Bioindicators and Heavy Metal Pollution in High-Andean Peruvian Lakes: A Limnological Approach.

Bioindicadores y contaminación por metales pesados en lagunas altoandinas peruanas: Un enfoque limnológico

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Highlights

- Water and sediment samples from the high-Andean lakes show evidence of heavy metal contamination.
- The results suggest that eutrophication is occurring in the three evaluated high-Andean lakes due to anthropogenic activity.
- The most abundant macroinvertebrate families were Corixidae (Hemiptera) and Dytiscidae (Coleoptera).

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ABSTRACT

Introduction. High-Andean lakes represent vital sociocultural, economic, and environmental assets for local communities and are ecologically significant ecosystems that require protection and conservation. Understanding their limnological characteristics is key to guiding both conservation and sustainable use strategies. **Objectives.** To assess the limnological characteristics of three high-Andean lakes in Quiruvilca, La Libertad region, Peru, located in an area influenced by mining activities. **Materials and Methods.** Semiannual sampling was conducted between 2017 and 2019. Measurements included physicochemical parameters—temperature, conductivity, pH, dissolved oxygen (DO), oxygen saturation, and transparency—as well as concentrations of heavy metals in water and sediments. Aquatic macroinvertebrates were identified to the family level. Water quality was evaluated using the Biological Monitoring Working Party (BMWP) index and the Andean Biotic Index (ABI). Descriptive statistics, ANOVA, and correlation analyses were applied to explore trends and variability. **Results.** The average values recorded for the physicochemical parameters were temperature of 12.6 °C, pH of 4.5, conductivity of 20.4 µS/cm, dissolved oxygen (DO) of 6.5 mg/L, oxygen saturation of 99.8%, and water transparency ranging from 0.37 to 3.0 meters. Heavy metals—arsenic, copper, mercury, and lead—exceeded permissible thresholds. The most abundant macroinvertebrate families were Corixidae, Dytiscidae, Hyalellidae, Planariidae, and Chironomidae. **Conclusions.** The lakes exhibited relatively stable limnological conditions but moderate contamination levels. Despite supporting aquatic life, the water is unsuitable for human or livestock consumption. Remediation strategies are therefore necessary to mitigate contamination risks.

RESUMEN

Introducción. Las lagunas altoandinas constituyen un patrimonio sociocultural, económico y ambiental para las comunidades locales, además de ser ecosistemas ecológicamente relevantes que requieren protección y conservación. El conocimiento de sus características limnológicas es fundamental para orientar estrategias de conservación y aprovechamiento sostenible. **Objetivos.** Evaluar las características limnológicas de tres lagunas altoandinas ubicadas en Quiruvilca, región La Libertad, Perú, en una zona con influencia minera. **Materiales y Métodos.** Se realizaron muestreos semestrales entre 2017 y 2019. Se midieron parámetros fisicoquímicos (temperatura, conductividad, pH, oxígeno disuelto, saturación de oxígeno y transparencia), así como las concentraciones de metales pesados en agua y sedimentos. Se identificaron macroinvertebrados acuáticos a nivel de familia. La calidad del agua se evaluó mediante los índices BMWP (Biological Monitoring Working Party) y ABI (Índice Biológico Andino). Se aplicaron análisis descriptivos, ANOVA y correlaciones para explorar tendencias y variabilidad. **Resultados.** Los valores promedios registrados paras los parámetros físicos químicos fueron, temperatura de 12,6 °C, pH de 4,5, conductividad de 20,4 µS/cm, Oxígeno Disuelto de 6,5 mg/L, Saturación de Oxígeno de 99,8% y transparencia entre 0,37 y 3,0 m. Los metales pesados (Arsénico, Cobre, Mercurio y Plomo) excedieron los límites permisibles. Las familias de macroinvertebrados más abundantes fueron Corixidae, Dysticidae, Hyalellidae, Planariidae y Chironomidae. **Conclusiones**. Las lagunas presentaron condiciones limnológicas relativamente estables, pero con niveles moderados de contaminación. Aunque aún sustentan vida acuática, el agua no es apta para el consumo humano ni animal. Por tanto, es necesario implementar estrategias de remediación para reducir los riesgos asociados a la contaminación.

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INTRODUCTION

High-Andean wetlands are critical ecosystems located on elevated plateaus across the Andes in Chile, Argentina, Peru, and Bolivia. These environments function as true oases, sustaining life in otherwise arid regions, and exhibit ecological dynamics that differ markedly from lowland tropical lakes due to their altitude and prevailing climatic conditions [(1) (2) (3)]. In recent decades, these aquatic systems have been increasingly impacted by anthropogenic pressures, including growing demands for water, food, and land. These pressures are linked to population expansion, unplanned urban development, and intensified economic activity. Such trends have sparked concern over the sustainability of water and land resources, particularly given projections of a 50% increase in global food demand and a 30% rise in clean water consumption by 2030—factors expected to further aggravate water scarcity [(4)].

Under these conditions, it is imperative to foster greater awareness and understanding of sustainable water management, especially in tropical developing countries where challenges related to water quality and supply are particularly acute [(5)]. Due to their high environmental heterogeneity, high-Andean wetlands are classified as fragile multifunctional ecosystems [(6)]. This heterogeneity results from complex interactions between geomorphology, climate, precipitation, hydrological regimes, and fluvial systems [(2) (7)]. Consequently, monitoring both biological diversity and physicochemical characteristics is essential for evaluating water quality [(8) (9) (10)].

Human activities—such as agriculture, urban development, dam construction, and hydrological alterations—frequently lead to changes in environmental conditions that affect the abundance and diversity of aquatic macroinvertebrates [(11) (12)]. Given their sensitivity to such environmental shifts, the richness and abundance of benthic macroinvertebrates are widely recognized as effective biological indicators of ecosystem health. As a result, research on the distribution patterns of these organisms in high-Andean ecosystems has gained increasing importance [(13)].

Limnological studies in tropical lakes—based on variables such as pH, dissolved oxygen, turbidity, and nutrient concentrations—are commonly used to assess environmental quality and guide sustainable use [(14)]. These variables also serve as predictors of biological community composition [(15)]. Advances in technology, such as the development of limnological sensors and reduced costs of analytical equipment, have allowed researchers to collect broader and more temporally extensive environmental data [(14)].

In Peru, however, progress in the classification, evaluation, and national inventory of wetlands has been limited. While the Ministry of the Environment has estimated that rivers, lakes, and lagoons cover 2,320,256 ha, floodplain tropical forests 15,361,839 ha, and high-Andean wetlands only 548,174 ha, the latter represent a much smaller surface area and are therefore more vulnerable to pollution—especially from mining activities [(13) (16)].

In the district of Quiruvilca, located in the province of Santiago de Chuco, La Libertad region, Peru, several high-Andean lakes are situated in a landscape impacted by mining, agriculture, livestock, and road infrastructure [(13)]. These pressures have resulted in socio-environmental conflicts linked to the degradation of lake water quality, which is vital for the survival of local communities that depend on these ecosystems.
It is therefore essential to investigate the limnological characteristics of these lakes and quantify the concentrations of heavy metals—such as lead (Pb), arsenic (As), and cadmium (Cd)—that may be introduced through mining activity. This information is crucial for evaluating water quality and for designing appropriate conservation or remediation strategies. Accordingly, the objective of this study is to characterize the

limnological conditions of three high-Andean lakes in Quiruvilca, Peru, determine the degree of heavy metal contamination, and analyze the structure of macroinvertebrate communities as indicators of environmental quality.

MATERIALS AND METHODS

Study Area. The lakes known as Las Verdes 1, 2, and 3 are located 140 km east of the city of Trujillo, in the district of Quiruvilca, La Libertad region, Peru. Lake 1 is 169 m from Lake 2, Lake 2 is 174 m from Lake 3, and Lake 1 is 438 m from Lake 3. Lake Las Verdes 1 is located at 7°58'40.94"S and 78°14'41.45"W at an elevation of 4079 m a.s.l.; Lake Las Verdes 2 at 7°58'36.06"S and 78°14'29.97"W, 4081 m a.s.l.; and Lake Las Verdes 3 at 7°58'41.81"S and 78°14'19.24"W, at 4099 m a.s.l. Their surface areas are 2.767, 0.274, and 0.306 hectares, respectively. All three lakes have irregular morphologies and glacial origins, occupying nearly the entire floor of a high-Andean plateau. They are considered small-basin lakes, surrounded by herbaceous vegetation **(Figure 1)**.

