(04-023) - Variation of water quality throughout the Katari Basin (Bolivia) and its relationship with anthropogenic activities

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Bolivia faces significant challenges in terms of water pollution. Industrial, mining, agricultural and domestic activities have a negative impact on the quality of the country's surface water resources due to the lack of management and adequate treatment. The Titicaca lake is the receiver of effluents from several river basins. The Katari RiverBasin is one of the most important due to its geographical density and the amount of residual water that reaches the lake. This study evaluates the influence of anthropogenic activities on water quality at different levels of the Katari Basin. The results of the physicochemical and biological parameters allowed to observe important changes in the composition of the water throughout the river basin. These changes can be attributed to the activities around the body of water, which confirms the contamination by untreated or poorly treated effluents in the different areas of the study. This research generates information to improve water management plans in the Katari River Basin to preserve economic activities, the health of the population and ecosystems.

Keywords: Pollution; Water management; Mining; River Basin

Variación de la calidad del agua en la Cuenca Katari (Bolivia) y su relación con las actividades antrópicas

Bolivia enfrenta desafíos importantes en términos de contaminación del agua. Las actividades industriales, mineras, agrícolas y domésticas tienen un impacto negativo sobre la calidad de los recursos hídricos superficiales del país por la falta de gestión y de tratamiento adecuado. El lago Titicaca es el receptor de los efluentes de varias cuencas, siendo la Cuenca Katari una de las más importantes por su densidad geográfica y la cantidad de agua residual que llega hacia el lago. Este estudio evalúa la influencia de las actividades antropogénicas sobre la calidad del agua a diferentes niveles de la Cuenca Katari. Los resultados de los parámetros fisicoquímicos y biológicos permitieron observar cambios importantes en la composición del agua a lo largo de la cuenca. Estos cambios pueden ser atribuidos a las actividades alrededor del cuerpo de agua lo que confirma la contaminación por efluentes no tratados o poco tratados en las diferentes zonas del estudio. Esta investigación genera información para la mejora de los planes de gestión del agua en la Cuenca Katari para preservar las actividades económicas, la salud de la población y los ecosistemas.

Palabras clave: Contaminación; Gestión del agua; Minería; Cuenca

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1. Introduction

The basin is recognized as the most appropriate territorial unit for the efficient management of water resources (Saavedra, 2018). However, the political/administrative limits do not always coincide with the territorial limits of the hydrological basins, making the process of using the hydrological cycle difficult in many cases (Dourojeanni, Jouravlev, & Chávez, 2002). To guarantee access to quality water, water resource management systems must be formulated in a comprehensive and preventive manner, in which all the involved actors collaborate (WHO, 2017). However, to start to propose management strategies for water resources, it is necessary to know the state of the resources at different levels of the basin. Depending on the activities around the water bodies, the water quality will be affected in different ways (Khatri & Tyagi, 2015). The mining activities lead to acidification of water bodies and metallic pollution (Adnan et al., 2024). Agriculture activities, and especially nutrient discharge, have different impacts on nitrogen and phosphorus biogeochemical cycles depending on the type of soil in the area (Kyllmar et al.,2006). The runoff of pesticides from treated plants and soil into surface water, and their infiltration and dynamics within groundwater affect the water quality and are linked to health and environmental toxic risk (Aktar, Sengupta, & Chowdhury, 2009). Regarding urban areas, the study of Chen et al. (2023) shows that the different zones of a city will affect differently the water quality. Thus, the residential zones will have more impact on water quality status than industrial zones or downtown. Constructed land and domestic were considered as the principal factors that aggravated the water quality pollution level. Consequently, the diversity of activities in a river basin leads to different influences on water quality from upstream to downstream. So, the dynamics of pollution will depend on the changes in the water quality parameters (Xu et al., 2022)

