Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2024, 12, 97-114
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Assessment of Water Quality in High-Pressure Peruvian Anthropic Sectors of Lake Titicaca Using a Calibrated Index

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How to cite this paper: Flores-Gómez, S., Da Costa, A. B., & Lobo, E. A. (2024). Assessment of Water Quality in High-Pressure Peruvian Anthropic Sectors of Lake Titicaca Using a Calibrated Index. *Journal of Geoscience and Environment Protection, 12,* 97-114.
https://doi.org/10.4236/gep.2024.128006

Received: July 19, 2024
Accepted: August 12, 2024
Published: August 15, 2024

Abstract

The world's lakes are in the process of degradation, with loss of water quality as a result of anthropic influences. This research aimed to evaluate water quality in high-pressure Peruvian anthropic sectors of Lake Titicaca using a calibrated index. The study considered ten important bays with influence from urban sectors. In each bay, surface waters were monitored for six years, considering physical, chemical and microbiological parameters. Water quality was assessed using the NSF Water Quality Index (NSF-WQI) and the one calibrated for Lake Titicaca (WQI_T). Comparing the efficiency of these two indices, the WQI_T showed a variation from moderately polluted bays to bad quality bays, such as Desaguadero and Yunguyo. These two bays were classified as hypereutrophic, therefore, the uses attributable to this condition are only irrigation and energy production. Applying the NSF-WQI, the results were not able to identify this significative difference, as all bays were classified as moderate quality waters. This result indicates that the WQI_T calibration was adequate, as it allows inferring and estimating the water quality of Lake Titicaca with greater precision. According to Peru's water quality standard for category 4, established for the conservation of the country's lakes, the parameters that exceeded the standard values were PO_4-P ($0.035\ \text{mg}\cdot\text{L}^{-1}$) and BOD_5 ($5\ \text{mg}\cdot\text{L}^{-1}$) in all bays, and TC ($1000\ \text{MPN mL}^{-1}$) in Yunguyo bay. These high values indicate eutrophication processes, one of the main problems in the study area. The WQI_T calibrated for Lake Titicaca can be used as an efficient tool to assess water quality in high Andean lentic waterbodies in South America.

Keywords

Andean Lakes, Water Quality Assessment, Eutrophication, Water Quality Index (WQI_T)

1. Introduction

Freshwater, which represents 3% of the planet's water (Gleick, 1993), is an indispensable resource for humanity and the subsistence of an enormous biodiversity of flora and fauna on all continents (Reid et al., 2019). Despite their importance, today, freshwaters are subject to environmental pressures from a set of anthropic factors along their shores (industrial, agricultural, water supply, recreation, etc.), which can deteriorate water quality (Huang & Zhou, 2021) and trigger eutrophication (Ali & Khairy, 2016), highlighting that associated with cases of eutrophication, the proliferation of algal blooms cause diseases in human health and compromise ecosystem services such as the reduction in food of aquatic origin, local tourism and availability of water for human consumption, among others (Lee et al., 2015; Huisman et al., 2018). According to results of studies in aquatic ecology, phosphorus is an essential element for all forms of life (Bunting et al., 2007); in high concentrations, together with nitrogen (Yao et al., 2018), it triggers the phenomenon of eutrophication (Vincon-Leite & Casenave, 2019), a condition of high production of algae and cyanobacteria that limit the availability of oxygen and cause mortality in aquatic fauna, highlighting that its scientific importance favored the study of the proliferation of harmful algal blooms (Paerl & Huisman, 2008; Burford et al., 2020).

The Water Quality Index (WQI) is a fundamental tool for assessing water quality, applied globally to surface waters (Uddin et al., 2021). The development of WQI models begins with the one developed in the 1960s by R. Horton, based on the 10 physical, chemical and biological parameters (Horton, 1965). Years later, Brown, with the support of the National Sanitation Foundation, developed the NSF-WQI model, together with a group of 142 experts on the current topic (Abbasi & Abbasi, 2012). Currently, there are a considerable number of indices have been developed for marine and continental environments (Uddin et al., 2021), and given the need for tools to evaluate waterbodies with particular characteristics, new models continue to be implemented (Chidiac et al., 2023).

The present research focuses on Lake Titicaca, a transboundary waterbody between Peru and Bolivia in South America, known for being the highest navigable lake in the world (Chura-Cruz et al., 2013), but also because it is the center of attention of researchers dedicated to the environmental problems that have been considered, including studies on eutrophication (Heredia et al., 2022), water quality assessment (Farfán et al., 2015; Delgado et al., 2022), remote sensing (Baltodano et al., 2022), antibiotic pollution (Archundia et al., 2017), heavy metals (Chui et al., 2021; Quiroga-Flores et al., 2021; Biamont-Rojas et al., 2023), algal blooms (Duquesne et al., 2021) and microplastics (Loayza et al., 2022), among others. Given the lack of tools to assess the evolution of the water condition in Lake Titicaca (Mancilla, 2016), the objectives of this research were first to calibrate a water quality index for Lake Titicaca (WQI_T) based on physical, chemical, and microbiological parameters; second, assess the water quality and trophic state of the highly anthropic sector of Lake Titicaca.

