4657
Jul_2021	75.3175	49.7442	61.4123	48.9060	57.3091	113.6282	45.0879	47.7698
Aug_2021	74.1250	50.3214	54.6756	38.8720	58.8274	175.1756	43.1030	54.7500
Sep_2021	63.2391	60.9028	82.4812	50.5625	75.8948	171.5069	63.1885	60.4683
Oct_2021	143.1091	61.8800	85.9157	37.8046	54.4752	197.9782	49.9355	48.2698
Nov_2021	55.1736	151.3819	44.0883	40.2282	44.3442	84.6270	38.1062	44.0258
Dec_2021	101.7073	57.5794	50.2292	42.4395	38.3115	56.7351	40.8423	49.3075

*WQI value equivalence: <50 – excellent; 50-100 – good; 100-200 – poor; 200-300 – very poor; and >300 – unsuitable for drinking (Hazarika et al., 2020)

Table 4: Extracted principal components.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Standard deviation	1.333	1.162	1.010	0.971	0.925	0.760	0.690
Proportion of variance	0.254	0.193	0.146	0.135	0.122	0.082	0.068
Cumulative proportion	0.254	0.447	0.593	0.727	0.849	0.932	1.000

Table 5: Factor loadings from the Principal Component Analysis (PCA).

Parameter	PC1	PC2	PC3	PC4	PC5	PC6	PC7
BOD	-0.098	0.563	-0.196	-0.581	0.318	0.419	0.144
FC	0.366	0.340	-0.200	0.352	0.630	-0.431	-0.064
DO	-0.617	0.041	-0.028	0.134	0.219	0.061	-0.740
pH	-0.428	0.294	-0.128	0.642	-0.095	0.241	0.485
Pi	0.390	0.231	0.633	0.270	0.026	0.514	-0.238
Ammonia	-0.201	0.564	0.448	-0.152	-0.337	-0.552	0.009
Nitrate	0.318	0.330	-0.551	0.110	-0.575	0.089	-0.368

Discussion

In this study, we report WQI as an aggregate metric that describes the overall water quality of LdB based on the relative contributions of different physico-chemical parameters. This metric relies on the assumption that key parameters, which define the utilization of the water body, are accounted for (Akhtar et al. 2021). The different parameters variably affect the dynamics and quality of LdB's surface water. Fecal coliform indicates the presence of animal or human fecal contamination, and, although not always, can also be correlated with the presence of human pathogens (Leight et al. 2018; Said et al. 2004). An increase in fecal coliform counts has been correlated to a decrease in water quality (Paragamac et al. 2021; Seo et al. 2019; Srivastava and Kumar 2013). The direct and indirect impact of these bacteria on human health contributes to their relevance in water quality monitoring, as evidenced by the parameter's classification as a primary parameter by the DENR. Similar analyses and tools have assigned larger weights to fecal coliforms as an essential parameter affecting water quality. Gradilla-Hernández et al. (2020) gave fecal coliform the largest weight in PCA, while Said et al. (2004) gave it the second largest weight based on their relative significance. Developed models, such as the National Sanitation Foundation Water Quality Index (NSFWQI) and Scottish Research Development Department (SRDD), recommend fecal coliform be given the second and third largest weight, respectively. Other studies adapted the parameter weights from the NSFWQI, and gave this parameter the second largest weight (Ewaid 2017; Shah 2013; Tomas et al. 2017), while Babaei Semirom et al. (2011) developed their own index by assembling a panel of water quality experts–a method similar to that used by the NSF–and assigned the largest weight to fecal coliform.

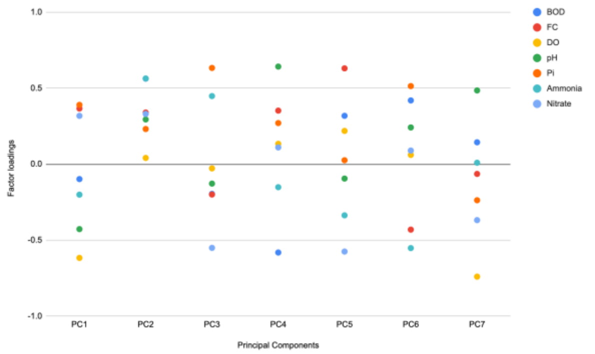

Figure 5: Scatter plot of factor loadings of variables to each principal component.

