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Article

Water Pollution Indexes Proposal for a High Andean River Using Multivariate Statistics: Case of Chumbao River, Andahuaylas, Apurímac

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Abstract: Pollution indexes are instruments that allow a quick interpretation of water quality, combining physical, chemical, and microbiological parameters to generate a numerical value. Our aim was to evaluate spatial and temporal-spatial water quality and propose a water pollution index (WPI) for high Andean rivers using multivariate statistics. Data on physical, chemical, and microbiological parameters were collected from the river water of the Chumbao sub-basin during the rainy and dry seasons at eight sampling points. The laboratory and field analysis methods were developed following the methodology proposed by the APHA. Spearman's correlation, cluster analysis, and discriminate analysis were applied to evaluate water quality's spatial and temporal variation and principal component analysis/factor analysis to identify critical parameters to formulate the Water Pollution Index (WPI). The parameters with the most incidence in water quality were color, conductivity, dissolved oxygen, biochemical demand oxygen, ammonia, total phosphorus, lead, chromium, and thermotolerant coliforms. The inorganic pollution index (IPI) was obtained from conductivity, lead, and chromium, reporting pollution levels for the river water between "none" to "high"; and the organic pollution index (OPI) was obtained from dissolved oxygen, biochemical demand oxygen, ammonia, total phosphorus, color, and thermotolerant coliforms, with levels of "low" to "very high" pollution. The proposed pollution indexes are water management instruments that evaluate water quality.

Keywords: organic pollution index; inorganic pollution index; high Andean River; multivariate analysis

1. Introduction

The high Andean rivers are a source of fresh water and allow the development of anthropic activities in the surrounding communities, such as agriculture, cattle raising, aquaculture, industry, energy, and water supply [1–4]. They are collectors of domestic, agricultural, and industrial wastewater, and transport organic and inorganic substances [5] that alter the natural composition and quality of water [6].

Assessing water quality involves monitoring spatial and temporal changes in parameters [7–12], which are subject to variations in flow, precipitation, surface runoff, tributaries, and effluents [1,13]. The practical and reliable water quality evaluation during monitoring programs is complicated and difficult to interpret, so it is crucial to develop new ways to approach and statistically interpret data for preventive or management purposes [6,14–16].

Multivariate statistical methods (MSM) are excellent research tools that help interpret complex sets of information, identify parameters responsible for water quality variation [17–25], and allow their selection to compose indexes that objectively evaluate the water resource [21,26,27].

MSM, as the correlation analysis, cluster analysis (CA), discriminant analysis (DA), principal component analysis (PCA), and factor analysis (FA), have been widely used to evaluate temporal and spatial variations in complex water quality datasets [1,6,10,14,19,24,28–32]. For example, Barakat et al. [3] used correlation, PCA, and CA to evaluate the spatial and seasonal variations of Oum Er Bia River surface water quality data; the PCA technique allowed the identification of the sources of water quality degradation. Alam et al. [33] applied the Pearson correlation matrix to detect interrelationships between variables; PCA/FA resulted in three principal components, showing that organic substances, anthropogenic activity, fertilization, chemical wastes, and sewage runoff are responsible for water quality deterioration. Hajigholizadeh and Melesse [10] used CA and DA to assess spatial and temporal variations in water quality in South Florida; for this, a dataset of 12 water quality variables was used. The CA grouped 16 monitoring sites into three groups based on the similarity of the water quality characteristics, while the DA reduced the data; both techniques allowed us to evaluate the state of water contamination. Ramírez et al. [34] used multivariate statistics to formulate four pollution indexes developed based on legislation from different countries according to the concentrations of other variables and potential water uses.

Many proposed water quality and pollution indexes make it possible to assess the state of the water body. They are widely used by institutions that modulate water quality in different countries [35–37]. Most of them are based on the criteria established by Horton [38], such as, altitudinal, geological, climatic conditions, physicochemical transformations of water, the use of nonoriginal parameters and different units, and the condition of water quality, with some parameters critical to determine its status.

These indexes are helpful instruments for the rapid interpretation of water quality, combining different physical, chemical, and microbiological parameters to generate a numerical value that allows specific pollution levels and to present the current state of water in rivers or bodies of water [24,39]; however, most of these indices do not adjust to the reality of each zone; their selection, weight assignment, and conversion to a scale, in most cases, are based on a subjective aspect [40].

The Chumbao River acts as a source of water for human consumption, irrigation, aquaculture, energy, industry, and habitat for aquatic organisms [2,4,41,42]; however, its waters have been affected by the excessive growth of the urban zone, intensive agricultural activities, and domestic and industrial wastewater discharges [16,17,43]. In this sense, the present study aimed to evaluate spatial and temporal-spatial water quality and propose a water pollution index (WPI) for high Andean rivers, using multivariate statistics, which was applied in the study of the Chumbao River in the city of Andahuaylas, Peru.

2. Materials and Methods

2.1. Study Area

The study area comprised the Chumbao sub-basin (Figure 1). Hydrographically, the Chumbao River is located in the Pampas River's lower part and right bank and originates in the high Andean zone at 4400 m. The sub-basin presents a Cwb climate according to Köppen, with marked seasons, in avenues with intense rainfall between October and March (from 500 to 1000 mm/year), and temperatures from 5 to 23 °C, and an average relative humidity of 55% [44].