The Katari Basin is located in The Andes of Bolivia, a highland region, that presents problems in the management of its water resources, which generates uncertainty about access to water in the future (Rivero, Morais, & Pereira, 2020). Katari Basin is made up of 7 provinces and 24 municipalities of the Department of La Paz. It represents approximately 11% of the Bolivian population (INE, 2020). It is considered one of the most inhabited and polluted basins in Bolivia (MMAyA & VRHR, 2021). According to anthropogenic influence, the Katari Basin is subdivided into 4 main areas: urban, mining, industrial, and agricultural (Archundia et al., 2017). The surface water bodies that flow through the Katari basin are severely impacted by growing urbanization and different economic activities in the region (Ede & Fuentes, 2019; MMAyA, 2014). Pollution of the natural water of the basin is directly related to public health problems and the degradation of ecosystems (Molina et al., 2017; Revilla, 2021). The water upstream in the basin is classified as poorly mineralized water with neutral pH as clean glacial waters. As the waters flow downstream, they mineralize because of the geological nature of the place and can also become naturally contaminated as a result of the influence of anthropogenic activities (Molina et al., 2017).

The Katari Basin was defined as a strategic basin according to the National Basin Plan of Bolivia (Saavedra, 2015). The Katari Basin discharges its untreated or poorly treated wastewater into Lake Titicaca, a transboundary body of water declared a Ramsar site of global importance. The Katari Basin Management Unit (UGCK by its acronym in Spanish) is the institution in charge of basin environmental management and water monitoring since 2016. The monitoring program of water resources was created to provide a general description of the water quality of the entire basin; however, the results have been poorly disseminated. Currently, few studies compare water quality parameters at different levels of the Basin.

2. Objective

This research studies the variation of water quality parameters at different levels of the Katari Basin linking it to the anthropogenic activities of the area. The control of physicochemical parameters allowed to observe important changes in the composition of the water throughout the basin. The impact of this work lies in generating information to improve the water management plan in the Katari Basin.