2. Methodology

2.1. Study Area

Lake Titicaca, a representative waterbody of the tropical Andes in South America, is located at an altitude of 3809 m.a.s.l., and is shared by Peru and Bolivia. It has two main sectors that are interconnected by the Strait of Tiquina, the first called Major Lake which has an area of 7131 km^2, an average depth of 100 m, and a maximum depth of 285 m. On the other hand, the second sector is called Minor Lake which has an area of 1428 km^2, average depth of 10 m and a maximum depth of 40 m (Dejoux & Iltis, 1992). Since 1971, Titicaca has been considered a Ramsar site due to its high richness in flora and fauna (Costantini et al., 2004).

To understand the spatiotemporal water quality evolution for Lake Titicaca, in this study 10 sampling stations were defined in the peripheral zone to monitoring water parameters, based on the bays of Desaguadero (De), Yunguyo (Yu), Pomata (Po), Juli (Ju), Pilcuyo (Pil), Chucuito-Barco (Chu), Capachica (Ca), Pusi (Pu), Vilquechico (Vilq) and Moho (Mo); main urban centers closed to Lake Titicaca in the Peruvian sector (**Figure 1**). Of the locations mentioned, the most worrying is Bay of Puno (15˚50'34" LS, 69˚59'43" LW) which is one of the sectors most affected by urban wastewater pollution from the city (Farfán et al., 2015), and heavy metals (Biamont-Rojas et al., 2023) that alter water quality, fisheries and biodiversity.

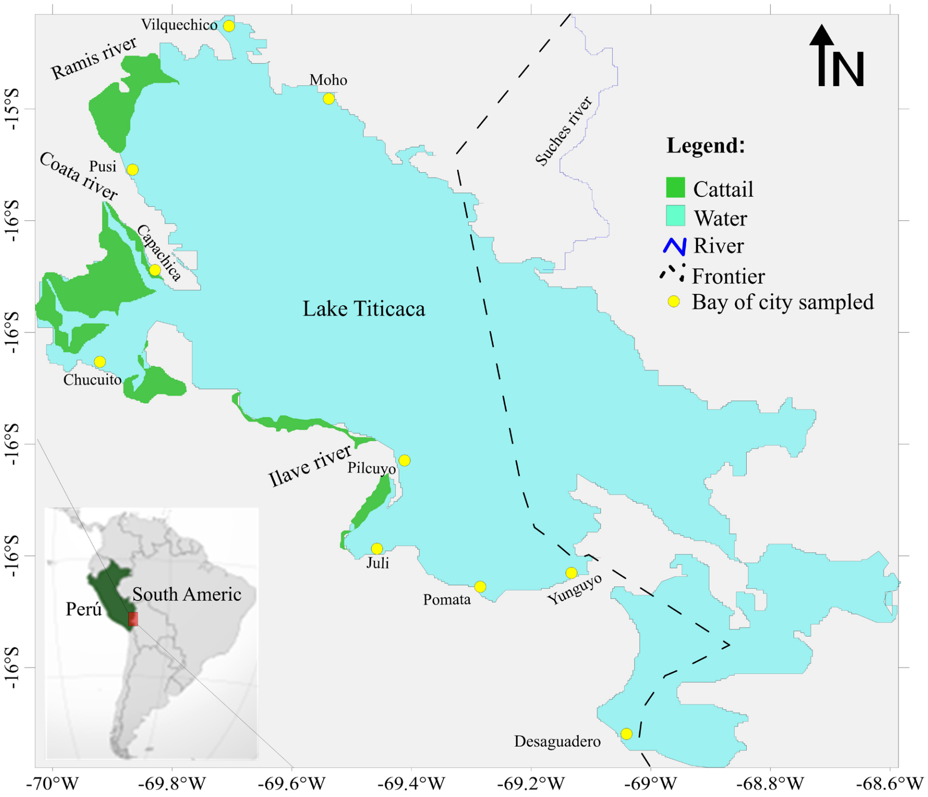


Figure 1. Location of sampling sites in Lake Titicaca, Peruvian sector.

2.2. Data Collection

The information analyzed in this article was obtained from the Lake Titicaca Special Project and corresponds to the annual period 2015-2020. The database matrix used corresponds to the average values of the dry and rainy seasons of each year. Surface water of each sampling station was analyzed to determine temperature (T), dissolved oxygen (DO), hydrogen potential (pH), and total dissolved solids (TDS) with use of Multiparameter HORIBA model U-50; turbidity (TU) was recorded using a turbidity meter HANNA model 2100Q; phosphate phosphorus (PO_4-P) and ammoniacal nitrogen (NH_3-N) were analyzed in spectrophotometer HACH DR/4000; biochemical oxygen demand (BOD_5) and thermotolerant coliforms (TC) determination was carried out following methodologies validated by APHA (1995).

2.3. Water Quality Index Calibration

The WQI_T was calibrated based on physical, chemical, and microbiological parameters (**Table 1**), based on the original model proposed by Brown et al. (1970) for the NSF-WQI, as well as the different valid and extensively explained indices by Uddin et al. (2021).

Table 1. Weight score of NSF-WQI parameters (Brown et al., 1970).