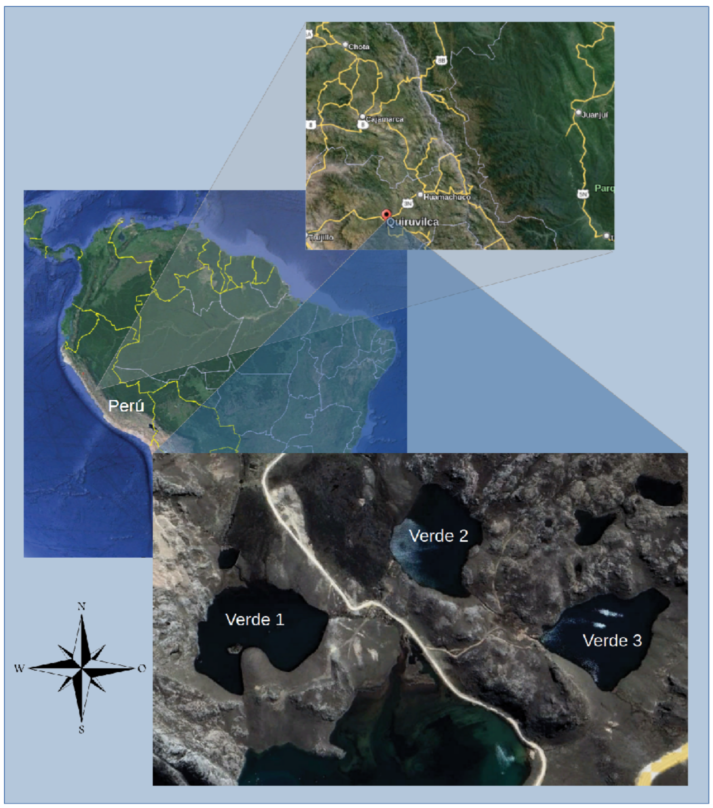

Figure 1. Geographic location of Las Verdes 1, 2, and 3 lakes in Quiruvilca, La Libertad region, Peru. *Source: Google Earth.*

Sampling Procedures. Water sampling followed the methodology established in section 6.5.2 of the *National Protocol for Monitoring the Quality of Surface Water Bodies*, issued by the National Water Authority of Peru under the Ministry of Agriculture and Irrigation [17], along with guidance from previous research methodologies [18] [19].

In each lake, two fixed sampling stations were established: one near the dam or shoreline, and the other at the center of the limnetic zone. Samples were collected at depths between 20 and 30 cm on a semiannual basis from 2017 to 2019. Surface water was collected using a pre-cleaned 10-liter bucket, rinsed with lake water prior to sampling. The water was then transferred into pre-rinsed containers and kept refrigerated during transport to the laboratory.

Sampling was conducted at the surface layer only, as the lakes are shallow, exposed to strong winds, located above 4000 m a.s.l., and thus considered polymictic. This classification was confirmed during pilot studies using vertical profiles of physicochemical parameters, which showed a homogeneous water column. Measured parameters included temperature (T), conductivity (C), pH, dissolved oxygen (DO), and oxygen saturation (OS).

In December 2019, ten sediment samples were collected using 250 mL self-sealing bags, following the *Soil Sampling Guide* standards [20]. Samples were taken from the center of each lake during the first week of December. Sediments were collected with a Van Veen grab sampler (sampling area: 0.05 m^2) and transported under refrigeration for further analysis. Chemical analysis was performed using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) to determine concentrations of heavy metals (arsenic, cadmium, chromium, copper, mercury, lead, and zinc). These concentrations were compared against the *Canadian Sediment Quality Guidelines for the Protection of Aquatic Life* [21].

Physicochemical and Biological Parameters. Water quality data from 2017 to 2019 were obtained using a HACH HQ40d multiparameter probe, which measures temperature, conductivity, pH, and dissolved oxygen, and is calibrated with certified standards. Transparency was measured using a Secchi disk [22].

Heavy metal concentrations in water and sediment. Heavy metals were quantified following the US-EPA 1994 guidelines, while total nitrogen was analyzed using the APHA-AWWA-WEF Method 4500 N (22nd edition, 2012) [23]. The results were interpreted based on threshold values established in the *Interim Sediment Quality Guidelines* (ISQG) and the *Probable Effect Level* (PEL).

Macroinvertebrate Monitoring. Aquatic macroinvertebrates were collected semiannually from 2017 to 2019 using two sampling methods along the shoreline. The first involved a Surber-type kick net (250 µm mesh size) for semi-quantitative analysis, composed of polyester monofilament. The second method was manual collection from different substrates following Roldán's protocol [24], which includes sweeping sandy substrate and removing material from rocky and macrophyte-covered areas directly into collection jars. Sampling accounted for both dry season (DS) and rainy season (RS) periods. Specimens were preserved in glass jars containing 70% ethanol and later identified in the laboratory using a ZEISS Stemi 508 stereomicroscope. Taxonomic identification to the family level was performed using keys by Domínguez & Fernández [25] and Huamantinco & Ortiz [26]. Water quality assessment based on macroinvertebrates was conducted using the *Biological Monitoring Working Party* index adapted for Colombia (BMWP/Col) [24] and the *Andean Biotic Index* (ABI) [27] [28].

Data Analysis. Descriptive data analysis was carried out using Microsoft Excel 2016. Bar graphs were used to visualize the results. To assess the significance of variation in physicochemical parameters by lake, year, and sampling station, a multifactorial analysis of variance (ANOVA) was applied. Pearson's multiple correlation analysis was used to explore relationships between parameters, both with a significance level of $\alpha = 0.05$. Statistical processing was carried out using Statgraphics Centurion XVII [29].

RESULTADOS

Physicochemical Parameters

The results of the physicochemical parameters measured in the three studied lakes are summarized in **(Table 1)**.

Table 1. Average physicochemical parameters of Las Verdes 1, 2, and 3 lakes from 2017 to 2019.

Lake	Sampling poin	Year	T (°C)	EC (µS/cm)	pH	OD (mg/L)	OS (%)	Transparency (m)
Verde 1	S	2017	12.8	13.3	4.0	6.3	100.9	0.50
		2018	13.4	14.6	4.2	6.6	102.5	
		2019	11.1	56.1	4.8	6.6	96.7	
	C	2017	14.1	15.3	4.5	6.8	104.2	3.00
		2018	10.3	16.7	4.0	6.1	93.2	
		2019	10.2	36.4	4.4	6.6	94.9	
Verde 2	S	2017	14.0	15.3	4.5	6.3	100.9	0.38
		2018	14.2	22.5	4.4	6.4	98.1	
		2019	12.2	17.1	4.4	6.6	96.7	
	C	2017	14.5	29.8	4.4	6.5	103.5	2.70
		2018	10.7	15.1	4.0	6.3	99.8	
		2019	11.45	16.1	4.2	6.45	98.25	
Verde 3	S	2017	13.8	16.0	4.5	6.4	104.0	0.37
		2018	13.9	16.6	4.7	6.5	103.8	
		2019	12.3	17.2	49	6.5	99.7	
	C	2017	14.0	17.2	5.0	6.6	103.6	3.00
		2018	11.2	15.5	4.5	6.2	97.6	
		2019	11.75	16.5	4.7	6.35	98.65	

T = Temperature; E**C** = Electrical conductivity; **DO** = Dissolved oxygen; **OS** = Oxygen saturation, **C** = center. **S**=Shoreline

Water temperature (T) values **(Table 1)**, ranged from 10.2 to 14.5 °C, with a total variation of 4.3 °C. The lowest temperature was recorded in 2019 at Lake Las Verdes 1, while the highest occurred in 2017 at Lake Las Verdes 2. The overall mean temperature across the three lakes was 12.55 °C, with a coefficient of variation of 11.8%, indicating moderate variability. Electrical conductivity (EC) ranged from 11.0 to 56.1 µS/cm, with the highest value in Lake Las Verdes 1 and the lowest in Lake Las Verdes 3. The total range was 42.8 µS/cm, and the mean conductivity was 20.4 µS/cm, with a coefficient of variation of 52.17%, reflecting a high degree of variability in this parameter. pH values ranged from 4.0 to 5.0, with a mean of 4.45 and a coefficient of variation of 6.69%. Higher pH values were observed in Lakes Las Verdes 2 and 3, while Lake Las Verdes 1 recorded the lowest values, confirming acidic conditions in all three lakes.

Dissolved oxygen (DO) concentrations ranged from 6.1 to 6.8 mg/L, with a mean of 6.45 mg/L and a coefficient of variation of 2.69%, indicating low variability among the lakes. Oxygen saturation (OS) ranged from 93.2% in Lake Las Verdes 1 (2018) to 104.2% in the same lake (2017), with a mean of 99.83% and a variation coefficient of 3.34%, also reflecting low variability.

Transparency values varied substantially, ranging from 0.37 to 3.0 m. The lowest value was recorded at the shoreline of Lake Las Verdes 3, and the highest at the center of that same lake and Lake Las Verdes 1. The total range was 2.63 m, and the mean transparency was 1.66 m. With a coefficient of variation of 75.2%, transparency was the most variable parameter measured, generally higher at lake centers than at the shorelines.

The multifactorial analysis of variance (ANOVA) revealed statistically significant differences in physicochemical parameters among the three lakes, monitoring years, and sampling locations, as summarized in **(Table 2)**.

