

Article

Drinking Water Service Diagnosis in a High-Elevation Andean City of Peru: A Quality and Deterministic and Probabilistic Approach to Health Risk

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Abstract

The quality of water for human consumption depends on the supply method and source type. Water may contain pathogens and excessive constituents that pose health risks, and timely monitoring and planned service provision help ensure its quality. This study assessed the supply system, quality, and health risks associated with the consumption of water from three sources in the high-elevation Andean city of Andahuaylas, Peru, managed by the Municipal Sanitation Service Provider Chanka (EMSAP). The sources were found to provide between 0.8 and 32 L/s, with consumption of about 17 m³ per connection per month, at a cost of 0.20 USD/m³. The system shows a current deficit and a projected deficit for 2027 due to increasing user debts and the absence of mechanisms for payment for ecosystem services (PESs), despite the existence of cross-subsidies. Water quality, assessed using the WQI-Pe, ranged from regular to excellent, although with high levels of heavy metals according to the Environmental Quality Standards for Water (EQS–Peru), which increases the non-carcinogenic health risk. Chronic non-carcinogenic exposure (HQ) from consumption and dermal contact exceeded one, mainly for arsenic (As), while the deterministically and probabilistically evaluated incremental lifetime cancer risk (ILCR) was linked to high levels of As, Cr, and Cd across all age groups (infants, children, adolescents, and adults). Overall, this study provides insight into the state of water in areas without conventional treatment, so the implementation of buffer zones in the basin's headwaters in localities with similar characteristics is vital.

Keywords: heavy metals; health risk; headwaters; supply system; water quality index



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1. Introduction

The high-elevation Andean areas of South America are characterized as watershed headwaters that supply surface water and groundwater. These ecosystems can be affected

by both anthropogenic and natural activities, including the area's climate and geomorphology [1,2]. Pollution from anthropogenic activities and overexploitation could make water scarcer, threatening water quantity and quality [3]. Water distribution and quality in developing countries depend largely on intact and functional supply areas. However, factors have been identified that affect the structure and composition of ecosystems, influenced by population growth, urbanization, climate change, and emerging practices [4,5].

Water quality for human consumption is essential to public health and societal well-being. For this reason, the World Health Organization periodically publishes guidelines on the quality of drinking water. These guidelines are intended to assist with the development of internal regulations in each country [6].

Most economically and socially developed countries have already implemented conventional water treatment processes, whereas in developing or emerging countries in Latin America, traditional treatment processes are still used, with some quality parameters that pose risks to human health, as they do not meet quality standards [1,7]. The lack of basic sanitation and access to clean, quality water can lead to disease. In Latin American countries, many people lack this resource, violating the vital right to safe water as set out in the Sustainable Development Goals [8,9]. Furthermore, in these countries, water quality has been degraded by heavy metals, causing not only ecological but also health problems, especially in Andean cities, leading to ecosystem imbalances and impacting human health. Countries such as Mexico, Colombia, and Chile have reported declines in the water quality index due to the bioaccumulation and biomagnification of heavy metals resulting from human activities in their watersheds, primarily from mining and agriculture, thereby increasing health risks [1,10–12].

Water for consumption can be collected from surface and underground sources, with varying physical, chemical, and microbiological compositions. Therefore, adequate water treatment, along with organized and systematic management, enables the timely supply of this resource, ensuring its quality and safety [13,14]. However, in many locations, this service is considered sufficient when water is supplied through pipes to a reservoir, where only chlorine is added as basic treatment. In the absence of technical controls, residual chlorine levels often fail to meet health regulations' limits [15,16]. Furthermore, the presence of metal ions and heavy metals is often overlooked due to limited infrastructure for their removal and monitoring. This issue is compounded by social conflicts, as communities or population centers near water sources tend to appropriate the resource, restricting access to higher-quality water for other sectors of the population.

Consuming water with high levels of heavy metals can cause bioaccumulation, leading to non-carcinogenic and carcinogenic diseases in different age groups [17–20]. Numerous studies have been conducted in areas with limited access to water or high anthropogenic activity, mainly mining, where high health risks from heavy metal content have been reported [21,22].

Water quality, including physical, chemical, and biological parameters, has been extensively studied, and the results help us understand the mechanisms of water transport and its conditions [23,24]. Quality standards have been established using water quality indices (WQIs). In Peru, the WQI-Pe has been established for various water sources and uses, based on the method proposed by the Canadian Council of Ministers of the Environment (CCME-WQI). This method reports a single value after a simplified calculation using different water quality parameters [25].

The city of Andahuaylas has several surface and groundwater sources used for human consumption. These are managed by the Water and Sanitation Management Boards (JASS) and the district municipalities. The Municipal Water and Sanitation Service Provider, Chanka (EMSAP), supplies water through three spring-fed intakes (Huasipara, Tonlinco,

and Ccoñeccpuquio) located in the Chumbao micro-basin. These sources are affected by anthropogenic activities (mining, agriculture, livestock farming) and population growth around them, so their quality index for human consumption has been altered [3,10].

In this investigation, the system that supplies water for human consumption was evaluated, followed by the determination of the physical, chemical, and microbiological parameters of the water and the subsequent calculation of the WQI-Pe. Additionally, both deterministic and probabilistic approaches were used to estimate the risk to human health posed by metals in the water in three supply systems managed by the Municipal Sanitation Services Provider Company Chanka S.A., EMSAP-Chanka, in the city of Andahuaylas.

2. Materials and Methods

2.1. Study Area Description

The study area comprises the water sources (springs) of the populated centers of Huasipara (H), Ccoñeccpuquio (C), and Tonlinco (Tn), which supply water to the urban area of Andahuaylas (Figure 1) and are managed by EMSAP Chanka.

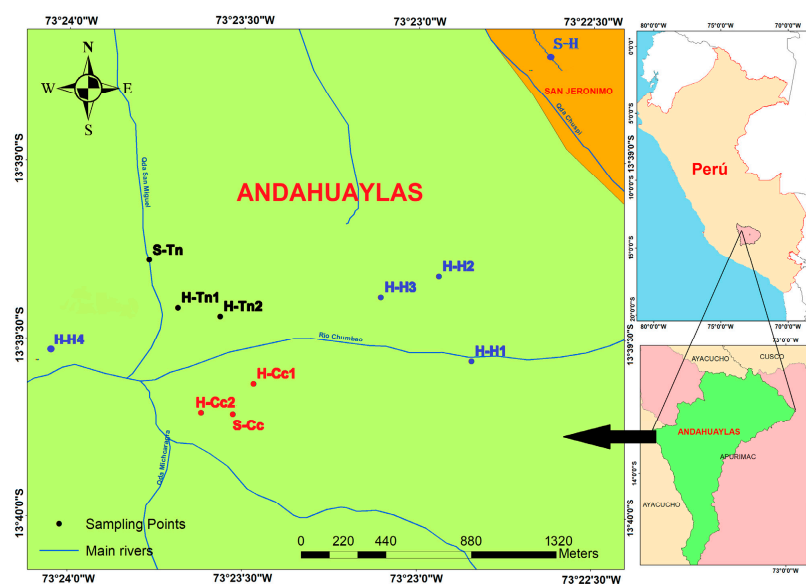


Figure 1. The study area.

The study area is part of the Chumbao micro-basin, located in the Peruvian Andes. It receives up to 1400 mm of rainfall per year, with a rainy season from December to March, temperatures ranging from 2 to 20 °C, and a Köppen climate classification of Cwb (temperate with a dry winter season and summer rainfall). The area surrounding the urban area is predominantly agricultural, with crops mainly consisting of potatoes, quinoa, corn, and beans, and extractive mining activity in the headwaters, mainly for iron, copper, and gold.

