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Physicochemical characterization and presence of heavy metals in the trout farming area of Lake Titicaca, Peru

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ABSTRACT

Certain areas of Lake Titicaca exhibit signs of contamination from urban drainage, mining tailings, and waste from trout cage farming. The objective of this study was to determine the physicochemical conditions of the water and the concentration of heavy metals in sediments of a trout (*Oncorhynchus mykiss*) farming area in Puno Bay, Lake Titicaca. Water samples were collected at depths of 1, 5, 10, and 15 meters from the surface, as well as from sediments at the bottom of the lake. Additionally, samples were taken 500 meters from the trout breeding area, where no farming activities took place. The study was carried out over a period of 10 months. Some physical-chemical measurements were taken in situ using a multiparametric device, while others were carried out at IMARPE's laboratory. The results indicate that the physical-chemical quality of the water does not exceed the tolerance limits recommended by the Environmental Quality Standards - ECA Peru. The water pH was 8.79 and the dissolved oxygen was 6.81. The heavy metals (Hg, Cd, Pb, Zn, Cu) found in the sediments were within the permissible limits compared to the ISQG Canada Standard. However, the concentration of As, at 41 mg kg^{-1}, exceeded the tolerance limit. Uncontrolled trends in trout production volumes could compromise water quality and sustainability.

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1. INTRODUCTION

Aquaculture has become one of the most dynamic and rapidly growing agricultural activities for feeding the human population. Approximately 50% of commercially available fish is produced in fish farms. In 2018, fish farming in Lake Titicaca, Peru-Bolivia, produced around 50,000 metric tons of trout for human consumption. However, the impact of this productive activity on the aquatic environment, particularly the physical and chemical quality of water, is still not well understood, especially in lakes, lagoons, and rivers in the Lake Titicaca basin, which is shared by both Peru and Bolivia (FAO, 2018; Novais et al., 2018).

Due to various reasons, pollution in Lake Titicaca is increasing. The untreated wastewater of the population is the main cause of water contamination in Lake Titicaca. Additionally, mining tailings and trout farming in floating cages are suspected to be major sources of waste contamination in Lake Titicaca (Ministerio del Ambiente, 2014; Monroy, Maceda-Veiga, Caiola, et al., 2014). Trout farming generates food waste and fish excrement that affect the lake's water quality (Fontúrbel, 2008; Montesinos López, 2018).

Unsustainable activities in the water area of Lake Titicaca can gradually degrade its water quality and environmental condition, endangering human health through the trophic chain if preventive measures are not taken. Scientific reports on impacts that affect Lake Titicaca, particularly the inner part of Puno Bay close to the city of Puno and Cohana Bay in Lake Little (Bolivia), demonstrate the process of severe eutrophication and heavy metal pollution, mainly caused by urban waste (Moreno Terrazas et al., 2018; Reichelt-Brushett et al., 2017).

The agents of eutrophication and toxic substances in aquatic bodies contribute to the formation of special sediments in the aquatic bottom. These sediments arise after being transported as solid matter that gives rise to the growth of algae, as well as being a repository for the cumulative concentration of nickel, calcium, chromium, copper, mercury, iron, lead, zinc, and other metals. Therefore, this research also examines metals in the sediments of the aquatic bottom, partly transported by the flow of water and probably by the residues of trout breeding (Fontúrbel, 2008; Montesinos López, 2018; Vélez et al., 2018).

This investigation was motivated by the desire to learn about the impact of fish food remains and their feces. Specifically, the objective was to determine the physical-chemical quality of the water and the concentration of heavy metals in sediments in the area of trout production in Puno Bay of Lake Titicaca, Peru.

2. MATERIALS AND METHODS

2.1. Study sites

The study area comprises the basins of Lake Titicaca located in the city of Puno, Peru (Fig. 1), the spatial area is 110,969 km^2, of which 44% is in Per, Geographic space studied more specifically belongs to the District of Chucuito and Puno belonging to the same region. Lake Titicaca is classified as the largest freshwater lake in South America and the highest of the world's great lakes at 3,812 m above sea level (Gómez-Arteta & Escobar-Mamani, 2022).