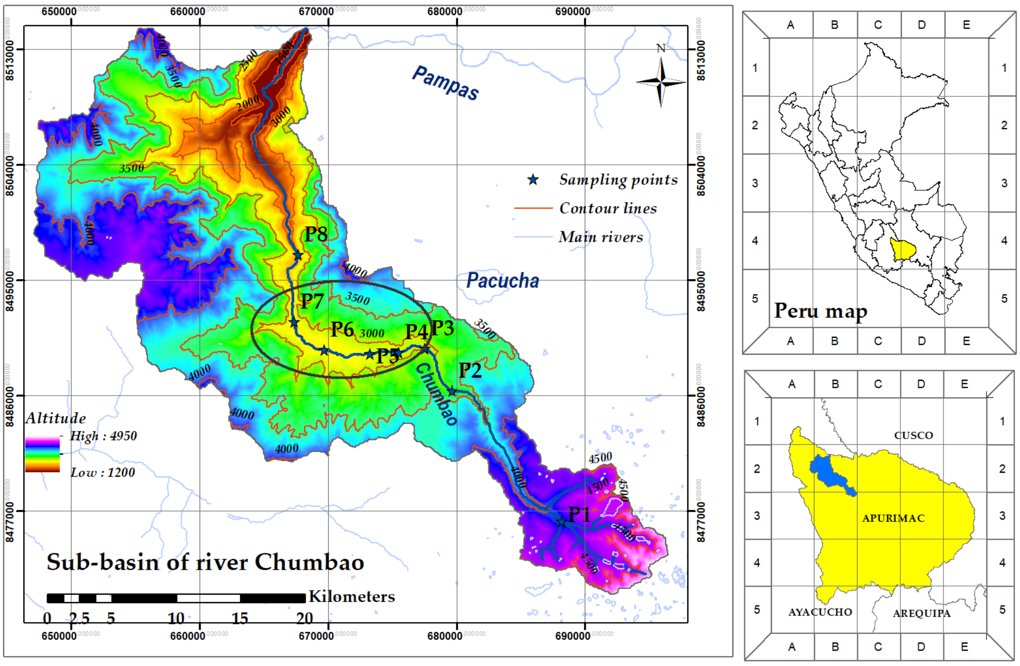


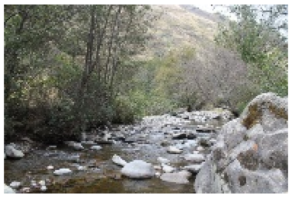
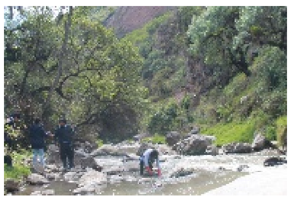
Figure 1. Study area Chumbao Sub-basin.

It has an approximate length of 61.92 km until it flows into the Pampas River and acts as a collector basin, covering 23.6% of soil use; agriculture and pasture cover a significant percentage of soil use, 60.7%, and 15.7% corresponds to the urbanized zone and limited industry [41].

2.2. Analysis of Water Quality Parameters

Water samples were collected at eight sampling points (Table 1) in the dry and rainy seasons during 2018 and 2019; the evaluated water quality parameters were selected in accordance with Peruvian regulations, specifically the environmental water quality standards, temperature (TEM), dissolved oxygen (DO), conductivity (CON), salinity (SAL), turbidity (TUR), total dissolved solids (TDS), and pH measured in the field; color (COL), alkalinity (ALK), hardness (HAR), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), chloride (CHL), phosphate (PHO), ammonia (AMM), nitrate (NITA), nitrite (NITI), total phosphorus (TP), lead (Pb), chromium (Cr), iron (Fe), bromine (Br), total coliforms (TCO), and thermotolerant coliforms (THC) determined in the laboratory. On the other hand, some heavy metals were considered in the study because, in the area, there is metallic and non-metallic extractive activity as well as some industries.

Table 1. Sampling points.

Sampling Points	Altitude (m)	Reference	Coordinates		Characteristics of the Area	Referential Photo
			South	West		
P1	4079	River headwater	13°46′38.4″	073°15′32.3″	Water collecting basin/native flora and fauna	
P2	3184	Hydroelectric	13°41′10.9″	073°20′19.7″	Water collection basin/limited agriculture and grazing	
P3	2978	Suylluhuacca bridge	13°39′23.4″	073°21′30.7″	Limited urbanization, agriculture, and intense grazing	
P4	2916	Andahuaylas coliseum	13°39′33.2″	073°22′38.2″	Increasing urbanization, limited agriculture and grazing, limited urban industry	
P5	2872	Engineering barracks	13°39′37.0″	073°23′52.7″	High urbanization and limited urban industry	
P6	2807	GREMAR college	13°39′27.4″	073°25′50.8″	High urbanization, limited agriculture, and grazing	
P7	2767	Chihuampata bridge	13°38′17.0″	073°27′10.6″	Limited urbanization, agriculture, and intense grazing	
P8	2572	Posoccoy bridge	13°35′26.4″	073°27′00.8″	Agriculture and intense grazing	

Sampling and sample preservation procedures (Table 2) were realized according to the National Protocol for monitoring the Quality of Superficial Water Resources [45] and analyses as per the methods proposed by APHA [46].

Table 2. Water Quality evaluation methods.

Parameter	Method	Reference
Color	Spectrophotometric	2120 B Standard Methods
Turbidity	Selective electrode (NFU)	User manual, Multiparameter
Conductivity	Selective electrode (Conductometer)	User manual, Multiparameter
Salinity	Selective electrode (Conductometer)	2520 B Standard Methods
TDS	Selective electrode (Conductometer)	2540 C Standard Methods
Temperature	Selective electrode (thermometer)	User manual, Multiparameter
Alkalinity	Spectrophotometric	User manual, Photometer
Hardness	Spectrophotometric	User manual, Photometer
Chloride	Chloride selective electrode (ISE)	User manual, Multiparameter
pH	Potentiometric	User manual, Multiparameter
Ammonia	Ammonia selective electrode (ISE)	4500-NH3 D Standard Methods
Nitrite	Spectrophotometric	User manual, Photometer
Nitrate	Nitrate selective electrode (ISE)	User manual, Multiparameter
Phosphate	Spectrophotometric	User manual, Photometer
DO	Selective electrode (oximetry)	User manual, Multiparameter
BOD	Respirometry/manometric	4500-0C y 5210 B Standard Methods
COD	Spectrophotometric	User manual, Photometer
Total phosphorus	Spectrophotometric	User manual, Photometer
Chromium	Spectrophotometric	User manual, Photometer
Lead	Spectrophotometric	User manual, ICP-OES
Iron	Spectrophotometric	User manual, Photometer
Bromine	Spectrophotometric	User manual, Photometer
Total coliforms	Fermentation	9221 B y 9221C Standard Methods
Thermotolerant coliforms	Thermotolerant coliform	9221 E Standard Method

2.3. Evaluation of Water Pollution Index (WPI)

For the formulation of the water pollution indexes (WPI), the degree of relevance of each variable was identified through PCA/FA, selecting those with the highest factorial load and indicated in the Peruvian regulations: "ESQ: Environmental Standard Quality of the water, category 4: Conservation of the Aquatic Environment" [47]. The classification was according to the source of organic and inorganic pollution, and parameter weights (W_i) which were obtained as per Equation (1).

$$W_i = \frac{Fl_i}{\sum_{i=1}^{i=n} Fl_i} \tag{1}$$

where Fl_i is the factor load of each selected parameter, $\sum_{i=1}^{i=n} Fl_i$ is the sum of the factor loadings as per the classification.

Subsequently, each selected parameter's nominal reason (Nr_i) was determined according to Equation (2), considering field/laboratory-measured and ESQ values.

$$Nr_i = \frac{C_i}{C_{ESQ}} \tag{2}$$

where C_i is the concentration of the selected and evaluated parameter; C_{EQS} is the concentration of the parameter established in the ESQ.

When the concentration of the evaluated parameter is greater than or equal to the concentration of the ESQ, the nominal ratio is equal to 1.

Condition: $C_i \geq C_{ESQ};\ Nr_i = 1$.

The WPI was formulated using the organic pollution index (OPI) and the inorganic pollution index (IPI).

$$OPI = \sum Nr_i W_i \quad (3)$$

$$IPI = \sum Nr_i W_i \quad (4)$$

Water pollution indexes were applied to evaluate the water quality of the high Andean River. The calculated WPI values were classified into five categories (Table 3) according to Ramírez et al. [34]. The scale makes it possible to quantify the degree of contamination of the waters for its general condition and not for specific contaminants.