Table 2. Multifactorial analysis of variance (ANOVA) for the average physicochemical parameters of Las Verdes lakes from 2017 to 2019.

Factor	T (ºC)	EC (µS/cm)	pH	DO (mg/L)	OS (%)	Transparency (m)
Year	0.0005*	0.0974	0.0811	0.1887	0.0292*	-----
Lake	0.0160*	0.1474	0.0149*	0.5792	0.2403	0.0000*
Sampling point	0.0023*	0.7181	0.3305	0.6253	0.3538	0.0000*

T = Temperature; **EC** = Electrical conductivity; **DO** = Dissolved oxygen; **OS** = Oxygen saturation; **(*)** = Indicates statistically significant variation ($p < 0.05$).

The physicochemical parameter that exhibited the greatest variation was temperature, which showed statistically significant differences across all three factors: spatially within individual lakes, between lakes, and temporally across the monitoring years. In contrast, conductivity and dissolved oxygen did not exhibit significant spatial or temporal variation. pH remained consistent over time and across sampling points, but varied significantly among lakes, indicating differing levels of acidity in each system. Oxygen saturation did not vary among lakes or sampling points, but did show significant interannual variation, indicating temporal differences. Although transparency values were generally similar, this parameter varied significantly both among lakes and between sampling points.

The Pearson correlation analysis **(Table 3)**, showed no statistically significant relationships among most of the measured physicochemical parameters. However, a significant positive correlation was found between temperature and oxygen saturation, indicating that these two variables were closely related across the study period.

Table 3. Results of Pearson's multiple correlation analysis for the average physicochemical parameters of Las Verdes lakes from 2017 to 2019.

Parameter		T (°C)	EC (µS/cm)	pH	DO (mg/L)	OS (%)
T (°C)	R	—				
	p - value	—				
CE (µS/cm)	R	- 0.2620	—			
	p - value	0.2936	—			
pH	R	0.2951	0.2771	—		
	p - value	0.2345	0.2656	—		
DO (mg/L)	R	0.3441	0.3163	0.4337	—	
	p - value	0.1621	0.2010	0.0721	—	
OS (%)	R	0.8234 ***	- 0.3284	0.2688	0.3819	—
	p - value	0.0000	0.1833	0.2807	0.1179	—
Transparency (m)	R	- 0.3782	- 0.0453	- 0.1143	- 0.0915	- 0.1815
	p - value	01217	0.8582	0.6515	0.7181	0.4710

T = Temperature; **C** = Electrical conductivity; **DO** = Dissolved oxygen; **OS** = Oxygen saturation; (***) = $p < 0.001$.

As shown in **(Table 3)**, most of the correlations among physicochemical parameters were weak [30] and not statistically significant ($p > 0.05$), indicating low interdependence among them. Transparency was notable for presenting negative correlations with all other parameters, ranging from weak to moderate in magnitude. The only strong and statistically significant correlation (R > 0.7) was found between temperature and oxygen saturation (R = 0.8234; p = 0.0000), suggesting that, under the conditions of this study, an increase in temperature is associated with a significant rise in oxygen saturation in the water of the high-Andean lakes. In terms of water quality, the concentrations of nitrogen and lead were found to exceed the permissible limits for lakes and lagoons established by Peruvian environmental legislation [31].

According to Peruvian environmental quality standards (ECA), the permissible limit for total nitrogen in lakes and lagoons is 0.315 mg/L. In this study, all measured values exceeded this threshold. The highest concentration was recorded at the center of Lake Las Verdes 2 (2.13 mg/L), while the lowest was found at the shoreline of Lake Las Verdes 3 (0.34 mg/L), which had the overall lowest nitrogen levels among the three lakes **(Figure 2)**.

For lead, the ECA limit is 0.001 mg/L; however, the concentrations recorded were well above this value. Notably, Lake Las Verdes 3 showed the highest lead levels, with 0.05322 mg/L at the center and 0.00675 mg/L at the shoreline. Similarly, Lake Las Verdes 1 exhibited elevated concentrations, ranging from 0.01352 mg/L at the center to 0.00357 mg/L at the shoreline **(Figure 2)**. In contrast, concentrations of arsenic and cadmium remained below the ECA thresholds established by Peruvian legislation, which are 0.01 mg/L and 0.004 mg/L, respectively **(Figure 2)**.

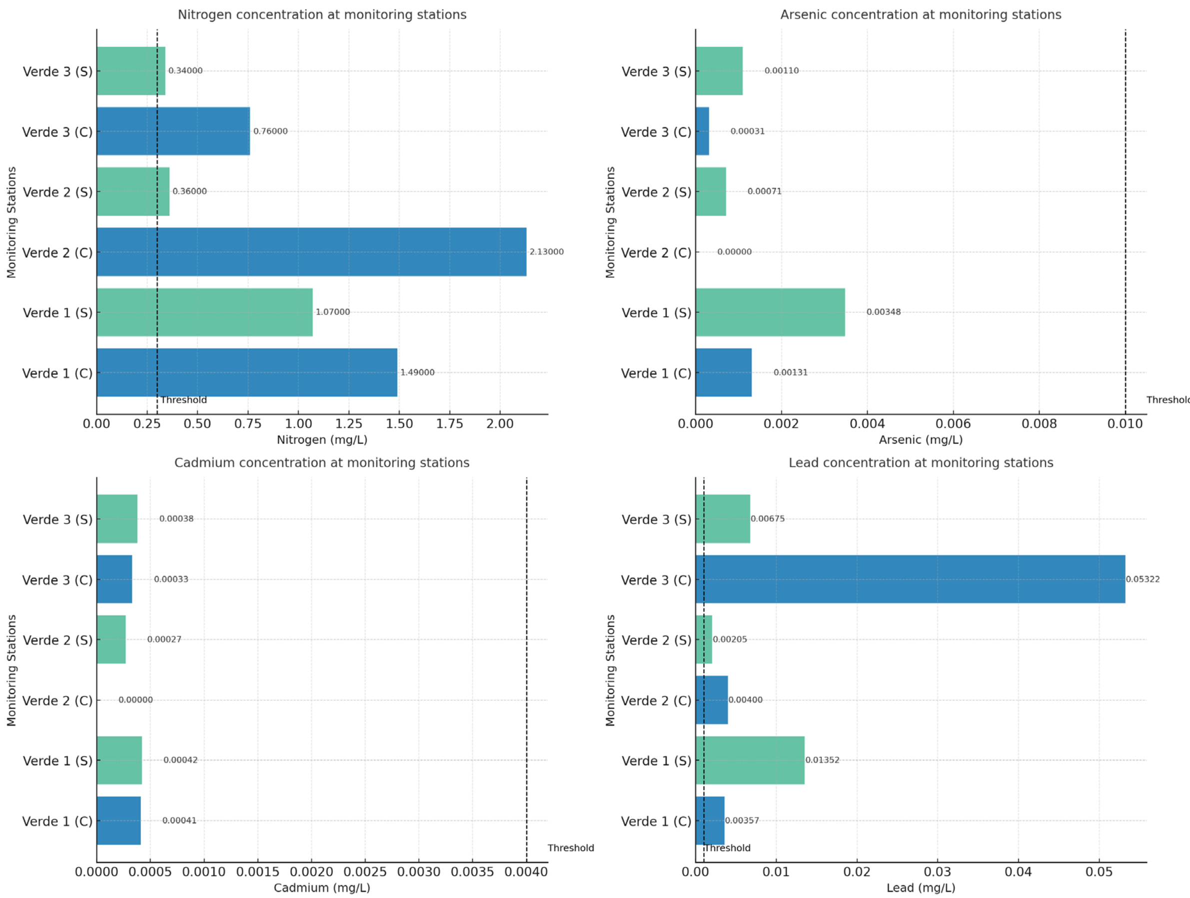

Figure 2. **Levels of nitrogen, arsenic, cadmium, and total lead in the water of Las Verdes 1, 2, and 3 lakes.** Permissible ECA thresholds are indicated by dotted lines

Arsenic concentrations in sediment remained below the PEL (Probable Effect Level) threshold of 17.0 mg/kg in most cases. A value of 8.7 mg/kg was reported at the center of Lake Las Verdes 3. However, significantly elevated concentrations were found in Lake Las Verdes 1, with 200.0 mg/kg recorded at the center and 78.9 mg/kg at the shoreline, far exceeding the permissible limit **(Figure 3)**. Cadmium concentrations in the sediment samples from the studied lakes did not exceed the PEL threshold of 3.5 mg/kg in any case. However, in Lake Las Verdes 1, values slightly surpassed the ISQG limit of 0.6 mg/kg, with maximum concentrations of 0.7959 mg/kg at the center and 0.7582 mg/kg at the shoreline **(Figure 3)**. Chromium was detected at low levels in all samples, remaining well below both the ISQG (37.3 mg/kg) and PEL (90.0 mg/kg) reference thresholds. The highest value was recorded at the shoreline of Lake Las Verdes 3 (3.2 mg/kg) **(Figure 3)**. In the case of copper, the highest concentrations were found in Lake Las Verdes 3, with 134.95 mg/kg at the shoreline and 39.86 mg/kg at the center. These were followed by Lake Las Verdes 1, with 85.57 mg/kg at the shoreline and 43.19 mg/kg at the center. Although most sampling points exceeded the ISQG limit of 35.7 mg/kg, none of the values surpassed the PEL threshold of 197.0 mg/kg **(Figure 3)**.