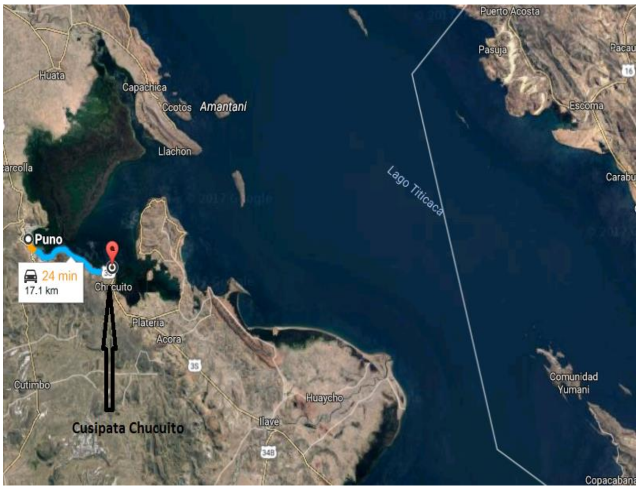

Figure 1. Satellite image of the place of study in Puno Bay, Lake Titicaca, Peru

2.2. Population and sample

In the Cusipata sector, there are 10 trout farming associations that produce trouts in floating cages. Each association has an average of 10 farming cages. We sampled this area of the lake 14 times between July 2017 and September 2018.

2.3. Sampling procedure and water quality analysis

Various water quality parameters were measured for the study at both the active and control sites. Parameters such as pH, temperature (T), electrical conductivity (EC), and total dissolved solids (TDS) were measured on-site using a YSI-PLUS multi-parameter instrument. Dissolved oxygen in water (DO) was measured with an optical oximeter. For nutrients such as phosphorus, nitrate, and ammonia, water samples were collected at depths of 1, 5, 10, and 15 meters using a Niskin water sampler. The water samples were preserved, labeled, and transported in a thermal box with ice to the laboratories of the Instituto del Mar del Perú (IMARPE) for analysis, where phosphate was analyzed by the ascorbic acid method (AWWA, 2017) (spectrophotometer Spectrumlab 22C) and nitrates by reduction with cadmium (Table 1).

Chlorophyll-a concentration was determined by the spectrophotometric method. Total nitrogen and total phosphorus were determined by digestion using the HACH test by spectrophotometer DR2800, while total suspended solids were determined by gravimetry (Lavilla et al., 2012; Martinez-Boubeta & Simeonidis, 2019).

Table 1. Water quality parameters measured at the study area in Puno Bay, Lake Titicaca, Peru

Parameters	Acronym	Units
Potential of Hydrogen	pH	UpH
Dissolved Oxygen	DO	mg L^{-1}
Temperature	TEMP	°C
Ammonium-Nitrogen	NH_4-N	mg L^{-1}
Electrical Conductivity	EC	µS cm^{-1}
Total dissolved solids	TDS	mg L^{-1}
Carbon dioxide	CO_2	mg L^{-1}
Salinity	SAL	PSU
Ammonia-Nitrogen	NH3-N	mg L^{-1}
Phosphate	PO_4	mg L^{-1}
Nitrate	NO_3	mg L^{-1}

2.4. Procedure for determining heavy metal levels in Lake Titicaca sediment

Sediment samples were collected from both active and control sites at a depth of 16-18 meters, and stored in ziploc bags (Autoridad Nacional del Agua, 2016). The samples were processed according to the methods described in the National Protocol for Monitoring Water Quality Resolution No. 010-2016-ANA (El Peruano, 2017), which are in accordance with those recommended by the scientific community (Archundia et al., 2016; Monroy, Maceda-Veiga, & de Sostoa, 2014).