2.2. Sampling

The study was conducted during the dry (T1) and rainy (T2) seasons of 2024. Samples were collected from the reservoirs in each zone (Huasipara, Ccoñeccpuquio, and Tonlinco) and from homes in each zone, for a total of 11 samples per season. The coordinates of these samples are shown in Table 1. Permission for sampling was obtained from EMSAP Chanka. Sampling followed the collection protocols established by Peruvian regulations [26].

Table 1. Sampling point coordinates.

Sampling Points	East	North	Altitude (m)
Sources			
Huasipara (S-H)	676,691	8,491,345	3194
Ccoñeccpuquio (S-Cc)	673,903	8,489,094	2911
Tonlinco (S-Tn)	673,471	8,489,892	2993
Residential			
Huasipara 1 (H-H1)	675,136	8,489,366	2941
Huasipara 2 (H-H2)	674,968	8,489,805	2931
Huasipara 3 (H-H3)	674,668	8,489,698	2950
Huasipara 4 (H-H4)	672,389	8,489,422	2908
Ccoñeccpuquio 1 (H-Cc1)	674,010	8,489,250	2919
Ccoñeccpuquio 2 (H-Cc2)	673,738	8,489,102	2921
Tonlinco 1 (H-Tn1)	673,620	8,489,645	2971
Tonlinco 2 (H-Tn2)	673,838	8,489,600	2974

2.3. Sample Analysis

Physical parameters such as temperature (T, °C), conductivity (EC, $\mu\text{S}/\text{cm}$), true color (TCU, uPtCo), total dissolved solids (TDS, ppm), and turbidity (NTU, NTU); chemical parameters such as pH, total hardness (TH, ppm), total alkalinity (TA, ppm), salinity (S, PSU), chlorides (Cl^- , ppm), free chloride (FC, ppm), nitrates (NO_3^- , ppm), sulfates (SO_4^{2-} , ppm), phosphates (PO_4^{3-} , ppm), fluorides (F^- , ppm), dissolved oxygen (DO, ppm), and biochemical oxygen demand (BOD_5 , ppm); and microbiological parameters such as total coliforms (TC, CFU/100 mL) and *E. coli* (CFU/100 mL) were determined, following the Standard Methods for the Examination of Water and Wastewater [27].

Metal ion analysis was performed according to the APHA method 3120-B [27] using an inductively coupled plasma optical emission spectrophotometer (ICP-OES 9820, Shimadzu, Tokyo, Japan). Runs were performed in axial mode, in quadruplicate, with 30 s rinses between samples at 60 rpm, an argon gas flow of 10 L/min, and 30 s plasma exposure.

A UV–Vis scan was also performed in the 200–700 nm range, following the APHA 5910 methodology [27]. Quartz cuvettes with a 1 cm optical path length and a spectrophotometer (Thermo Fisher Scientific, Genesys 150 model, Waltham, MA, USA) were used. The regions analyzed were 200–230 nm, which includes nitrates and low-molecular-weight organic compounds; 250–280 nm, which involves natural aromatic organic matter, humic acids, and fulvic acids; and 400–450 nm, which includes true color and color associated with Fe–organic complexes.

2.4. Quality Control and Assurance of Measurements and Data

To ensure data quality, control standards and blank samples were measured before each analytical procedure. Similarly, the uncertainty and precision of the methods were considered, respectively, for pH (1.0% and 0.01), EC (1.0% and 0.01 $\mu\text{S}/\text{cm}$), STD (1% and 0.01 ppm), DO (1.0% and 0.01 ppm), and S (1.0 and 0.01 PSU), measured with a field multiparameter meter (model HI-9828, Hanna, RI, USA). For the turbidity measurement, it was 2.0% and 0.01 NTU, measured in a turbidimeter (model TL2300, Hach, China); TH (4.0% and 5 ppm), TA (5.0% and 5 ppm), Cl^- (5.0% and 0.5 ppm), FC (3.0% and 0.02 ppm), TCU (5.0% and 10.0 uPtCo), NO_3^- (10.0% and 0.5 ppm), SO_4^{2-} (3.0% and 5.0 ppm), PO_4^{3-} (4.0% and 1.0 ppm), and F^- (3.0% and 0.03 ppm) were measured using a benchtop photometer (model Iris HI-1801, Hanna, RI, USA). The instruments were calibrated according to the protocols for each unit.

For metal ion analysis, ultrapure water acidified with HNO_3 was used as the blank. Standard curves were prepared in advance using a multimetal stock solution diluted with 5% HNO_3 (Plasma Cal, SCP Science, Baie-d’Urfé, QC, Canada). The curves had an $R^2 > 0.995$.

For quality control of measurements on the UV–Vis spectrophotometer, a scan was performed using ultrapure water as the blank over the range 200 to 700 nm.

2.5. Water Quality Index Calculation—WQI-Pe

The methodology proposed by the National Water Authority of Peru [24,25] was applied. The application of the WQI-Pe allows for the free selection of water quality parameters. The index considers three factors: F1—range or amplitude, which indicates the percentage of parameters that do not comply with the Environmental Quality Standards of Peru (EQS–Peru) for Category 1, which are waters that can be made potable through disinfection, established in Supreme Decree No. 004-2017-MINAM [28]. F2—frequency, which indicates the percentage of individual measurements that fall outside the EQS–Peru. F3—magnitude, which indicates the deviation or intensity of the parameters with respect to the permissible limit established in the EQS–Peru. The WQI-Pe establishes nominal quality values between zero and 100, according to Table 2.

Table 2. WQI-PE classification and criteria.

WQI-Pe		Interpretation
90–100	Excellent	Water quality is free of threats or damage. Conditions are close to natural or desired levels.
75–89	Good	Water quality deviates slightly from its natural conditions; these desirable conditions may have minor threats or damage.
45–74	Regular	Water quality is occasionally threatened or impaired; the quality deviates from desirable values. Most uses require treatment.
30–44	Bad	Water quality does not meet quality objectives, and desirable conditions are threatened or impaired; most uses require treatment.
0–29	Poor	Water quality does not meet quality objectives, and its quality is always threatened or impaired; all uses require treatment.

Note: Source: [25].

2.6. Human Health Risk Assessment

The risk to human health from contaminants such as metal ions in water intended for consumption is assessed by comparing the average exposure dose (through ingestion and dermal contact) to reference levels that may cause toxicity.

This evaluation helps determine the health impact on exposed populations, including infants (>2 years), children (2 to 6 years), teenagers (7 to 16 years), and adults (>16 years) [29,30]. The United States Environmental Protection Agency (USEPA) has proposed quantified indices such as the chronic daily intake (CDI), the hazard quotient (HQ), and the incremental lifetime cancer risk (ILCR) [31,32].

The CDI (mg/kg-day) was evaluated for the metals Al, Fe, Zn, As, Cd, Cr, Pb, Sb, B, Ba, Ca, K, M, Mn, and Na. This parameter relates bodily factors, intake, and metal concentration in water. Its calculation determines the biologically active internal dose that poses health risks.

The CDI for oral ingestion (CDI_{ing}), the most common exposure event, describes the dose of metal ions consumed through water, whereas the CDI for dermal contact (CDI_{derm}) represents the dose absorbed through the skin during personal hygiene activities, which is

limited by skin permeability [32,33]. The calculation of CDI_{ing} (Equation (1)) and CDI_{derm} (Equation (2)) was performed for different age groups (Table 3).

$$CDI_{ing} = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

$$CDI_{derm} = \frac{C \times SA \times K_p \times ET \times EF \times ED \times ABS_d}{BW \times AT} \quad (2)$$

where C (mg/L) is the concentration of the metal ions; IR (L/day) is the water intake rate by age, the values of which are shown in Table 3; EF (days/year) is the exposure frequency (Table 3); ED (years) is the exposure duration (Table 3); BW (kg) is the average body weight; AT (days) is the average time for non-carcinogenic and carcinogenic effects; SA (cm²) is the average area of exposed skin (Table 3); k_p (cm/h) is the skin permeability coefficient (values in Table 4); ET (h/day) is the average skin exposure time; and ABS_d is the fraction of dermal absorption.