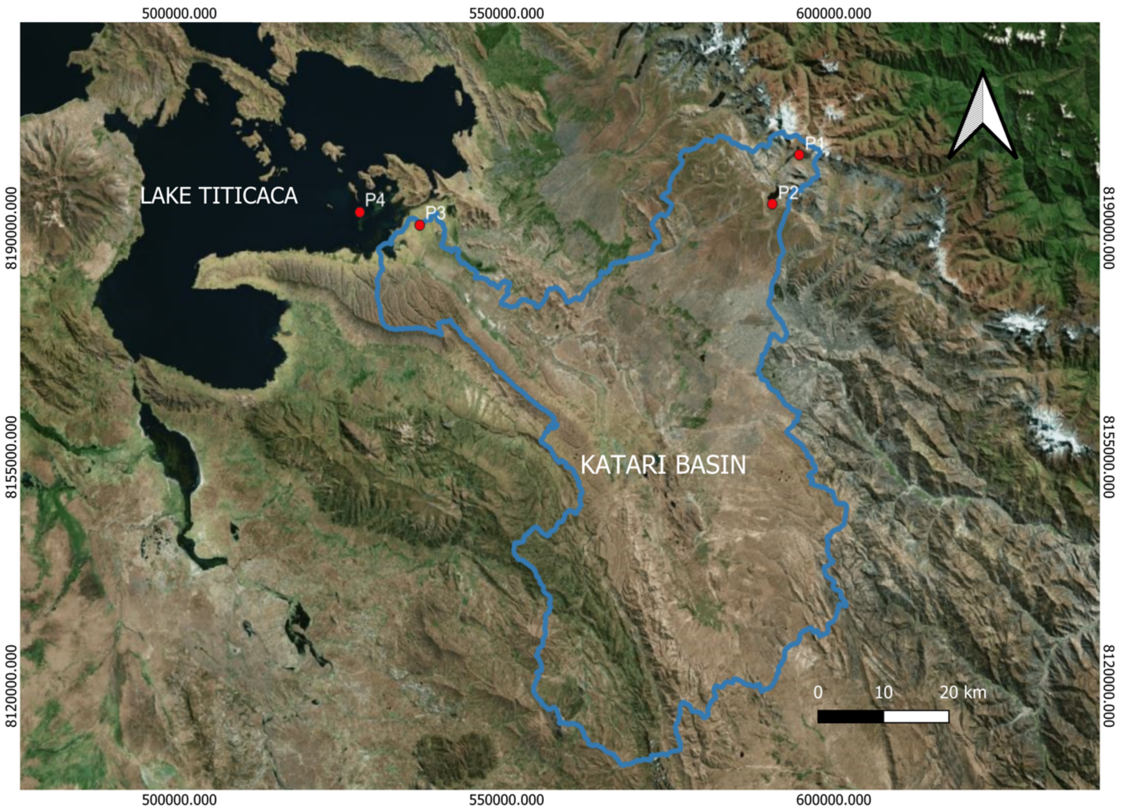
3. Methodology

This section has two parts, the first describes the study area, and the second exposes the research methodology.

3.1 Study area

Four sampling points were defined based on the representativity of the expected results (Figure 1). The points are located at the head of the basin (sampling points P1 and P2) and at the end of the basin (sampling points P3 and P4) to evaluate the impact of the different anthropogenic activities present in the basin on water characteristics.

Figure 1: Location of the sampling points in the Katari basin



The sampling points are described in Table 1. P1 corresponds to the water sample least impacted by human activities as it comes from the mountain runoff that is principally formed by snowmelt. P2 sample comes from an artificial lake built with a dam, to receive acid mine drainage of the area. At the medium of the basin, the city of El Alto presented a contribution to the pollution of water bodies with domestic wastewater. This water of the river Katari is then used in agriculture for irrigation and livestock activities until P3. Finally, a P4 sample was taken in Lake Titicaca at the exit of the estuary to see how this pollution of the main river of the basin is then diluted.

Table 1: Description of sampling points

Sampling point	UTM coordinates	Area description and anthropogenic activities
P1	19 K 592880 E 8196900 S	Mountain runoff
P2	19 K 589143 E 88190506 S	Mining dam of Milluni
P3	19 K 537761.15 E 8187388.62 S	River Katari, agriculture, city of El Alto upstream
P4	19 K 529004.23 E 8189155.74 S	Estuary in Lake Titicaca called Cohana Bay, agriculture and fishing activities

3.2 Sampling Protocol

The water sampling step was performed following 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 glass container. The in-situ analyses were carried out directly in the sampling containers. The preservation of the water samples was performed based on Nollet and De Gelder (2007) considerations.

3.3 Water quality parameters

The physicochemical and microbiologic parameters were determined in order to evaluate the influence of anthropogenic activities in the Katari basin on water quality. The parameters of the study are presented in Table 2.

Table 2: physicochemical and microbiological parameters

Parameter	Analysis site	Technique, material
pH	In-situ	Hach HQ 40D multiparameter with Hach PHC201 probe
Electrical conductivity (EC)	In-situ	Hach HQ 40D multiparameter with Hach CDC401 probe
Dissolved oxygen (DO)	In-situ	Hach HQ 40D multiparameter with Hach LDO101 probe
Turbidity	In-situ	HACH 2100Q turbidimeter
Fecal coliforms	Laboratory of Universidad Católica Boliviana San Pablo (La Paz)	Bolivian Standard 32005 for Microbiological Tests - Coliform bacteria count (First revision), from 2003

Ammoniacal Nitrogen (NH_3)	Laboratory of Universidad Católica Boliviana San Pablo (Cochabamba)	Kjeldahl nitrogen procedure, FAO (2023)
Sodium	Laboratory of Universidad Católica Boliviana San Pablo (Cochabamba)	"Analytical Methods for Atomic Absorption Spectroscopy" (Perkin, 1996), Perkin Elmer AAnalyst 200
Metals	E2LIM UR 24133 laboratory of the University of Limoges (France)	Agilent 7700x laser ablation inductive coupling-induced plasma mass spectrometry

The results were then compared with the Regulation on Water Pollution (RMCH, 1995) in annex A-1 with water categories A, B, C, and D that define the water use possibility as presented in the Table 3.