The sediment samples were dried at room temperature for two weeks in the Mega Research Laboratory of the National University of the Altiplano (UNA) Puno, in a closed environment with sufficient natural light and ventilation. Subsequently, the sediments were ground and sieved with a 100 µm sieve (Ali et al., 2016; Bhardwaj et al., 2017; Castro & Valdés, 2012; Gnanou Besse et al., 2019; Perks et al., 2017). Finally, the amount of heavy metals (Hg, As, Cd, Pb, Zn, Cu) was measured by ICP OES.

Table 2. Results of the evaluation of the water physical and chemical parameters (average values) at the trout farming and control sites in Puno Bay, Lake Titicaca, from July 2017 to September 2018

Study Area	Depth (m)	Temp. (°C)	EC (µS cm^{-1})	TDS (mg L^{-1})	SAL (PSU)	pH (UpH)	NH_4-N (mg L^{-1})	NH_3-N (mg L^{-1})	DO (mg L^{-1})	DO (%)	CO_2 (mg L^{-1})
Puno Bay, 500 m from the trout farming area (control site)	1	14.9	1559.1	1017.2	0.79	8.75	0.85	0.14	6.93	97.97	0.23
	5	14.4	1555.9	1017.9	0.79	8.81	0.79	0.14	6.97	107.6	0.25
	10	14.2	1557.4	1018.6	0.79	8.81	0.69	0.14	6.89	95.73	0.37
	15	14.1	1556.1	1017.9	0.78	8.83	0.81	0.14	6.85	93.99	0.41
Trout farming area, Puno Bay	1	14.9	1561.2	1010.5	0.79	8.77	0.78	0.13	6.75	85.27	0.1
	5	14.4	1557.6	1008.6	0.78	8.79	0.83	0.14	6.72	104.31	0.22
	10	14.3	1561.1	1011.8	0.79	8.81	0.84	0.14	6.74	93.67	0.35
	15	14.2	1562.4	1012.8	0.79	8.79	0.83	0.14	6.68	91.95	0.34
	Average	14.4	1558.9	1014.4	0.79	8.79	0.8	0.14	6.81	96.31	0.28
	Maximum	17	1731	1124.5	0.88	9.09	1.64	0.26	7.65	116.2	1.5
	Minimum	12.3	1482	962	0.75	8.24	0.04	0.03	6.02	0.26	0
	Variance	2	6100.8	2956.1	0.002	0.03	0.1	0.003	0.2	892.5	0.1

Table 3. Range values of temperature, pH, OD, CO_2, PO_4, and NO_3 were found in the trout farming area at Puno Bay, Lake Titicaca. Also, we can see established values by ECA, FAO, and PRODUCE.

Parameters	Acronym	Unit	Values			ECA	FAO		PRODUCE	
			Min	Max	Average		Rank	Optimum	Rank	Optimum
Temperature	TEMP	(°C)	12.3	17.0	14.4	Δ 3.0	13 - 18	15	6– 18	10-5
pH	pH	UpH	8.24	9.09	8.79	6,0-9,0	6.5- 8.5	7	7–9	7
Dissolved Oxygen	DO	(mg L^{-1})	6.00	7.65	6.81	>=5	7.5- 12	8.5	6–10	8
Carbón Dióxide	CO_2	(mg L^{-1})	0.00	1.5	0.28				0–4	0–2
Phosphates	PO_4	(mg L^{-1})	0.00	0.28	0.09	0.025				
Nitrates	NO_3	(mg L^{-1})	0.00	0.64	0.01	0.02				

Notes: ECA: Environmental Quality Standard; FAO: Food and Agriculture Organization; PRODUCE: Peruvian Secretary of Production

2.5. Data analysis

Data collected from the active trout farming site were compared with the Environmental Quality Standards of Peru (Supreme Decree No. 004-2017-MINAM). The heavy metal levels in the sediments from the trout farming location were also compared with those established in Supreme Decree No. 011-2017-MINAM, and the "Canadian Sediment Quality Guidelines for the Protection of Aquatic Life". A statistical analysis ANOVA was performed to determine the variability of the physical-chemical data from the two sample sites using the SPSS v23 program. We also applied correlation and multiple regression tests to the water physicochemical data.