Table 3. Water pollution index classification.

WPI	Pollution	Color Scale	Characterization
0.0–0.2	None	Blue	Pure waters, perhaps with biogenic contributions
>0.2–0.4	Low	Green	Mild anthropic incidence
>0.4–0.6	Medium	Yellow	Notable anthropic activity
>0.6–0.8	High	Orange	Important incidence of pollution
>0.8–1.0	Very high	Red	Highly polluted areas

2.4. Statistical Analysis

The normality of the data was tested using the Kolmogorov–Smirnov test [40]. Spearman's correlation analysis was applied to determine the relationship between the parameters. The clustering of sampling points was performed through a CA, using the Ward method to evaluate the distance between clusters and the squared Euclidean distance as an index of proximity or similarity. The DA was used to assess spatial and temporal variations in water quality. The PCA/FA was performed to determine the factors and sources of pollution that affect water quality. The Kaiser–Meyer–Olkin (KMO) sphericity and Bartlett's test [48] were previously applied to evaluate the effectiveness of the data in executing the PCA/FA. Origin Pro 2022b software (OriginLab Corporation, Northampton, MA, USA) was used, and 5% was used as the significance level.

3. Results and Discussion

3.1. Analysis of Water Quality Parameters

The physical water parameters (Figure 2) levels were high during the dry season, especially for COL, CON, SAL, and TDS, with average values of 91.67 PCU, 907.17 µS/cm, 0.46 PSU, and 453.00 mg/L, respectively. The TUR reported high levels during the rainy season, associated with increased flow and removal of particulate material [33,49]. The CON, SAL, and TDS presented high levels in the populated zone; TEM reported values with an increasing and varied trend during the rainy and dry seasons, respectively.

The chemical parameters of the water are shown in Figure 3; the DO reported levels higher than 5.00 mg/L except for points P6 and P7 of the dry season, which show the degree of pollution, demonstrating the behavior of rivers in urban areas [50]. The COD reported higher values than the BOD_5; this would be due to the presence of degradable and oxidizable organic substances [51]; however, a limitation of the COD test is its inability to differentiate between biodegradable and biologically inert organic matter on its own [52]; regarding pH, neutral values were mostly reported. Although, slightly alkaline values were reported in the populated zone; this parameter is related to the toxicity of some compounds in the water [53]. The ALK and HAR reported high levels of up to 61.67 mg/L and 212.65 mg/L, respectively, while the basin headwater showed a decreasing trend; the variability of these parameters is subject to pH changes [50,54,55]. The presence of NITA was reported only during the rainy season, especially in the populated zone. Regarding the concentration of NITI and AMM, average values were 5.44 mg/L and 11.85 mg/L, respectively. The CHL levels in the water were high in the basin headwater and downstream of the populated zone; their presence may cause water and soil salinization, plant growth inhibition [56], and corrosion [57]. The PHO and TP concentrations were high in the populated zone with values of up to 3.53 mg/L and 0.99 mg/L, respectively; their increase in the water led to a rise in nutrients, causing irreversible damage to aquatic life [58].

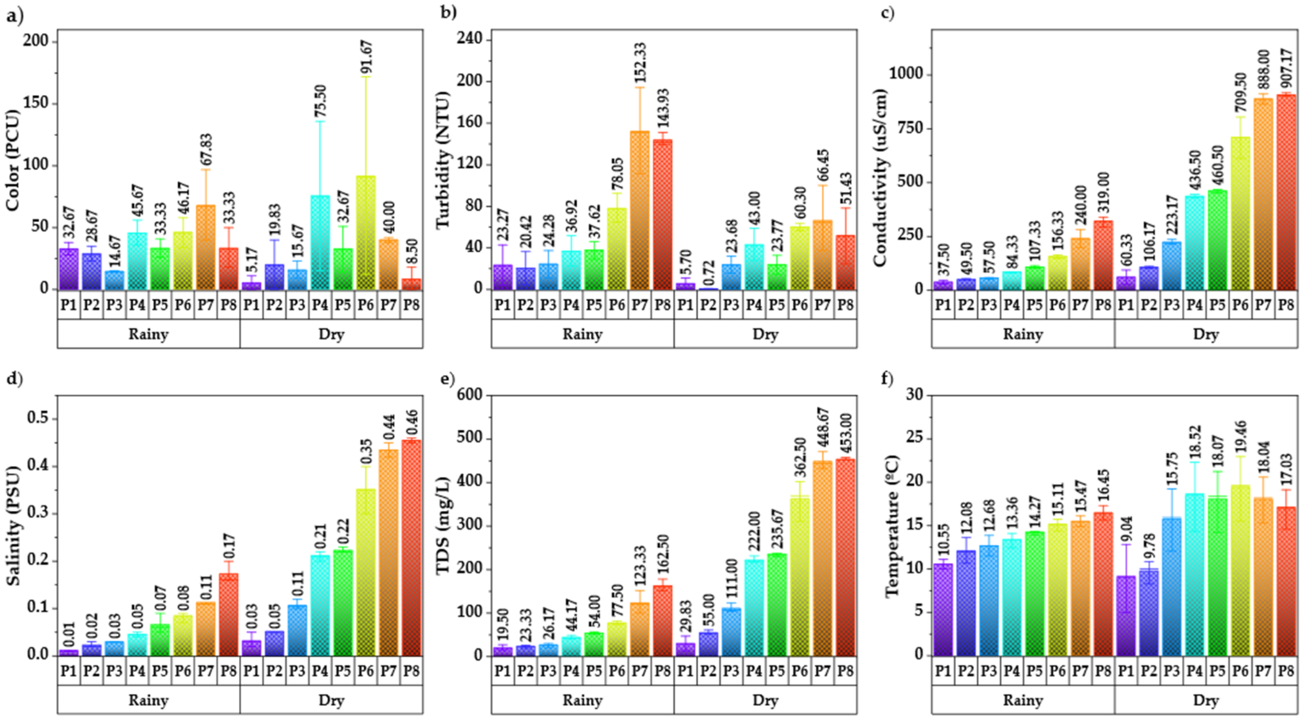


Figure 2. Values of physical parameters: (**a**) Color, (**b**) Turbidity, (**c**) Conductivity, (**d**) Salinity, (**e**) TDS, (**f**) Temperature.

The concentration of Br, Fe, Cr, and Pb (Figure 4) presented values of up to 0.28 ppm, 0.48 ppm, 64.00 ppb, and 1.20 ppb, respectively. The level of Cr and Pb indicates the extent to which industrial activities have developed in the study zone [59–61].

Heavy metals such as Cr and Pb bioaccumulate in the body. The effects of toxicity range from mild irritation to the eyes, nose, and skin to severe headaches, stomach pain, diarrhea, hematemesis, vomiting, and dizziness, to organ dysfunctions such as cirrhosis, necrosis, low blood pressure, hypertension, and gastrointestinal upset [62].