Table 3. Parameters for risk calculation by age group.

Parameter	Infant	Children	Teenager	Adult
IR (L/day)	0.9	1.25	1.6	1.8
EF (day/year)	365	365	365	365
ED (year)	1	4	13	30
BW (kg)	12	20	50	70
AT (day)	ED × 365	ED × 365	ED × 365	ED × 365
SA (cm ²)	2800	6600	10,000	18,000
ET (h/day)	0.58	0.58	0.58	0.58

Note: Source: [31,34–37].

Table 4. Parameter values for calculating risks according to metal.

Parameter	Al	Fe	Zn	As	Cd	Cr	Pb	Sb	B	Ba	Ca	K	Mg	Mn	Na
RfD _{ing}	1.0000	0.7000	0.3000	0.0003	0.0005	0.00300	0.00360	0.0004	0.200	0.0700	73.330	2.44	7.330	0.1400	48.88
RfD _{derm}	0.0010	0.0007	0.0750	0.0003	0.0005	0.00006	0.00053	0.0027	0.006	0.0049	583.33	19.44	58.330	0.0018	388.88
K _p	0.0001	0.0001	0.0006	0.0010	0.0010	0.00100	0.00050	0.0002	0.001	0.0010	0.0010	0.001	0.0010	0.0002	0.001
ABS _d	0.001	0.0010	0.0100	0.0300	0.0010	0.10000	0.00100	0.0100	0.030	0.0100	7.9549	7.967	7.9577	0.0010	7.9558
CSF _{ing}				1.5000	0.3800	0.50000	0.00850								
CSF _{derm}				1.5000	6.3000	41.000	0.04200								

Note: Source: [30,35,37–39].

The assessment of non-carcinogenic risks derived from chronic exposure was determined using the hazard quotient (HQ) for ingestion and skin contact (Equation (3)), which considers the reference dose (RfD, mg/kg/day), defined as the maximum daily amount of a metal ion that can be ingested or absorbed through the skin (derm) without a probability of producing appreciable adverse effects on human health. These values are defined for each metal (Table 4). If $HQ < 1$, there is no evidence of risk, while $HQ > 1$ indicates the probability of non-carcinogenic risk [40,41].

The carcinogenic risk assessment due to heavy metals was determined using the ILCR (Equation (4)), which determines the probability of increasing the risk of cancer over a lifetime. This considers the carcinogenic slope factor for ingestion and dermal contact (CSF, (mg/kg × day)^{−1}), which indicates the probability of cancer developing in the long term or over a lifetime. If $ILCR < 1 \times 10^{-6}$, there is no carcinogenic risk; if $ILCR > 1 \times 10^{-4}$, there is a high risk of developing cancer; and if $1 \times 10^{-6} < ILCR < 1 \times 10^{-4}$, the risk is acceptable for humans [40,42].

$$HQ = \frac{CDI}{RfD} \quad (3)$$

$$ILCR = CDI \times CSF \quad (4)$$

2.7. Probabilistic Uncertainty Analysis Using Monte Carlo Simulation

The data obtained from ILCR are calculated using unique values. However, in reality, variability arises from anthropometric behavior, individual characteristics, and various environmental factors. These introduce uncertainty into deterministic statements [42,43]. To present a more realistic picture of the behavior, it is recommended to apply stochastic methods to assess health risks. The USEPA has therefore recommended the Monte Carlo simulation (MCS) technique to minimize uncertainty in ILCR [30,44]. The uncertainty analysis in this study was performed using an MCS simulation with 10,000 iterations. A lognormal distribution was assumed, and random values for the concentration of heavy metal ions were generated from their respective means and standard deviations. Based on the average probabilistic ILCR, the expected value for one case per n exposed individuals was determined. The risk probability (P) exceeding the established limit for each metal in each study area and season was also calculated. The analysis was performed using Excel spreadsheets.

2.8. Data Analysis

Data were collected in triplicate and reported as the mean, standard deviation, maximum, and minimum. Box-and-whisker plots and bubble charts were also created to show the mean values for each parameter at the 5% significance level. These values were converted into relative position data (range) to enable a comparison of parameters on different scales. Comparisons between sampling points were performed using ANOVA and Tukey's test at a 5% significance level. OriginPro 2025 software and Excel spreadsheets were used.

3. Results and Discussion

3.1. Diagnosis of the System and Water Quality in the Urban Area of Andahuaylas

The city of Andahuaylas is located in the Peruvian Andes at an altitude between 2850 and 3100 m. According to EMSAP-Chanka, the population was 40,637 in 2021, projected to increase to 45,524 by 2027. The water supply sources are springs located in the highlands or headwaters of the watershed, above 4000 m above sea level. These sources are primarily from the Huasipara area, which supplied approximately 32 L per second (L/s) in 2012 and is projected to increase to 37 L/s by 2027; Ccoñcupuquio, with 11.7 L/s in 2012 and a projected increase to 12.0 L/s; and Tonlinco, which shows a decreasing trend from 1.5 L/s in 2012 to 0.8 L/s. Projected production by 2027 will reach 2.09 million m^3 per year, while actual demand will be 1.37 million m^3 per year, indicating social dissatisfaction due to considerable physical and commercial losses [45]. This would mainly be due to a lack of infrastructure projects by local governments, as well as population growth, and, more importantly, possible scenarios of water stress, as found in research conducted in rural areas [11,46,47].

The water quality of these springs is compromised by formal, informal, and illegal mining in the headwaters, as well as the indiscriminate use of agrochemicals and the lack of waste control. Soil erosion and subsequent infiltration during the rainy season also contribute dissolved and suspended solids, leading to increased water turbidity and color, as well as dissolved organic matter that promotes the formation of fulvic and humic substances.

Another critical issue is the lack of buffer zones in catchment areas, where grazing by domestic and native livestock is widespread. Animal manure is transported into the soil through rainwater infiltration, introducing pathogenic microorganisms that pose risks to human health. This situation is further exacerbated by the use of non-technified chlorination systems in storage reservoirs, thereby compromising water safety. Moreover, the water supplied by EMSAP does not undergo conventional treatment processes, adversely

affecting its sensory, physical, chemical, and microbiological quality. Such conditions are common in emerging cities, particularly in South America, and pose significant challenges for governments in terms of the organization, infrastructure, distribution, and management of water supply systems [48,49].

The average water consumption in the urban area of Andahuaylas has been estimated at 17 m³ per connection per month, which falls within the typical range for developing cities (10–25 m³ per connection per month), although it remains relatively low compared to developed countries [50,51]. However, the existing infrastructure and supply system are limited to chlorination and storage, with no treatment processes for removing turbidity or chemical contaminants, particularly heavy metals, thereby increasing health risks [52,53].

This aspect would be difficult to overcome due to the cost of residential water service. The payment in the social category, made by the user, amounts to USD 0.20/m³, with a maximum allocation of 20 m³ per month, with this being the majority; while in the domestic category, it is USD 0.26/m³ with an allocation of 20 m³ per month; and for larger volumes, it is USD 0.44 per additional m³, with a fixed monthly charge of USD 0.73, compared to other cities, where it far exceeds the established rates [45].

