(04-001) - Degradation of the water quality of Lake Titicaca by the main effluent of the Katari Basin

Paredes, Nicolas [1]; Soria, Freddy [1]; Balderrama-Canedo, Tania [1]; D'abzac, Paul [2]; Alvizuri-Tintaya, Paola Andrea [1]

[1] Centro de Investigación en Agua, Energía y Sostenibilidad, Universidad Católica Boliviana San Pablo, [2] Universidad Católica Boliviana San Pablo, Centro de Investigación en Ciencias Exactas e Ingenierías (CICEI)

The Bolivian portion of Lake Titicaca has been and continues to be negatively impacted by partially treated wastewater from the region. The present investigation is based on the analysis of physicochemical and biological parameters to determine the contribution of the contaminated waters of the Katari Basin to the degradation of the water quality of Lake Titicaca. Simple monitoring was carried out at representative points located at the end of the Katari River, and around the river's discharge towards Lake Titicaca. The monitoring campaign was carried out during the dry season of 2023, a critical season due to high pollutant loads. The laboratory results were compared with the parameters established in national and international water quality standards. The main product of this research is a first diagnosis of the degradation of the quality of the water coming from the main tributary of Lake Titicaca on the Bolivian side. The results allow to understand and socialize the repercussions that water pollution in the Katari Basin has on ecosystems, activities, and the health of the communities.

Keywords: liquid discharges;water quality index;safe water

Degradación de la calidad del agua del Lago Titicaca por el efluente principal de la Cuenca Katari

La parte boliviana del Lago Titicaca ha sido y continúa siendo impactada de manera negativa por aguas residuales parcialmente tratadas provenientes de la región. La presente investigación se basa en el análisis de parámetros fisicoquímicos y biológicos para determinar el aporte de las aguas contaminadas de la Cuenca Katari en la degradación de la calidad del agua del Lago Titicaca. Se realizó un monitoreo simple de puntos representativos ubicados al final del Río Katari, y alrededor de la descarga del río hacia el Lago Titicaca. La campaña de monitoreo se realizó durante la época de estiaje del 2023, temporada crítica por las altas cargas contaminantes. Los resultados de laboratorio fueron comparados con los parámetros establecidos en normas de calidad de agua nacionales e internacionales. El producto principal de esta investigación es un primer diagnóstico de la degradación de la calidad del agua proveniente del principal tributario del Lago Titicaca de la parte boliviana. Los resultados permiten entender y socializar las repercusiones que la contaminación hídrica de la Cuenca Katari tiene sobre ecosistemas, actividades y salud de las comunidades.

Palabras clave: descargas liquidas;índice de calidad de agua;agua segura

Correspondencia: palvizuri@ucb.edu.bo

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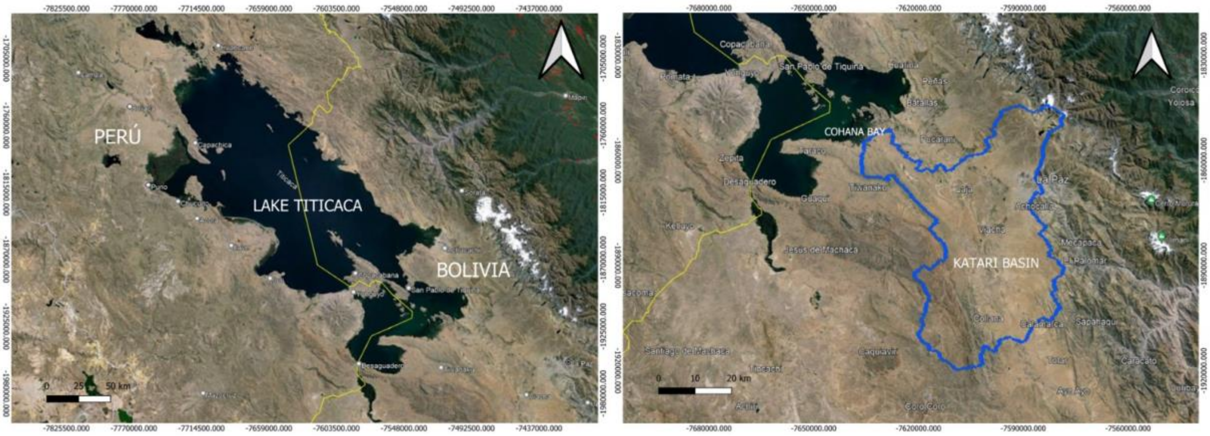
1. Introduction