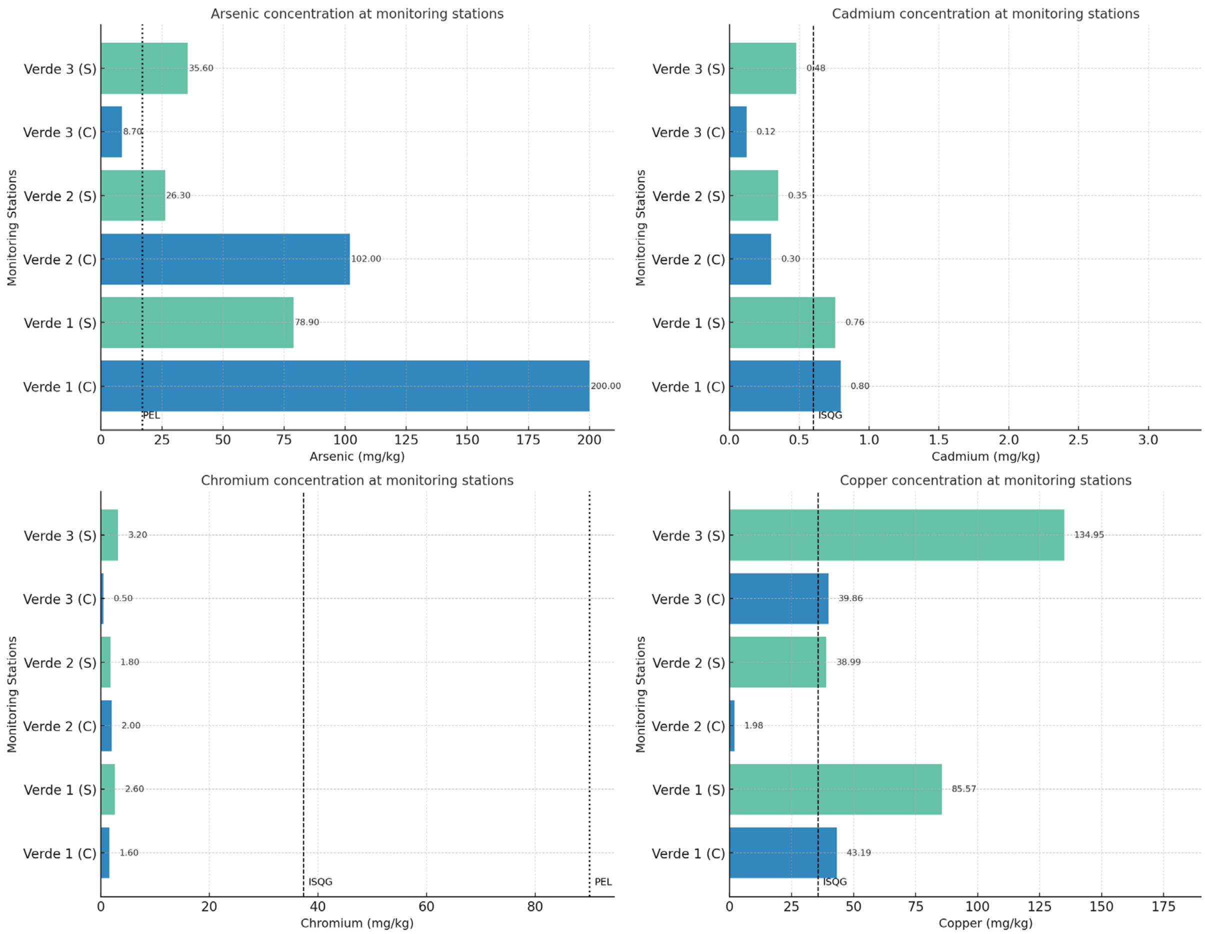

Figure 3. Concentrations of heavy metals (Arsenic, cadmium, chromium, and copper) in sediment samples, compared to the reference values established by the ISQG (Interim Sediment Quality Guidelines) and the PEL (Probable Effect Level). C=center, **S**= shoreline.

Lead concentrations exceeded the ISQG guideline in most sampling points, except at the shoreline of Lake Las Verdes 2 (31.421 mg/kg) and at the center of Lake Las Verdes 3 (9.649 mg/kg). The PEL limit for lead (91.3 mg/kg) was exceeded at the center of Lake Las Verdes 2 (91.399 mg/kg) and at the shoreline of Lake Las Verdes 3 (100.47 mg/kg) **(Figure 4)**. Mercury exceeded all established limits, with values above both the ISQG (0.17 mg/kg) and the PEL (0.486 mg/kg). The highest concentrations were observed in Lake Las Verdes 1, with 1.49 mg/kg and 1.50 mg/kg at the center and shoreline, respectively. Elevated levels were also recorded at the center of Lake Las Verdes 2 (1.31 mg/kg) **(Figure 4)**. Zinc concentrations were well below the ISQG (123 mg/kg) and PEL (315 mg/kg) thresholds across all samples. The highest values were found in Lake Las Verdes 3 (73.50 mg/kg at the shoreline), followed by Lake Las Verdes 1 (50.13 mg/kg at the center) **(Figure 4)**

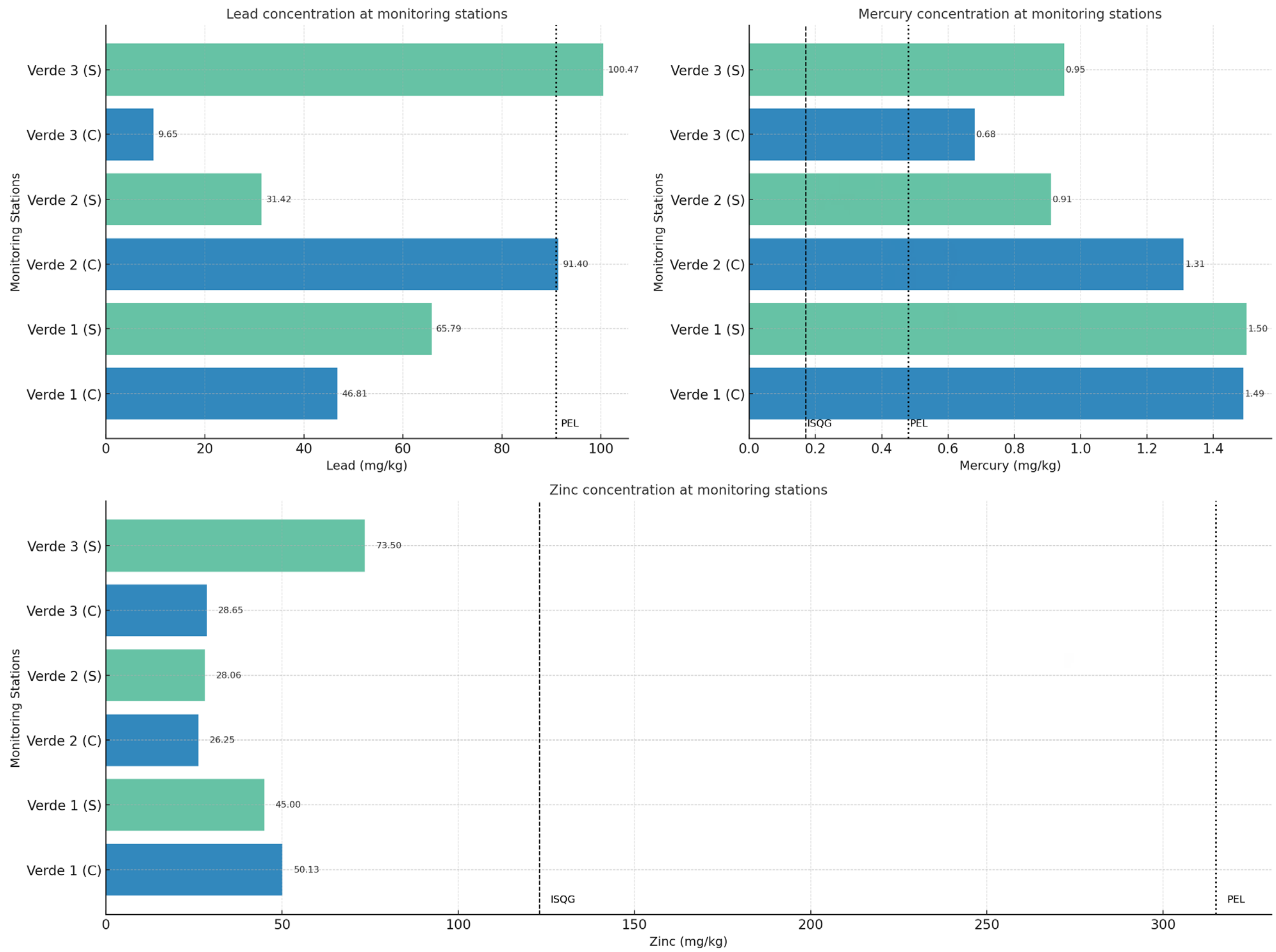

Figure 4. Concentrations of heavy metals (Lead, Mercury and Zinc) in sediment samples, compared to the reference values established by the ISQG (Interim Sediment Quality Guidelines**) and the PEL (**Probable Effect Level**). C**=center, **S**= shoreline.