Fecal coliforms are influenced by physico-chemical parameters such as phosphate and suspended solids (Seo et al. 2019), as well as nitrate and DO (Arab and Arab 2017). Nitrate gives an estimate of the oxidized form of nitrogen present in the water column (Srivastava and Kumar 2013). According to several studies, high concentrations of this nutrient can be toxic to freshwater animals, including fish (Camargo et al. 2005; Gomez Isaza et al. 2020; Hazarika et al. 2020). The weight for this parameter varies across studies. For instance, while Hazarika et al. (2020) gave nitrate the largest weight, nitrate ranked fourth in NSFWQI weight assignments, as demonstrated by Ewaid (2017), Said et al. (2004), and Shah (2013), as well as in the study of Srivastava & Kumar (2013). Meanwhile, nitrate ranked seventh in weight assignments by Gradilla-Hernández et al. (2020), and fourth in weight assignments in the study of Said et al. (2004), following the Watershed Enhancement Program Water Quality Index (WEPWQI). Relative to studies and models that included both nitrates and fecal coliform, nitrate always ranked lower than fecal coliform in terms of weight assignment (Ewaid 2017; Gradilla-Hernández et al. 2020; Said et al. 2004; Shah 2013; Srivastava & Kumar 2013).

Ammonia was given the largest weight in the study of Caabay (2020), while fecal coliform and nitrate were not included in the parameters selected. Meanwhile, Srivastava and Kumar (2013) and Said et al. (2004), as well as studies that employed NSFWQI, such as Ewaid (2017), Gradilla-Hernández et al. (2020), and Shah (2013), did not include ammonia in the selected parameters for analysis.

Biochemical oxygen demand (BOD) indicates the total amount of oxygen required to degrade organic waste in the water column (Bora and Goswami 2017). For this reason, BOD is often used as an indicator of organic pollution, such that higher values suggest greater levels of organic waste pollution. While Caabay (2020) and the WEPWQI model as described by Said et al. (2004) did not include BOD in the list of parameters for WQI computation, BOD ranked third in terms of weight, following DO (first) and fecal coliform (second), in the study of Srivastava & Kumar (2013) as well as in studies employing the NSFWQI (Ewaid 2017; Gradilla-Hernández et al. 2020; Shah 2013). Notably, when BOD was ranked third, nitrate was always one step above or below it, suggesting a relatively flexible and similar influence of both parameters on the water quality. Moreover, in all the studies that included both fecal coliform and BOD, fecal coliform was always given more weight over BOD (Ewaid 2017; Gradilla-Hernández et al. 2020; Said et al. 2004; Shah 2013; Srivastava and Kumar 2013).

Dissolved oxygen (DO) indicates the concentration of oxygen as influenced by physical, chemical, and biological activities within and around the water body (Bora and Goswami 2017; Srivastava and Kumar 2013). The influence of BOD reaches over to the amount of DO, such that a larger BOD entails a more rapid depletion of oxygen in the water body (Bhateria and Jain 2016). Since an acute drop in the DO can be highly damaging and even fatal to fishes, estimation of this parameter is critical in managing economically important water bodies (Bora and Goswami 2017). The NSFWQI gives DO the largest weight, as shown in the studies of Ewaid (2017), Gradilla-Hernández et al. (2020), Said et al. (2004), and Shah (2013), possibly due to the parameter being a key factor in the survival of aquatic life which influence the cycle of nutrients in the water column (Gradilla-Hernández et al. 2020; Shah 2013). In contrast, Caabay (2020), whose study area was LdB, gave a significantly larger weight to ammonia than to DO. Levels of DO can be affected by phosphate in such a way that an increase in the latter causes an overgrowth of algae and other aquatic plants, ultimately leading to eutrophication and the depletion of DO (Hazarika et al. 2020; Wang et al. 2008). Despite phosphates frequently being given the same weight assignment as that of nitrate, as in studies employing the NSFWQI (Ewaid 2017; Gradilla-Hernández et al. 2020; Said et al. 2004; Shah 2013), it is important to consider that the use of LdB, aside from aquaculture and agricultural irrigation, also includes recreational activities. Moreover, many activities of anthropogenic nature, such as the construction of urban settlements, contribute to the varying water quality fed into the lake from the different river basins affected by human influences (Tanganco et al., 2019). As nitrates have a more direct possibility of affecting severe illness in infants and domestic animals, it would be reasonable to assign more weight to nitrates over phosphates (Matthews 2014). Levels of phosphates and nitrates in the abstracted raw water from the lake are expected to be low as the water undergoes treatment prior to distribution. Putatan Water Treatment Plant 1 employs microfiltration and reverse osmosis to ensure the potability of treated raw water from the lake (Maynilad 2020).