EMSAP has reported that the costs associated with maintenance, distribution, and water service provision are in deficit, thereby requiring cross-subsidies. This situation is further exacerbated by rising user delinquency, leading to declines in service quality and the timely provision of water [45].

In response, the implementation of payment mechanisms for ecosystem services (PMESs) has been proposed, but these have not been properly applied and are therefore currently nonexistent. This is due to a lack of awareness among social actors and the beneficiary population, as well as insufficient timely follow-up by government actors. Proper and timely application of PMES would enable the protection, conservation, and monitoring of headwaters and buffer zones, ensuring that in the future, water supply volume, water quality, water security, public health, and service sustainability are not subject to significant risks [54,55].

3.2. Physical, Chemical, and Microbiological Water Parameters

Temperature is a parameter influenced by seasonality, which in turn conditions the physical, chemical, and biological processes of water [56,57]. Values up to 17.95 °C were observed, within the range recommended by EQS–Peru [28], with low variability between sampling points and seasons (between 79.2 and 10.32%) (Table 5). The levels found would not allow for the rapid proliferation of microorganisms, which occurs in warm climates where water temperatures reach up to 30 °C [58,59].

Furthermore, the importance of dissolved salts, which control thermal increase and ionic mobility of water, was evaluated using conductivity (EC) [60], with values ranging from 141.75 to 722.30 µS/cm. This parameter is related to water mineralization, which is also assessed through total dissolved solids (TDSs), with values ranging from 70.90 to 371.90 ppm, being higher during dry seasons. This indicates that groundwater, and its concentration, decreases during the rainy season due to increased precipitation. The reported values across sampling points and seasons show variability of approximately 50%, although they fall within the EQS–Peru (Table 5).

Regarding color (TCU), which is due to the presence of dissolved organic and inorganic matter, undetected values were observed (around zero), in contrast to the low values of suspended solids evaluated by turbidity (NTU) for both seasons. The drinking water from the Tonlinco area showed higher values for physical parameters (Figure 2a,c); this may be due to the geomorphological characteristics of the water source (underground spring).

This suggests that the water at the study sites, despite not undergoing treatment, meets the quality standards established by Peruvian regulations.

Table 5. An overview of physical and chemical water parameter values ($n = 32$).

Season		T	EC	TCU	TDS	NTU	pH	TH	TA	S	Cl ⁻	FC	NO ₃ ⁻	SO ₄ ²⁻	PO ₄ ³⁻	F ⁻	DO	BOD ₅
Dry	Max	17.9	722.30	N.D.	371.9	0.79	8.05	94.00	85.00	0.36	15.40	0.51	0.30	60.00	0.31	0.31	4.71	3.80
	Min	13.0	341.20	N.D.	169.4	0.06	7.66	71.00	0.00	0.10	0.00	0.00	0.00	19.00	0.04	0.00	2.35	0.00
	$\bar{x}$	15.7	494.65	---	247.8	0.23	7.88	80.09	25.88	0.24	5.72	0.15	0.07	34.48	0.16	0.14	3.94	1.07
	$\pm s$	1.2	150.13	---	77.2	0.19	0.12	5.34	34.18	0.08	5.11	0.18	0.11	14.22	0.08	0.09	0.62	1.45
	CV	7.9	30.35	---	31.1	82.47	1.55	6.67	132.1	33.1	89.3	117.4	154.9	41.23	50.2	62.9	15.6	135
Rainy	Max	17.9	709.70	N.D.	355.1	0.51	8.16	70.00	81.00	0.35	13.50	0.50	3.80	59.00	0.62	0.27	6.97	3.30
	Min	12.0	141.75	N.D.	70.9	0.06	7.33	44.00	0.00	0.05	0.40	0.00	0.00	13.50	0.19	0.01	5.11	0.00
	$\bar{x}$	15.9	369.83	---	185.2	0.19	7.71	58.03	22.61	0.17	4.93	0.21	0.38	33.95	0.33	0.13	5.93	0.49
	$\pm s$	1.64	193.01	---	96.9	0.12	0.26	5.44	29.90	0.10	4.50	0.20	1.09	14.64	0.16	0.08	0.55	0.98
	CV	10.3	52.19	---	52.4	63.02	3.39	9.37	132.3	55.4	91.3	94.1	290.4	43.11	47.7	64.2	9.25	199
EQS-Peru		---	<1500	<15	<1000	<5.0	6.5–8.5	<500	---	---	<250	>0.5	<50	<250	---	<1.5	≥6.0	<3.0

Notes: Max is the maximum value; Min is the minimum value; $\bar{x}$ is the arithmetic mean; $\pm s$ is the standard deviation; CV is the coefficient of variation; EQS is the environmental quality standards for Category 1—waters that can be made potable through disinfection, established in Supreme Decree No. 004-2017-MINAM [28].

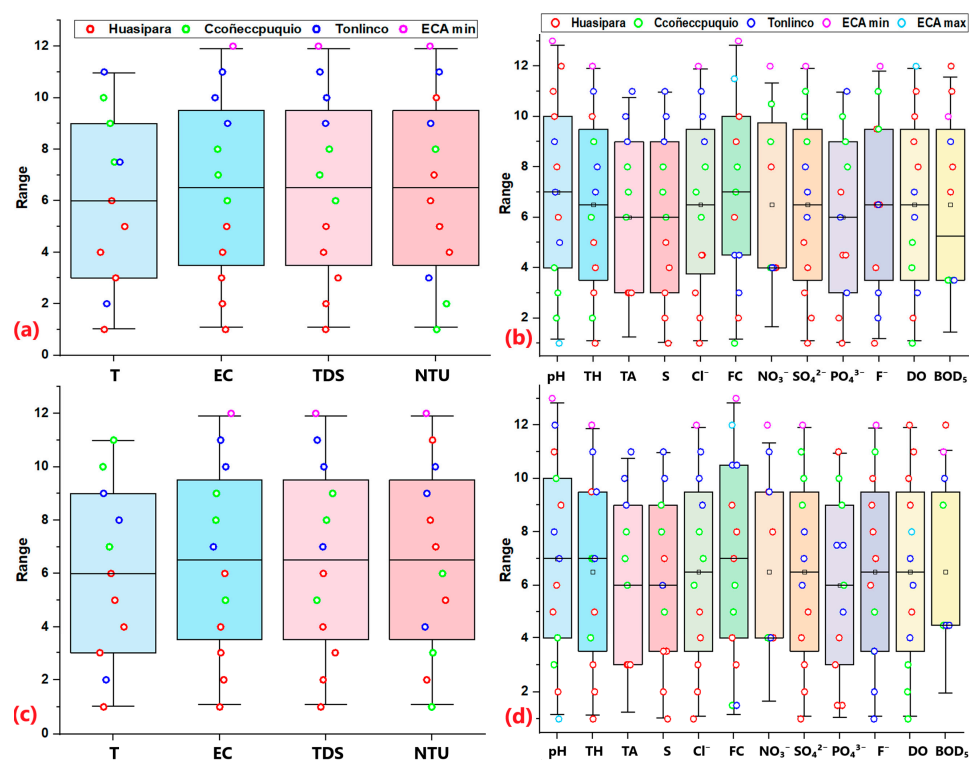


Figure 2. The dispersion of water quality data by sectors: (a) physical parameters in the dry season, (b) chemical parameters in the dry season, (c) physical parameters in the rainy season, and (d) chemical parameters in the rainy season.

The pH was found to be within the limits established by the EQS-Peru [28] (Table 5). This indicates that the water from the sampled sources meets acceptable quality standards, suggesting stable chemical speciation and metal ion solubility; these values also enable adequate disinfection by agents such as chlorine [61,62].