Lake Titicaca was declared a Ramsar Site on January 20, 1997, due to its ecological importance. The United Nations Environment Program (UNEP) in 2011 made a call to the governments of Bolivia and Peru to carry out coordinated and urgent actions to stop environmental degradation. This environmental degradation began to be exposed with reports in 2002, on the Bolivian side, with the overflow of the Katari River (CGEPB, 2014).

On the Bolivian side, Cohana Bay in Lake Titicaca is a sensitive area, where untreated discharges flow, and measures to control pollution have had limited impact. In 2006, Cohana Bay was declared an environmental disaster area, calling for urgent attention to local authorities (ECLAC, 2014). In 2016, it was created the "Lake Titicaca Sanitation Program" to promote tourism and improvements to water quality; the program identified Cohana Bay as a critical area of the Katari basin, the main watershed collecting the untreated waste to the Lake. The latter mentioned program included actions such as the construction of wastewater treatment plants, the implementation of environmental management systems in companies, and the promotion of sustainable agricultural practices (IDB, 2016). In 2019, a conference addressing environmental issues in the Katari basin suggested a series of strategies and actions for the sustainable management of water (Ede & Fuentes, 2019).

The accelerated population growth and the lack of regulatory capacity of the Bolivian government have given rise to the problem of water pollution in the Katari Basin to increase, and serious repercussions are observed in Cohana Bay. The sources of water pollution are found since the head of the Katari Basin, where there are mining liabilities that were generated by the company Comsur that exploited lead and zinc in Milluni, causing low pH levels and the presence of heavy metals in the water (Revilla, 2021). Following the course of the Katari Basin, the next source of pollution is found in the leachate runoff caused by the Villa Ingenio Landfill in the city of El Alto (Arze, 2019). El Alto is the youngest city in Bolivia, and due to its rapid growth, its activities have caused water pollution from industrial and domestic wastewater. It also should be highlighted that agriculture and artisanal mining spread in different areas of the Katari Basin, which also affect the availability and quality of water resources. Below Figure 1 presents Lake Titicaca and Cohana Bay.

Figure 1: Delimitation of Lake Titicaca – Katari Basin



The Katari Basin is home to 9% of Bolivia's population. Water pollution in the basin places different communities at risk, especially those close to the main wastewater discharge such as Catavi, Lacaya, Chojasivi, Cohana, Cumaná, Cascachi, Pajchiri, and Quehuaya, in addition to the Suriqui and Pariti Islands, making an approximate total of more than 26,000 inhabitants (LIDEMA, 2013). In this sense, the present study seeks to quantify the impact of wastewater from the Katari Basin on Cohana Bay to expose the existing risk to ecosystems and public health.

2. Objective

This study aims to evaluate the impact of wastewater discharge from the Katari Basin on water quality degradation of the Lake Titicaca by calculating the Water Quality Index (WQI) at specific points of Cohana Bay.

3. Methodology

First, the identification of the study area was carried out. Second, a sampling protocol was developed, taking into account in-situ and ex-situ parameters and respecting the guidelines of the Bolivian Institute of Standardization (IBNORCA) for laboratory work. Finally, the Water Quality Index (WQI) was calculated in specific points of Cohana Bay belonging to the Lake Titicaca on the Bolivian side.

