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Water Storage–Discharge Relationship with Water Quality Parameters of Carhuacocha and Vichecocha Lagoons in the Peruvian Puna Highlands

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Abstract: Most Andean lakes and lagoons are used as reservoirs to manage hydropower generation and cropland irrigation, which, in turn, alters river flow patterns through processes of storage and discharge. The Carhuacocha and Vichecocha lagoons, fed by glaciers, are important aquatic ecosystems regulated by dams. These dams increase the flow of the Mantaro River during the dry season, supporting both energy production and irrigation for croplands. Water quality in the Carhuacocha and Vichecocha lagoons was assessed between storage and discharge events by using the Canadian Council of Ministers of the Environment Water Quality Index ($CCME_{WQI}$) and multivariate statistical methods. The quality of both lagoons is excellent during the storage period; however, it decreases when they are discharged during the dry season. The most sensitive parameters are pH, dissolved oxygen (DO), and biochemical oxygen demand (BOD). This paper details the changes in water quality in the Carhuacocha and Vichecocha lagoons during storage and discharge events.

Keywords: Andean lagoons; discharge; water quality; physical−chemical parameters

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1. Introduction

The growth in population, coupled with economic expansion and urban industrial development, has led to an increased demand for water in both urban areas and agricultural lands. In Peru, nearly nine million residents of Lima depend on highland water bodies for nearly half of their drinking water [1], while highland populations use intermontane valleys for agricultural activities [2]. Similarly, hydropower developments depend on highland lakes and water transfer, which modify river flow patterns. In order to overcome these issues, most parts of the Andean lakes and lagoons are dammed to provide an essential freshwater resource, modifying in the process the characteristics of the ecosystems' hotspots for biological species through a complex interaction between geographical reconfiguration and, therefore, changing the sociopolitical scene [3]. Climate change has led to alterations in rainfall patterns and higher temperatures in highland regions. This has led to heavy rainfall events, and current trends indicate that these changes are likely to persist, resulting in increased runoff [4] and glacier retreat [5]. Consequently, flood runoff is a potential pollution source for Andean lagoons.

Water quality is a critical environmental concern globally that must be assessed across various contexts to safeguard public health and safety. It should also be integrated into policies to prevent specific hazards through an adaptable and participatory approach [6]. The diminishing of water quality restricts the potential uses of freshwater sources and adversely impacts ecosystems related to them by leading to conditions such as hypoxia (low oxygen levels), excessive algal growth (algal blooms), reduced species diversity, and the accumulation of heavy metals and toxins [7]. Lagoons acquire basin-specific characteristics which make them unique. Even if they are in the same area, they can respond differently to similar stimuli.

The Peruvian Environmental Quality Standard (EQS) for water [8] regulates 104 parameters and categorizes water use into four distinct groups: public and recreational use; cultivation, extraction, and other coastal and inland fishfarming activities; irrigation of crops and livestock watering; and the preservation of aquatic ecosystems. Regarding each water body, it is necessary to measure certain parameters, according to the National Classification of the Superficial Continental Water Bodies [9]. Lagoons are in category four. For this study, the physical, chemical, and microbiological parameters specified in the methodology were evaluated. These parameters influence habitats and the diversity of biological communities, and their impacts are managed through the analysis of various environmental indicators According to Panhwar et al. [10], pH and electrical conductivity (EC) are some of the most important parameters for biological processes.

The Carhuacocha and Vichecocha lagoons are aquatic ecosystems sustained by glaciers and the runoff from other small glacier-fed ponds. They hold significant economic value as they regulate dams designed to enhance the flow of the Mantaro River during the dry season, thereby supporting cropland irrigation and electricity generation at the Santiago Antúnez de Mayolo hydroelectric power plant [11]. These areas are considered as habitats for an array of bird species. Their administration, which is in charge of the Nor yauyos Cochas Landscape reserve, has the objective of preserving biodiversity while regulating human activities around the lagoons.

Due to the unpredictable nature of floods, the complexity of hydrodynamic processes, and harsh environmental conditions, conducting field experiments is very challenging. Consequently, there is still a lack of field measurements and simulation studies on the effects of flood discharge for canyon-shaped drinking water reservoirs. In addition, there is limited research on the water quality of regulated lagoons in Peru. To fill this knowledge gap, we conducted this research to assess the impact of storage–discharge events on the physical−chemical properties of water in the Carhuacocha and Vichecocha lagoons. Water quality data were collected in situ during storage and discharge events of these two lagoons, while assessment was conducted using the Canadian Council of Ministers of the Environment Water Quality Index ($CCME_{WQI}$) and multivariate statistical methods.

2. Materials and Methods

2.1. Study Area

The Carhuacocha and Vichecocha lagoons are situated at the head of the Pachacayo river sub-basin, within the Mantaro basin, at elevations of 4420 and 4480 m.a.s.l., respectively. They are surrounded by moraine and puna grasslands. These lagoons are in the territory of the Tupac Amaru livestock system, affiliated with the Canchayllo community and managed under the Nor Yauyos Cochas Landscape Reserve (Figure 1). The climate in this area is cold, with an average annual temperature of 3.4 °C and annual precipitation reaching 814 mm. Rainfall typically occurs from January to March, with dry periods from June to August. However, rainfall increases between August and September, becoming more significant from October until reaching maximum values in February [12].

2.2. Water Extension

We used Planet−NICFI imagery surface reflectance four-band imagery (blue, green, red, and near-infrared) in composite (NIR–GREEN−RED), from January 2023 to February 2024, and analyzed this in the GEE platform [13]. In order to estimate the extension for the two lagoons, we used the Normalized Difference Water Index (NDWI), calculated as the difference between green and near-infrared reflectance (Band 2–Band 4) divided by the sum of green and near-infrared reflectance (Band 2 + Band 4/5) [14]. This index yields values ranging from −1 to 1, where values close to 1 indicate open-water pixels, which are more distinguishable from non-water pixels. These products combined with band composition NIR−GREEN−RED help to set the boundaries for both lagoons by photointerpretation in the same platform. After that, we contrasted the area with the dry and rainfall season of two weather stations close to the lagoons (Figure 2).