Parameter	Weight mean
DO, $mg \cdot L^{-1}$	0.17
FC, $MPN/100mL^{-1}$	0.16
pH	0.11
BOD_5, $mg \cdot L^{-1}$	0.11
T, ˚C	0.10
NO_3, $mg \cdot L^{-1}$	0.10
PO_4, $mg \cdot L^{-1}$	0.10
TU, NTU	0.08
TS, $mg \cdot L^{-1}$	0.07

The calibration methodology used corresponds to Moretto et al. (2012). The IQAData software proposed by Posselt et al. (2015), and the NSF-WQI and WQI_T indices were used to calculate water quality indices by sampling stations and annual periods. The WQI_T values were described using the original categories proposed by Brown et al. (1970) which consider five classes of water quality: very bad, bad, moderate, good, and excellent (**Table 2**), and according to the colors assigned to each class (Chidiac et al., 2023).

Table 2. Colors and definitions used in the classification of pollution by the NSF-WQI (Chidiac et al., 2023).

Colors	NSF-WQI Score	Definition
Red	0 - 25	Very bad
Orange	26 - 50	Bad
Yellow	51 - 70	Moderate
Green	71 - 90	Good
Blue	91 - 100	Excellent

2.4. Data Analysis

The records of the physical, chemical, and microbiological parameters were evaluated with the calibrated WQI_T index and Peru's water quality standards (Supreme Decree No. 004-2017-MINAM), considering category 4 (Conservation of the aquatic environment). Furthermore, the correspondence between the NSF-WQI water quality categories and the trophic state categories proposed by Carlson (1977) is presented in **Table 3**, following El-Serehy et al. (2018).

Table 3. Correspondence between NSF-WQI water quality categories and the Trophic State Index (TSI) categories, following El-Serehy et al. (2018).

Water quality	NSF-WQI	TSI	Rank
Very bad	0 - 25	Hypereutrophic	<80
Bad	26 - 50	Eutrophic	60 - 80
Moderate	51 - 70	Mesoeutrophic	50 - 60
Good	71 - 90	Mesotrophic	40 - 50
Excellent	91 - 100	Oligotrophic	<40

Regarding phosphate, the classification for the main eutrophication categories adopted by Barreto et al. (2013) was used, which was developed for lake ecosystems (**Table 4**). The different degrees of eutrophication linked to the water uses were adopted following the classification proposed by Thornton & Rast (1994), as presented in **Table 5**.

Table 4. Values of the total phosphate levels for the main categories of eutrophication. Modified from Barreto et al. (2013).

Eutrophication categories	Phosphate concentration (PO_4-P mg·L^{-1})
Ultraoligotrophic	≤0.006
Oligotrophic	0.007 - 0.026
Mesotrophic	0.027 - 0.052
Eutrophic	0.053 - 0.211
Hypereutrophic	>0.211

Table 5. Water uses and trophic state in a waterbody (Thornton & Rast, 1994).

Use/Trophic state	Oligotrophic	Mesotrophic	Mesoeutrophic	Eutrophic	Hypereutrophic
Drinking water supply	Desirable	Tolerable			
Process water supply		Desirable	Tolerable		
Cooling water supply				Tolerable	
Primary contact recreation		Desirable	Tolerable		
Secondary contact recreation		Desirable		Tolerable	
Landscaping			Tolerable		
Fish farming (sensitive species)		Desirable	Tolerable		
Fish farming (tolerant species)				Tolerable	
Irrigation					Tolerable
Energy production					Tolerable

Descriptive statistics were used to determine the mean and standard deviation of each parameter. Likewise, for comparative purposes, analysis of variance (ANOVA) was used, after proving the normality of the data and the homogeneity of variances (Zar, 1984). Fisher's Least Significant Difference (LSD) test was used to compare means between bays. Principal Components Analysis (PCA), a powerful statistical analysis, was performed with the aim of calibrating the water quality index, following the guidelines of Gauch (1982), Moretto et al. (2012), and Bajaña et al. (2022). For statistical analyses, the PAST (Hammer et al., 2001) and R (The R Development Core Team, 2013) software were used.

3. Results

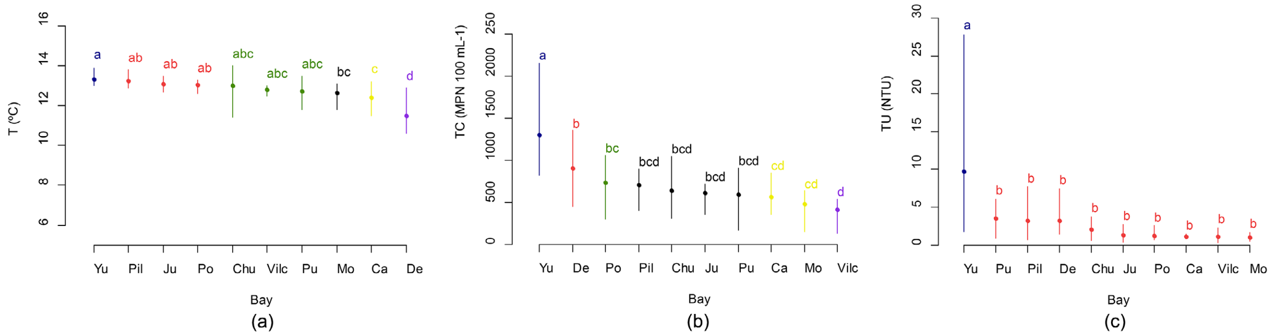
3.1. Statistical Characteristics of Water Quality Parameters