3. RESULTS

3.1. Water physical and chemical parameters in the trout farming area

The average water temperature was recorded at 14.4 ± 2°C, the water pH was 8.79 ± 0.03, and the dissolved oxygen in the water was 6.81 ± 0.2 mg L^{-1}. There was no difference in these parameters between the trout farming and control sites. Our data shows that the water pH ranged from 8.24 ± 0.03 to 9.09 ± 0.03 with an average of 8.79 ± 0.03 (Table 2 and Table 3).

3.2. Measurement of heavy metals in sediments at the trout farming area

Mercury (Hg) levels in sediments at the trout farming area and the control point were 0.05 and 0.02 mg kg^{-1}, respectively, in May 2017. These levels rose slightly to 0.07 and 0.09 mg kg^{-1} in September. The Hg concentration in sediments was higher in the trout farming area in May, increasing slightly in September. This same pattern occurred in the control area, suggesting that the accumulation of Hg in the sediments could be due to water flow and winds (Table 4).

Analysis of sediment revealed that there was 25.7 mg kg^{-1} arsenic (As) in the trout farming area, and 41.1 mg kg^{-1} in the control area in May 2018. The levels measured in September of the same year were 27.30 mg kg^{-1} and 23.90 mg kg^{-1}, in the trout farming and control areas respectively.

Cadmium (Cd) was found at very low levels at both the trout farming and control sites. In the trout farming area, the Cd levels were recorded at 0.2 mg kg^{-1} in May and 0.5 mg kg^{-1} in September 2018 (Table 4). Additionally, lead (Pb), zinc (Zn), and copper (Cu) levels were measured in the sediments at both the trout farming area and the control sites (Table 4).

3.3. Correlation of physicochemical parameters of water and multiple regression indicators

All environmental variables are interrelated, and they independently affect environmental setbacks. Additionally, the P-value obtained is less than 0.05, indicating a statistically significant relationship between the variables with a confidence level of 95.0%.

The matrix of positive or negative correlations between the environmental variables analyzed in the study ranges from very weak to strong, with a tendency toward strong correlation indicating a positive correlation. This means that the values of both compared variables tend to increase together. Inverse correlations between the physical-chemical parameters indicate a negative correlation, where the environmental values obtained tend to increase while the values of the other variable decrease (Table 5).

The results of the following sentence show that the multiple linear regression model describes the relationship between pH (dependent variable) and the 15 independent variables that would influence it individually. Among them, the environmental variables that do not influence the model have been removed, leaving only seven that influence the model, as shown in Equation 1 (denominations expressed in Table 1).

pH= 9.62644 - 0.00123*ce - 0.00904* nh4n + 2.36717* nh3n +
(0.41617) (0.0023) (0.00674) (0.40109)
+ 0.12316* od1- 0.00118* od2 + 0.06554* co2 +
(0.02583) (0.00054) (0.03065)
0.28803*po4 + 0.09278*no3 .... [1]
(0.21338) (0.04975)

N = 80.00
F(8, 71) = 66.03
Prob > F = 0.00
R-squared = 0.79

In the P>t (probability of occurrence) column of Table 6, it is observed that the p-value is less than 0.05. This indicates that there is a statistically significant relationship between the variables with a confidence level of 95.0% and 99.0%. Meanwhile, the R-Squared statistic indicates that the model explains 0.79% of the variability in pH.

4. DISCUSSION

The temperature of the water plays an important role in regulating the growth of trout in captivity. In Puno Bay, it varied between 12.3°C and 17°C, with an average of 14.4°C. This average value is close to the optimal temperature recommended by the FAO (15°C) for raising trout. The average temperature for trout farming in the study area varied in a range from 6 to 18°C. The Ministry of Production - PRODUCE and the National Fund for Fishing Development - FONDEPES recommend an average of 10-15°C (Table 3).