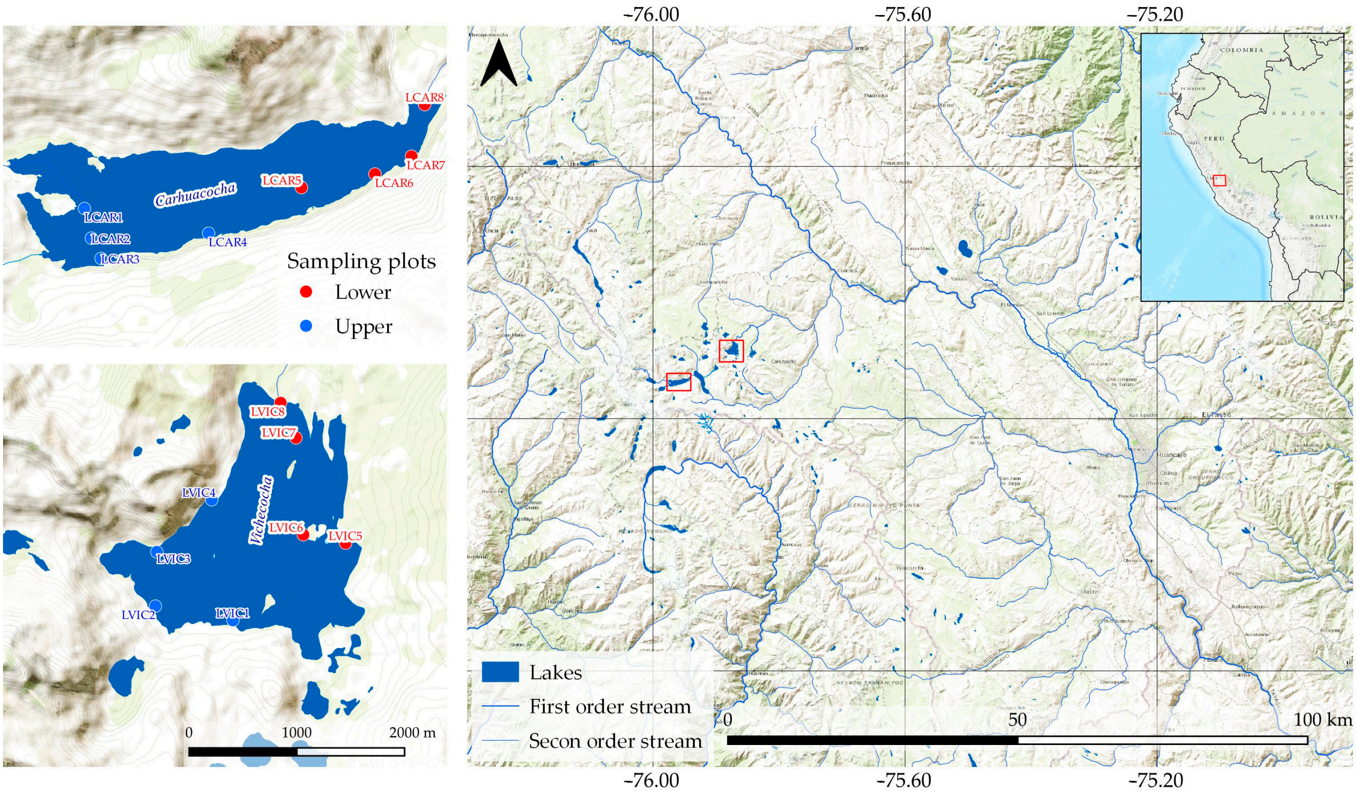

Figure 1. Locations where water samples were taken from Carhuacocha and Vichecocha lagoons.

2.3. Sampling and Analytical Procedure

Eight sampling stations were set up around each lagoon, with four samples taken per station during two events (storage and discharge). In total, 128 water samples were collected (64 samples per lagoon) between July and December 2023. Sampling was carried out during this period because, from April to July, rainfall decreases drastically and, from August onwards, it increases until it reaches its maximum values in February [15]. Electrical conductivity (EC), pH, temperature, and dissolved oxygen (DO) were measured in field with a HANNA ® HI98129 and HI9146−10 multiparameter, respectively.

Water samples were collected using 500 mL glass bottles, which were sterilized and rinsed with distilled water prior to microbiological analysis. Additionally, two extra bottles were used for chemical analysis and heavy metal testing, respectively. For heavy metal analysis, the samples were preserved by adding 1.5 mL of concentrated nitric acid per liter of water, following the procedures outlined by the American Public Health Association (APHA) [16]. After collection, the water samples were transported to the laboratory and stored at 4 °C until preparation and analysis. All analyses were conducted in triplicate, and the findings were reported as the mean value. Detailed procedures for each analyzed parameter are outlined in Table 1.