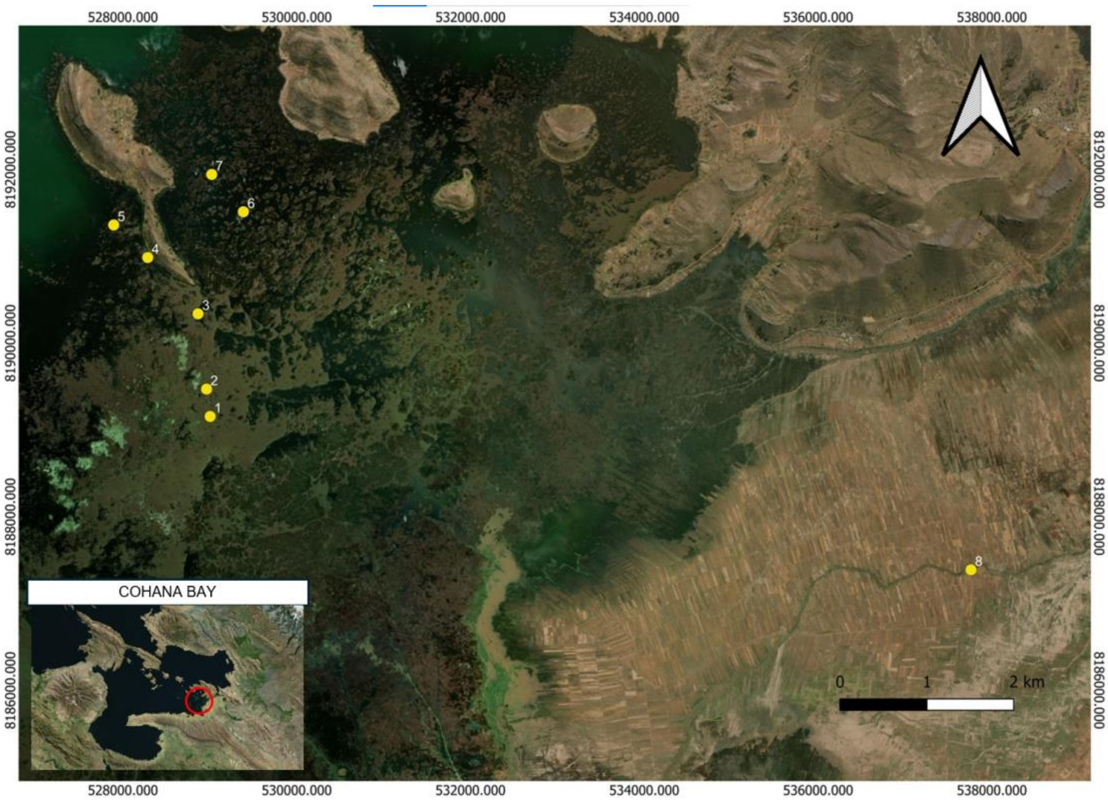
3.1 Study Area

The study area is Cohana Bay, the wastewater discharge point of the Katari Basin, and the vicinity of Pariti Island within Lake Titicaca. Wastewater sources are urban and industrial. The study was carried out during the dry season when pollutants concentration is high due to the decrease in water volume. Fieldwork was carried out on June 28, 2023 and sampling was made between 10:00 A.M. and 4:00 P.M. Sampling points were at the Katari River outlet and in Cohana Bay. The monitoring point at the watershed outlet served as a reference for the concentrations of water quality parameters entering Cohana Bay. The other seven sampling points were located in Cohana Bay in the vicinity of Pariti Island in Lake Titicaca. Table 1 shows the coordinates of the sampling points and Figure 2 shows their spatial distribution.

Table 1: Coordinates of the sampling points

Sampling point	UTMX	UTMY
1	529004.233	8189155.74
2	528962.828	8189471.07
3	528864.606	8190338.02
4	528285.496	8190986.52
5	527894.089	8191361.91
6	529386.525	8191513.88
7	529022.197	8191943.95
8	537761.147	8187388.63

Figure 2: Sampling points in Cohana Bay



3.2 Sampling Protocol

There were followed the Guide for Wastewater Sampling of the Ministry of Environment and Water of 2015 and the binational Protocol for monitoring the water quality of Lake Titicaca of 2020. Samples were collected directly from the source using a clean container. The study was designed under a cross-sectional approach (Montesinos-López, 2015).