Macroinvertebrate assemblages, summarized in **(Table 4)**, by family, year, lake, and season (dry season [DS], rainy season [RS]), revealed consistent dominance by Corixidae (Hemiptera) and Dytiscidae (Coleoptera) in Lake Las Verdes 1 across all years (2017–2019). Notably, Planariidae emerged as the second most abundant group during the 2019 dry season.

Table 4. Taxonomic identification of aquatic macroinvertebrates used as water quality indicators in Lakes Las Verdes 1, 2, and 3.

Family	Verde 1						Verde 2						Verde 3					
	2017		2018		2019		2017		2018		2019		2017		2018		2019	
	DS	RS	DS	RS	DS	RS	DS	RS	DS	RS	DS	RS	DS	RS	DS	RS	DS	RS
Corixidae	17	18	18	11	14	17	17	18	18	11	14	17	10	9	11	9	5	16
Dysticidae	20	12	17	14	7	11	20	12	17	14	7	11	26	6	17	11	6	10
Glossiphoniidae	0	15	0	3	0	6	0	15	0	3	0	6	0	7	5	2	0	0
Chironomidae	14	0	14	0	23	7	14	0	14	0	23	7	0	15	19	10	29	0
Planariidae	0	15	0	25	26	20	0	15	0	25	26	20	48	34	33	48	34	49
Hydrachnidae	0	0	19	15	0	10	0	0	19	15	0	10	0	0	0	0	0	0
Simulidae	15	0	0	0	0	7	15	0	0	0	0	7	1	3	0	6	0	4
Tipulidae	0	0	0	6	0	7	0	0	0	6	0	7	0	0	0	0	0	0
Ephydridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3	7
Stratiomyidae	0	4	0	15	0	5	0	4	0	15	0	5	0	0	0	0	0	0
Ceratopogonidae	14	16	14	0	0	0	14	16	14	0	0	0	0	9	0	0	0	4
Hydrobiosidae	8	0	0	0	2	4	8	0	0	0	2	4	0	0	0	3	0	2
Glossosomatidae	0	3	0	5	0	2	0	3	0	5	0	2	0	9	0	4	0	5
Hyalellidae	11	17	2	6	28	0	11	17	2	6	28	0	14	8	2	5	24	0
Tubificidae	0	0	15	0	0	4	0	0	15	0	0	4	0	0	15	0	0	3
Total Family	7	8	7	9	6	12	7	8	7	9	6	12	5	9	7	10	6	9

Data represent absolute abundance. **DS**=Dry season; **RS**= rainy season

In Lake Las Verdes 2, Dytiscidae was the most abundant family during the 2017 dry season, while Corixidae dominated in the rainy season. By 2019, Planariidae became the most abundant family in both seasons, accompanied by a notable increase in Hyalellidae during the dry period. In contrast, Lake Las Verdes 3 exhibited lower macroinvertebrate family diversity, with Planariidae consistently dominating across all three study years (2017–2019). Water quality assessments using the BMWP/Col and ABI indices reflected these ecological patterns, highlighting differences among the lakes (Table 5).

Table 5. Water quality classification based on the Biological Monitoring Working Party index adapted for Colombia (BMWP/Col) and the Andean Biotic Index (ABI) for Las Verdes 1, 2, and 3 lakes.

Lake	Year	Season	BMWP /Col		ABI	
			Value	Condition	Valor	Condición
Verde 1	2017	Dry	24+4.9	Severely Polluted	16+4.8	Poor
		Wet	44+5.7	Doubtful – Moderately Polluted	34+5.3	Fair
	2018	Dry	29+6.1	Severely Polluted	22+5.3	Poor
		Wet	45+5.0	Doubtful – Moderately Polluted	36+4.1	Fair
	2019	Dry	25+6.1	Severely Polluted	15+5.9	Poor
		Wet	40+3.7	Doubtful – Moderately Polluted	31+4.7	Fair
Verde 2	2017	Dry	45+4.1	Good – Slightly Polluted	33+3.5	Fair
		Wet	47+4.4	Good – Slightly Polluted	37+2,3	Fair
	2018	Dry	33+5.2	Doubtful – Moderately Polluted	25+3.3	Fair
		Wet	51+3.4	Good – Slightly Polluted	42+3,7	Fair
	2019	Dry	41+4.1	Doubtful – Moderately Polluted	29+2.9	Poor
		Wet	64+3.1	Good – Slightly Polluted	50+2.9	Fair
Verde 3	2017	Dry	38+3.1	Doubtful – Moderately Polluted	24+3,4	Poor
		Wet	53+2.5	Doubtful – Moderately Polluted	40+3.8	Fair
	2018	Dry	36+3.7	Doubtful – Moderately Polluted	25+4.1	Poor
		Wet	54+4.1	Doubtful – Moderately Polluted	37+3.9	Fair
	2019	Dry	34+3.6	Severely Polluted	21+4.2	Poor
		Wet	53+3.7	Doubtful – Moderately Polluted	38+3.7	Fair

Overall, the studied lakes exhibited a range of water quality conditions, classified as critical (heavily polluted), questionable (moderately polluted), and good (slightly polluted).

According to the BMWP/Col index, Lake Las Verdes 2 was the least polluted, showing good water quality in most cases, with only one questionable condition reported during the dry season of 2018. In contrast, Lake Las Verdes 1 had the highest levels of pollution, with critical conditions recorded during the dry seasons of all three years and questionable quality during the rainy seasons. Lake Las Verdes 3 was generally classified as moderately polluted throughout the study period, with a single critical condition reported during the dry season of 2019.

Based on the ABI index, the general condition of the three lakes ranged from fair to poor. Only one good condition was recorded for Lake Las Verdes 2 during the rainy season of 2019, along with two poor conditions, making it the lake with the lowest level of contamination. The remaining two lakes presented 50% fair and 50% poor conditions, indicating moderate levels of pollution.

RESULTS

Water temperature (T) values **(Table 1)**, ranged from 10.2 to 14.5 °C, with a total variation of 4.3 °C. The lowest temperature was recorded in 2019 at Lake Las Verdes 1, while the highest occurred in 2017 at Lake Las Verdes 2. The overall mean temperature across the three lakes was 12.55 °C, with a coefficient of variation of 11.8%, indicating moderate variability.

Electrical conductivity (EC) ranged from 11.0 to 56.1 µS/cm, with the highest value in Lake Las Verdes 1 and the lowest in Lake Las Verdes 3. The total range was 42.8 µS/cm, and the mean conductivity was 20.4 µS/cm, with a coefficient of variation of 52.17%, reflecting a high degree of variability in this parameter.
pH values ranged from 4.0 to 5.0, with a mean of 4.45 and a coefficient of variation of 6.69%. Higher pH values were observed in Lakes Las Verdes 2 and 3, while Lake Las Verdes 1 recorded the lowest values, confirming acidic conditions in all three lakes.

Dissolved oxygen (DO) concentrations ranged from 6.1 to 6.8 mg/L, with a mean of 6.45 mg/L and a coefficient of variation of 2.69%, indicating low variability among the lakes. Oxygen saturation (OS) ranged from 93.2% in Lake Las Verdes 1 (2018) to 104.2% in the same lake (2017), with a mean of 99.83% and a variation coefficient of 3.34%, also reflecting low variability.

Transparency values varied substantially, ranging from 0.37 to 3.0 m. The lowest value was recorded at the shoreline of Lake Las Verdes 3, and the highest at the center of that same lake and Lake Las Verdes 1. The total range was 2.63 m, and the mean transparency was 1.66 m. With a coefficient of variation of 75.2%, transparency was the most variable parameter measured, generally higher at lake centers than at the shorelines. A multifactorial ANOVA **(Table 2)**, revealed statistically significant differences in physicochemical parameters across lakes, years, and sampling locations. Temperature showed significant spatial and temporal variation.

In contrast, conductivity and dissolved oxygen did not vary significantly between lakes or across years. pH remained stable over time and across locations, but differed significantly among lakes. Oxygen saturation varied significantly between years but not spatially. Transparency, although generally similar, showed significant differences both among lakes and between sampling points.