Finally, different pH levels affect the behavioral and respiratory functions of aquatic organisms, so the maintenance of pH balance is critical to managing an ecosystem (Hazarika et al. 2020). Acidity in water can be attributed to pollution, reduced photosynthetic activity, and the mixing of carbon dioxide and bicarbonates into the water column (Bhateria and Jain 2016; Tucker and Moore 2021). Extremely low pH has been proven to aggravate nitrite toxicity (Gomez Isaza et al. 2020).

Among the parameters required by DENR to be monitored, six primary parameters (fecal coliform, nitrate, inorganic phosphate, BOD, DO, and pH) and one secondary parameter (ammonia) have been routinely monitored by the LLDA from 44 (9 major, 35 minor) monitoring stations until the year 2021, when 6 major and 1 minor monitoring stations were added, totaling to 51 monitoring stations overall at present. Measurements of the parameters are conducted once a month and are reported quarterly. However, the pandemic has limited routine monitoring. As a result, no water quality report was published for the 2nd quarter of 2020, while reports for the 3rd quarter of 2020 and the 2nd quarter of 2021 only covered 10 major monitoring stations. This is in contrast to the water quality reports prior to the start of the pandemic, which had data points for all parameters in each month. Nevertheless, in both cases, data points still tend to be very complicated to describe, especially for non-experts.

Plotting the computed WQI values (Table 3) over 24 months covering the study period (Figures 4a and 4b) revealed that the end of 2020 had the best water quality (WQI values < 50). In particular, all eight stations demonstrated good to excellent ratings during this period. Low WQI values can be partly attributed to the heightened restrictions across the National Capital Region (NCR) (Bureau of Quarantine 2020). Industrial companies were forced to abide by strict guidelines, possibly lessening their impact on the lake. Mobility was also heavily regulated through the implementation of community quarantine guidelines. From March 16 to April 14, 2020, the entirety of Luzon was placed under Enhanced Community Quarantine, allowing access to only essential goods and services (Inter-Agency Task Force 2020). By May 2020, Laguna province and Metro Manila were placed under Modified Enhanced Community Quarantine until July 2020, partially relaxing mobility for the workforce (CNN Philippines 2020; Esguerra 2020). Businesses on the lakeside, as well as those near water tributaries, suffered the consequences of limited mobility, especially during the first few months of quarantine (Yumol 2020). This led to a fraction of businesses that were required to obtain a wastewater discharge permit annually to stop operations completely, effectively removing a few sources of pollution. The end of 2021 saw the highest WQI values, particularly in Stations I, II, V, and XVI, and this suggests that the water quality deteriorated in a span of one year. Station XVI has the highest WQI values from Q2 to Q4 of 2021, which means "poor" in terms of water quality (Figure 4b). The drop in water quality can be attributed in part to the slow easing of COVID-19 restrictions in the second quarter of 2021, allowing pollution sources, such as nearby industries, to recover their routines (Reuters 2021). Also, agriculture and aquaculture activities were allowed to continue amid the COVID-19 pandemic (Yumol 2020; Department of Agriculture 2020). Prior to the start of restrictions due to the pandemic, the general consensus that the lake's health is deteriorating is supported by the report of the GEF-Global Nutrient Cycling (GNC) Project, wherein the lake's ecosystem health was assessed. LdB scored 76% in terms of water quality (categorized as a C-). For fisheries, it was categorized as an F (48%). The increase in population, changing land use from agricultural to residential-industrial, and high rates of industrialization within the area, have all contributed to the continuous decline of lake water quality (GEF-Global Nutrient Cycling Project 2018). A study on the total pollutant loading of the Laguna de Bay-Pasig River-Manila Bay watershed concurs, with its reported increase in the estimates of BOD, phosphorus, and nitrogen loadings for the years 2010, 2015, and 2020. The study concludes that next to domestic sources, industrial and commercial sources together with agricultural sources and inputs, contribute to heavy pollutant loads in the lake (GEF-Global Nutrient Cycling Project 2013).