The sampling points were strategic as they provided a comprehensive view of the water quality passing through the Katari Basin and ending in Cohana Bay. One sampling point was located at the basin outlet and seven sampling points were in Cohana Bay near Pariti Island. The criteria to select the sampling points were: water homogeneity, flow velocity, and sampling hour. Special care was taken during sampling to prevent any contact with suspended solids or settled solids, minimizing disturbance of the water at the sampling point.

A Hach HQ 40D multiparameter was used to measure parameters in-situ. The equipment had a half-hour conditioning to the environmental conditions of the area before the measurements. The following parameters were determined in-situ:

- pH using the HACH PHC201 probe, calibrated using buffer solutions of 4.00, 7.00, and 10.00.
- Electrical conductivity (EC) with Hach CDC401 probe, a standard solution of 1000 μS/cm was used for calibration.
- Dissolved oxygen using the Hach LDO101 probe previously calibrated following the HACH user manual.
- Water temperature with the previous probes.
- Turbidity was measured using the HACH 2100Q turbidimeter, using calibration solutions of 0, 1, 10, and 100 NTU.

3.3 Determination of ex-situ parameters

Samples were stored and transported following the protocols established by NB 5667 "Water quality – Sampling General sampling techniques (part 2)". The measurement of ex-situ parameters was carried out following the IBNORCA Regulations, Standard methods, and other international guides:

- Total dissolved solids (TDS). Bolivian Standard 64006 for Water Quality - Gravimetric Method, from 2005 was used.
- Fecal coliforms. Bolivian Standard 32005 for Microbiological Tests - Coliform bacteria count (First revision), from 2003 was applied.
- phosphorus. The guide: "Analytical Methods for Atomic Absorption Spectroscopy" (Perkin, 1996) was used.
- Nitrogen. It was determined by the methodology based on the Kjeldahl procedure, a methodology approved and published by the FAO (2023) in which all nitrogen exists in the water sample, is distilled and collected in the presence of boric acid.

To carry out the water samples, nitric acid (HNO_3) was used to preserve acidic conditions for metal analysis. The analyzed metals were aluminum, titanium, vanadium, sodium, manganese, iron, cobalt, nickel, copper, zinc, arsenic, strontium, molybdenum, silver, tin, antimony, barium, tungsten, palladium, and uranium. To determine metal levels in water samples at the E2LIM UR 24133 laboratory of the University of Limoges (France), an Agilent 7700x laser ablation inductive coupling-induced plasma mass spectrometry was used. The results were compared with the Regulation on Water Pollution (RMCH) in its annex A -1 with categories A, B, and C because, at the time of sampling, it was evident that the communities of Chojasivi, Bahia de Coaha, Pariti Island, and Cumana use the water from the Katari Basin as water for their livestock, agriculture, other uses and even for supply in extreme cases.

3.4 Determination of WQI

To calculate the WQI, the methodology proposed by Brown in 1970 was used. The index provides a quantitative measure of water quality, to identify critical areas and determine control points (Prat, 1998). Brown's methodology uses 9 basic parameters, including specific interpolation tables for each.

The parameters proposed by Brown for determining the WQI are Dissolved Oxygen (DO), pH, Biological Oxygen Demand (BOD), temperature, Total Dissolved Solids (TSD), fecal coliforms, phosphorus, nitrogen, and turbidity. BOD was not considered because wastewater is untreated; BOD was going to be a predominant parameter that would make the rest irrelevant. Dismissal of BOD requires a recalculation of the weighted value of the variables, following Brown´s recommendations in case of not having all the required parameters. Table 2 presents the weights that were defined for the evaluated parameters.