Pearson correlation analysis **(Table 3)**, indicated that most relationships among physicochemical parameters were weak and not statistically significant ($p > 0.05$), suggesting low interdependence. Transparency showed weak to moderate negative correlations with all other variables. The only strong and statistically significant correlation ($R = 0.8234$; $p = 0.0000$) was between temperature and oxygen saturation, indicating that increases in temperature were associated with higher oxygen saturation under the study conditions.

In terms of water quality, nitrogen and lead concentrations exceeded the permissible limits for lakes and lagoons established by Peruvian legislation [28]. The limit for total nitrogen is 0.315 mg/L. In this study, all values surpassed that threshold, with the highest concentration (2.13 mg/L) observed at the center of Lake Las Verdes 2, and the lowest (0.34 mg/L) at the shoreline of Lake Las Verdes 3.

For lead, the legal limit is 0.001 mg/L, yet all recorded concentrations were substantially higher. Lake Las Verdes 3 had the highest lead levels, with 0.05322 mg/L at the center and 0.00675 mg/L at the shoreline. Lake Las Verdes 1 also showed elevated levels, from 0.01352 mg/L at the center to 0.00357 mg/L at the shoreline. In contrast, arsenic and cadmium concentrations in water remained below the ECA thresholds (0.01 mg/L and 0.004 mg/L, respectively).

In sediments, arsenic concentrations were generally below the PEL threshold of 17.0 mg/kg, with 8.7 mg/kg reported at the center of Lake Las Verdes 3. However, Lake Las Verdes 1 showed critically high values: 200.0 mg/kg at the center and 78.9 mg/kg at the shoreline, far exceeding permissible levels.
Cadmium concentrations in sediment did not exceed the PEL limit of 3.5 mg/kg, although Lake Las Verdes 1 slightly surpassed the ISQG threshold of 0.6 mg/kg, with 0.7959 mg/kg at the center and 0.7582 mg/kg at the shoreline.

Chromium levels remained low across all sites, well below ISQG (37.3 mg/kg) and PEL (90.0 mg/kg) thresholds. The highest concentration (3.2 mg/kg) was found at the shoreline of Lake Las Verdes 3.
Copper concentrations were highest in Lake Las Verdes 3 (134.95 mg/kg shoreline; 39.86 mg/kg center), followed by Lake Las Verdes 1 (85.57 mg/kg shoreline; 43.19 mg/kg center). Most values exceeded the ISQG guideline (35.7 mg/kg), but none surpassed the PEL threshold (197.0 mg/kg).

Lead in sediment exceeded ISQG in most samples, except at the shoreline of Lake Las Verdes 2 (31.421 mg/kg) and the center of Lake Las Verdes 3 (9.649 mg/kg). The PEL limit (91.3 mg/kg) was surpassed at the center of Lake Las Verdes 2 (91.399 mg/kg) and the shoreline of Lake Las Verdes 3 (100.47 mg/kg).

Mercury concentrations exceeded both ISQG (0.17 mg/kg) and PEL (0.486 mg/kg) thresholds in all affected sites. The highest levels were observed in Lake Las Verdes 1 (1.49 and 1.50 mg/kg at center and shoreline, respectively) and in Lake Las Verdes 2 (1.31 mg/kg at the center).

Zinc levels remained below guideline thresholds (ISQG: 123 mg/kg; PEL: 315 mg/kg). The highest concentration was observed at the shoreline of Lake Las Verdes 3 (73.50 mg/kg), followed by Lake Las Verdes 1 (50.13 mg/kg at the center).

Macroinvertebrate assemblages **(Table 4)**, organized by family, year, lake, and season (dry [DS], rainy [RS]), revealed consistent dominance by Corixidae (Hemiptera) and Dytiscidae (Coleoptera) in Lake Las Verdes 1 across all years (2017–2019). Planariidae ranked second during the 2019 dry season. In Lake Las Verdes 2, Dytiscidae dominated during the 2017 dry season, while Corixidae dominated in the rainy season. By 2019, Planariidae became the most abundant group in both seasons, with a notable increase in Hyalellidae during the dry season. In contrast, Lake Las Verdes 3 exhibited lower macroinvertebrate diversity, with consistent dominance of Planariidae throughout the study period.

Biological water quality assessments using the BMWP/Col and ABI indices **(Table 5)**, reflected these ecological patterns. The lakes exhibited a range of water quality conditions, from good (slightly polluted) to critical (Severely polluted).

According to the BMWP/Col index, Lake Las Verdes 2 showed the best conditions, with mostly good quality and only one questionable rating during the 2018 dry season. Lake Las Verdes 1 had the poorest quality, with critical conditions in all dry seasons and questionable ratings during rainy seasons. Lake Las Verdes 3 was consistently classified as moderately polluted, except for one critical condition in the 2019 dry season.

The ABI index showed a general water quality status ranging from fair to poor. Lake Las Verdes 2 registered the best condition (good) during the 2019 rainy season, along with two poor conditions. The remaining lakes exhibited 50% fair and 50% poor conditions, indicating moderate pollution levels.

DISCUSSION

The analysis of physicochemical parameters revealed that temperature exhibited the greatest variability, depending on the monitoring year, the sampling location within each lake, and differences among lakes **(Table 1)**. These fluctuations were primarily influenced by seasonal changes, the geographic location of each lake, and variation in water temperature with depth, which affected readings at different sampling points. The average temperature of 12.55 °C is consistent with findings from a study on sixteen high-Andean lakes in the Rímac and Mantaro river basins, which reported a mean temperature of 12 ± 1 °C. Furthermore, those authors indicated an optimal temperature range for lake ecosystems between 11 and 13 °C [(32)]. Therefore, temperatures above this range could negatively impact the biological components of these ecosystems, as observed in 2017, when temperatures of 14 °C or higher were recorded in three lakes.

In contrast, the mean water conductivity was 20.4 µS/cm, significantly lower than values reported for other high-Andean lakes in Peru, such as 177 µS/cm in a lake in the Lima region and 250 µS/cm in four Peruvian high-Andean lakes [(33)]. This low conductivity is characteristic of freshwater systems [(33)] and indicates a limited presence of dissolved electrolytes necessary for conducting electrical currents, confirming the freshwater nature of the studied lakes.

The pH values recorded in the Las Verdes lakes suggest acidic water conditions, with a slight but statistically non-significant increase in pH at locations with higher temperatures **(Table 2)**. Variability in pH was not significant across sampling points **(Table 2)**, but rather differed among lakes, likely due to their specific geochemical characteristics. pH fluctuations may be related to the edaphic conditions [(34)] of the aquatic systems or potentially to wastewater inputs [(6)]. pH is one of the most critical physicochemical variables, as it influences other water quality parameters, particularly metal concentrations, through its role in chemical processes such as solubility and acid-base reactions [(35)].

Regarding water transparency, measurements across the three lakes indicated low turbidity **(Table 1)**, with Secchi depth readings just beyond 1.7 m in Lake Las Verdes 1 and up to 3.1 m in Lake Las Verdes 3. Transparency may be influenced by water mixing and turbulence [(35)], solar radiation, optical attenuation, suspended particles, and phytoplankton abundance [(36)].

Dissolved oxygen (DO) levels consistently exceeded 6 mg/L across all sampling years and lakes, showing no significant variation **(Table 2)**. These values meet the minimum standard set by Peruvian regulations (5 mg/L) for supporting aquatic life. DO levels, closely linked with temperature, are essential for species richness and the distribution of benthic macroinvertebrate families [(37)]. Oxygen saturation in the three lagoons ranged from 93.2% at 10.3 °C to 104.2% at 14.1 °C **(Table 1)**. A significant positive correlation was found between temperature and oxygen saturation, indicating that higher temperatures were associated with increased oxygen levels in the water **(Table 3)**. This pattern is ecologically important, as it affects aquatic life and ecosystem functioning. Values between 80% and 125% are favorable for aerobic organisms [(38)], and the observed values fall within this range. However, oxygen saturation typically decreases as temperature increases [(39)]. The opposite trend observed here may reflect eutrophication in Las Verdes lagoons, likely caused by anthropogenic nutrient inputs, especially nitrogen [(40)]. Elevated nitrogen concentrations support this interpretation, though further study is needed.

Concentrations of heavy metals in both sediments and water exceeded quality standards for four of the six metals analyzed (arsenic, copper, mercury, and lead), suggesting contamination from nearby mining activities **(Figure 3 and Figure 4)**. Heavy metals interfere with nutrient uptake in aquatic plants, inhibiting growth and reducing macroinvertebrate diversity. They are toxic, non-biodegradable, and bioaccumulative, posing risks to aquatic life and human health [41]. These results contrast with previous studies reporting lower heavy metal concentrations in high-Andean lake sediments, except for chromium [42], highlighting the elevated impact in the Las Verdes lakes, likely due to mining operations. Mining-impacted water bodies often receive metal contaminants through leachates and waste discharge [43], aligning with reports of acute lead poisoning cases in humans linked to these lakes.