Regarding the Peruvian regulations, some chromium values exceed the limit (11 ppb), while lead is within the limit (2.5 ppb). The level of Cr and Pb indicates the extent to which industrial activities have developed in the study zone [59,61].

The presence of TCO and THC in the water (Figure 5) is indicative of pollution by human or animal fecal waste [49]; levels were high, especially during the dry season and in zones with higher population density, as a result of domestic effluents and the lack of wastewater collection and treatment infrastructure.

In general, it was observed that most of the parameters are within the limit established by Peruvian regulations [47], except for COL, DO, BOD_5, AMM, pH, TP, Cr, and THC. However, no reference value exists for TUR, SAL, TDS, COD, NITI, PHO, CHL, ALK, Fe, Br, and TCO (Table 4).

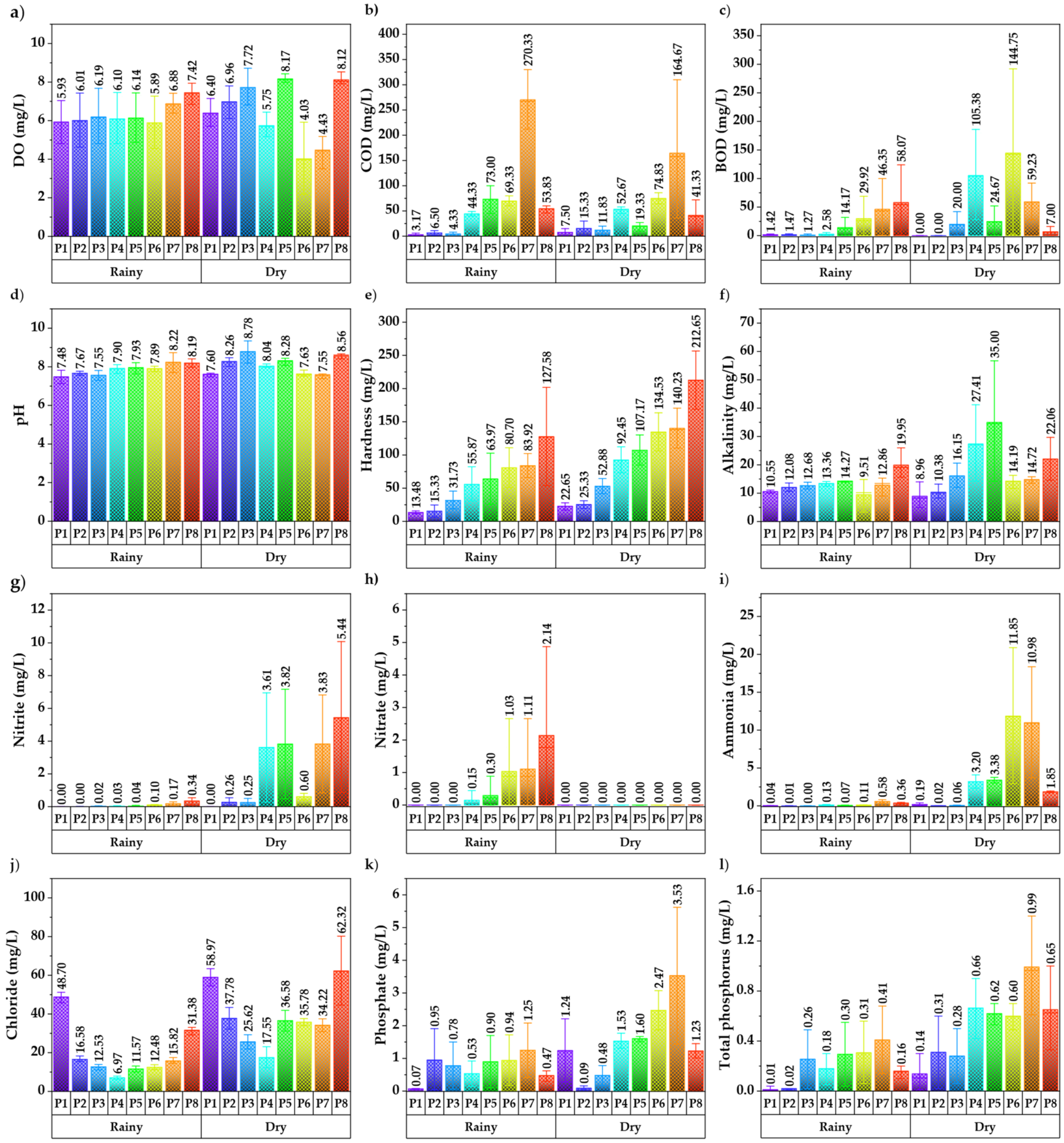


Figure 3. Values of chemical parameters: (**a**) DO: Dissolved oxygen, (**b**) BOD: Biochemical oxygen demand, (**c**) COD: Chemical oxygen demand, (**d**) pH, (**e**) Hardness, (**f**) Alkalinity, (**g**) Nitrite, (**h**) Nitrate, (**i**) Ammonia, (**j**) Chloride, (**k**) Phosphate, (**l**) Total phosphorus.

3.2. Correlation of Water Quality Parameters

Most of the parameters were correlated, except CHL (Figure 6). Values of r > 0.99 were observed for CON, SAL, and TDS. These parameters would be associated with dissolved ions in the water due to evaporation and mineral weathering [63,64]. Likewise, a significant correlation was observed between COL and BOD_5 (r = 0.71), TUR, and COD (r = 0.77), which are related to the organic and inorganic load from agricultural and domestic sources; similarly, for ALK and HAR (r = 0.92), which would be linked to the geology of the study zone.