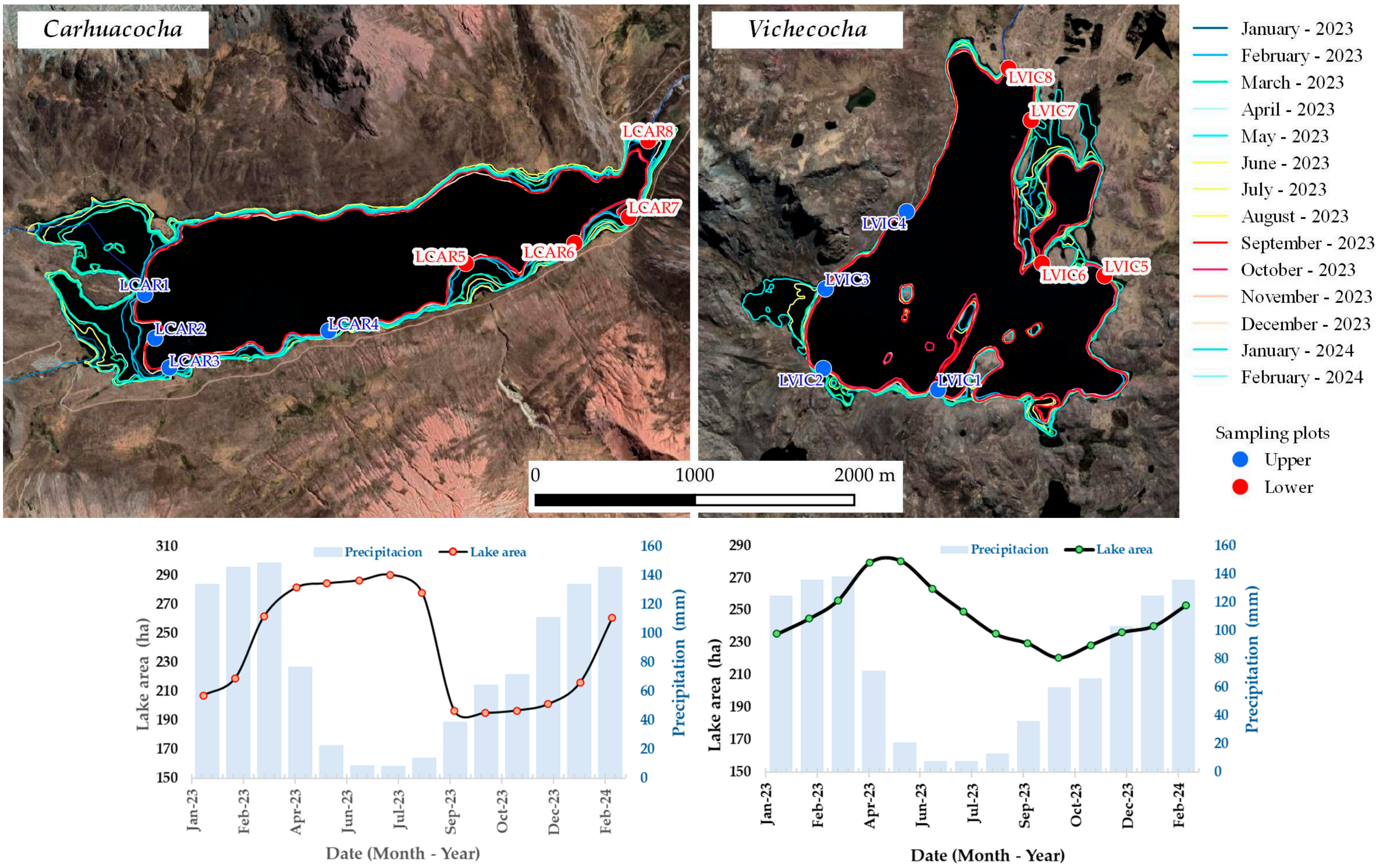

Figure 2. Lake shorelines delineated from PlanetScope from period January 2023–February 2024 for Carhuacocha and Vichecocha lakes.

Table 1. Details of the instrumentation used, methods employed, and quality control measures implemented during the analysis.

Parameter	Used Instrumentation and Methods/Solutions	Accuracy (Sensitivity)	Range Test
pH Conductivity (EC, µS/cm) Temperature (T, °C)	HANNA ® HI98129	±0.05 ±1 ±0.5	0–14 0–3999 0.0–60.0
Dissolved oxygen (DO, mg/L)	HANNA ® HI9146−10,	±0.06	0.00–45.00
Chemical oxygen demand (COD, mg/L)	Chemical Oxygen Demand, Closed Reflux Colorimetric Method SMEWW−APHA−AWWA–WEF Part 5220 D. 23 rd. 2017.	±0.4	0–2
Biochemical oxygen demand (BOD_5, mg/L)	Biochemical Oxygen Demand (BOD). 5−Day BOD Test SMEWW−APHA−AWWA–WEF Part 5210B. 24th Ed. 2022.	±2	0–5
Thermotolerant coliforms (TC, NMP/100 mL)	Multiple-Tube defermentation Technique for Members of the Coliform Group. *E. coli* Procedure Using Fluorogenic Substrate. Simultaneous Determination of Thermotolerant Coliforms and *E. coli.*	±1.8	−−
Chloride (Cl^-, mg/L) Nitrate (NO_3^-, mg/L) Sulfate (SO_4^{2-}, mg/L)	Determination of inorganic anions by ion chromatography Environmental Protection Agency. Methods for Chemicals Analysis (EPA)	±0.02 ±0.2	0.02–0.300 2–70
Phosphorus (P, mg/L)	Ascorbic Acid Method SMEWW−APHA−AWWA–WEF Part 4500–P B (Item 5) y E, 24th Ed. 2023.	±0.002	

Table 1. *Cont.*

Aluminum (Al, mg/L)	Determination of trace Elements in Water and Waste Inductively Coupled Plasma–Mass spectrometry. Method 200.8 Revision 5.4 1994	±0.001
Bario (Ba, mg/L)		±0.00008
Boron (B, mg/L)		±0.0003
Calcium (Ca, mg/L)		±0.001
Copper (Cu, mg/L)		±0.0001
Strontium (Sr, mg/L)		±0.00002
Iron (Fe, mg/L)		±0.001
Lithium (Li, mg/L)		±0.00003
Magnesium (Mg, mg/L)		±0.0006
Manganese (Mn, mg/L)		±0.00002
Potassium (K, mg/L)		±0.003
Silica (SiO_2, mg/L)		±0.001
Silicon (Si, mg/L)		±0.0002
Sodium (Na, mg/L)		±0.0003
Vanadium (V, mg/L)		±0.0001

Note(s): EPA: US Environmental Protection Agency. Methods for Chemicals Analysis; SMEWW: Standard Methods for the Examination of water and Wastewater; APHA: American Public Health Association.

2.4. Data Analysis

Statistical analysis and data processing were conducted using R Studio software (Version 3.4.3). The modified Shapiro−Wilks test was employed to assess the normality of the data. Pearson correlation analysis was utilized to explore the degree of correlation among the water parameters. Principal component analysis (PCA) was utilized to assess the suitability of the data for factor analysis. Kaiser−Meyer−Olkin (KMO) and Bartlett's tests were conducted. KMO assesses sampling adequacy by indicating the proportion of variance that might be attributable to underlying factors. A high KMO value (approaching 1) typically suggests that factor analysis is appropriate, while a value below 0.5 indicates it may not be useful. Bartlett's test of sphericity determines whether the correlation matrix resembles an identity matrix, which would indicate that variables are unrelated [17]. This analysis is used to identify possible associations with the physicochemical parameters of both lagoons.