Table 3: Water use based on its classification (RMCH, 1995)

Water use	Class A	Class B	Class C	Class D
Domestic drinking water supply	Without any prior treatment, or with simple bacteriological disinfection	Physical treatment and bacteriological disinfection.	Complete physical-chemical treatment and bacteriological disinfection.	In extreme cases of public need, requires an initial pre-sedimentation process, and then complete physical-chemical treatment, and special bacteriological disinfection against eggs and intestinal parasites.
Primary contact recreation (swimming, skiing, diving)	YES	YES	YES	NO
Protection of hydrobiological resources	YES	YES	YES	NO
Irrigation of vegetables consumed raw and fruits with thin peels	YES	YES	NO	NO
Industrial supply	YES	YES	YES	YES
Natural and/or intensive breeding (aquaculture) of species intended for human consumption	YES	YES	YES	NO
Animal watering	NO	YES	YES	NO
Navigation	NO	YES	YES	YES

3.4 Microplastic characterization

Firstly, clarify that the present study was made with a common protocol for microplastic (MP) extraction and a physical characterization (concentration, size, and shape) of the extracted particles. Indeed, the lack of chemical characterization does not ensure that the particles found

are synthetic polymers (Rios Mendoza & Balcer, 2019). However, the procedure used during the study allows the extraction of particles with some similar properties to MP. Therefore, the microparticles found can be described as microplastic-like (MP-like).
The extraction protocol of MP-like particles used is based on the work of Gago et al. (2019). The first step corresponds to a digestion of the sample to eliminate organic matter (H_2O_2 30% for 48 h). Then a density separation of particles was performed with $ZnCl_2$ solution (final solution density of 1.37 g/mL). Nile red staining was used to later identify MP-like particles with the fluorescence microscope Optika B-1000LD4 with 4X and 10X magnification.
Finally, the MP-like particles were characterized according to their shape and size. Regarding the shape, thanks to the microscopic observation, the particles were classified into pellets, fibers, films, foams, and fragments. Likewise, according to their size, the considered size groups were 0.45-100 µm, 100-350 µm, and 350 µm-5 mm.

4. Results

The results obtained in the study are presented below.

4.1 Physicochemical and microbiological parameters

As shown in Table 4, the physicochemical and microbiological characteristics of the water samples change throughout the basin. Sample P1 has properties with milder levels because they are almost due to the biogeochemical and atmospheric balances between the water and its environment. At point P2, a significant decrease in pH is observed due to water pollution by acid mine drainage in the area. This influences the conductivity results of the sample. In sample points P3 and P4, the high conductivity can be correlated with the high sodium concentration. Indeed, the area is naturally saline because it was previously an ocean that dried up due to the formation of the Andes, the salts are leached from the soil and Lake Titicaca acts as a receptor where the salts accumulate. Thus, throughout the basin, the concentration of salts and the conductivity increase with a maximum value in the lake. In addition to that, due to the presence of the city of El Alto in the middle of the basin, the contribution of untreated or poorly treated domestic wastewater increases this water salinity. The contribution of groundwater can be corroborated by the presence of fecal coliforms, the increase in turbidity, and the high concentration of ammoniacal nitrogen. In addition, the high nitrogen concentration may be due to the leaching of fertilizers used in the area for crops. The soil in the area is very sandy, which facilitates the mobilization of contaminants present in the soil. This anthropogenic contribution of nutrients leads to an intense eutrophication of the Katari River. This phenomenon can explain the high concentration of dissolved oxygen in the surface part of the water due to the large amount of algae present in the river.

Table 4: Results of physicochemical and microbiological measurements in water samples

Sample points	pH	EC (mS/cm)	Turbidity (NTU)	DO (mg O_2/L)	Na (mg Na/L)	NH_3 (mg N/L)	Fecal coliforms (UFC/100 mL)
P1	9.3	0.257	0.53	7.66*	1.20	ND	<LOD
P2	2.7	0.003	2.95	7.34*	2.04	ND	<LOD
P3	9.4	2.580	49.60	20.32	146.90	49.47	45.00
P4	9.0	3.950	31.65	13.00	262.70	11.97	1.33