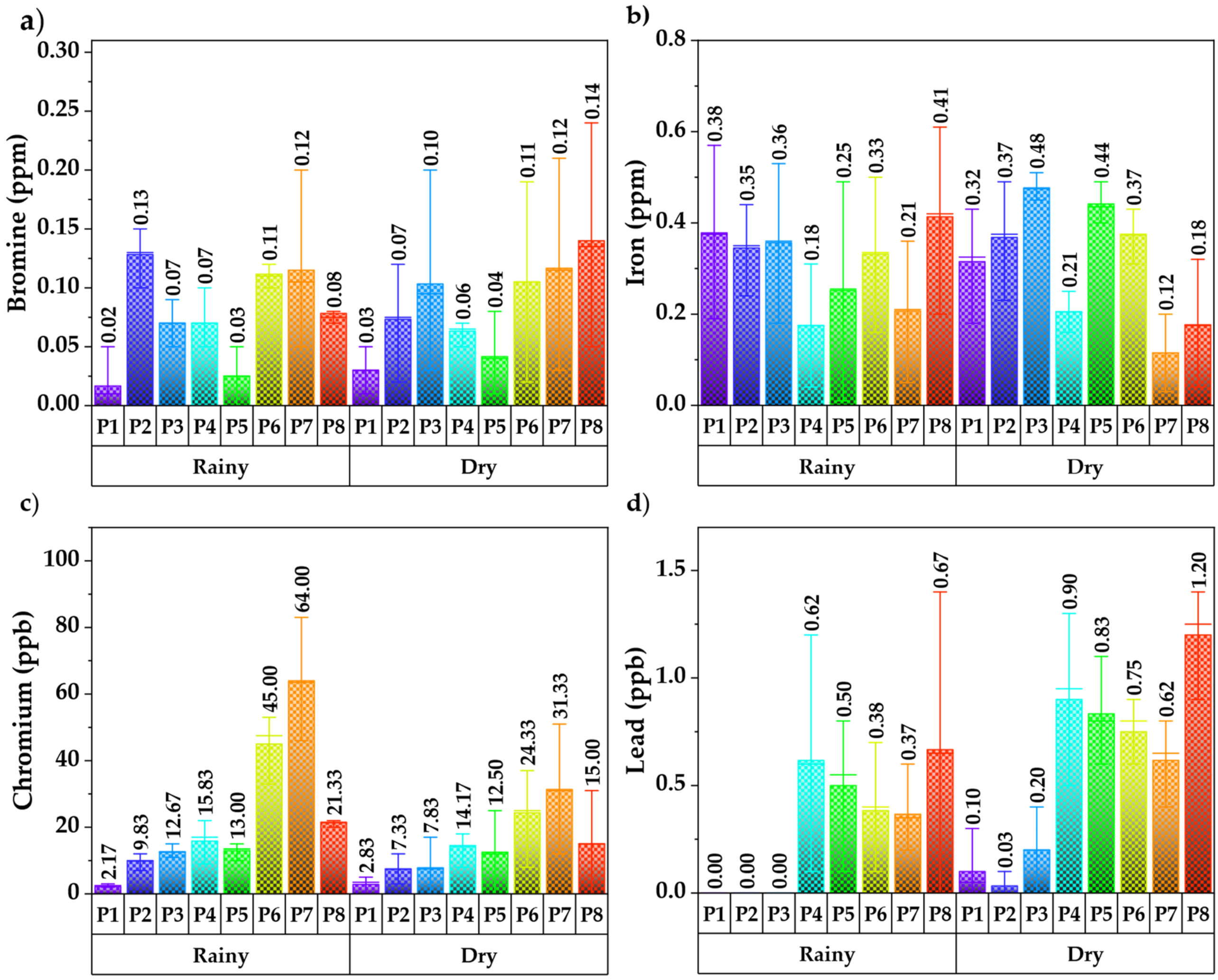


Figure 4. Values of: (**a**) Bromine, (**b**) Iron, (**c**) Chromium, (**d**) Lead.

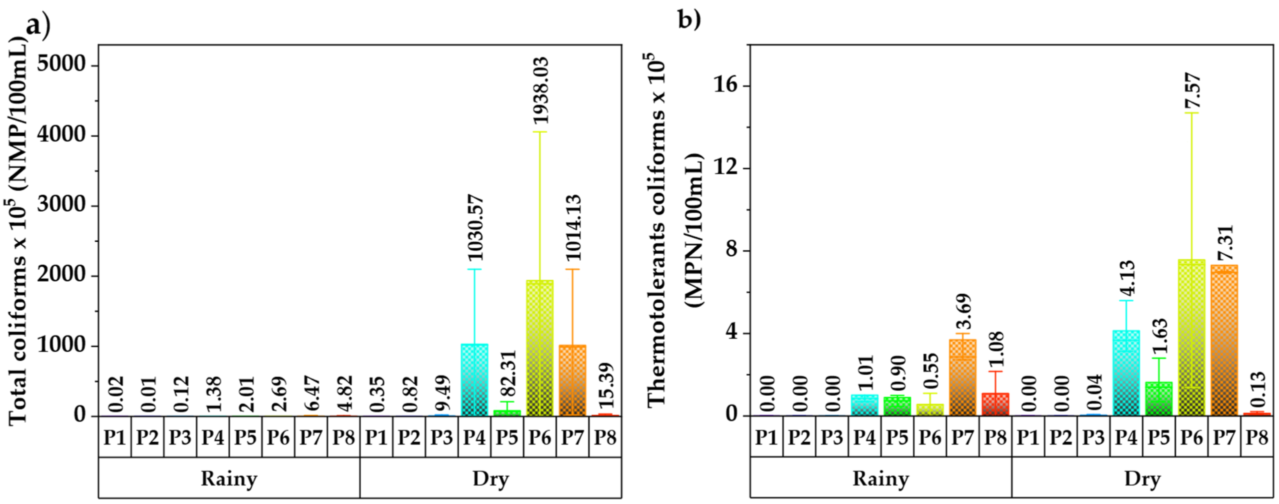


Figure 5. Values of microbiological parameters: (**a**) Total coliforms, (**b**) Thermotolerant coliforms.

Table 4. Statistical summary of water quality parameters of the high Andean River.

Parameters	N	Min	Max	Mean	SD	CV	ESQ	Units
Color	96	0.00	172.00	36.96	36.08	97.62	20	PCU
Turbidity	96	0.60	194.60	49.49	45.97	92.89	NA	NTU
Conductivity	96	27.00	917.00	302.68	290.68	96.03	1000	µs/cm
Salinity	96	0.01	0.46	0.15	0.14	95.36	---	PSU
TDS	96	13.00	471.00	153.01	146.86	95.98	NA	mg/L
Temperature	96	4.99	22.96	14.73	3.86	26.22	3	°C
DO	96	2.18	8.72	6.38	1.51	23.59	5	mg/L
BOD_5	96	0.00	292.00	32.27	62.20	192.77	10	mg/L
COD	96	0.00	330.00	57.02	77.77	136.39	NA	mg/L
Nitrate	96	0.00	4.87	0.30	0.90	305.99	13	mg/L
Nitrite	96	0.00	10.08	1.16	2.55	220.67	NA	mg/L
Phosphate	96	0.04	5.62	1.13	1.14	101.47	NA	mg/L
Ammonia	96	0.00	20.89	2.05	4.72	229.88	0.88	mg/L
Chloride	96	6.10	80.20	29.05	17.49	60.19	NA	mg/L
Alkalinity	96	2.90	74.40	30.12	19.24	63.86	NA	mg/L
Hardness	96	6.30	256.60	78.78	61.09	77.55	NA	mg/L
pH	96	7.13	9.34	7.97	0.44	5.57	6.5–9.0	
Total phosphorus	96	0.00	1.40	0.37	0.34	92.35	0.05	mg/L
Lead	96	0.00	1.40	0.45	0.44	98.89	2.5	ppb
Chromium	96	0.00	83.00	18.70	18.09	96.73	11	ppb
Iron	96	0.01	0.61	0.31	0.17	55.91	NA	ppm
Bromine	96	0.00	0.35	0.09	0.08	81.21	NA	ppm
Total coliforms	96	0.00	4.06×10^8	2.57×10^7	8.18×10^7	3.19×10^2	NA	MPN/100 mL
Thermotolerant coliforms	96	0.00	1.47×10^6	1.75×10^5	3.02×10^5	1.72×10^2	2000	MPN/100 mL

N is the data number; Min is the minimum value; Max is the maximum value; SD is the standard deviation; CV is the coefficient of variation; ESQ: Environmental Standard Quality of the water, category 4: Conservation of the Aquatic Environment; NA is Not applicable.