Water Quality Assessment

To evaluate the health of aquatic ecosystems, we employed the Canadian Council of Ministers of the Environment's Water Quality Index ($CCME_{WQI}$) [18]. This index consists of three factors (F1, F2, and F3), scaled between 0 and 100, respectively. The values of the three measures of variance from selected objectives for water quality are combined to create a vector in an imaginary "objective exceedance" space. The length of the vector is then scaled to range between 0 and 100 and subtracted from 100 to produce an index which is 0 or close to 0 for very poor water quality and close to 100 for excellent water quality. Since the index is designed to measure water quality, it was considered that the index should produce higher numbers for better water quality indicators. The mathematical formulation of $CCME_{WQI}$ is given below.

$$CCME_{WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \quad (1)$$

where:

F1 (Scope) assesses the extent of noncompliance with the water quality standards over a specified period; F2 (Frequency) indicates the proportion of individual tests that fail to meet the set objectives ("failed tests"); and F3 (Amplitude) measures the degree to which the failed test values deviate from their objectives.

The $CCME_{WQI}$ scores are grouped into five categories of water quality: poor (0–44), marginal (45–64), fair (65–79), good (80–94), and excellent (95–100). Previously, water quality index scores were determined for 11 physicochemical parameters.

3. Results

3.1. Spatial Variability of Water Parameters Content

Descriptive statistics for physicochemical parameters from Carhuacocha and Vichecocha lagoons, encompassing both storage and discharge events, are presented in Table 2. These statistics are compared with the Environmental Quality Standards (EQS) established by Peruvian regulations for the conservation of aquatic environments [8]. The pH levels of water in both lagoons exhibit only minor variations between events, consistently falling within the acceptable ranges for the preservation of lacustrine and aquatic environments (6.5–9.0) and recreational use (6.0–9.0). However, at most sites, the pH values exceed the recommended range for drinking water (6.5–8.5), with particularly higher values observed in Vichecocha Lagoon. Average temperature values ranged from 12.69 to 13.98 °C in Carhuacocha Lagoon and from 11.41 to 12.06 °C in Vichecocha Lagoon. There were no significant differences in temperature between storage and discharge events in either lagoon.

Dissolved oxygen (DO) concentrations measured in both lagoons during storage events fall within the range specified by the Peruvian EQS and meet the World Health Organization's recommended minimum of $\geq$5.5 mg/L for the overall health of aquatic systems [8].

However, during discharge events, this parameter falls below the expected range and shows a significant difference. The average EC in water samples ranged from 104.38 to 235.75 μS/cm, with the lowest mean EC recorded in Vichecocha, showing a significant difference between events. For both lagoons, EC values are below the upper limit (1000 μS/cm).

The mean BOD_5 values recorded for Carhuacocha did not surpass the EQS water standard (5 mg/L) for the conservation of the aquatic environment. Although, in Vichecocha, this parameter exceeds the EQS water standard during discharge events, although, statistically, there is no significant difference between events. The mean values of chemical oxygen demand (COD) did not exceed the category 3 EQS water standard (40 mg/L) for vegetable irrigation and animal drinking. The thermotolerant coliform counts at all sampling sites for both lagoons did not exceed the EQS water standards.

The mean total phosphorus values at all sampling sites in both lagoons are lower than the Peruvian EQS water standard (0.035 mg/L). The mean chloride values vary between events for both lagoons. Nitrate values remain consistent between events and are below the Peruvian EQS water standard (13 mg/L) at all sampling sites in both lagoons. Sulfate levels decrease during discharge events in the Vichecocha lagoon, while silica content increases during discharge events in the Carhuacocha lagoon. The concentrations of the remaining elements in the water samples varied by sector and event, with the order of abundance in the Carhuacocha lagoon being Ca > Mg > Si > Na > K > Sr > Fe > Ba > Mn > Al > B > V > Cu > Li.

For Vichecocha, the order of abundance was Ca > Si > Na > Mg > K > Sr > Al > Fe > Mn > B > Ba > Cu > V > Li. The results reveal significative difference between water parameters (DO, Cl^-, Al, B, Ca, Cu, Sr, Fe, Mg, SiO_2, Si, and Na) for Carhuacocha lagoon and (DO, Cl^-, B, Na, EC, SO^{-2}, Li, and V) for Vichecocha between events. Significant variations in the described parameters were observed with each event for both lagoons.

Table 2. Event variation in physicochemical parameters and thermotolerant coliforms in Carhuacocha and Vichecocha Lagoons during 2023.