While there is no readily available data on weather conditions that may be analyzed along with the monitoring data, weather influence must be considered given its effects on water systems. For instance, river networks undergo dilution by natural run-off, which may affect the concentration of certain variables, such as BOD (Wen et al. 2017). This mechanism may be compromised in weather events, such as storms, which could increase nutrient and sediment load onto rivers from agricultural areas and sewage overflows. On the other hand, high temperatures could result in the reduction of dilution capacities and an increase in phosphorus concentrations from bed-sediment (Arnell et al. 2015).

PCA revealed that nutrient concentrations (inorganic phosphate, nitrate, and ammonia) exerted significant influence over the variance of the data. This is likely because nutrients affect both microbial composition and organic matter degradation within the water column (Reddy et al. 2010). Conversely, both the type of organic matter and its rate of degradation influence nutrient concentrations. For instance, labile organic matter (low total organic carbon:total nitrogen:total phosphorus ratios–TOC:TN:TP) is more susceptible to degradation, while refractory organic matter (high TOC:TN:TP) is said to be degradation-resistant and can even cause nitrogen uptake from the water column (Logan and Longmore, 2008). Furthermore, even a modest increase in limiting nutrients, such as nitrate and phosphate, can set off a series of undesirable events (Bhateria and Jain 2016). Along with the consequences of an increase in nutrient availability is an increase in heterotrophic microbial activity due to the warm temperatures of the region (Bhateria and Jain 2016).

Nutrients also exert some degree of influence on the DO (Coffin et al. 2021; Lin et al. 2020) and BOD (Abu Shmeis 2018). BOD indicates the amount of oxygen needed by microbes in breaking down organic matter; high concentrations of nutrients facilitate microbial growth and hence, high demand for oxygen. This is likely why BOD also accounts for a high variance in PC2 along with ammonia. The interaction between nutrients and oxygen supply (DO) and demand (BOD) is demonstrated during eutrophication events, i.e., due to an excess in nutrient supply, algal blooms occur, thereby depleting DO (Bhateria and Jain 2016). This event has been reported in LdB, with a recent one in 2020 involving fish kills (De Vera-Ruiz 2020). Variations in nutrient supply can also lead to an abundance of plankton, which can decrease DO (Hazarika et al. 2020). DO along with BOD, were found to have the highest influence in the WQI scores in the water quality assessment of the Kolong River in India (Bora and Goswami 2017).

Our exploratory analysis shows that the quarter data from each monitoring station clustered together (Figure 3). The observed clustering may be attributed to each station having unique environmental states that generally overlap with one another. In the current study, this is supported by the results of the non-parametric testing for multivariate variation, which revealed the similarity shared by the major monitoring stations in terms of all the physico-chemical parameters considered. Only fecal coliform significantly differed for Stations XVI and XVII ($p = 0.0209$). Furthermore, while land and water use of most major monitoring stations include aquaculture and agricultural sites, station parameters may be influenced by other land or water uses that are unique only to some of the eight monitoring stations considered in the study (e.g., livestock and poultry raising in Station II, recreational and industrial use in Station V) (Japan International Cooperation Agency 1992; Vargas-Nguyen 2015). Overlap in the PCA placements of data points representing quarterly data per station may be attributed to similar land cover use, such as most stations, excluding Stations I, V, and XVII, being surrounded by agricultural land with mostly plantations, as opposed to grasslands and arable lands (GEF-Global Nutrient Cycling Project 2013). This can introduce nutrient run-off from fertilizers and other chemical substances (Shah et al. 2022). Furthermore, while evidence exists that individual septic compartments in residential areas are common near lakeshore areas (Santos-Borja and Nepomoceno 2006), the lack of sanitary toilets in residential areas surrounding all stations has progressively increased from 2010 to 2020 (GEF-Global Nutrient Cycling Project 2013).