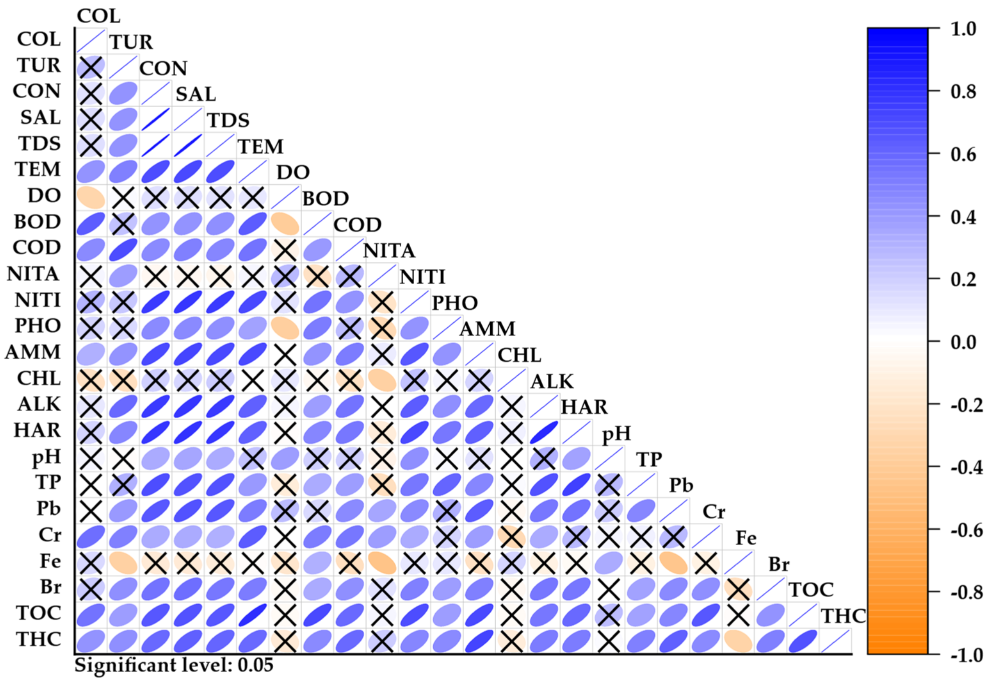


Figure 6. Correlation of water quality parameters of the high Andean River; X is not significant.

3.3. Spatial Similarity and Site Clustering

The dendrogram showed the clustering of three groups with a similarity index of 60% (Figure 7). Cluster I comprised points P1, P2, and P3, which are low pollution (LP) sites located in the headwater of the basin, where there is no anthropogenic presence.

Cluster II included sites P4, P5, and P8, considered medium polluted (MP) sites, located in zones dedicated to agricultural and livestock activities, and sites P6 and P7 were part of Cluster III, which are highly polluted sites (HP), directly receiving domestic and industrial wastewater discharges.

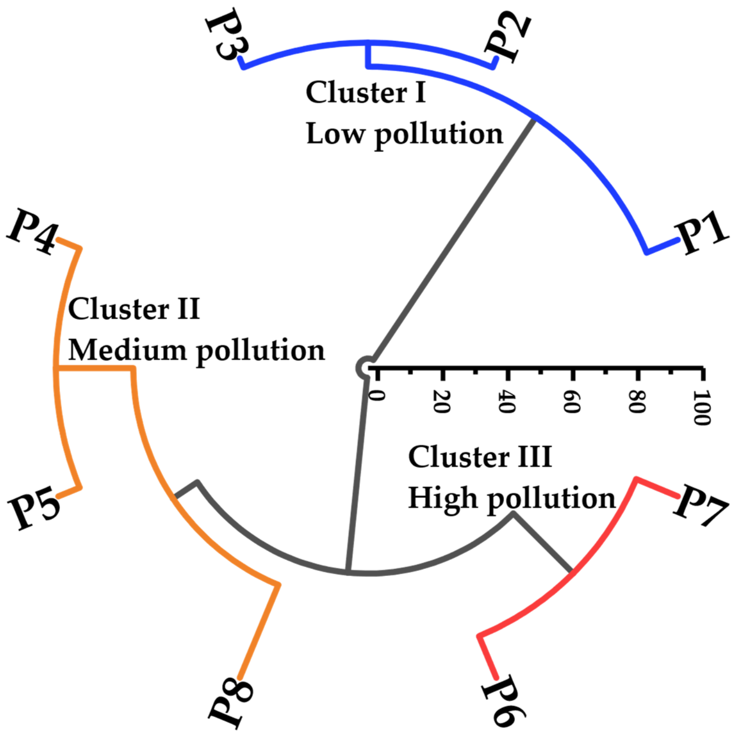


Figure 7. Dendrogram of sampling points of the high Andean River.

3.4. Spatial and Season Variation of River Water Quality

The spatial DA indicated that CON, NITI, HAR, Pb, Cr, and TCO are the parameters responsible for spatial variation (Figure 8). The evaluation showed that water CON was low in the LP zone with significant spatial variations, indicating that the dissolution of geological soil components and organic and inorganic substances introduced to the river channel caused an increase in water conductivity in the MP and HP zone. Likewise, the MP and HP sites reported high concentrations of HAR associated with cations in the water due to the study zone's lithological origin and geological complexity [65]. The concentrations of Pb and Cr were high in the MP and HP zones, respectively, which is related to wastewater from mining and agricultural activities developed in the zone. This behavior is characteristic of zones of anthropogenic activity [59–61], while the presence of these metals in the LP zone could be due to their natural form in rocks or surface mineral grains that are mobilized by natural means or artificial recharge [66,67]. The presence of high concentrations of NITI in the MP zone would be associated with crop residues and nitrogen fertilizers [68,69]. The TCO levels were high at the HP zones, suggesting a critical level of microbial pollution. The spatial relationships between the variables showed more significant environmental pollution problems in the PM and HP zones.