Parameter	Carhuacocha				Vichecocha				*EQS Water—Conservation of the Aquatic Environment*
	Storage Upper	Low	Discharge Upper	Low	Storage Upper	Low	Discharge Upper	Low	
pH	8.3500 ± 0.3836 a	8.5225 ± 0.2405 a	8.1250 ± 0.0954 b	8.1900 ± 0.1227 ab	8.6575 ± 0.2061 a	9.0925 ± 0.2965 a	8.7075 ± 0.3917 a	8.6825 ± 0.5789 a	6.5–9.0
Temperature (°C)	11.8500 ± 2.1825 a	13.5250 ± 2.4446 a	13.9250 ± 1.8998 a	14.0250 ± 0.7500 a	11.6250 ± 1.5218 a	12.5000 ± 0.5354 b	12.3250 ± 0.6850 b	10.5000 ± 0.4967 ab	Δ 3
DO (mg/L)	7.6775 ± 0.1420 a	7.9125 ± 0.3836 a	2.2525 ± 0.1335 b	2.2225 ± 0.4665 b	7.7075 ± 0.2317 a	8.1050 ± 0.3743 a	1.6400 ± 0.3222 b	1.4700 ± 0.2082 b	≥5
EC (μS/cm)	195.2900 ± 78.5408 a	249.0000 ± 3.1623 a	235.0000 ± 36.3043 a	236.5000 ± 8.3865 a	113.7500 ± 3.5940 a	118.0000 ± 10.9545 a	102.0000 ± 9.3452 b	106.7500 ± 1.8930 b	1000
BOD (mg/L)	4.9900 ± 0.0000 a	4.9900 ± 0.0000 a	4.9900 ± 0.0000 a	4.9900 ± 0.0000 a	4.9900 ± 0.0000 a	4.9900 ± 0.0000 b	5.6950 ± 1.1530 a	4.9900 ± 0.0000 a	5
COD (mg/L)	1.9900 ± 0.0000 a	1.9900 ± 0.0000 a	1.9900 ± 0.0000 a	1.9900 ± 0.0000 a	1.9900 ± 0.0000 a	1.9900 ± 0.0000 a	2.2675 ± 0.5550 a	1.9900 ± 0.0000 a	40
TC(NMP/100 mL)	2.4750 ± 1.3500 ab	1.7900 ± 0.0000 ab	2.4675 ± 1.3550 a	2.4675 ± 1.3550 b	1.7900 ± 0.0000 a	1.7900 ± 0.0000 b	8.2750 ± 3.5132 a	2.4675 ± 1.3550 a	1000
P (mg/L)	0.0059 ± 0.0000 a	0.0059 ± 0.0000 a	0.0059 ± 0.0000 ab	0.0059 ± 0.0000 b	0.0059 ± 0.0000 a	0.0059 ± 0.0000 b	0.0220 ± 0.0109 a	0.0079 ± 0.0040 a	0.035
Cl^- (mg/L)	0.3232 ± 0.4445 a	0.1045 ± 0.0013 a	0.9900 ± 0.0000 b	0.9900 ± 0.0000 b	0.1085 ± 0.0013 a	0.1125 ± 0.0013 a	0.9900 ± 0.0000 b	0.9900 ± 0.0000 b	−−
NO_3^- (mg/L)	0.1870 ± 0.1680 a	0.1292 ± 0.1605 ab	0.4175 ± 0.3931 b	0.5600 ± 0.4968 ab	0.1648 ± 0.0773 ab	0.1320 ± 0.1000 a	0.4250 ± 0.3779 b	0.4125 ± 0.3958 b	13
SO_4^{2-} (mg/L)	44.9525 ± 19.3041 a	57.1100 ± 0.6914 ab	56.4250 ± 13.8454 b	54.8250 ± 0.6602 a	19.0875 ± 0.2617 ab	19.3650 ± 0.2525 a	16.6500 ± 2.1810 c	18.7000 ± 0.2000 bc	−−
SiO_2 (mg/L)	3.1677 ± 0.6338 a	3.6868 ± 0.0823 a	4.8045 ± 0.8920 b	4.1830 ± 0.1450 b	4.9533 ± 0.3605 a	4.4910 ± 0.2667 b	5.3595 ± 1.1776 ab	4.1242 ± 0.5154 b	−−
Al (mg/L)	0.0029 ± 0.0000 a	0.0029 ± 0.0000 a	0.0932 ± 0.0455 b	0.0257 ± 0.0180 b	0.0442 ± 0.0655 a	0.0680 ± 0.0232 b	0.1735 ± 0.2116 b	0.0150 ± 0.0109 ab	−−
Ba (mg/L)	0.0089 ± 0.0040 a	0.0132 ± 0.0019 ab	0.0128 ± 0.0039 ab	0.0138 ± 0.0023 b	0.0056 ± 0.0021 a	0.0039 ± 0.0004 ab	0.0058 ± 0.0057 b	0.0019 ± 0.0012 b	0.7
B (mg/L)	0.0009 ± 0.0000 a	0.0009 ± 0.0000 a	0.0174 ± 0.0013 b	0.0168 ± 0.0004 b	0.0091 ± 0.0113 a	0.0009 ± 0.0000 a	0.0126 ± 0.0023 b	0.0144 ± 0.0011 ab	−−
Ca (mg/L)	0.0090 ± 0.0000 a	0.0090 ± 0.0000 ab	0.0002 ± 0.0000 bc	0.0002 ± 0.0000 c	0.0090 ± 0.0000 a	0.0090 ± 0.0000 ab	0.0002 ± 0.0000 b	0.0002 ± 0.0000 b	−−
Cu (mg/L)	0.0002 ± 0.0000 a	0.0002 ± 0.0000 a	0.0007 ± 0.0002 b	0.0008 ± 0.0001 b	0.0002 ± 0.0000 ab	0.0085 ± 0.0055 a	0.0057 ± 0.0008 a	0.0025 ± 0.0025 b	0.1
Sr (mg/L)	0.1846 ± 0.0821 a	0.2434 ± 0.0044 a	0.2809 ± 0.0646 ab	0.2629 ± 0.0094 b	0.0790 ± 0.0031 a	0.0765 ± 0.0012 b	0.0695 ± 0.0111 b	0.0827 ± 0.0056 ab	−−
Fe (mg/L)	0.0360 ± 0.0094 a	0.0437 ± 0.0250 ab	0.0720 ± 0.0488 b	0.0988 ± 0.0153 b	0.0510 ± 0.0442 a	0.0302 ± 0.0075 b	0.1143 ± 0.1330 b	0.0055 ± 0.0006 b	5
Li (mg/L)	0.0001 ± 0.0000 a	0.0001 ± 0.0000 ab	0.0001 ± 0.0000 b	0.0001 ± 0.0000 b	0.0001 ± 0.0000 a	0.0001 ± 0.0000 a	0.0023 ± 0.0027 b	0.0014 ± 0.0003 b	−−
Mg (mg/L)	2.3093 ± 0.8920 ab	2.9712 ± 0.0830 a	3.5375 ± 0.3057 bc	3.2715 ± 0.1133 c	0.8914 ± 0.0328 a	0.9264 ± 0.0448 a	0.8728 ± 0.0796 a	0.9498 ± 0.1216 a	−−
Mn (mg/L)	0.0059 ± 0.0021 a	0.0090 ± 0.0022 a	0.0086 ± 0.0048 a	0.0057 ± 0.0023 a	0.0251 ± 0.0269 a	0.0127 ± 0.0087 b	0.0091 ± 0.0066 b	0.0014 ± 0.0015 b	−−
K (mg/L)	0.7888 ± 0.0763 a	0.7480 ± 0.0157 b	0.8875 ± 0.0561 a	0.7685 ± 0.0471 a	0.1752 ± 0.0439 a	0.1942 ± 0.0688 b	0.1305 ± 0.0515 ab	0.2115 ± 0.0583 ab	−−
Si (mg/L)	1.4782 ± 0.2958 a	1.7203 ± 0.0385 a	2.2422 ± 0.4163 b	1.9520 ± 0.0677 b	2.3116 ± 0.1682 a	2.0958 ± 0.1244 b	2.5010 ± 0.5495 ab	1.9246 ± 0.2407 b	−−
Na (mg/L)	1.1654 ± 0.3604 a	1.4573 ± 0.0237 a	1.5747 ± 0.3018 ab	1.5274 ± 0.0297 b	1.8290 ± 0.0181 a	1.8021 ± 0.0833 b	1.9106 ± 0.2413 b	2.9350 ± 1.2264 b	−−
V (mg/L)	0.0003 ± 0.0000 a	0.0003 ± 0.0000 a	0.0003 ± 0.0000 ab	0.0003 ± 0.0000 b	0.0003 ± 0.0000 a	0.0003 ± 0.0000 b	0.0017 ± 0.0008 a	0.0008 ± 0.0006 a	−−