It has been reported that the level of oxygen saturation at recorded temperatures during the winter season, due to the solubility of oxygen, decreases with the decrease in water temperature. On the other hand, at the other extreme of the temperature range, proteins won't be metabolized effectively, as is the case addressed by (Ali et al., 2016) and (Tate et al., 2017). This situation occurs because extreme diurnal variations of factors such as solar radiation, temperature, oxygen saturation, and humidity oscillate permanently between 1 and 18°C in Puno highlands (Archundia et al., 2016; Li & Liu, 2019b).

The pH values are slightly higher than the pH values recommended by the ECA (6.0-9.0), (Supreme Decree No. 004-2017-MINAM), FAO (6.5 to 8.5), and the Ministry of Production (PRODUCE) 7.0 to 9.0. Both FAO and PRODUCE suggest 7 as the optimum pH of water. Thus, pH 9.09 ± 0.03 would be considered close to the upper end (Table 3). In acidic lakes, the pH of the water can be as low as 5.0. At this low pH, only a few organisms can survive (Li & Liu, 2019b; Wessels et al., 2017).

Table 4. Heavy metals (mg/kg) in sediments at the study area (trout farming and control), compared with values established for the quality of freshwater sediments (SSQQ, dry weight), probable effect limits (PEL, dry weight), and incidence (%) of adverse biological effects in concentration ranges defined by these values and the Peruvian Environmental Quality Standard

	May 2018		September 2018		Canadian Norm		Peru ECA's Norm
Heavy Metal	Trout farming	Control	Trout farming	Control	ISQG*	PEL**	Soil
Hg	0.05	0.02	0.07	0.09	0.17	0.49	6.6
As	25.7***	41.1***	27.3***	23.9***	5.9	17	50
Cd	0.2	0.2	0.5	0.5	0.6	3.5	1.4
Pb	1	1	5	6	35	30.43	70
Zn	19.5	15.1	13.8	28.8	123	271	
Cu	6.7	4.3	0.8	0.8	35.7	65.5	108

Notes: * Concentration on sediments **< ISQG** = **Rare** Biological Effects
** Concentration on sediments **> ISQG, < PEL** = Occasional Biological Effects
*** Concentration on sediments **> PEL** = F**recuentes** Biological Effects
# **ECA**, Peruvian Environmental Quality Standard

Table 5. Correlation matrix

	EC	NH_4-N	NH_3-N	DO1	DO2	CO_2	PO_4	NO_3
EC	1.000							
NH_4-N	0.011	1.000						
NH_3-N	0.490	-0.253	1.000					
DO1	-0.533	0.062	-0.227	1.000				
DO2	-0.133	-0.001	-0.024	0.240	1.000			
CO_2	0.486	-0.123	0.658	-0.351	-0.052	1.000		
PO_4	0.660	0.086	0.091	-0.633	-0.109	0.151	1.000	
NO_3	0.152	-0.033	-0.027	-0.180	-0.062	0.043	0.035	1.000

Table 6. Multiple Regression – pH

pH	Coef.	Std. Err	t	P>t	[95%	Conf.Interval]
EC	-0.00123	0.00023	-5.39***	0.00000	-0.00168	-0.00077
NH_4-N	-0.00904	0.00674	-1.34	0.18400	-0.02249	0.00441
NH_3-N	2.36717	0.40109	5.9***	0.00000	1.56742	3.16692
DO1	0.12316	0.02583	4.77***	0.00000	0.07167	0.17466
DO2	-0.00118	0.00054	-2.2**	0.03100	-0.00226	-0.00011
CO_2	0.06554	0.03065	2.14**	0.03600	0.00443	0.12664
PO_4	0.28803	0.21338	1.35	0.18100	-0.13744	0.71350
NO_3	0.09278	0.04975	1.87*	0.06600	-0.00641	0.19197
_cons	9.62644	0.41617	23.13***	0.00000	8.79663	10.45626

Notes: ***: Significant al 1%, **: Significant al 5% y *: Significant al 10%

However, the indicators in our study show a slight tendency to increase, probably due to the higher alkaline loading of trout in the cages. Vásquez Quispesivana et al. (2015) have reported a correlation between higher pH and increased trout load. The high pH in the trout farming area in our study might have been caused by the fish population raised in cages in the farm area.