The carbonate and bicarbonate content, represented as total water hardness (TH), helps us understand water–soil interactions in underground systems. The water sources in the study areas exhibit this characteristic, as they originate in the basin’s headwaters and emerge in the lower areas as springs. Although high levels do not indicate toxicity, they affect the sensory quality of the water; values of up to 94 ppm have been reported. This suggests that the water from these sources has low scaling potential within distribution

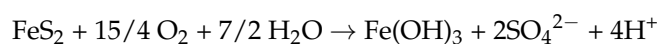
systems; similarly, its sensory characteristics—particularly taste—are likely to remain relatively neutral.

Alkalinity, a measure of the water's buffering capacity against changes in pH and acidity, was reported at up to 85 ppm (Table 5). These levels demonstrate the low mineralization of the water, as reported in the low content of chlorides (Cl^-), sulfates (SO_4^{2-}), fluorides (F^-), and salinity (S). These results indicate that the water in the consumption areas is soft, being low in mineralization and low in corrosion risk, while having good sensory acceptability and chemical stability [63,64]. This behavior is attributed to the upper basin acting as a natural filtration system due to its hydrogeological characteristics, such as porous and fractured media that facilitate groundwater infiltration, thereby promoting filtration and the adsorption of contaminants and dissolved solids. This behavior is characteristic of spring-type water sources in high-altitude regions of Peru, where permeable geological conditions support the natural purification of water, as observed in the sources supplying the city of Andahuaylas.

Free chlorine (FC), a traditional and effective disinfectant in water, showed values below the Environmental Quality Standards for Water (EQS–Peru), ranging from 0.00 to 0.51 ppm, with high variability among sampling points (~117.4%). It was lowest or nonexistent in the Huasipara and Ccoñeccpuquio areas for both seasons (Figure 2b,d). This is attributed to chlorination systems, malfunctioning infrastructure, or inadequate training and monitoring in chlorine dosage control within water reservoirs, thereby compromising the biological safety of the water in these areas. This creates a high risk of contracting acute diarrheal infections (ADIs) and, consequently, a risk of anemia in infants and the elderly [65,66].

Nitrates (NO_3^-) and phosphates (PO_4^{3-}) originate from organic matter, agricultural fertilizers, and manure as a residue from grazing in the upper reaches of the watershed. Values were reported below the limits established by the EQS–Peru (Table 5), posing no risk to water quality or consumer health. However, these low values over time could lead to microbial growth and biofilm accumulation in water distribution networks, a situation exacerbated by low FC levels. NO_3^- content is higher during the rainy season, indicating infiltration of organic matter, and is highest in the Tonlinco area (Figure 2d).

Dissolved oxygen (DO) ranged from 2.35 to 6.97 ppm (Table 5), which is considered an acceptable value according to the EQS–Peru [28] during the rainy season. DO concentrations above 5 mg/L indicate oxidizing conditions, which are essential for the oxidative dissolution of sulfide minerals commonly associated with iron, copper, and gold mining activities, as observed in the headwaters of the basin. Under these conditions, sulfides can oxidize, releasing dissolved sulfate, hydrogen ions, and hydroxides into the aquatic system, according to the following reaction:



Similarly, oxidizing environments enable Fe^{2+} to be oxidized to Fe^{3+} and, in the absence of dissolved organic matter, stabilize iron in solution; Fe^{3+} precipitates as hydroxide. Conversely, low DO levels, characteristic of groundwater or high-altitude Andean zones, reflect reducing conditions that favor the mobility and persistence of Fe^{2+} and Mn^{2+} in solution, directly influencing water color [67]. These processes, regulated by redox potential, help explain the variability and distribution of dissolved iron species and associated metals at sampling points. Therefore, understanding the hydrogeochemical behavior surrounding mining activities in the basin is important.

On the other hand, BOD_5 ranged from 0.00 to 3.80 ppm, with higher values observed in the Huasipara area (Figure 2d). This may be attributed to nutrients (NO_3^- and PO_4^{3-}) derived from infiltration in lower-elevation areas, associated with the excessive use of

agrochemicals in rural crops, as well as the input of organic matter from livestock waste and feces during grazing, which infiltrate into subsurface flows. Additionally, microbiological growth or recontamination within the water distribution network may also contribute to these elevated values.

Regarding the microbiological analysis, it was observed that the Tonlinco water intake exceeded the permissible limits established in Supreme Decree No. 031-2010-SA [68] in both seasons (Figure 3). However, after disinfection with chlorine, these levels decreased to acceptable values, with total coliforms (TCs) and *E. coli* absent in the household water sources. In H-H1 (residential 1 in the Huasipara area), total coliforms were detected, indicating microbiological contamination. This may be due to pathogens and could be associated with nitrogen compounds and leaks in the water network, as the contamination was localized.

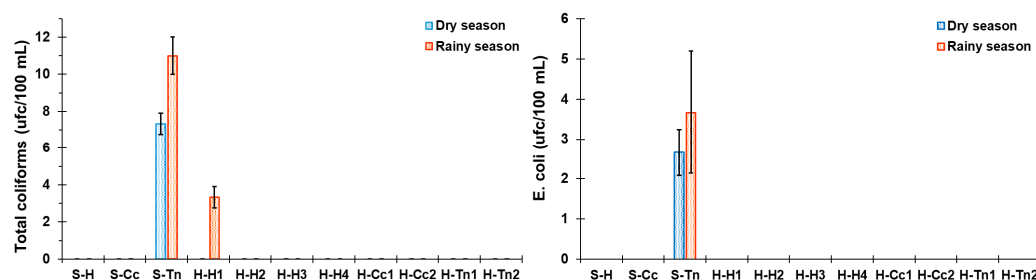


Figure 3. The microbiological parameters of drinking water.

3.3. Analysis of Metal Ions in Water

Al levels reached up to 0.194 mg/L (Table 6), slightly higher in the dry season, although levels in the study areas do not exceed the limits established by EQS–Peru. Fe content is considerably higher during rainfall due to the presence of iron minerals in the basin’s headwaters, which are more soluble under anaerobic underground conditions and dissolve and infiltrate into the water body.

Table 6. An overview of metal ion, heavy metal, and mineral values (ppm) ($n = 32$).

Season		Metal Ion				Heavy Metal Ion				Mineral Ion						
		Al	Fe	Ti	Zn	As	Cd	Cr	Pb	B	Ba	Ca	K	Mg	Mn	Na
	λ (nm)	394.40	234.35	334.94	213.86	228.81	226.50	267.72	220.35	249.68	455.40	317.93	769.90	280.27	257.61	589.59
Dry	max	0.194	0.272		0.003	0.037			0.031		0.061	133.720	0.250	18.998	0.091	11.032
	min	0.004	0.051		0.000	0.009			0.000		0.021	55.120	0.030	8.978	0.025	2.085
	$\bar{x}$	0.087	0.154	<D.L.	0.000	0.021	<D.L.	<D.L.	0.008	<D.L.	0.045	81.932	0.118	12.936	0.054	5.791
	$\pm s$	0.053	0.066		0.001	0.008			0.009		0.012	27.618	0.062	3.871	0.022	3.489
	CV	61.4	42.6		324.4	37.6			105.1		26.8	33.7	52.9	29.9	40.4	60.2
Rainy	max	0.167	0.960	0.005	0.019	0.030	0.011	0.059	0.194	0.054	0.054	79.130	1.110	4.022		1.210
	min	0.043	0.210	0.000	0.002	0.002	0.003	0.011	0.000	0.000	0.011	17.740	0.380	1.232		0.000
	$\bar{x}$	0.103	0.675	0.002	0.007	0.012	0.007	0.031	0.049	0.016	0.022	39.701	0.785	2.217	<D.L.	0.549
	$\pm s$	0.030	0.187	0.001	0.004	0.008	0.002	0.013	0.044	0.013	0.013	18.114	0.189	0.854		0.386
	CV	29.3	27.7	56.8	50.0	71.7	23.3	41.2	89.3	81.3	56.6	45.6	24.1	38.5		70.2
EQS		0.9	0.3	---	3	0.01	0.003	0.05	0.01	2.4	0.7	---	---	---	0.4	---

Notes: D.L. is the detection limit; λ is the wavelength; Max is the maximum value; Min is the minimum value; $\bar{x}$ is the arithmetic mean; $\pm s$ is the standard deviation; CV is the coefficient of variation; EQS is the environmental quality standards for Category 1—waters that can be made potable through disinfection, established in Supreme Decree No. 004-2017-MINAM [28].