In terms of macroinvertebrate diversity **(Table 4)**, greater abundance and family richness were observed in 2018 and 2019, while no significant differences were recorded in 2017. According to water quality indices, the lakes are classified as moderately to slightly polluted. The most abundant families were Corixidae (Hemiptera) and Dytiscidae (Coleoptera), which are also commonly reported as dominant insect groups in freshwater ecosystems [44]. In contrast, Chironomidae, the most abundant family in lakes of the Mantaro River basin [6], ranked fifth in abundance in this study, suggesting variability in macroinvertebrate family composition among high-Andean lake systems. Another frequently observed family was Hyalellidae—amphipods of the order Peracarida—typically found in aquatic vegetation, feeding on decomposing organic matter [45]. Species of this genus inhabit a wide range of freshwater environments, from sea level to elevations above 4,000 m [46].

The aquatic macroinvertebrates identified in this study mostly belong to low-scoring families according to the BMWP/Col and ABI indices, indicating a degraded water quality status, with the lakes considered highly polluted under these indices **(Table 5)**. It is well-established that biological communities undergo natural cycles and respond to various physical, chemical, and biological stressors [47]. Consequently, the quality of high-Andean aquatic environments varies in relation to the diversity of benthic macroinvertebrate communities, as observed across different regions of the Andean range [6] [48].

Finally, this study faced limitations due to restricted access to the study area, seasonal weather conditions, and difficulties in collecting deep-water samples. These constraints underscore the need for future research with expanded depth profiles and a more detailed assessment of eutrophication processes and their driving factors.

CONCLUSIONS

The high-Andean lakes of Quiruvilca (Peru) showed stable physicochemical properties, with temperature displaying the greatest temporal and spatial variation. The lakes were acidic, with low conductivity, limited transparency, and sufficient dissolved oxygen to support aquatic life. High levels of heavy metals in water and sediments, mainly from mining activities, indicated pollution with potential risks to environmental and human health.

Despite the contamination, diverse macroinvertebrate families were recorded—particularly Corixidae, Dytiscidae, Hyalellidae, Planariidae, and Chironomidae—demonstrating the tolerance of some species to polluted conditions.

The BMWP and ABI indices classified the lakes as moderately polluted, suggesting that their waters were unsuitable for human or animal use. These findings highlighted the need for remediation of both water and sediments to ensure safe and sustainable use by local communities.

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DECLARATION OF COMPETING INTEREST

The authors have declared no conflict of interest.

REFERENCIAS

1. **De La Fuente A, Meruane C, Suárez F.** Long-term spatiotemporal variability in high Andean wetlands in northern Chile. Science of The Total Environment [Internet]. 2021 eb;756:143830. https://doi.org/10.1016/j.scitotenv.2020.143830
2. **Rascón J, Corroto F, Leiva-Tafur D, Gamarra OA**. Variaciones limnológicas espaciotemporales de un lago altoandino tropical al norte de Perú. Ecología Austral [Internet]. 2021 Ago;31(2):343-56. https://doi.org/10.25260/EA.21.31.2.0.1200
3. **Viviroli D, Kummu M, Meybeck M, Kallio M, Wada.** Increasing dependence of lowland populations on mountain water resources. Nature Sustainability [Internet]. 2020 Jul;3(11):917-28. https://doi.org/10.1038/s41893-020-0559-9
4. **Yang L, Lv , Jiang D, Fan J, Zhang X, He W.** Whether CCS technologies will exacerbate the water crisis in China? -A full life-cycle analysis. Renewable and Sustainable Energy Reviews [Internet]. 2020 Dic;134:110374. https://doi.org/10.1016/j.rser.2020.110374
5. **Mishra B, Kumar P, Saraswat C, Chakraborty S, Gautam A.** Water Security in a Changing Environment: Concept, Challenges and Solutions. Water [Internet]. 2021 Feb;13(4):490. https://doi.org/10.3390/w13040490
6. **Custodio M, Peñaloza R, Chanamé F, Yaranga R, Pantoja R.** Assessment of the Aquatic Environment Quality of High Andean Lagoons using Multivariate Statistical Methods in Two Contrasting Climatic Periods. Journal of Ecological Engineering [Internet]. 2018 Nov;19(6):24-33. https://doi.org/10.12911/22998993/92677
7. **Damanik-Ambarita MN, Lock K, Boets P, Everaert G, Tien TH, Eurie MA, et al.** Ecological water quality analysis of the Guayas river basin (Ecuador) based on macroinvertebrates indices. Limnologica [Internet]. 2016 Mar;57:27-59. https://doi.org/10.1016/j.limno.2016.01.001
8. **Dong JY, Wang X, Zhang X, Bidegain G, Zhao L.** Integrating multiple indices based on heavy metals and macrobenthos to evaluate the benthic ecological quality status of Laoshan Bay, Shandong Peninsula, China. Ecological Indicators [Internet]. 2023 Sep;153:110367. https://doi.org/10.1016/j.ecolind.2023.110367
9. **Visitación-Bustamante K, Visitación-Bustamante L, Visitación-Figueroa L.** Caracterización hidroquímica de una subcuenca altoandina en el departamento de Moquegua, Perú. Tecnología y ciencias del agua [Internet]. 2023 Sep;14(5):257-90. https://doi.org/10.24850/j-tyca-14-05-06
10. **Delgado-Fernández E, Cruz D, Ayavaca R, Benítez Á, Hernández B.** Microalgal Diversity as Bioindicators for Assessing and Sustaining Water Quality in the High Mountain Lakes of Quimsacocha, Azuay, Ecuador. Sustainability [Internet]. 2025 Feb;17(4):1620. https://doi.org/10.3390/su17041620
11. **Jerves-Cobo R, Benedetti L, Amerlinck Y, Lock K, De Mulder C, Van Butsel J, et al.** Integrated ecological modelling for evidence-based determination of water management interventions in urbanized river basins: Case study in the Cuenca River basin (Ecuador). Science of The Total Environment [Internet]. 2020 Mar;709:136067. https://doi.org/10.1016/j.scitotenv.2019.136067

12. **Torres-Ramírez P, Bustos-Espinoza L, Figueroa S, León-Muñoz J, Jerez R, Galán A.** Influence of the Hydrological Variability on Water Quality and Benthic Macroinvertebrates in a Chilean Estuary During a Megadrought. Estuaries and Coasts [Internet]. 2024 Dec;47(3):724-42. https://doi.org/10.1007/s12237-023-01311-w
13. **Rodríguez-Castillo A, Roldán-Rodríguez J, Bopp-Vidal GM.** Macroinvertebrates bentons biological quality indicators of the water of highaltitudeandean lagoons, La Libertad-Peru. REBIOL [Internet]. 2021 Jul;41(1):91-101. https://doi.org/10.17268/rebiol.2021.41.01.09
14. **Salgado J, Vélez MI, González-Arango C, Rose NL, Yang H, Huguet C, et al.** A century of limnological evolution and interactive threats in the Panama Canal: Long-term assessments from a shallow basin. Science of The Total Environment [Internet]. 2020 Ago;729:138444. https://doi.org/10.1016/j.scitotenv.2020.138444
15. **Arrieira RL, Alves GM, Schwind LTF, Lansac-Tôha FA.** Local factors affecting the testate amoeba community (Protozoa: Arcellinida; Euglyphida) in a neotropical floodplain. Journal of Limnology [Internet]. 2015 Feb;74(3):444-52. https://doi.org/10.4081/jlimnol.2015.1078
16. **Romero-Mariscal G, Garcia-Chevesich A, Morales-Paredes L, Arenazas-Rodriguez A, Ticona-Quea J, Vanzin G, et al.** Peruvian Wetlands: National Survey, Diagnosis, and Further Steps toward Their Protection. Sustainability [Internet]. 2023 May;15(10):8255. https://doi.org/10.3390/su15108255
17. **Autoridad Nacional del Agua. Protocolo Nacional de Monitoreo de la Calidad de Cuerpos Naturales de Agua Superficiales.** Resolución Jefatural. Lima: Ministerio de Agricultura y Riego; 2016. N° 0.10-2016-ANA. https://www.ana.gob.pe/sites/default/files/publication/files/protocolo_nacional_para_el_monitoreo_de_la_calidad_de_los_recursos_hidricos_superficiales.pdf.
18. **Custodio M, Chávez E. Quality of the aquatic environment of high Andean rivers evaluated through environmental indicators: a case of the Cunas River, Peru.** Ingeniare. Revista chilena de ingeniería [Internet]. 2019 Sep;27(3):396-409. https://doi.org/10.4067/S0718-33052019000300396
19. **García-Avila F, Loja-Suco P, Siguenza-Jeton C, Jiménez-Ordoñez M, Valdiviezo-Gonzales L, Cabello-Torres R, et al.** Evaluation of the water quality of a high Andean lake using different quantitative approaches. Ecological Indicators [Internet]. 2023 Oct;154:110924. https://doi.org/10.1016/j.ecolind.2023.110924
20. **MINAM.** Guía para Muestreo de Suelos. Resolución Ministerial. Lima: Ministerio del Ambiente; 2014. 085-2014-MINAM.https://www.minam.gob.pe/disposiciones/resolucion-ministerial-n-085-2014-minam/.
21. **Canadian Environmental Quality Guidelines. Canadian Sediment Quality Guidelines for the Protection of Aquatic Life.** Winnipeg: Canadian Council of Ministers of the Environment; 2002. https://ccme.ca/en/resources/sediment#.
22. **Delegido J, Urrego P, Vicente E, Sòria-Perpinyà X, Soria JM, Pereira-Sandoval M, et al.** Turbidez y profundidad de disco de Secchi con Sentinel-2 en embalses con diferente estado trófico en la Comunidad Valenciana. Rev. teledetec. [Internet]. 2019;54:15-24. https://doi.org/10.4995/raet.2019.12603
23. **Baird RB, Eaton AD, Rice EW.** Standard Methods For the Examination of Water and Wastewater 23th edition. Washington: American Public Health Association; 2017. https://www.academia.edu105197442/Standar_Methods_For_Examination_23th_edit.
24. **Roldán GA.** Bioindicación de la calidad del agua en Colombia: propuesta para el uso del método BMWP Col. Primera ed. Medellín: Editorial Universidad de Antioquia; 2003.
25. **Domínguez E.** Macroinvertebrados bentónicos Sudamericanos. Sistemática y Biología Domínguez E, Fernández HR, editors. Tucumán: Fundación Miguel Lillo; 2009
26. **Huamantinco AA, Ortiz W.** Clave de géneros de larvas de Trichoptera (Insecta) de la Vertiente Occidental de los Andes, Lima, Perú. Revista Peruana de Biología [Internet]. 2010 Abr;17(1):75-80. https://doi.org/10.15381/rpb.v17i1.54