Also, pH can impact the biological productivity in aquatic systems and the viability of aquatic life. Aquatic organisms cannot survive in very low (acidic) or very high pH (alkaline) environments (pH less than 5 or over 9). Most aquatic organisms can thrive between pH 6.0 and 9.0. Water pH levels outside this range can cause stress on the organisms and reduce hatching and survival rates (Li & Liu, 2019b; Pablo Pablo & Hernández Santana, 2016). Very low or very high pH can also affect the solubility and toxicity of chemicals and heavy metals in water.

The matrix of positive or negative correlations between the environmental variables of water and heavy metals in the sediments studied in caged trout rearing in Lake Titicaca ranges from very weak to strong, with a tendency to strong correlation. That is, a slow bioaccumulation of heavy metals is accentuated, which could have adverse long-term consequences (Guédron et al., 2018; Keshavarzi et al., 2019).

The regression estimates show that the dependent variable (pH) has a strong relationship with the other environmental variables (15 independent variables), and that only seven of them were later modeled, those that individually or jointly influence the behavior of the water quality of Lake Titicaca. However, the environmental parameters studied are within the permitted range for all sampling stations and have a bioaccumulative trend. The regression model indicates that there is a statistically significant relationship between the variables with a confidence level of 95.0% and 99.0%, and the R-Squared statistic explains the variability in pH compared to reported studies (Das et al., 2022; Mahmoud Ali et al., 2021).

A strong variability of the environmental parameters studied can weaken the model, which implies the need to reduce the contributions of organic material to this body of water, generated by the excreta of farmed trout and concentrated food residues. These residues, in turn, contribute to a greater bioaccumulation of sediments and therefore the variability of heavy metals, representing a threat to aquatic life and the environment, as well as to the food chain (Balogun & Tella, 2022).

The findings presented (Table 5 and 6) indicate that the interviewed producers of trout in cages are aware of the sustainability risks, which implies that regulatory pressures or the distortion of environmental variables can influence positively or negatively and with it the statistical significance in the regression model or the correlation of the same can always change. For them, the adoption of good ecological production practices, and consequently, consistency with other reported studies, can be a good reputation for environmental performance (Baah et al., 2021).

According to the ECA of Peru, DO levels must be lower than 5 mg L^{-1}. Our results indicate that the average DO in the active trout farming area ranged between 6.00 ± 0.2 to 7.65 ± 0.2 mg L^{-1}, with an average of 6.81 ± 0.2 (Table 3) and extreme values within the range. These values are well within the recommended DO levels by the FAO (7.5 to 12 mg L^{-1}) but lower than the optimum DO recommended by PRODUCE (8.5 mg L^{-1}). Since sufficient levels of DO are crucial for the survival of fish, it is imperative to continuously monitor the trout loading in the cages for the growth of healthy fish.

Low DO levels can adversely affect the growth of trout and its production process. Dissolved oxygen and its temperature can be regulated by several environmental factors such as the wind, solar radiation, air temperature, relative humidity, currents, and photosynthesis (Li & Liu, 2019a). Low levels in DO in the aquatic ecosystem are caused by factors such as temperature, turbidity, decomposing organic matter, and algae blooms, as well as other variables such as algae respiration, plants, animals, and even natural chemical oxidations. Heterotrophy aerobic microorganisms found in the environment are essential to metabolize organic matter (Camargo et al., 2011).

It has been reported that in the afternoon, the wind speed generates waves and turbulence in the water, coinciding with the end of trout feeding, allowing oxygen exchange between the surface layer and the water column. While the maximum level of oxygen occurs in the early hours of the afternoon, with the passing of the hours, near to the night, it gradually decreases with the intensity of light (Ocola Salazar & Laqui Vilca, 2017; Samanez Valer et al., 2014). However, the movement of these waters induces their variability due to the effect of other elements in the environment at the trout production area, as symptoms of aquatic pollution (Mantilla Mendoza, 2008).