Al concentrations reached up to 0.194 mg/L (Table 6), with slightly higher values observed during the dry season; however, these levels remain within the limits established by EQS–Peru. In contrast, iron concentrations were significantly higher during the rainy season, likely due to the presence of iron-bearing minerals in the basin’s headwaters. These

minerals become more soluble under anaerobic subsurface conditions and are subsequently mobilized, dissolved, and transported into the water body during rainfall events.

The areas of Ccoñecpuquio and Tonlinco reported higher levels, as did some points in Huasipara (Figure 4b). High levels of Fe have been found in areas near iron ore mines, leading to changes in water color and deterioration of water quality [6–8]. Ti and Zn were found at low levels, and their concentrations were similar across sampling points (Figure 4a,b).

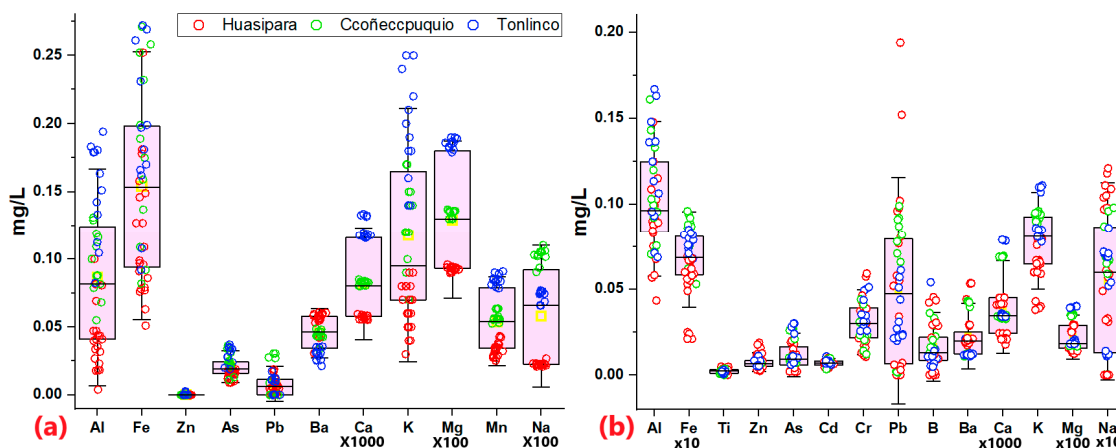


Figure 4. The variability of metal concentration by sampling point in the study areas: (a) dry season; (b) rainy season.

Heavy metal ions are bioaccumulative and highly harmful, posing a toxicological risk to health when they exceed established limits. They are associated with skin, lung, dermal, bladder, and kidney cancers; bone demineralization; metabolic disorders; impaired fetal and infant neurological development; and gastrointestinal disturbances [40,69,70].

It was observed that, on average, As, Cd, Cr, and Pb significantly exceeded the minimum values established by EQS-Peru (Table 5). Although Cd and Cr were not detected during the dry season, suggesting that their source of contamination is at the basin headwaters, during the rainy season, soils and rocks are leached and incorporated into groundwater through infiltration.

This may also be due to the uncontrolled use of pesticides, which is more frequent during the rainy season. Additionally, the areas of Tonlinco and Ccoñecpuquio reported a higher frequency of excessive levels of these heavy metals, while Huasipara showed lower levels (Figure 4a,b). This is likely because the Huasipara catchment is located in the upper zone and receives little surface water infiltration.

3.4. UV–Vis Scanning Analysis of Water

The UV–Vis scan shows differences in the behavior of naturally occurring organic matter and water-soluble inorganic compounds between sampling points and seasons. The 220–230 nm range was dominated by $\pi \rightarrow \pi^*$ transitions, indicating the presence of low-molecular-weight organic compounds such as simple organic acids, with small contributions from naturally occurring nitrates [71,72]. This is more pronounced in residential water (Figure 5b), likely due to the transport of easily leachable compounds, whereas in the dry season, the sources (S-H, S-Tn, S-Cc) exhibit higher absorbances (Figure 5a), indicating higher concentrations of organic matter. This is likely due to lower flow rates and longer residence times in the aquifer, while lower absorbance was reported in residential water, indicating partial degradation and dilution during storage and distribution.

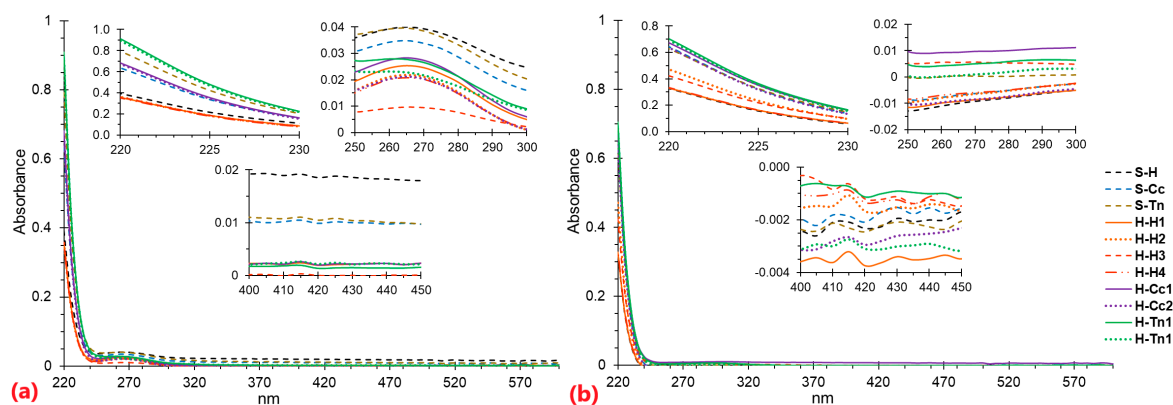


Figure 5. UV–Vis scanning of water samples by sampling points: (a) dry season; (b) rainy season.

The spectrum between 250 and 300 nm is frequently associated with $n \rightarrow \pi^*$ transitions of humic and fulvic acids [71,72]. During the dry season, more defined spectra with higher absorbance were observed for the sources (S-H, S-Tn, S-Cc), which is consistent, since water transports a greater amount of mature organic matter with higher aromaticity and degree of humification; during rainfall, linear spectra are observed, indicating a low concentration of these substances. The water in residences showed low absorbance signals, which could be due to the digestibility of these substances by residual chlorine oxidation or to natural processes that occur during transport and storage in the water distribution system.

Conjugated aromatic compounds, such as Fe–organic matter complexes, contribute to the color and taste of water, manifesting in the 400–450 nm range [71,72] (Figure 5a,b). During the dry season, water sources are slightly affected by these compounds, although physical and chemical analyses do not detect this sensory alteration. However, in homes during the dry season and at all sampling points during the rainy season, considerable dilution of these compounds is observed, manifested by spectra that tend toward zero absorbance.

This gives the water a very low apparent color, greater transparency, and a high reduction in chromophoric species, suggesting chlorine decay.