RMCH Class A	6 to 8.5		<10	>5.2	200	0,05	5<FC<50 UFC/100 mL in 80% of samples
RMCH Class B	6 to 9		<50	>4.55	200	1	200<FC<1,000 UFC/100 mL in 80% of samples
RMCH Class C	6 to 9		<100	>3.89	200	2	1,000<FC<5,000 UFC/100 mL in 80% of samples
RMCH Class D	6 to 9		<200	>3.25	200	4	5,000<FC<50,000 UFC/100 mL in 80% of samples

Note: ND Not Determined // LOD Limit Of Detection
*Data from Alvizuri et al. (2022)

Concerning the classification of water according to the RMCH (1995), we want to clarify that since the analysis of all the parameters of the RMCH has not been carried out, the samples will only be categorized based on the parameters of interest in the study. Sample P1 is classified as Class A due to the little influence of human activities. Sample P2 is the most problematic due to the worst overall classification, due to the high contamination of the lake due to mining activities in the area. Samples P3 and P4 could be categorized into Class A or B but the high concentration of ammoniacal nitrogen is outside the limit concentrations of this categorization.

4.2 Metal levels

The concentrations of metals found in the samples are presented in Table 5. In this case, differences in metal concentrations between the samples can also be observed.

Table 5: Metal levels in the water of sampling points

	Al (µg/L)	Cr (µg/L)	Mn (µg/L)	Fe (µg/L)	Ni (µg/L)	Cu (µg/L)	Zn (µg/L)	As (µg/L)	Cd (µg/L)	Pb (µg/L)
P1*	78	0.27	3	136	0.50	0.67	5	25.19	0.02	2.27
P2*	4,041	1.71	7,008	71,920	84.98	542.94	34,062	49.42	113.41	16.49
P3	119	0.68	299	155	5.83	6.60	40	57.33	0.11	1.71
P4	136	0.82	413	112	3.78	4.48	53	34.55	0.13	2.54
RMCH Class A	200	50 (Cr tot)	500	300	50	50	200	50	5	50
RMCH Class B	500	50 (Cr VI)	1,000	300	50	1,000	200	50	5	50
RMCH Class C	1,000	50 (Cr VI)	1,000	1,000	500	1,000	5,000	50	5	50
RMCH Class D	1,000	50 (Cr VI)	1,000	1,000	500	1,000	5,000	100	5	50

*Data from Alvizuri et al. (2022)

As explained in the previous part, the physicochemical characteristics of sample P1 reflect the natural biogeochemistry of the area. Thus, metal concentrations are due to the mineral wealth of the upper part of the basin. The main metals are iron, aluminum, arsenic, zinc, and lead. At point P2, as the water body is fed by liquid mining waste, it is normal to find such high concentrations of metals. The concentration of metals at point P3 is lower than point P2 and can be explained by a phenomenon of water dilution, but also by the precipitation of metals in the sediments throughout the basin due to the increase in pH of the water (Table 4). At points P3 and P4, different behaviors are observed depending on the metals. For most metals, the trend is a decrease in concentration compared to point P2 but with levels higher than point P1. In the case of arsenic, the concentration in P3 is higher than P2. This can be explained by the increase in salinity in the lower part of the basin, which favors the solubility and therefore the mobility of the metals present in the soils. The study of Montero Loroño and Palomino Lopéz (2011) highlighted the solubility of arsenic in saline soils in the study area. In addition, the city of El Alto, through the generation of industrial effluents, contributes to the pollution of metals to the lower part of the basin.

Regarding the categorization of water samples based on their metal levels, sample P1 corresponds to Class A. Sample P2 is out of categorization due to its high concentrations. But the water from this point is not used in the area. Part of it is sent and later treated to supply the city of El Alto. The concern in terms of metal pollution is more at point P3 due to the level of arsenic. The determined concentration leads to a Class D classification that does not allow the use of water for irrigation and livestock feeding. Finally, at point P4 the concentrations are close to the limits, but the water has a Class A categorization.

4.3 Microplastic pollution

In table 6, the results of the characterization of particles MP-like extracted from the water samples P2, P3, and P4 are presented.