It has been pointed out that the number of trout in cages that exceeds the natural carrying capacity causes competition for nutrients (Fontúrbel, 2008). This situation can have adverse consequences for the future of trout farming (Montesinos López, 2018). The amount of Hg in sediments in the trout farming area of Puno Bay in Lake Titicaca is within the range recommended by the Canadian Standard (ISQG = 0.17 mg kg^{-1}).

Regarding the As levels in sediments in the trout farming area and in the control area during the studied period, they exceeded the maximum limits of the Canadian Standard ISQG (i.e., 5.99 mg kg^{-1}) and the Peruvian PEL of 17.0 mg L^{-1}. However, our results do not exceed the maximum allowable limit of ECA Peru for sediments of 50 mg kg^{-1} (DS. 011-2017-MINAM). Likewise, the results indicate that the process of As pollution is evident, taking the Canadian standard as a reference.

Although the As values are within the ECA's limits, they exceed the Canadian limits, suggesting that these sites in Puno Bay are contaminated with As. In addition, Cd values did not exceed the Canadian ISQG standard for cadmium of 0.7 mg kg^{-1}. Furthermore, the measured values are much lower than the PEL (3.5 mg kg^{-1}). These results suggest that Cd is not a pollutant of concern in the cage trout farming area in Puno Bay.

Lead (Pb), Zinc (Zn), and Copper (Cu) levels (Table 4), similar to Cd, did not exceed the minimum values and were within the tolerable maximum limits established by the Canadian standard (ISQG) and the PEL standard. These data suggest that these metals would have a low or no impact on the trout farming area in Puno Bay. However, the presence of heavy metals found even at a minimum level, in the long term, could generate negative impacts on the ecosystem (Mantilla Mendoza, 2008; Ocola Salazar & Laqui Vilca, 2017). However, Monroy, Maceda-Veiga and de Sostoa (2014) reported that in the Ramis River, a tributary of Lake Titicaca, they found concentrations of heavy metals such as Cu, Zn, Cd, Hg, and Pb, with the exception of Co and Fe, that exceeded the tolerance limits established by international law. These results differ from those found in our research. An important fact is that the Ramis River carries discharges from La Rinconada Mining Center, a place of great informal mining industry.

Gammons et al. (2006), analyzing concentrations of mercury in tissue samples of silverside (*Basilichthyes bonariensis*) and carachi (Genus Orestias), found that 27% of silverside and 75% of carachi samples exceeded the EPA criterion levels for fish tissue of 0.30 ug g^{-1}. Also, they pointed out that in the case of silverside (*Basilichthyes bonariensis*), mercury levels increased with the size of the fish, but not in the case of carachi. Therefore, it is clear that Hg used to obtain gold constitutes a source of Hg pollution in Lake Titicaca, in addition to other metals coming from mining centers such as La Rinconada. Likewise, it is known that metals accumulate over time through the components of the trophic chain to reach the fish.

In addition, it must be taken into account that the sediments at the bottom of the lake can disperse heavy metals, constituting one of the main sources of heavy metals entering the aquatic ecosystem (Guédron et al., 2018). Heavy metals can also accumulate in aquatic animals (Keshavarzi et al., 2019; Monroy, Maceda-Veiga, & de Sostoa, 2014). The heavy metals in the sediments evaluated in this research increased slightly in September 2018, both in the trout breeding site and in the control site, except for Cu. This increase is mainly attributed to the influx of agricultural waste, sewage, and sludge carried by runoff from the rains and floods in autumn ((Rajeshkumar et al., 2018).