Comparing different seasons allows us to understand the dynamics of water quality. The rainy season is controlled by dilution and the addition of fresh and mature organic matter, while the dry season is characterized by the accumulation, humification, and concentration of aromatic organic matter, mainly in springs. In terms of sensory quality, water from reservoirs and residential homes can be considered acceptable, although it has low concentrations of natural organic matter.

3.5. Water Quality Index Analysis

The parameters used to calculate the WQI-Pe were temperature, turbidity, TDS, color, pH, conductivity, chloride, hardness, fluoride, phosphate, nitrate, sulfate, DO, BOD, and heavy metals (As, Cd, Cr, and Pb). Water quality was between good and excellent during dry seasons, while during rainy seasons, it ranged from regular to excellent (Table 7). The generally good quality is due to the low anthropogenic pressure of the sources, which is typical in the high-elevation Andean regions of South America [5,13], where percolation through geological strata enables the filtration of organic and inorganic particles, although these sources are vulnerable to mining activity.

During the rainy season, most points shift from excellent to good or fair; this decrease is due to surface runoff associated with soil porosity and composition, which allows particulate matter to infiltrate and increase metallic ion levels (Table 6), thereby negatively impacting the WQI-Pe.

Table 7. WQI-Pe values.

Source		Dry		Rainy	
S-H	95.88	Excellent		92.86	Excellent
S-Cc	86.38	Good		82.03	Good
S-Tn	89.86	Good		83.17	Good
H-H1	97.05	Excellent		85.18	Good
H-H2	96.75	Excellent		70.26	Fair
H-H3	96.87	Excellent		92.90	Excellent
H-H4	93.80	Excellent		80.22	Good
H-Cc1	92.25	Excellent		76.98	Good
H-Cc2	88.13	Good		78.35	Good
H-Tn1	91.14	Excellent		86.24	Good
H-Tn2	93.16	Excellent		95.92	Excellent

3.6. Human Health Risk

3.6.1. Non-Carcinogenic Risk of Metals

Chronic exposure to metals was assessed using the hazard quotient (HQ), which provides an estimate of the non-carcinogenic risk from consumption and contact with drinking water in the study areas. It is suggested that if $HQ > 1$ [41], there is a high non-carcinogenic risk in the age groups. It was observed that, during the dry season, As levels in all study areas could pose a non-carcinogenic risk across all age groups, as determined by HQ_{ing} (Figure 6), whereas no adverse data were observed for HQ_{derm} .

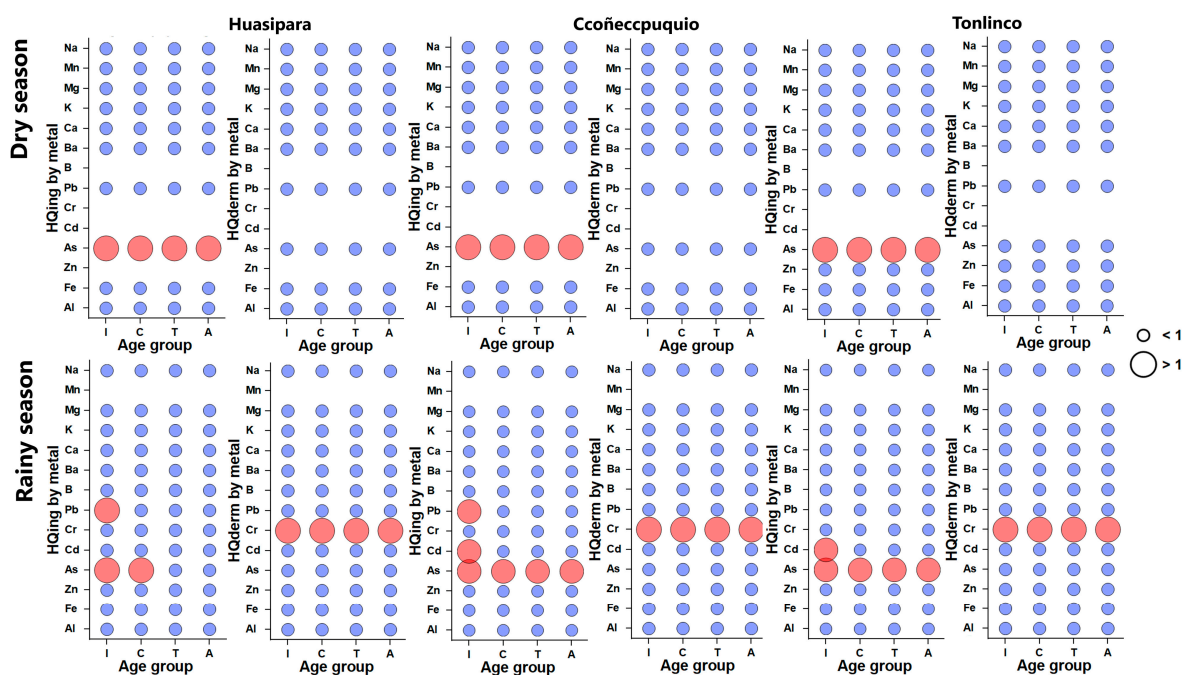


Figure 6. A representation of the non-carcinogenic risk from ingestion and dermal contact for age groups, evaluated by HQ for metals for the study areas and seasons.

This behavior varies during the rainy season, when HQ_{ing} for As exceeds one in all age groups at the Ccoñecpuquio and Tonlinco reservoirs, with a higher risk for infants and children in the Huasipara area. Similarly, HQ_{ing} for Pb exceeds one in infants from the Huasipara and Ccoñecpuquio areas, while $HQ_{ing} > 1$ was observed for Cd in infants at Ccoñecpuquio and Tonlinco. On the other hand, $HQ_{derm} > 1$ was reported for Cr across all age groups and study areas.

Arsenic is the metalloid with the highest redundancy at non-carcinogenic risk due to water consumption in the study areas, indicating that the levels found greatly exceed the reference dose (RfD 0.0003 mg/kg/day, Table 4). This metalloid exhibits high gastrointesti-

nal absorption, binds to sulfhydryl groups, and inhibits cellular metabolic processes at the mitochondrial level, increasing the likelihood of adverse health effects.

In infants (Is), it is associated with neurological development disorders, low body weight, and increased susceptibility to infections due to hepatic deficiencies. In children (C), it presents as skin lesions, cognitive impairment, and mild hematological abnormalities. In teenagers (Ts), metabolic, endocrine, and dermatological abnormalities have been reported. Adults (As) experience skin, liver, and kidney problems, including melanosis, hyperkeratosis, peripheral neuropathy, diabetes, vascular problems, and type 2 diabetes mellitus [17,19,20].

Although Pb was found at two points, its risk significance lies in its detection in infants, which could affect neurological development, slow cognitive development, and cause behavioral disorders. Anemia has also been reported due to the inhibition of hemoglobin synthesis [38,73]. Regarding dermal exposure to Cr, observed across all locations and age groups, this metal can cause dermatitis, erythema, and early allergies in infants and children, while in adolescents, it can lead to eczema. In adults, chronic exposure could cause ulcerations and allergic dermatitis with prolonged local effects [74,75].

3.6.2. Carcinogenic Risk Assessment

The probability of a person developing cancer in age groups due to chronic exposure to a heavy metal was determined using ILCR, which enables the identification of risks associated with neurotoxic or nephrotoxic problems, which can cause cancerous changes after prolonged exposure [17,29,73].