Note(s): means with different letters in the same column for each event level are statistically different (LSD Fisher, α = 0.05). TC: thermotolerant coliforms.

3.2. Correlation Analysis

Figure 3 shows how the different physical−chemical parameters and metals in the water samples relate to each other. The analysis identified clusters of parameters that tend to be present together. One group, including potassium (K), barium (Ba), sulfate (SO_4^{2-}), magnesium (Mg), strontium (Sr), and calcium (Ca), likely comes from the same source and seems to influence electrical conductivity (EC) and temperature. Another group, including aluminum (Al), phosphorus (P), vanadium (V), lithium (Li), silicon dioxide (SiO_2), silicon (Si), and iron (Fe), might be linked to higher biological oxygen demand (BOD) and chemical oxygen demand (COD).

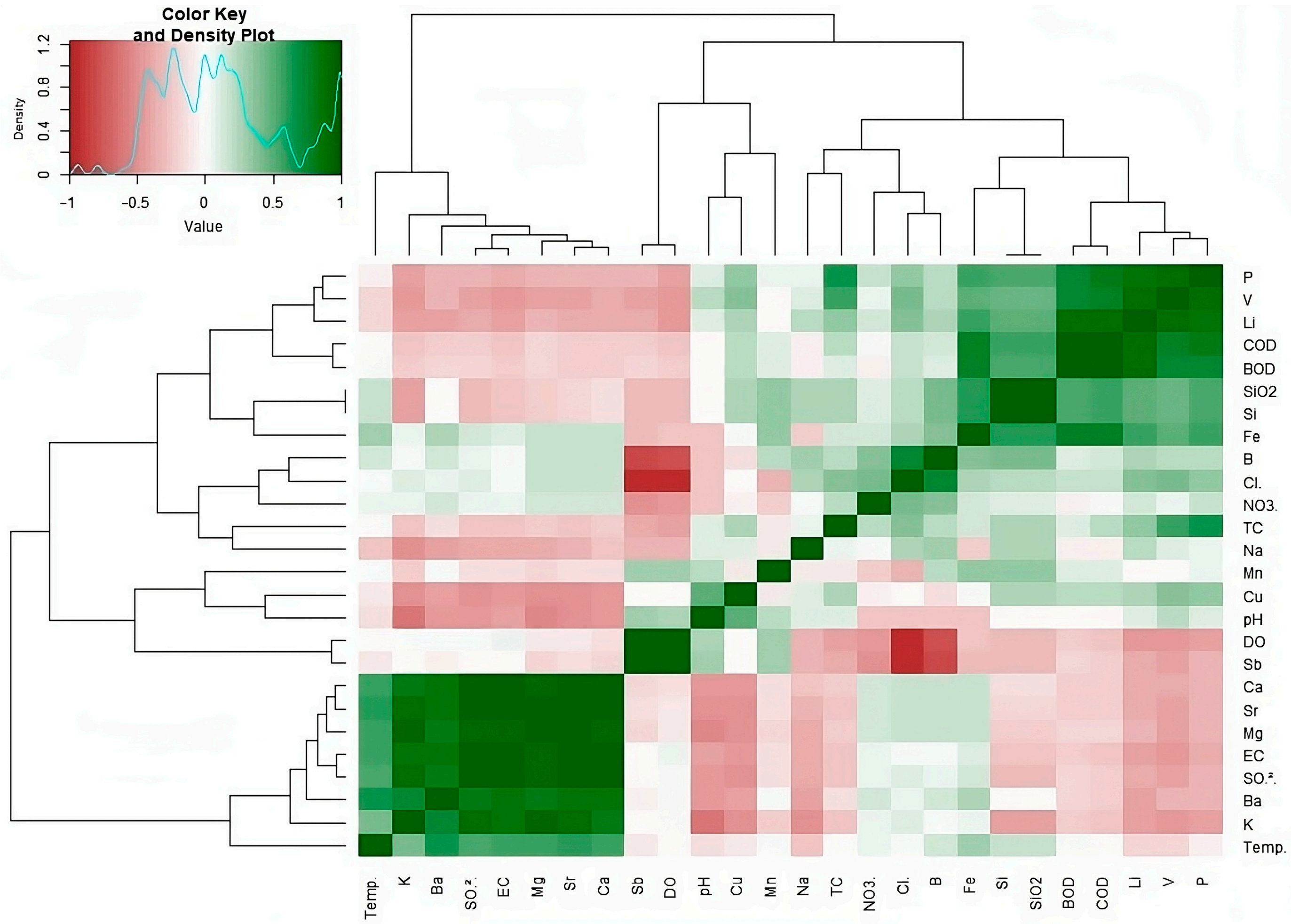

Figure 3. Pearson's correlation coefficients between physical–chemical parameters and metals in the water samples.