The increases in the WQI values throughout the study period suggest that unusual events, such as pandemics and accompanying lockdowns, can cause disruptions in water quality parameters affecting overall water quality, as can be inferred from metrics such as WQI, and further reflected through approaches such as PCA.

LdB's ecosystem has long been affected by human activities brought about by its proximity to the densely populated Metro Manila. The water quality of this freshwater ecosystem is aggravated by the problems associated with rapid population growth, high urban development rates, and changes in land use. Possible water contamination associated with dense populations, such as wastewater and sewage polluted by nutrients and fecal material, might be a contributing factor in the high correlation between nutrients and microbiological load. Lower WQI values indicating better water quality support this suggestion. While most of the monitoring stations were found to generally have similar physico-chemical profiles, outlier data from Stations I, V, and XVI in 2021, a year that already saw an ease in restrictions, shows the effect of economic activity in the fluctuations of overall water quality of LdB. In addition, fishing activities were still carried out during the pandemic, resulting in poorer water quality in some stations in the West Bay even while mobility and economic activities were limited.

Local studies on the use of WQI as a tool for water quality monitoring of freshwater resources are limited. Caabay (2020), utilized WQI to describe the status of the LdB, and included some of the parameters used in this study (DO, pH, phosphate, ammonia), with the addition of electrical conductivity, temperature, and alkalinity. The study reports that the water quality of Stations I, II, and V was good, while that of Station XV was excellent. However, because this study only considered one set of data, variations across time may have not been accounted for.

While LdB has been assessed using physico-chemical and microbial parameters, the use of WQI as a single metric may be relatively new. As an aggregate metric that combines multiple water quality parameters and their potential contributions to ecosystem dynamics, WQI is a useful tool in freshwater resource monitoring and management. As demonstrated in this study, the utility of WQI in quality assessment and monitoring extends beyond its informative value. In cases where measurements of monitoring data are not possible, e.g. inaccessibility of sampling sites, available data can still be used to assess water quality.

CONCLUSION

WQIs were computed to assess the water quality of Laguna de Bay during the COVID-19 pandemic from 2020 to 2021. Monitoring data in different stations of the lake were used. It was found out that microbial load (fecal coliform) and nutrients (inorganic phosphate, nitrate, BOD, and ammonia) are the major sources of variation among the monitoring sites. Spatial trends and differences inferred from the computed WQIs suggest varying sensitivity and responses of LdB stations to nutrient loadings, industrial activities, and other possible factors. The limited economic activity during the lockdown brought about by the pandemic is deemed to cause an improvement in the lake's water quality, as indicated by lower WQIs during this period. Overall, there is concordance between the WQl values and water and land use, suggesting the practicality of WQl as a multi-component metric.

It is recommended to monitor other parameters relating to microbiological quality, such as DENR-recognized primary parameters, e.g., temperature and total suspended solids, to better infer which mitigation efforts and policies to prioritize, especially in the case of stations with unique conditions, such as station XVI in the West Bay. Moreover, efforts for the rehabilitation of the LdB might need to focus on more stringent regulation of point sources (industrial, agricultural, residential, etc.) of nutrients around the major monitoring stations assessed in this study. While WQI is a relatively new tool employed to assess the lake, the development and use of an ecosystem-specific water quality index (ES-WQI) tailored to the context of LdB is a way forward. Environmental agencies may consider the use of WQl for evaluating other water bodies, especially those with readily available monitoring data.

SUPPLEMENTARY FILES

All raw data, figures, tables, and analysis codes that are not presented in the main text are available as Supplementary Files.

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AUTHOR CONTRIBUTIONS

Pierre Angeli P. Barbaso (PAPB), Arizaldo E. Castro (AEC), and Marie Christine M. Obusan (MCMO) conceptualized and designed the study. PAPB gathered and analyzed data. AEC analyzed data. PAPB, AEC, and MCMO prepared and approved the final draft of the manuscript. MCMO received the funding for the project.

CONFLICT OF INTEREST

Authors declare no conflict of interest.

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