The main results of water quality parameters for the 10 bays of Lake Titicaca (Peruvian sector), are presented in **Table 6**. According to the results obtained, Capachica bay was characterized by waters with a lower average temperature (12.4˚C ± 0.6˚C) in contrast to the other bays. The average DO ranged from 6.6 ± 0.8 to 7.6 ± 1.3 mg·L^{-1} in the Pilcuyo bay and Vilquechico bay, respectively. The average number of TC was higher than 400 MPN ml·L^{-1} in all bays, being higher in Yunguyo bay (1301.8 ± 502 MPN ml·L^{-1}). The maximum BOD_5 was observed in Yunguyo bay (9.6 ± 3.4 mg·L^{-1}) and the lowest in Moho Bay (5.5 ± 1.7 mg·L^{-1}). PO_4-P was greater than 0.05 mg·L^{-1} in all bays, with the highest concentration in Yunguyo (0.46 ± 0.4 mg·L^{-1}). NO_3-N was low and was above 0.5 mg·L^{-1} in all bays, with Capachica having the highest value (0.93 ± 0.6 mg·L^{-1}). The pH ranged from 8.0 to 8.9. TDS ranged from 865 ± 142 to 1397 ± 1034 mg·L^{-1} in Yunguyo bay and Pusi bay, respectively. Finally, TU ranged from 0.9 ± 0.4 to 9.7 ± 9.7 NTU in Moho Bay and Yunguyo bay, respectively.

Table 6. Average values (±standard deviation) of water quality parameters (n = 6) for bays of Lake Titicaca, annual period 2015-2020.

Bay	Water quality parameter								
	T (°C)	DO ($mg \cdot L^{-1}$)	TC (MPN 100 $ml \cdot L^{-1}$)	BOD_5 ($mg \cdot L^{-1}$)	PO_4-P ($mg \cdot L^{-1}$)	NO_3-N ($mg \cdot L^{-1}$)	pH	TDS ($mg \cdot L^{-1}$)	TU (NTU)
Vilquechico	12.8 ± 0.2	7.6 ± 1.3	407.6 ± 162	5.2 ± 1.7	0.21 ± 0.1	0.77 ± 0.5	8.0 ± 0.8	986.6 ± 93	1.0 ± 0.7
Pusi	12.7 ± 0.6	7.2 ± 1.2	589.4 ± 282	6.4 ± 3.4	0.39 ± 0.6	0.79 ± 0.5	8.7 ± 0.4	1397.1 ± 1034	3.5 ± 2.4
Moho	12.6 ± 0.4	7.0 ± 1.1	473.7 ± 172	5.5 ± 1.7	0.14 ± 0.1	0.67 ± 0.4	8.4 ± 0.5	998.1 ± 87	0.9 ± 0.4
Capachica	12.4 ± 0.6	7.5 ± 1.3	567.0 ± 194	5.8 ± 2.1	0.15 ± 0.1	0.93 ± 0.6	8.9 ± 0.5	959.5 ± 104	1.0 ± 0.2
Chucuito	13.0 ± 0.9	7.2 ± 0.7	636.6 ± 261	6.8 ± 1.1	0.27 ± 0.2	0.83 ± 0.6	8.6 ± 0.4	991.0 ± 79	2.0 ± 1.1
Pilcuyo	13.2 ± 0.3	6.6 ± 0.8	709.7 ± 181	7.7 ± 3.0	0.27 ± 0.4	0.70 ± 0.6	8.6 ± 0.5	940.9 ± 137	3.2 ± 2.5
Juli	13.0 ± 0.2	7.2 ± 0.9	607.2 ± 146	6.6 ± 1.2	0.14 ± 0.1	0.62 ± 0.5	8.7 ± 0.6	991.0 ± 89	1.2 ± 0.9
Yunguyo	13.3 ± 0.3	7.0 ± 0.4	1301.8 ± 502	9.6 ± 3.4	0.46 ± 0.4	0.89 ± 0.5	8.8 ± 0.8	865.1 ± 142	9.7 ± 9.5
Pomata	13.0 ± 0.2	7.0 ± 0.7	730.4 ± 263	5.8 ± 2.6	0.09 ± 0.1	0.85 ± 0.6	8.6 ± 0.5	996.6 ± 88	1.2 ± 0.6
Desaguadero	11.5 ± 0.8	7.3 ± 0.7	901.9 ± 343	7.4 ± 2.9	0.31 ± 0.4	0.79 ± 0.4	8.9 ± 0.6	1234.0 ± 113	3.2 ± 2.2

Significant differences were determined between the bays for the parameters T, TC and TU ($p \leq 0.05$), highlighting Yunguyo bay as the one with the highest values in the three mentioned parameters (**Figure 2**).



(a) (b) (c)

Figure 2. Average (±standard deviation) of water parameters, where (a) is temperature, (b) is TC, (c) is TU, in 10 bays of Lake Titicaca. Different letters indicate a statistically significant difference between the bays ($p \leq 0.05$).