These findings emphasize the importance of monitoring these parameters together to understand water quality. The analysis also revealed negative correlations between some parameters. For example, calcium (Ca), strontium (Sr), magnesium (Mg), sulfate (SO_4^{2-}), barium (Ba), and potassium (K) showed negative correlations with silicon (Si), silicon dioxide (SiO_2), lithium (Li), vanadium (V), phosphorus (P), and aluminum (Al). This suggests different dissolved solute sources or environmental behaviors for these opposing parameter groups. Interestingly, the water quality parameter dissolved oxygen (DO) had a negative co-relationship with chloride (Cl^-) and boron (B). These results suggest that Cl^- and B could come from different sources or have contrasting effects in the environment. While some correlations, such as those involving alkali−nonferrous metals, could point to a common source in the transported material, others probably originate from anthropogenic inputs [19].

3.3. Water Quality

The results of the water quality assessment based on the $CCME_{WQI}$ for all sampling sites in the Carhuacocha and Vichecocha lagoons are shown in Table 3. These results indicate excellent water quality at all sites in Carhuacocha lagoon and at six of eight sites in Vichecocha lagoon during the storage event. However, during the discharge event, water quality in Carhuacocha lagoon decreased from excellent to good, while, in Vichecocha lagoon, it deteriorated from excellent to good and fair. These findings confirm a noticeable decline in water quality following the discharge event.

Table 3. Water quality of Carhuacocha and Vichecocha lagoons according to the Canadian Council of Environment Ministers Water Quality Index ($CCME_{WQI}$).

Event	Lagoon	Sampling Site	F1	F2	F3	CCME $_{WQI}$	WQI according to Color
Storage	Carhuacocha	1	–	–	–	100.00	Excellent
		2	–	–	–	100.00	Excellent
		3	–	–	–	100.00	Excellent
		4	–	–	–	100.00	Excellent
		5	–	–	–	100.00	Excellent
		6	–	–	–	100.00	Excellent
		7	–	–	–	100.00	Excellent
		8	–	–	–	100.00	Excellent
	Vichecocha	1	–	–	–	100.00	Excellent
		2	–	–	–	100.00	Excellent
		3	–	–	–	100.00	Excellent
		4	–	–	–	100.00	Excellent
		5	–	–	–	100.00	Excellent
		6	–	–	–	100.00	Excellent
		7	9.09	9.09	0.23	93.00	Good
		8	9.09	9.09	0.43	93.00	Good
Discharge	Carhuacocha	1	9.09	9.09	17.19	88.00	Good
		2	9.09	9.09	15.92	88.00	Good
		3	9.09	9.09	16.38	88.00	Good
		4	9.09	9.09	17.79	87.00	Good
		5	9.09	9.09	17.12	88.00	Good
		6	9.09	9.09	13.88	89.00	Good
		7	9.09	9.09	17.19	88.00	Good
		8	9.09	9.09	21.29	86.00	Good
	Vichecocha	1	18.18	18.18	21.24	81.00	Good
		2	9.09	9.09	26.67	83.00	Good
		3	9.09	9.09	22.34	85.00	Good
		4	9.09	9.09	18.29	87.00	Good
		5	9.09	9.09	20.90	86.00	Good
		6	9.09	9.09	23.02	85.00	Good
		7	9.09	9.09	27.14	83.00	Good
		8	18.18	18.18	24.52	79.00	Fair

Note(s): F1: range factor; F2: frequency factor; F3: amplitude factor.

3.4. Analysis of Main Components

Principal component analysis (PCA) was performed to analyze the water quality data from the Carhuacocha and Vichecocha lagoons. This analysis considered various parameters and elements measured during storage and discharge events. The suitability of the data for PCA was confirmed by two tests: the KMO sample adequacy measure (scoring 0.55) and Bartlett's test of sphericity (with a p-value of 0.01).

The PCA identified two main components (PC1 and PC2) that explained over 60% of the overall variation in the data (Figure 4). For Carhuacocha lagoon during discharge events, PC1 was strongly linked to factors like temperature, electrical conductivity (EC), and concentrations of barium (Ba), calcium (Ca), strontium (Sr), magnesium (Mg), sulfate (SO_4^{2-}), and potassium (K). In contrast, PC1 for the Vichecocha lagoon showed a stronger association with factors like pH, sodium (Na), and copper (Cu).