Table 6: Results of particles MP-like characterization in water samples

		Size: % of total particles MP-like			Shape: % of total particles MP-like				
	Microplastic-like (particles/L)	0.5-100 µm	100-350 µm	350-5,000 µm	Pellet	Fiber	Film	Foam	Fragment
P2	400.0	100.0				100.0			
P3	6,400.0	89.5	7.0	3.5		65.8	2.4		31.8
P4	3,000.0	90.4	8.6	1.0		57.1			42.9

The presence of particles MP-like is directly linked to human activities around the water bodies in the river basin. At point P2, there are few human activities and population density, so lower values of 400 particles/L were found. At point P3 there is the influence of the city of El Alto, which leads to great contamination with solid waste in the area. In the rainy season, the level of the rivers increases drastically, which carries this waste lower into the basin and generates the formation of microplastics. The conditions of the basin are favorable to the degradation of large plastic waste into microplastics due to abrasion (wind and torrentiality of the river in the rainy season), UV radiation due to height, and temperature (Crawford & Quinn, 2016; Vásquez et al., 2018). At point P4, the concentration of particles remains high despite the dilution in the lake, which could have an effect on the activities in the area. Indeed, microplastics can generate toxic effects on exposed organisms (Reimonn et al., 2019), and in the Lake Titicaca area, fishing and aquaculture are the main activities.

5. Discussion

The Katari basin has an area of 2,022 km^2 with a great geomorphological variety from summits in the Cordilla Real (up to 6,000 m) to the shallow sedimentary valleys in the lower part that includes the Lake Titicaca (Archundia et al., 2017). In addition, this basin has different types of anthropic pressure with mining in the upper part, urban activities in the middle part with the city of El Alto, and agriculture in the lower part (Archundia et al., 2017). These activities affect the characteristics of water bodies in different ways (Ede & Fuentes, 2019). The results of this work contribute to a better understanding of the impact of anthropogenic activities in the Katari basin on the quality of water resources.

The upper part of the basin is characterized by high mining activity. The results show an acidification of the surface water with a high metallic soluble fraction. These conditions affect the hydrobiological health of water bodies, limiting the environmental services they generate for ecosystems (Luís et al., 2022). Furthermore, the presence of these acid mine drainages in the area can generate an acceleration of mechanical erosion (Jiang & Yin, 2014) and harm livestock activities that are also found in the upper part of the basin.

In the middle part of the basin, a partial recovery of the environmental conditions of the water body is observed, which leads to a decrease in the dissolved metallic fraction. Nevertheless, the urban area generates other types of changes in terms of the characteristics of the water. The increase in salinity associated with the presence of high levels of fecal coliforms and the concentration of nitrogen confirms the contamination of the Katari River by domestic wastewater (Gomez, 2012). Additionally, high concentrations of dissolved metals may come from industrial effluents from the city of El Alto. These domestic and industrial wastewaters are disposed of directly into the Katari River.

Due to the high concentration of nitrogen in the lower part of the basin, the contribution of agricultural activities using fertilizers can also be suspected (Wang et al., 2024). Agriculture, natural erosion, and climate change are factors that favor the remobilization of soil salts, and thus, the salinization of water bodies (Balakrishnan et al., 2024).

The Katari River is very important to supply agricultural activities downstream of the river basin. The use of bad-quality water in these activities leads to the pollution of the soils and aquifers in the area (Yan & Qing, 2014). This transfer of contamination favored by the high salinity of the soil can lead to generating risks for the activities and health of the population in the area.

6. Conclusions

This study aims to understand better the influence of anthropogenic activities on the dynamic of water quality in the Katari basin. It has been shown that the most important activities in the basin completely change the characteristics of the water in the area, degrading its properties to different levels and limiting its possible use. The management of water quality in a basin is essential with an integrated vision of resource management, to sustain quality water for the population and their activities. This study proves that, in the whole basin, water services are affected at a social, environmental, and economic level. These results are important to highlight the need for an integrated water management at the basin level.

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