The spatial analysis of trout rearing studied in Puno of Lake Titicaca, Peruvian Lake, compared to the total space is a key factor for the evaluation of the transport of polluting effects through air, soil, and water (Biamont-Rojas et al., 2023). The indicators presented suggest that anthropogenic activities contribute to these events, increasing the production, deposition, and later concentration of certain elements in a short period, which can lead to adverse consequences in the long term. Therefore, the degradation of water quality in Lake Titicaca must also take into account the role of long or short rainy seasons in the transport of various organic pollutants (mainly nutrients and organic matter), as well as inorganic pollutants (metals) that disturb the aquatic environment over time (Montes-Avila et al., 2019).

Although our data suggest that the metal levels in the trout farming area sediment do not exceed the maximum permissible limits except for As, we must take into consideration the reports by Ali et al. (2016), which suggest that heavy metal pollution in sediments constitutes a global crisis due to its high toxicity. Metals enter the trophic chain, affecting the environment, are not degradable in nature, and accumulate in living aquatic organisms. Eventually, they enter the human food chain when these organisms are consumed, impacting human health. Metals represent a permanent threat to human health and the sustainability of productive activities such as aquaculture (Paul, 2017).

Although the low levels of heavy metals found in the sediments of Lake Titicaca suggest that there is slow bioaccumulation of them, this could have adverse long-term consequences (Guédron et al., 2018; Keshavarzi et al., 2019). In addition, the contamination process due to trout farming activity in Lake Titicaca is evident, as reported by Mantilla Mendoza (2008) and Ocola Salazar and Laqui Vilca (2017). Meanwhile, it is also possible to say that the presence of As found in the environment of the installed trout cages, based on the geological and chemical composition of the basin, has a natural origin.

The projection of water quality measured by pH shows that the variability of environmental parameters turned out to be slight in general, with a slight reduction of the environmental setbacks in the second quarter and a rise again in the third quarter (9.52, 9.55, 9.52, and 9.64). This suggests that water quality is self-recycled by the same water currents of the immensity of Lake Titicaca. Moreover, the collection of water for the drinking water supply in the city of Puno occurs in the outer bay where the trout cages are located. As a result, As could represent a problem for public health, and continuous monitoring is required.

Finally, the data obtained in this investigation indicate that food waste, fish excrement, mesh degradation of trout farming nets in floating cages, plastics, rubber residues, and other polluting components contribute to the generation of slight distortions. Therefore, the quality of the water and the concentration of metals in the sediments, despite the fact that the aquatic biota of Lake Titicaca remains acceptable (Guédron et al., 2020). However, it could represent a problem for public and environmental health in the long term, which requires continuous monitoring by the institutions in charge of its surveillance.

Consequently, the occurrence of fluctuations in water quality levels due to climate variability, combined with inorganic agents, can induce the appearance of diseases, as well as the presence of antibiotics during the productive phase of trout farming in floating cages (Lima-Quispe et al., 2021; Vilca et al., 2021). Similarly, it could be a consequence of trout mortality that has appeared in the last decade (Medina et al., 2020). Therefore, the sanitary authorities in charge of public health, together with the Ministry of Production, including the Ministry of the Environment of Peru, should implement preventive measures to safeguard local and global citizenship, including the preservation and environmental conservation of Lake Titicaca.

In short, the environmental indicators analyzed indicate that there is a slow bioaccumulation of adverse substances with probable biological effects that could have serious long-term consequences beyond a certain tolerance limit, facts that compromise the sustainability of Lake Titicaca, as reported in other studies. Among them, cultural eutrophication as the main cause would be the degradation of water quality worldwide, from which Lake Titicaca is not exempt. Therefore, traditional monitoring of eutrophication and other polluting agents requires more time and greater research efforts.

5. CONCLUSIONS

The physicochemical parameters of the water in Lake Titicaca indicate that the water quality in the trout farming area was healthy and suitable for farming. The heavy metals in the sediments, with the exception of As, were found to be within the tolerance margins established by the Environmental Quality Standards. Only As exceeded the tolerance limit for ISQG. These heavy metals tend to bioaccumulate in the environment over time and may exceed the recommended limits, compromising the sustainability of Lake Titicaca.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear and influence the work reported in this paper.

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