3.2. Multivariate Analysis and Water Quality Index Calibration

The PCA results are shown in **Table 7**, with the first three main components concentrating 62.1% of the total variance, derived from the eigenvalues (Moretto et al., 2012).

Table 7. PCA Eigenvalues.

Component	Eigenvalue	% Total variance	% Cumulated
Component 1	2.663	29.6	29.6
Component 2	1.572	17.5	47.1

Continued

Component 3	1.358	15.1	62.1
Component 4	1.199	13.3	75.5
Component 5	0.689	7.7	83.1
Component 6	0.610	6.8	89.9
Component 7	0.451	5.0	94.9
Component 8	0.259	2.9	97.8
Component 9	0.198	2.2	100.0

Table 8 displays the eigenvectors that were used to interpret the primary components. Despite positive or negative associations with weight signals, the most significant factors are those with the greatest weight. The eigenvector of the principal components, which includes the microbiological, chemical, and physical characteristics determined at 10 sampling sites, is displayed in Table 7. PC1 positively correlated with TC and BOD_5 (r = 0.78), PO_4-P (r = 0.76) and TU (r = 0.74), reflecting indicators of eutrophication. In relation to PC2, NO_3-N (r = 0.60) and TDS (r = −0.68) showed the highest correlation.

Table 8. Eigenvectors are used to interpret the principal components. The most important variables are those with the highest weight, whether positive or negative values.

Principal component	T	PH	DO	TU	NO_3-N	PO_4-P	TC	BOD_5	TDS
Component 1	0.12	0.20	−0.38	**0.74**	−0.12	**0.76**	**0.78**	**0.78**	0.32
Component 2	**0.20**	0.01	0.34	0.27	**0.60**	−0.49	0.45	0.28	**−0.68**
Component 3	−0.16	**−0.81**	**0.62**	0.34	−0.26	−0.06	0.14	−0.03	0.27
Component 4	−0.81	0.22	0.18	−0.11	0.53	0.05	0.19	−0.05	0.36
Component 5	0.50	0.02	0.14	0.04	0.40	0.15	0.04	−0.32	0.37
Component 6	0.08	0.46	0.55	−0.08	−0.28	0.07	0.02	0.07	0.01
Component 7	0.13	−0.14	0.01	−0.44	0.05	−0.11	0.08	0.39	0.20
Component 8	−0.02	−0.12	0.11	−0.10	0.13	0.37	−0.15	0.08	−0.21
Component 9	0.00	0.05	0.03	0.18	0.09	−0.09	−0.31	0.20	0.10

The WQI_T was calibrated using the eigenvalues of each component and each parameter (Table 8), and the results are shown in Table 9. To acquire the new weights for the chosen parameters, a mathematical transformation of the coefficient values must be carried out after the sum (S) of the parameter weights (wi) is equal to 1. This can be done by dividing the value of each coefficient by the sum of the coefficients.

Table 9. Eigenvectors transformation to calibrate WQI_T.

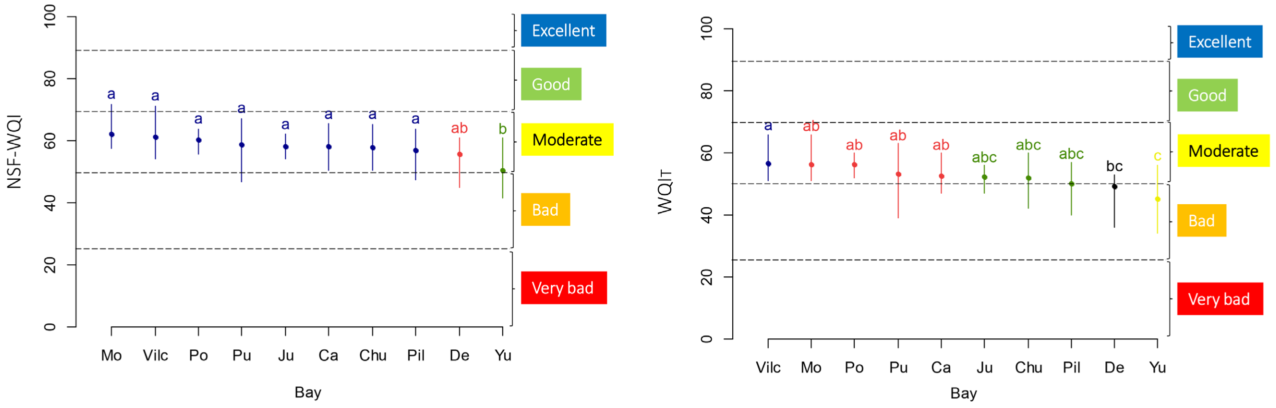
Parameters	Eigenvector	Original weight (wi) (Brown et al., 1970)	Calibrated weight (wi) (WQI_T)
T, ˚C	0.20	0.10	0.04
pH	0.81	0.11	0.15
DO, $mg \cdot L^{-1}$	0.62	0.17	0.11
TU, NTU	0.34	0.08	0.06
NO_3, $mg \cdot L^{-1}$	0.60	0.10	0.11
PO_4, $mg \cdot L^{-1}$	0.76	0.10	0.14
TC, $MPN/100mL^{-1}$	0.78	0.16	0.14
BOD_5, $mg \cdot L^{-1}$	0.78	0.11	0.14
TDS, $mg \cdot L^{-1}$	0.68	0.07	0.12
Σ=	5.57	1.00	1.00

The study's critical variables, pH, PO_4-P, TC and BOD_5 presented the highest relative weights. These weights were equivalent to 15% in first parameter and 14% in the next three of the total sum of WQI weights, respectively. This represents an increase of 7.0% and 6.0% in relation to the previous weights (Table 9). It is important to note that the selected eigenvectors were the highest values for each parameter, except for TU, to give weight to other more relevant parameters (e.g., pH, PO_4-P, TC, BOD_5), criteria adopted in several index, as indicated by Uddin et al. (2021).