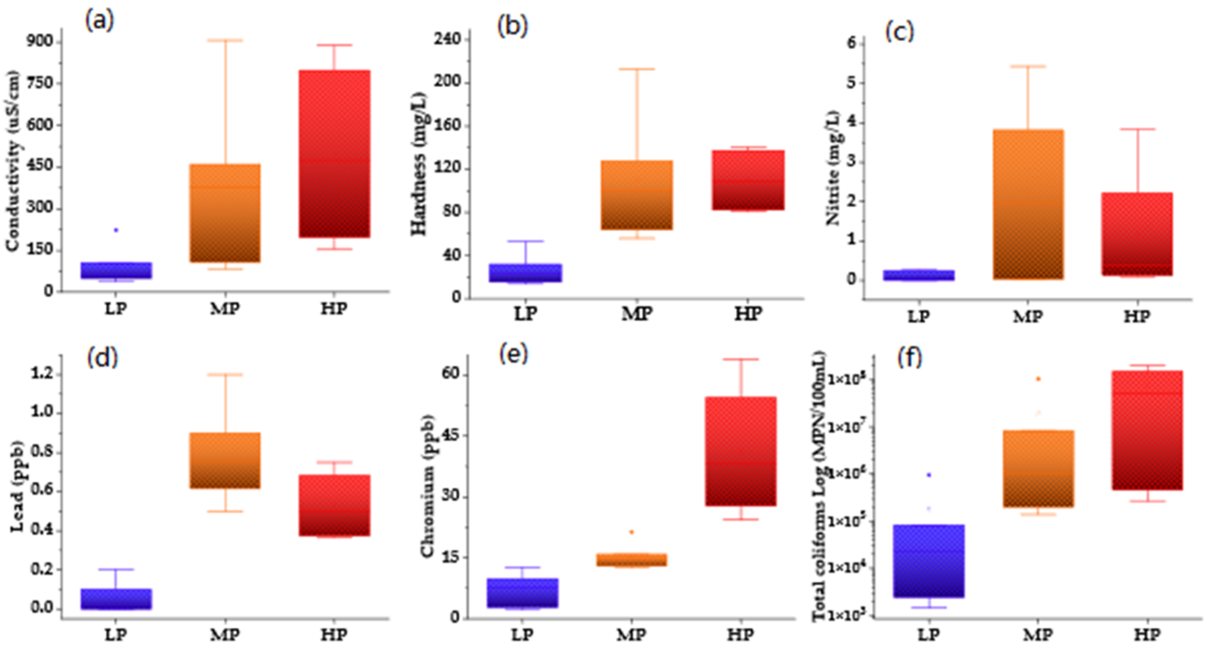


Figure 8. Spatial variations of: (**a**) Conductivity, (**b**) Hardness, (**c**) Lead, (**d**) Chromium, (**e**) Nitrite, (**f**) Total coliforms.

The temporal AD showed that TDS, ALK, Br, and TCO are responsible for the variations (Figure 9), being higher in the dry season due to the concentration of organic and inorganic substances present in the water in a natural or anthropic form [50,70–74].

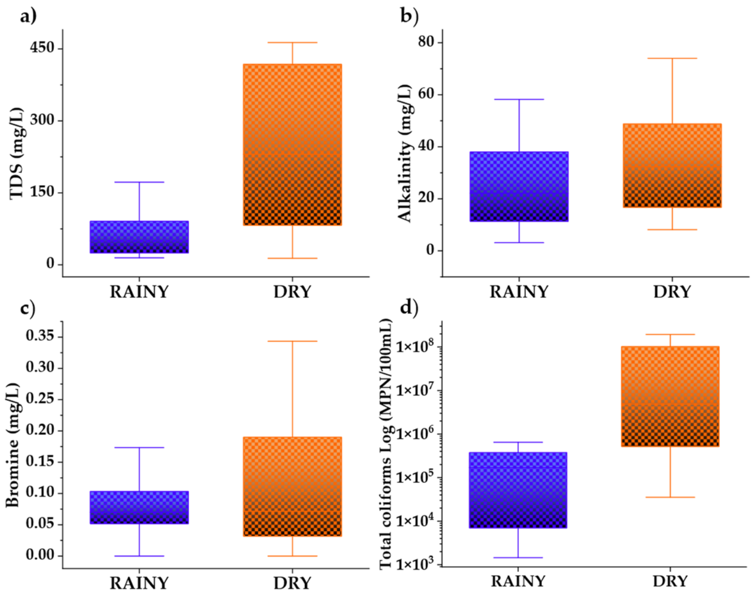


Figure 9. Season variations of: (**a**) TDS, (**b**) Alkalinity, (**c**) Bromine, (**d**) Total coliforms.

3.5. Identification of Source of Pollution

The KMO sphericity analysis was 0.62, and Bartlett's test was significant ($p = 0.00$); therefore, the data are adequate to reduce the dimensionality of the information by PCA/FA. The PCA/FA with a normalized Varimax rotation identified three factors, which explained 66.85% of the total variance (Table 5). The first factor (F1) explained 38.73% of the total variance, presenting strong positive loadings (>0.70) for CON, SAL, TDS, ALK, HAR, Br, TP, and Pb. This F1 is related to natural sources of dissolution of geological components of the soil, especially inorganic ones such as anions and cations dissolved in the water due to the mineral weathering process or anthropogenic sources [32,75]. In addition, a Spearman's correlation test applied to environmental parameters showed that TDS was significantly correlated with SAL, ALK, HAR, Br, TP, and Pb, indicating that these components are the principal source of TDS. The second factor (F2) accounted for 16.22% of the total variance, with moderate loads for COL, BOD_5, TCO, and THC and a negative contribution of DO to this factor. This F2 represents the contributions of nutrients and organic matter from untreated domestic wastewater, effluents, and agricultural runoff. The negative contribution of DO to this factor is due to the increase in nutrients that raises the concentration of organic matter; therefore, the degradation of organic matter reduces the DO concentration [6,76]. The third factor (F3) shows 11.91% of the total variance and presents a heavy positive load for TUR, COD, and Cr. This F3 represents the sediments coming from erosion, suspended solids, and urban runoff responsible for the TUR of the water and a high concentration of COD; the contribution of Cr to this factor is an indicator of pollution from industrial activities [61].

Table 5. Factor loadings (Varimax normalized).

Parameters	F1	F2	F3
COL	−0.03	0.87 *	0.19
TUR	0.22	0.06	0.85 *
CON	0.94 *	0.30	0.03
SAL	0.95 *	0.29	0.04
TDS	0.94 *	0.30	0.03
TEM	0.52	0.56	0.19
DO	0.11	−0.72	0.08
BOD_5	0.17	0.89 *	0.04
COD	0.24	0.17	0.73 *
NITA	−0.08	−0.18	0.66
NITI	0.58	0.22	−0.28
PHO	0.46	0.60	−0.11
AMM	0.39	0.82 *	−0.09
CHL	0.43	−0.11	−0.51
ALK	0.83 *	0.03	0.40
HAR	0.86 *	0.04	0.15
pH	0.32	−0.26	0.00
TP	0.70 *	0.14	0.08
Pb	0.70 *	−0.06	0.33
Cr	0.09	0.36	0.70 *
Fe	−0.21	0.17	−0.45
Br	0.75 *	0.17	0.17
TCO	0.17	0.92 *	−0.09
THC	0.32	0.86 *	0.23
Eigenvalue	9.29	3.89	2.86
%Total variance	38.73	16.22	11.91
Cumulative %	38.73	54.95	66.85

* Indicates factor loading > 0.7.