Table 2: Weighted weights without BOD

i	Sub i	wi
1	Dissolved Oxygen	0.184
2	pH	0.124
3	Temperature	0.114
4	Total Dissolved Solids	0.084
5	Fecal coliforms	0.174
6	Phosphorus	0.114
7	Nitrogen	0.114
8	Turbidity	0.092

The WQI expressed as a percentage, categorizes water quality into five ranges: excellent, good, average, bad, and terrible, each of the above designated by a color as seen in Table 3.

Table 3: Classification of WQI proposed by Brown

Water Quality	Color	Value
EXCELLENT	🟦	91-100
GOOD	🟩	71-90
REGULAR	🟨	51-70
POOR	🟥	26-50
BAD	⬛	0-25

To determine the value of the WQI there are two equations proposed by Brown. The arithmetic and exponential equations applied to determine the WQI are presented below.

$$WQI = \Sigma\ (wi*pp)\ /\ \Sigma wi \tag{1}$$

$$WQI = \Sigma\ (wi\wedge pp)\ /\ \Sigma wi \tag{2}$$

Where:

WQI = Water Quality Index

wi = Value of parameter i

pp = Weighted weight of parameters

WQI interpretation requires a balanced criterion, recognizing its advantages, but being aware of its limitations. Its effective application involves considering specific contexts and complementing its use with more detailed assessments when necessary for a comprehensive understanding of water quality.

4. Results

4.1 In-situ parameters

Table 4 presents the results of the measurements carried out at on-site sampling points. pH and turbidity were analyzed with Maximum Permissible Limits (MPL) according to classes A, B, and C of the RMCH. EC was analyzed with the NB 512 for drinking water. At most sampling points, pH values are close to the maximum limit of 9, indicating that the water tends to be basic, and exceeding the highest allowable range of pH at points 1 and 8. Most of the sampling points are within the maximum permissible limits of turbidity. EC values are very high in all the sampled points, which indicates a significant presence of dissolved salts in water, turning waters unsuitable for human consumption, according to Bolivian Standard 512. Gigh DO values in points 1, 2, 7, and 8 are due to the high presence of aquatic plants and the low water levels (<1 m).

Table 4: In-situ parameters

Sampling point	pH	Turbidity NTU	EC mS/cm	T°C	OD mg/L
1	9.04	31.65	3.95	8.7	13.00
2	9.02	24.35	4.00	8.3	12.00
3	8.93	16.85	4.00	7.7	11.00
4	8.12	10.41	4.40	8.65	8.55
5	7.49	3.88	4.85	9.65	6.1
6	7.22	2.82	4.85	9.75	6.25
7	6.83	1.71	4.80	9.9	6.45
8	7.79	1.30	4.60	10.35	6.55
RMCH Class A Limits	6 - 8.5	<10	1.5		
RMCH Class B Limits	6 - 9	<50			
RMCH Class C Limits	6 - 9	100-2000			

4.2 Ex-situ parameters

Table 5 shows the parameters analyzed compared with MPL according to classes A, B, and C of the RMCH. In most of the samples, sodium and sulfates exceed maximum values. This excess of sodium corroborates the high conductivity reported before. The high concentration of sulfates could be attributed to industrial and mining activities from the headwaters of the basin as mentioned above.

Table 5: Ex-situ parameters

Sampling point	Fecal coliforms UFC/100	TDS mg/L	Nitrogen mg/L	Phosphorus mg/L	Sodium mg/L	Sulfates mg/L
1	1.33	623	11.97	0,57	262,7	318,57
2	4.00	640	8.60	0,5	268,4	368,60
3	0.00	715	2.03	0,12	298,7	845,88
4	0.33	720	1.87	0,04	296,7	722,16
5	2.00	604	2.03	0,09	298,1	663,49
6	0.00	632	2.80	0,05	295,3	682,38
7	2.00	687	2.60	0,01	293,5	551,20
8	45.0	370	49.47	6,14	146,9	/
RMCH Class A Limits	50<y<5 UFC/100 in 80% of the sample	1000	5	20	200	300
RMCH Class B Limits	1000<y<200 UFC/100 in 80% of the sample	1000	12	20	200	300
RMCH Class C Limits	5000<y<1000 in 80% of the sample	1500	12	20	200	400