3.3. Water Quality Assessment

According to the ANOVA and MDS tests, a statistically significant difference ($p \leq 0.05$) in water quality between bays was determined, considering NSF-WQI and the WQI_T. In the first case, average NSF-WQI values were statically similar in all bays, except for Desaguadero and Yunguyo bays (**Figure 3(a)**), but all bays within the moderate range. In the second case, the bays of Moho, Pomata, Pusi and Capachica presented similar average WQIT values, as the bays of Juli, Chucuito and Pilcuyo, but with a significant difference between these two groups ($p \leq 0.05$), however, all bays within the moderate range. Yunguyo and Desaguadero bays showed a significant difference with these two groups ($p \leq 0.05$), as they were characterized as having bad water quality (**Figure 3(b)**).

The moderate pollution category recorded in all bays, except Desaguadero and Yunguyo bays (**Figure 3**), is related to mesoeutrophic waters (**Table 3**), which in turn are tolerable for manufacturing process water supply, primary contact recreation, landscaping and fish farming for sensitive species (**Table 5**). Still, the bad pollution category in Desaguadero and Yunguyo bays (**Figure 3**) is related to eutrophic waters (**Table 3**), which in turn are tolerable for cooling water supply, secondary contact recreation and fish farming of tolerant species (**Table 5**).



(a)

(b)

Figure 3. Assessment of water quality in the bays of Lake Titicaca. (a): Results obtained through the NSF-WQI. (b): Results obtained using WQI_T. The colors indicate water quality category. Different letters indicate a statistically significant difference between the bays ($p \le 0.05$).

3.4. Spatial-Temporal Analysis of Water Quality

Based on information from the 2015-2020 annual period, the bays in permanent condition of moderate water quality were Moho, Vilquechico and Pomata. On the other hand, the other bays are in the moderate and bad quality water category, where the bays of Yunguyo and Chucuito have more years with bad quality water. In 2020, most bays had water of moderate quality except Yunguyo and Capachica, which had bad water quality (**Figure 4**).

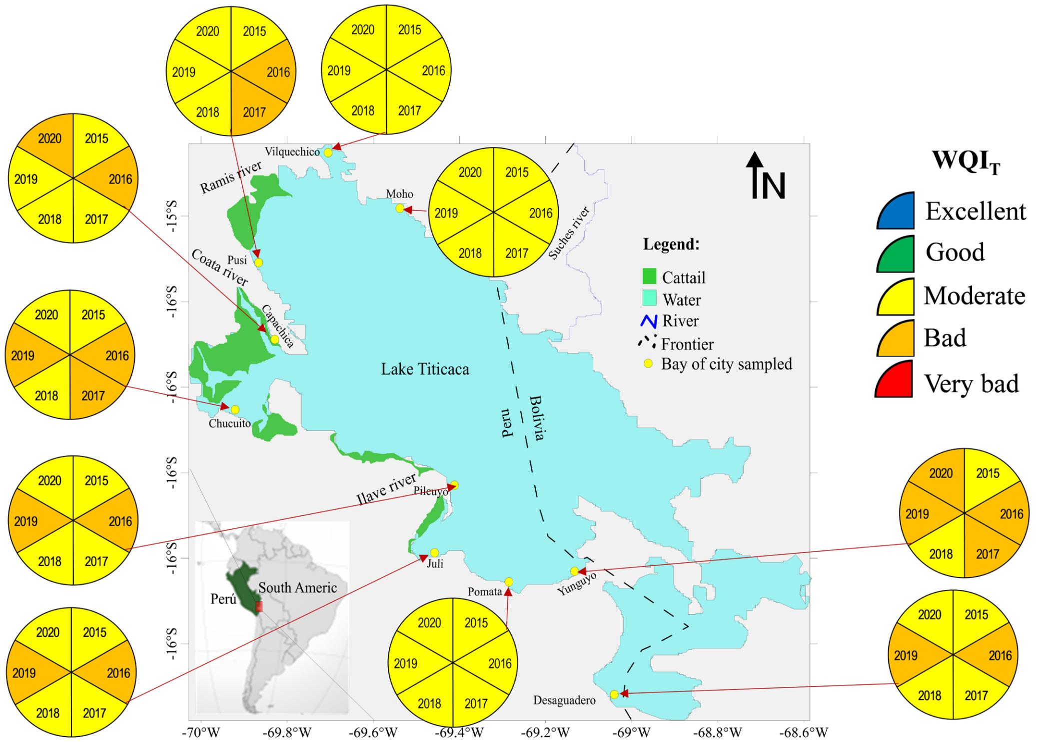


Figure 4. Comparative map of water quality on the 10 bays of Lake Titicaca according to WQI_T during the six years (2015-2020). The pie chart content on each piece slice is a WQI_T color category.