27. **Acosta R, Ríos B, Rieradevall M, Prat N.** Propuesta de un protocolo de evaluación de la calidad ecológica de ríos andinos (CERA) y su aplicación a dos cuencas en Ecuador y Perú. Limnetica [Internet]. 2009 Jun;28(1):35-64. https://doi.org/10.23818/limn.28.04
28. **Rios-Touma B, Acosta R, Prat N.** The Andean Biotic Index (ABI): revised tolerance to pollution values for macroinvertebrate families and index performance evaluation. Revista de Biología Tropical [Internet]. 2014 Abr;62:249. https://doi.org/10.15517/rbt.v62i0.15791
29. **StatPoint Technologies, Inc. Statgraphics Centurion XVII**, version 17.2.00. Warrenton (VA): StatPoint Technologies, Inc.; 2023.
30. **Hernández-Sampieri R, Mendoza C.** Metodología de la investigación. Las rutas cuantitativa, cualitativa y mixta Ciudad de México: Mc Graw Hill Education; 2018.
31. **MINAM.** Estándares de Calidad Ambiental (ECA) para Agua y establecen Disposiciones Complementarias. Decreto Supremo. Lima: Ministerio del Ambiente; 2017. N° 004-2017-MINAM. https://www.minam.gob.pe/wp-content/uploads/2017/06/DS-004-2017-MINAM.pdf.
32. **Tapia L, Sánchez T, Baylón M, Jara E, Arteaga C, Maceda D, et al.** Invertebrados bentónicos como bioindicadores de calidad de agua en Lagunas Altoandinas del Perú. Ecología Aplicada [Internet]. 2018 Dic;17(2):149. https://doi.org/10.21704/rea.v17i2.1235
33. **Huanaco JL.** Evaluación de la diversidad del fitoplancton de la laguna La Viuda (Lima, Perú) en agosto-noviembre 2016. Arnaldoa [Internet]. 2018 Dic;25(3):1027-40. https://doi.org/10.22497/arnaldoa.253.25314
34. **Azouzi R, Charef A, Ayed, Khadhar S.** Effect of Water Quality on Heavy Metal Redistribution and Mobility in Polluted Agricultural Soils in a Semi-Arid Region. Pedosphere [Internet]. 2019 Dic;29(6):730-9. https://doi.org/10.1016/S1002-0160(17)60367-9
35. **Saalidong BM, Aram SA, Otu S, Lartey PO.** Examining the dynamics of the relationship between water pH and other water quality parameters in ground and surface water systems. PLOS ONE [Internet]. 2022 Ene;17(1):e0262117. https://doi.org/10.1371/journal.pone.0262117
36. **Ma, Wang L, Li X, Qu X, Yin J, Zhao X, et al.** The oasis regional small and medium lake water transparency monitoring research and impact factor analysis based on field data combined with high resolution GF-1 satellite data. Journal of Freshwater Ecology [Internet]. 2021 Ene;36(1):77-96. https://doi.org/10.1080/02705060.2021.1883753
37. **Belal AAM, El-Sawy MA, Dar A.** The effect of water quality on the distribution of macro-benthic fauna in Western Lagoon and Timsah Lake, Egypt.I. Egyptian Journal of Aquatic Research [Internet]. 2016 Dic;42(4):437-48. https://doi.org/10.1016/j.ejar.2016.12.003
38. **López-Martínez ML, Jurado-Rosero GA, Páez- Montero ID, Madroñero-Palacios SM.** Estructura térmica del lago Guamués, un lago tropical de alta montaña. Luna Azul [Internet]. 2017 Abr;(44):94-119. https://doi.org/10.17151/luaz.2017.44.7
39. **De la Mora C, Flores HE, Durán Á, Ruiz JA.** Cambio climático y el impacto en la concentración de oxígeno disuelto en el Lago de Chapala. Revista Mexicana de Ciencias Agrícolas [Internet]. 2011 Oct;2(Esp. 2):381-394. https://www.scielo.org.mx/pdf/remexca/v2nspe2/v2spe2a16.pdf.
40. **Chapa C, Guerrero R.** Eutrofización: Abundancia que mata. Revista cómo ves [Internet]. 2010 Ene;134:22-5. https://www.comoves.unam.mx/numeros/guia/134.
41. **Pabón SE, Benítez R, Sarria RA, Gallo JA.** Contaminación del agua por metales pesados, métodos de análisis y tecnologías de remoción. Una revisión. Entre ciencia e ingeniería [Internet]. 2020;14(27):9-18. https://doi.org/10.31908/19098367.1734
42. **Custodio M, Espinoza C, Peñaloza R, Peralta-Ortiz T, Sánchez-Suárez H, Ordinola-Zapata A.** Microbial diversity in intensively farmed lake sediment contaminated by heavy metals and identification of microbial taxa bioindicators of environmental quality. Scientific Reports [Internet]. 2022 Ene;12(1):80. https://doi.org/10.1038/s41598-021-03949-7

43. **Ndur SA, Nyarko SY, Quaicoe I, Osei LB.** Heavy Metal Loading in Surface Sediments along the Kawere Stream, Tarkwa, Ghana. Ghana Mining Journal [Internet]. 2020 Dic;20(2):77-85. https://doi.org/10.4314/gm.v20i2.9
44. **Balian EV, Segers H, Lévêque C, Martens K.** An introduction to the Freshwater Animal Diversity Assessment (FADA) project. Hydrobiologia [Internet]. 2007 Dic;595(1):3-8. https://doi.org/10.1007/s10750-007-9235-6
45. **Waller A, González ER, Verdi A, Tomasco IH.** Genus Hyalella (Amphipoda: Hyalellidae) in Humid Pampas: molecular diversity and a provisional new species. Arthropod Systematics & Phylogeny [Internet]. 2022 Jun;80:261-78. https://doi.org/10.3897/asp.80.e79498
46. **Peralta MA, Isa ÁV.** A new species of Hyalella (Crustacea, Amphipoda, Hyalellidae) from the Puna biogeographic province in Argentina. ZooKeys [Internet]. 2019 Jul;865:87-102. https://doi.org/10.3897/zookeys.865.32878
47. **Turley MD, Bilotta GS, Chadd RP, Extence CA, Brazier RE, Burnside NG, et al.** A sediment-specific family-level biomonitoring tool to identify the impacts of fine sediment in temperate rivers and streams. Ecological Indicators [Internet]. 2016 Nov;70:151-65. https://doi.org/10.1016/j.ecolind.2016.05.040
48. **Miserendino ML, Brand C, Di Prinzio CY.** Assessing Urban Impacts on Water Quality, Benthic Communities and Fish in Streams of the Andes Mountains, Patagonia (Argentina). Water, Air, and Soil Pollution [Internet]. 2008 Oct;194(1-4):91-110. https://doi.org/10.1007/s11270-008-9701-4