3.6. Identification of Sources of Pollution

The results of the weights were calculated from Equation (1) and shown in Table 6. The factor loads were grouped into two sources of contamination. The inorganic source showed that CON presented the most significant weight, followed by Pb and Cr. While the organic source revealed that the BOD5, COL, and THC presented higher weights, followed by AMM, DO, and TP.

Table 6. Weights of water quality parameters.

Source of Pollution	Parameters	Factor Loading	Weight (W_i)
Inorganic	CON	0.94	0.40
	Pb	0.70	0.30
	Cr	0.70	0.30
	Total	2.34	1.00
Organic	DO	0.72	0.15
	BOD_5	0.89	0.18
	AMM	0.82	0.17
	TP	0.70	0.14
	COL	0.87	0.18
	THC	0.86	0.18
	Total	4.86	1.00

Other studies obtained the relative weights by combining physical, chemical, and microbiological parameters; for example, Khanoranga and Khalid [75] combined 21 parameters to calculate the relative weights, weighting the values according to the WHO standard to calculate the groundwater quality index. Dimri [49] used 11 parameters according to the drinking water quality standard to calculate the relative weights and calculated the water quality index for the Ganga River.

The values of the nominal reason are shown in Table 7. The nominal reason represents the scale of assessment of water contamination, which was obtained by dividing the concentration observed by the concentration regulated in the regulations. In terms of the evaluation, it was possible to appreciate values close to one, especially for TP, THC, BOD_5, and chromium. Regarding temporality, the dry season showed high classification scales, which would be associated with the low flow of the river water that concentrates the pollutants. Furthermore, Khanoranga and Khalid [75] applied the quality rating scale to obtain a groundwater quality index.

Table 7. Nominal reason water quality parameters.

Sampling Points	Season	DO	BOD_5	AMM	TP	COL	THC	CON	Pb	Cr
P1	Rainy	0.84	0.14	0.04	0.27	0.30	0.00	0.03	0.00	0.20
P2	Rainy	0.83	0.15	0.01	0.33	0.30	0.00	0.03	0.00	0.89
P3	Rainy	0.81	0.13	0.00	1.00	0.31	0.00	0.01	0.00	1.00
P4	Rainy	0.82	0.26	0.15	1.00	0.30	1.00	0.05	0.25	1.00
P5	Rainy	0.81	1.00	0.08	1.00	0.31	1.00	0.03	0.20	1.00
P6	Rainy	0.85	1.00	0.12	1.00	0.29	1.00	0.05	0.15	1.00
P7	Rainy	0.73	1.00	0.66	1.00	0.34	1.00	0.07	0.15	1.00
P8	Rainy	0.67	1.00	0.41	1.00	0.37	1.00	0.03	0.27	1.00
P1	Dry	0.78	0.00	0.21	1.00	0.32	0.00	0.01	0.04	0.26
P2	Dry	0.72	0.00	0.02	1.00	0.35	0.00	0.02	0.01	0.67
P3	Dry	0.65	1.00	0.07	1.00	0.39	1.00	0.02	0.08	0.71
P4	Dry	0.87	1.00	1.00	1.00	0.29	1.00	0.08	0.36	1.00
P5	Dry	0.61	1.00	1.00	1.00	0.41	1.00	0.03	0.33	1.00
P6	Dry	1.00	1.00	1.00	1.00	0.20	1.00	0.09	0.30	1.00
P7	Dry	1.00	1.00	1.00	1.00	0.22	1.00	0.04	0.25	1.00
P8	Dry	0.62	0.70	1.00	1.00	0.41	1.00	0.01	0.48	1.00

The evaluation of water quality is shown in Figure 10. It was observed that the OPI values ranged from 0.25 to 0.78 during rains, indicating "low" to "high" pollution, and from 0.35 to 0.86 during the dry season, meaning "low" to "very high" pollution, evidencing slight anthropogenic incidence and highly contaminated areas, especially in the populated zone, which would be related to the presence of organic substances and decomposing plant material from domestic and agricultural activities [6,49,76,77]. The IPI presented mild biogenic contributions and notable anthropic activity in the populated zone, with values that fluctuated between 0.07 and 0.39 during the rainy season, indicating "none" and "low" pollution, and between 0.09 and 0.45 during the dry season, indicating "none" to "medium" pollution; this index would be indicative of industrial activities developed in the zone [59–61,66,67].

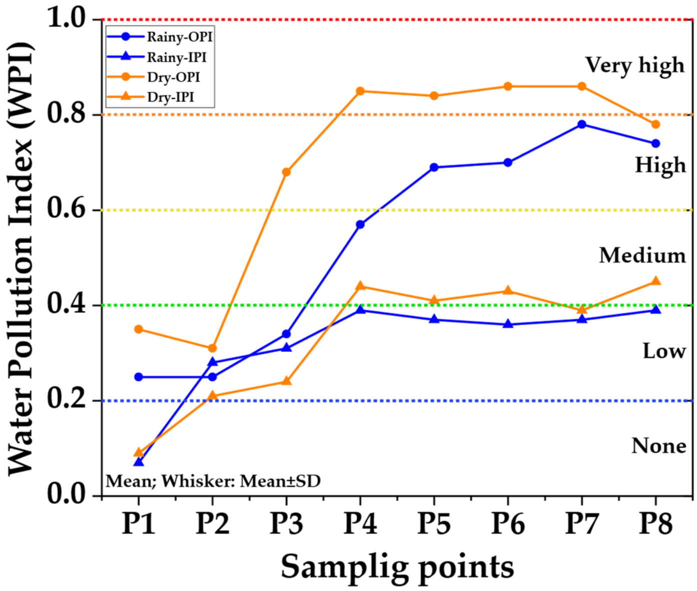


Figure 10. Water pollution index of the high Andean River.

4. Conclusions

The study applied different multivariate statistical techniques to evaluate spatial and temporal variations and identify possible sources of contamination of surface water quality in the Chumbao sub-basin.

The AC grouped the eight sampling points into three seasonal groups with identical water quality characteristics. The DA substantially reduced both temporal and spatial data, and the AF/PCA allowed extracting and recognizing the factors responsible for changes in water quality.

The parameters with the most significant impact on water quality were identified, which allowed the formulation of the IPI constructed from the parameters CON, Cr, and Pb, and the OPI with the parameters DO, BOD_5, AMM, TP, COL, and THC. The water quality of the high Andean River reported pollution levels between "none" and "medium" for the IPI and between "low" and "very high" for the OPI. The proposal of an ICO provides a water quality management instrument.

The indices can be applied to high Andean rivers with similar characteristics located at an altitude of at least 2500 m. Finally, the indices can be used as a management instrument to assess water quality.

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