3.5. Water Quality Assessment

According to Peru's water quality standard (Supreme Decree N° 004-2017-MINAM), category 4, established for the conservation of the country's lakes, the parameters that exceeded the standard values were PO_4-P (0.035 $mg \cdot L^{-1}$) and BOD_5 (5 $mg \cdot L^{-1}$) in all bays, and TC (1000 NMP mL^{-1}) in Yunguyo bay. DO and pH were within accepted standards (**Figure 5**).

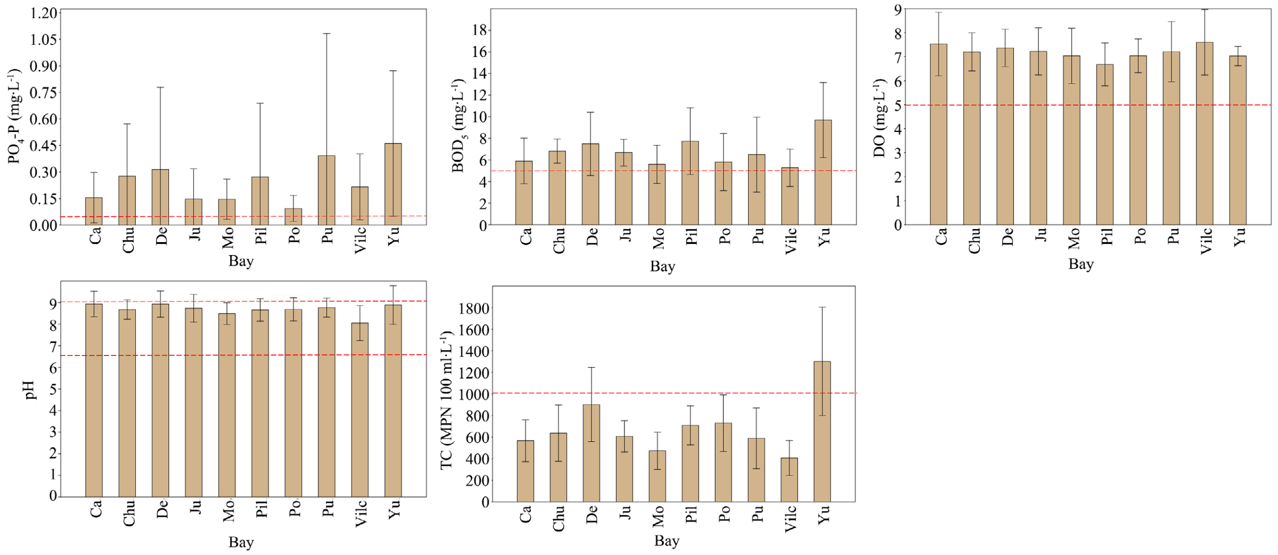


Figure 5. Water quality assessment in the 10 bays of Lake Titicaca according to Standard Water Quality (SWQ) of Peru (annual period 2015-2020), bar: average values, whiskers: standard deviation, the red dashed horizontal line indicates the SWQ (Supreme Decree N° 004-2017-MINAM, category 4, lakes and lagoons).

4. Discussion

Our study focused on developing a water quality assessment of Lake Titicaca, a waterbody of high ecological, economic and social importance in southern Peru (Zilov, 2013). The deterioration of the lake's health is caused by complex pollution related to urban demographic growth, inadequate management of solid waste and wastewater, and inadequate sanitary practices (Quispe, 2024).

Given the need to integrate technical information from the different water quality parameters carried out by Peruvian state agencies, in order to efficiently interpret the water quality condition of Lake Titicaca, we propose the use of the water quality index model, which has the ability to convert multiple variables into a single value that describes water quality (Banda & Kumarasamy, 2020). To this end, we calibrated a Water Quality Index for Lake Titicaca, the WQI_T, based on the original index proposed by Brown et al. (1970) for the US National Sanitation Foundation, the NSF-WQI. Comparing the efficiency of these two indices, the WQI_T revealed important differences in relation to the NSF-WQI, presenting water quality weights of less importance for the parameters T, DO and TU, and weights of greater importance for the parameters pH, NO_3, PO_4-P, TC, BOD_5 and TDS, highly related to eutrophication processes.

In fact, the water quality of Lake Titicaca established by applying the WQI_T showed a variation from moderate polluted bays to bad quality bays, such as Desaguadero and Yunguyo, and no bay reached good or very good quality. On the contrary, applying the NSF-WQI all bays were classified as waters of moderate quality. The water quality assessment of the Yunguyo and Desaguadero bays applying the WQI_T showed a significant difference with the others bays ($p \leq 0.05$), being characterized as having bad water quality.