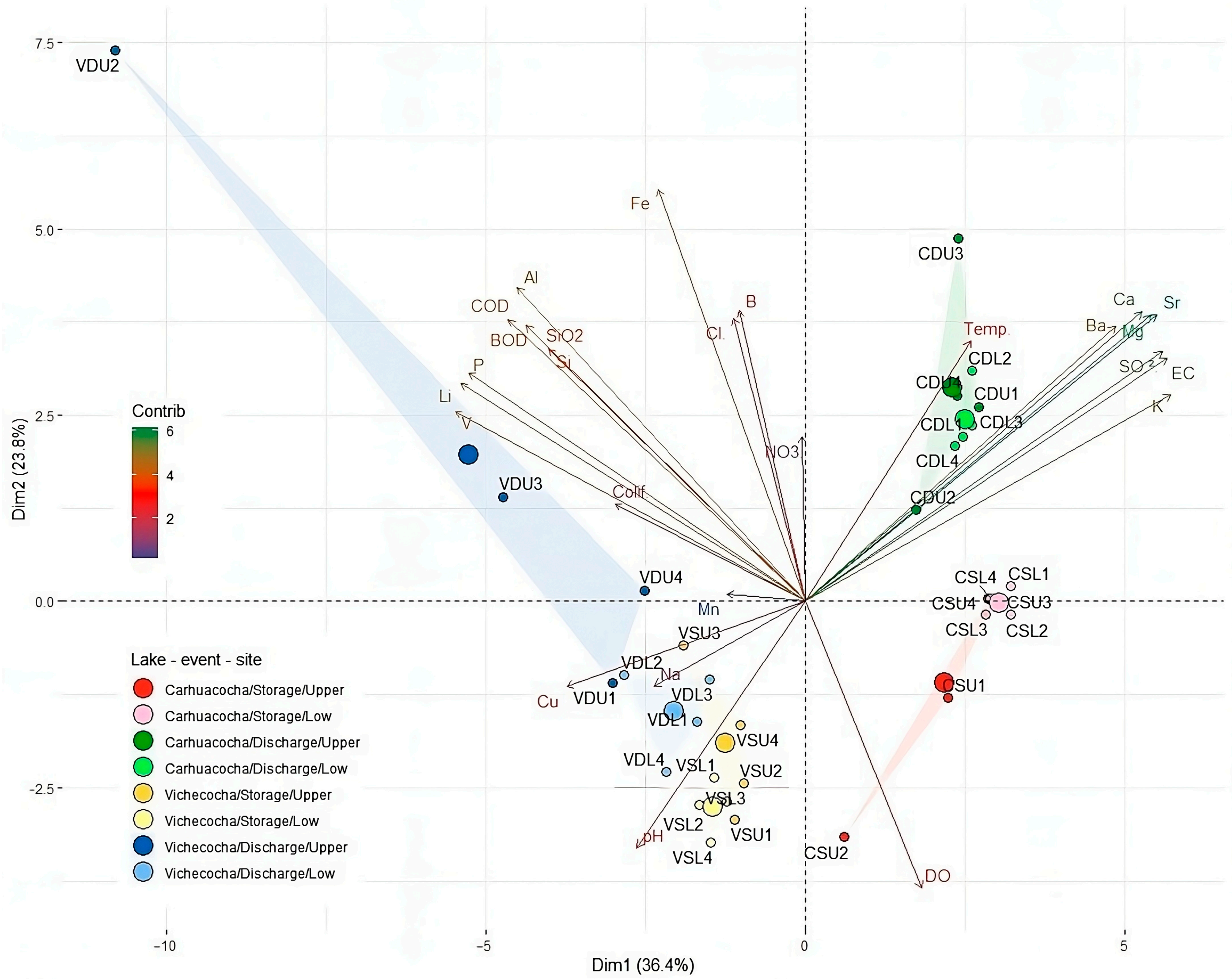

Figure 4. Principal component analysis (PCA) for 27 water parameters for storage and discharge events in Carhuacocha and Vichecocha lagoons.

4. Discussion

The quality of aquatic ecosystems around the world is declining due to a double threat: natural processes like weathering and atmospheric transport and human activities linked to population growth and rapid economic development. This decline threatens our global water security [20]. According to the individual evaluated parameters, water quality in the Carhuacocha and Vichecocha lagoons for storage and discharge events revealed variability (Table 2). However, in both lagoons the concentration levels of most of the parameters did not exceed the environmental water quality standards for Peruvian lentic system waters established by MINAM (acronym for the Ministry of Environment in Spanish) [21]. Water pH results showed an increasing trend towards alkalinity. This pH behavior would be related to pond sediment conditions, photosynthetic activity, and agricultural activities in the area [22]. It is well documented that DO and temperature as a function of depth in the water column are factors that determine aquatic life [23].

Custodio et al. [24] evaluated the water quality of Peruvian high Andean lagoons with similar characteristics to the mentioned lagoons in this study and found results of physicochemical parameters that are consistent with our results. However, the average DO concentration during discharge events in both lagoons fell below the minimum regulatory value of $\geq$5.0 mg/L. This decline may be attributed to the impact of agricultural activities on these water bodies. Our findings are in line with the observations reported by Arenas-Sánchez et al. [25]. They found that lower oxygen levels could be explained by several factors: increased organic matter from a shrinking ecosystem, faster respiration rates at higher temperatures, and reduced oxygen solubility in the water. Our measurements of COD and BOD in the Carhuacocha and Vichecocha lagoons varied across locations. This spatial difference likely stems from fish farm activities in nearby areas. This finding aligns with research by Xiao et al. [26], who identified a positive correlation between COD and land-use changes, highlighting the impact of agriculture on water quality. Other studies point out that changes in land use influence all water quality indicators [27]. Therefore, to ensure that the COD concentration in the studied lagoons remains within the Environmental Quality Standards (EQS) for water, it is essential to promote the responsible use of fertilizers in agricultural areas. Although the average concentrations of most physical–chemical elements, metals, and heat-tolerant coliforms fell within the acceptable range for protecting aquatic life (EQS), a significant positive correlation between certain parameters (Figure 3) indicates a potential common source of environmental pressure. Specifically, COD and BOD were positively correlated with Al, P, V, Li, SiO_2, Si, and Fe. This finding highlights the importance of monitoring these elements together, as several are linked to human activities like agriculture. Furthermore, the analysis revealed statistically significant differences in one third (33.33%) of the water quality parameters evaluated.

The quality of water is impacted by natural processes like erosion and by human actions such as industrial waste [28]. Rainfall throughout the year can influence water quality by washing away and diluting pollutants. This can cause seasonal fluctuations in contaminant levels [29]. Farming practices can significantly increase the amount of phosphorus, nitrogen, nitrate, ammonia, and sediment in waterways. Fertilizers and pesticides commonly used in agriculture can contribute to water pollution and eutrophication, which harms aquatic ecosystems. In addition, changes in water flow patterns caused by dams can also affect how pollutants move from land to water [30]. Our study revealed that, according to the $CCME_{WQI}$, the water quality of the Carhuacocha and Vichecocha lagoons was predominantly classified as good or excellent quality at most sampling sites. However, one site in the Vichecocha lagoon was classified as having medium water quality. Our findings in the Vichecocha lagoon align with Mohamed et al. [31]. They point out that external sources of phosphorus, such as those from fish farms like the one in our study, can significantly influence water quality.

5. Conclusions

This study evaluated the water quality of the Carhuacocha and Vichecocha lagoons throughout the storage and discharge events using the WQI method. The results showed excellent water quality in both lagoons during storage. However, the water quality declined when the lagoons discharged water during the dry season. Ammonia, nitrate, and phosphate were identified as the key factors most directly affecting the WQI when their influence was analyzed individually.

Our study identified pH, dissolved oxygen (DO), and biological oxygen demand (BOD) as the most sensitive indicators of water quality in the lagoons. Since limited research exists for the Mantaro head basin, this fact highlights the need for the managers of the Carhuacocha and Vichecocha lagoons to implement mitigation measures. These measures should aim to maintain or improve the water quality to ensure the lagoons remain suitable for their various uses.

Author Contributions: S.P. and P.V.-M. designed the methodology; P.V.-M. and D.C. provided and validated field data; S.P. and P.V.-M. performed the data processing; S.P. and P.V.-M. analyzed the data; R.S.-A. managed funding acquisition; S.P., P.V.-M. and M.C. wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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