Table 6 shows the MPL of concentrations of metals established in classes A, B, and C of the RMCH. Figure 3 maps metals concentration for Iron, Aluminum, Manganese, and Arsenic, because they were found at concentrations close to the LMP. The analysis was made at the University of Limoges, France. A greater concentration is seen at sampling point 8, at the outlet of Katari Basin and the entrance to Cohana Bay, where the Lake Titicaca subsequently acts as a diluting factor. A reduction in the concentration of metals is observed in the remaining sampling points, with points 1 and 2 being where the concentrations remain close to those of point 8.

Table 6: Metal concentration limits for different uses

	Fe mg/L	Al mg/L	Mn mg/L	As mg/L
RMCH Class A Limits	0.30	0.5	0.2	0.05
RMCH Class B Limits	0.30	1	0.5	0.05
RMCH Class C Limits	1	1	1	0.05

Figure 3: Concentration of Metals

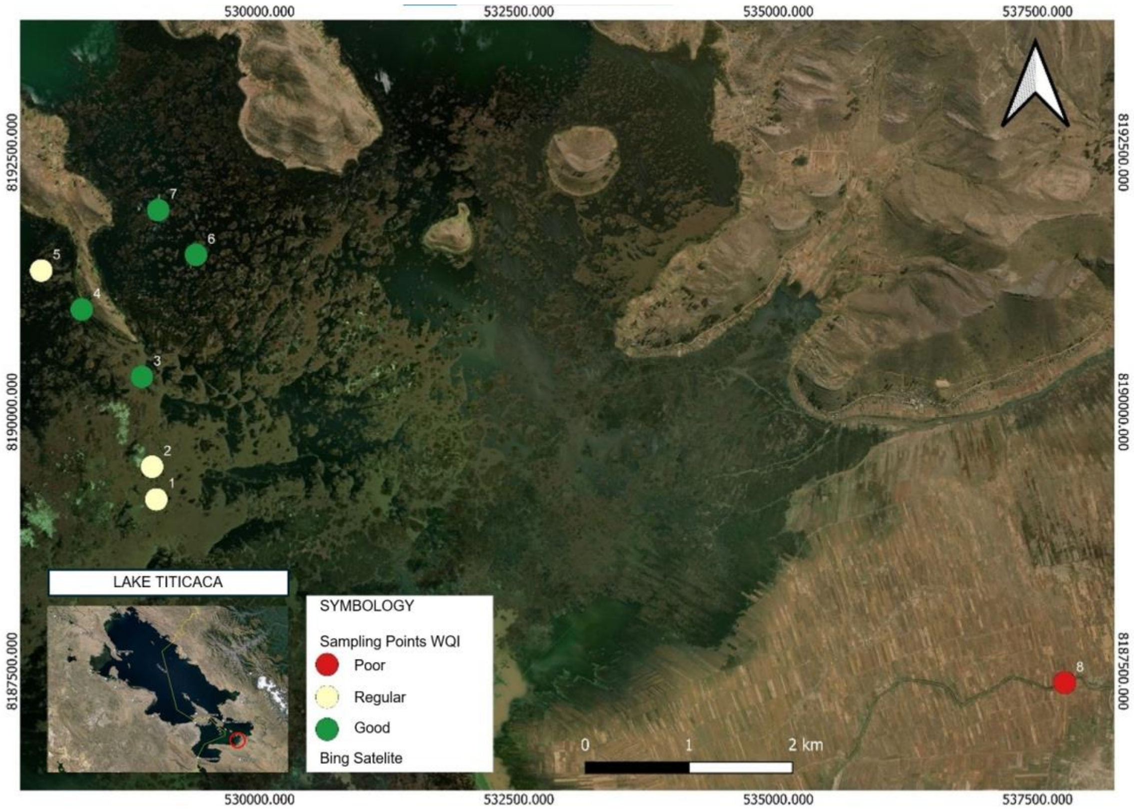
4.3 WQI

Table 7 shows the WQIs and Figure 4 shows their spatial distribution. In general, the lowest water quality is found at sampling point 8, on the river discharging to Cohana Bay, and WQIs improve as the sampling points are located after the aquatic vegetation, which acts as a buffer towards the inner part of the Lake. These are natural controls, however, have their limitations and questions remain on the fate of the polluted vegetation and their final disposition. In addition, point 5 has a regular water type, this is related to the anthropogenic activities identified on Pariti Island.