Regarding phosphate, one of the parameters most related to eutrophication, these two bays had an average concentration of 0.38 ± 0.4 $mg \cdot L^{-1}$, and can be classified as hypereutrophic, as this average exceeded the maximum limit concentration for this category, 0.211 $mg \cdot L^{-1}$, following the classification adopted by Barreto et al. (2013), as shown in **Table 4**. Therefore, the uses attributable to this condition are only irrigation and energy production (**Table 5**). The results applying the NSF-WQI were unable to identify this significative difference, as all bays were classified as waters of moderate quality. This result indicates that the calibration of the WQI_T was adequate, as it allows inferring and estimating the water quality of Lake Titicaca with greater precision, where the water ecosystem health is deteriorated by wastewater pollution, a common occurrence in urbanized lakes (Radwan et al., 2019), or aquaculture pollution, a triggering factor for the proliferation of cyanobacteria bloom according to studies carried out in lakes where this aquaculture activity takes place (Buley et al., 2021; Xu et al., 2022). Thus, the WQI_T calibrated for Lake Titicaca can be used as an efficient tool to assess water quality in high Andean lentic waterbodies in South America, which do not exist (Uddin et al., 2021).

According to Peru's water quality standard for category 4, established for the conservation of the country's lakes, the parameters that exceeded the standard values were PO_4-P (0.035 $mg \cdot L^{-1}$) and BOD_5 (5 $mg \cdot L^{-1}$) in all bays, and TC (1000 MPN mL^{-1}) in Yunguyo bay. These high values are directly related to eutrophication processes. A similar situation was found by Bajaña et al. (2022), working in two reservoirs in the Paute River Hydrographic Basin, south inter-Andean region of Ecuador, where the PCA results indicated that the eutrophication gradient was positively correlated with phosphate (r = 0.83) and BOD_5 (r = 0.83), where the average total phosphate concentration was 0.73 ± 1.51 $mg \cdot L^{-1}$, classifying the basin water as hypereutrophic. Eutrophication is also one of the main environmental problems in aquatic systems in southern Brazil (e.g., Lobo et al., 2010, 2015; Klamt et al., 2019), highlighting that the increase of nutrients in a waterbody, mainly phosphate, is one of the main sources of eutrophication, mostly by agricultural fertilizers, animal waste, domestic and industrial sewage. Eutrophication is a process that can render an aquatic ecosystem unusable for human supply, power generation, and leisure area (Powley et al., 2016).

Eutrophication and algal bloom events are common in waterbodies with high population density, such as Lake Taihu in China (Yan et al., 2022), Lake Victoria in Africa (Simiyu et al., 2022), Lake Ontario in Canada (Molot et al., 2022) or Lake Erie in the United States (Francy et al., 2016). For South America, we show the context of water quality in Lake Titicaca, where algal blooms were reported in the inner bay of Puno (Farfán et al., 2015) and Cohana (Achá et al., 2018), places with high phosphorus loads from untreated waters in Puno (Peru) in the first case, and La Paz (Bolivia) in the second case, a worrying situation. However, in our study, we reported a eutrophication process based on high values of PO_4-P (0.09 to 0.46 $mg \cdot L^{-1}$) for all bays of Lake Titicaca, critical because the waters could develop algal blooms at these levels (Walker & Havens, 1995; Gu et al., 2020; Song et al., 2024). Likewise, we draw attention to the high levels of coliforms (>1000 MPN $ml \cdot L^{-1}$) in the Yunguyo and Desaguadero bays, which is risky for human health (Soller et al., 2010), since these places are frequented by tourists (Gascón, 2022).

The high BOD_5 values in the bays in Lake Titicaca are mainly influenced by wastewaters from nearby cities (Farfán et al., 2015; Heredia et al., 2022) and the aquaculture industry (Tanjung et al., 2024), which focuses on rainbow trout aquaculture developed in the littoral zone of the Lake Titicaca (Chura & Mollocondo, 2016). BOD_5 plays an important role in assessing water pollution (Koda et al., 2017; Tanjung et al., 2019), highlighting that this parameter explains the biological oxidation processes, knowledge necessary to understand the water quality state (Qi et al., 2021; Aguilar-Torrejón et al., 2023). Organic matter originates from various anthropic wastes and natural process (Pivokonsky et al., 2006; Tanjung et al., 2022).

5. Conclusion

We concluded that the WQI_T calibration was adequate, as it allows inferring and estimating the water quality of Lake Titicaca (Peruvian sector), with greater precision, based on physical, chemical, and microbiological parameters, where the predominant condition was moderate quality and bad quality in the 10 bays analyzed.

The deterioration of the lake's health is caused by complex pollution related to urban growth, inadequate solid waste and wastewater management, and inadequate sanitation practices, highlighting the need for water management to mitigate the eutrophication process. In the future, it is necessary to have information available that allows estimating lake quality indices, so it is extremely important that the competent authorities carry out periodic monitoring (seasonal frequency) in the evaluated sectors and expand new sampling locations that need to be evaluated to improve water quality management.

The WQI_T calibrated for Lake Titicaca can be used as an efficient tool to assess water quality in high Andean lentic waterbodies in South America.

Acknowledgements

We would like to thank the University of Santa Cruz do Sul, Brazil, for granting an institutional scholarship to the first author to pursue a postgraduate course in the Environmental Technology Program. We also thank the Lake Titicaca Special Project of the Ministry of Agriculture and Irrigation of Peru.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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