Table 7: Categorization of sampled points

Sampling point	wi*pp	wi^pp	Wáter quality
1	63.45	60.27	Regular
2	65.99	63.51	Regular
3	82.18	79.56	Good
4	80.12	77.53	Good
5	71.34	68.30	Regular
6	79.81	76.58	Good
7	76.84	73.17	Good
8	34.89	29.47	Bad

Figure 4: WQIs at the sampling points



5. Discussions

Several indigenous communities in the Bolivian part of Lake Titicaca are exposed to pollution from the Katari River, whose waters flow into Cohana Bay. Katari River was classified as inappropriate for any use (Revilla, 2021). The results of this study revealed the presence of pollutants that don't exceed the maximum permissible limits but are near to them in congruence with previous studies (Adriazola, 2015). The above shows that water quality continues to represent a risk to public health and ecosystems.

Regarding the WQI, the site at the watershed outlet is classified as “poor” or "inappropriate" according to the parameters established by the WQI methodology. As the river flows toward the Cohana Bay, it should be expected that it will affect the surrounding communities as well. It is relevant to note that, although the term "bad" may seem subjective, this categorization reflects parameters that exceed permissible limits in terms of water quality, this information being consistent with what Lino (2022) exposes.

As the polluted water flows into the lake, the water body dilutes the pollutants, significantly reducing the concentration of metals. In addition, the abundant presence of different species of algae and plants, such as cattails, at the mouth of the basin towards the lake, it could be inferred that the decrease in metal concentrations is due to phytoremediation.

It is observed that, unlike other metals, sodium (Na) does not decrease its concentration at the points of the lake, but rather increases. It is suggested that more exhaustive research be carried out focused on this metal since the consequences of a lake with high Na concentrations directly affect ecosystems and greatly affect agriculture for which lake water is used. The above can cause a salinization effect in the soil, reducing its permeability, and fertility, and eroding it in the short term. In humans, consuming water with high concentrations of Na, in the long term, produces high blood pressure and cardiovascular diseases (Zehnder, 2010). The salinity of Lake Titicaca dates back to its origins since it was a volume of water that was separated from the sea during the formation of the Andes Mountains. Thus, the high concentrations of Na in the lake are due to soil leaching and accumulation processes. Nevertheless, the wastewater discharges from the surrounding basins are a non-negligible contribution to the Na levels in the lake.

Another relevant parameter that deserves attention is sulfate (SO_4), which has shown significantly elevated concentrations. A study carried out by Campos and Ulloa (2016) indicates that sulfated waters may be the result of mining and agricultural activity in the area. It is important to note that sulfate concentrations can vary depending on local activities, the authors point out.

6. Conclusions

This research presents an evaluation of water quality parameters to determine the contribution of liquid discharges from the Katari basin to the degradation of water quality in Cohana Bay of Lake Titicaca. Physicochemical and biological characterization of the water samples was carried out by determining in-situ and ex-situ parameters. The WQIs are a key tool to understand, in simplified and concrete terms, the state of water quality in the study area. Additionally, a mapping of the concentrations of the prevalent metals in the sampled points was carried out to graphically expose their presence and identify the most dangerous ones. Future research can use this work as a baseline of water quality in Cohana Bay to deepen water quality studies and identify critical control and monitoring points to reduce the risk to ecosystems and public health.

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Communication aligned with the Sustainable Development Goals

6 AGUA LIMPIA Y SANEAMIENTO

13 ACCIÓN POR EL CLIMA

OBJETIVOS DE DESARROLLO SOSTENIBLE