During the dry season, water consumption could increase the risk of cancer due to As concentrations in all age groups (Figure 7), which could increase the probability of developing skin and lung neoplasms in children and adolescents. Moreover, bioaccumulation in adults could lead to skin, bladder, and lung cancer [19,70]. During the rainy season, the risk is higher, since, in addition to As, the metals Cd and Cr are the main promoters of cancer risk due to consumption and dermal contact with water [38,75]. Although Pb levels exceed those established in EQS–Peru, the risk it poses is very low. The most vulnerable groups regarding water intake are infants and children across all sampling areas (Figure 7).

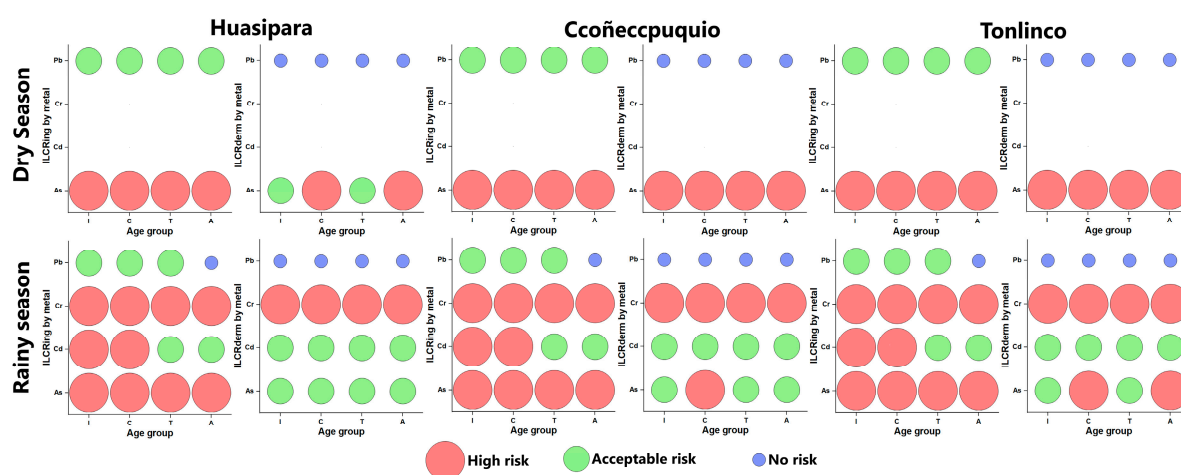


Figure 7. A graphical representation of carcinogenic risk from ingestion and dermal contact for age groups, assessed using ILCR for heavy metals for the study areas and seasons.

The probabilistic analysis using MC simulation yielded values similar to those calculated deterministically (Table 8), except for Pb. This is likely due to its high variability (Figure 4), a common characteristic of environmental events [30,76]. Therefore, cancer risk depends on cumulative dose, not average dose, thereby considerably increasing the

risk. For this reason, probabilistic simulation is important because it accounts for these conditions, making it more realistic, unlike the deterministic method, which provides a single point estimate.

Table 8. A comparison of ILCR conducted using deterministic and probabilistic methods for heavy metals.

Season	Source	Age Group	Deterministic Method				Monte Carlo Method (MC)											
			As	Cd	Cr	Pb	As			Cd			Cr			Pb		
			(10^{-3})	(10^{-3})	(10^{-3})	(10^{-3})	ILCR (10^{-3})	*	P (%)	ILCR (10^{-3})	*	P (%)	ILCR (10^{-3})	*	P (%)	ILCR (10^{-3})	*	P (%)
Dry	Hua	I	1.72			0.004	1.77	566	50.0							0.043	23,190	2.6
		C	1.43			0.003	1.50	665	50.0							0.030	33,602	1.8
		T	0.73			0.002	0.74	1348	50.0							0.014	71,385	1.1
		A	0.59			0.001	0.59	1684	50.0							0.009	109,460	0.9
	Cco	I	2.69			0.008	2.79	359	50.0							0.597	1675	5.7
		C	2.24			0.007	2.37	423	50.0							0.521	1918	5.3
		T	1.15			0.003	1.16	862	50.0							0.645	1550	3.9
		A	0.92			0.003	0.94	1069	50.0							0.342	2920	3.5
	Ton	I	3.08			0.005	1.94	516	50.0							0.225	4438	3.7
		C	2.57			0.004	2.71	369	50.0							0.143	7005	3.6
		T	1.32			0.002	1.33	749	50.0							0.045	22,125	2.3
		A	1.06			0.002	1.07	935	50.0							0.043	23,336	1.9
Rainy	Hua	I	0.92	0.19	1.11	0.035	1.03	975	49.4	0.19	5240	48.0	1.18	845	49.9	4.687	213	48.4
		C	0.76	0.15	0.92	0.029	0.85	1173	49.1	0.16	6160	46.4	0.99	1006	50.0	3.831	261	48.0
		T	0.39	0.08	0.47	0.015	0.43	2335	45.0	0.08	12,447	6.3	0.49	2035	49.7	1.831	546	45.0
		A	0.31	0.06	0.38	0.012	0.33	2998	42.6	0.06	15,571	0.5	0.39	2542	49.3	1.511	662	43.5
	Cco	I	1.58	0.20	0.99	0.036	1.73	578	50.0	0.21	4800	49.1	1.04	960	50.0	2.683	373	24.8
		C	1.31	0.17	0.82	0.030	1.45	690	50.0	0.18	5688	49.0	0.89	1129	50.0	2.201	454	23.3
		T	0.67	0.09	0.42	0.015	0.72	1380	49.8	0.09	11,409	9.4	6.44	155	50.0	0.948	1055	17.4
		A	0.54	0.07	0.34	0.012	0.57	1753	49.5	0.07	14,331	0.1	5.10	196	50.0	0.880	1136	15.5
	Ton	I	1.72	0.22	1.39	0.021	28.01	36	50.0	3.33	300	50.0	21.17	47	50.0	0.336	2975	32.3
		C	1.43	0.18	1.16	0.018	23.28	43	50.0	2.84	353	50.0	17.96	56	50.0	0.284	3517	28.8
		T	0.73	0.09	0.59	0.009	11.52	87	50.0	1.39	719	49.5	8.89	113	50.0	0.140	7162	12.6
		A	0.59	0.08	0.48	0.007	9.32	107	50.0	1.12	893	48.6	7.08	141	50.0	0.114	8803	7.8

Notes: Hua indicates Huasipara, Cco indicates Ccoñecpuquio, Ton indicates Tonlinco, I indicates an infant, C indicates a child, T indicates a teenager, A indicates an adult, and P indicates the probability. * indicates one expected case per n exposed persons.

One aspect to consider is that As presents the highest probability of cancer exposure in the Tonlinco area. In infants (Is), one expected case was observed per 36 exposed infants, with 50% of infants exceeding the health risk limit. A similar pattern is seen for children (C), teenagers (Ts), and adults (As), although the risk is very high during the rainy season. In this area, a similar pattern was observed in carcinogenic risks associated with Cr.

The risks from Pb in the dry season are lower in almost all areas, followed by the risks from Cd in the Huasipara and Ccoñecpuquio areas during the rainy season. The probabilistic analysis shows results that could indicate metal exposure from consuming water with a high cancer risk in the study areas.

4. Conclusions

The availability of quality water in a population enables the sustainable development of a community. Assessment of the service provided by EMSAP-Chanka revealed an operating system with a supply ranging from 0.8 to 32 L/s, but it is vulnerable due to user delinquency and faces a projected deficit linked to population growth, low protection of watershed headwaters, and the absence of mechanisms for payment for ecosystem services (PESs). The physical, chemical, and microbiological parameters remained within EQS–Peru standards, although water chlorination is deficient, with levels between 0.00 and 0.51 mg/L, putting the microbiological safety of the system at risk. High levels of minerals (Ca, Mg, Na, and K) were found due to water–rock interaction, but they were not associated

with toxicity. However, the levels of heavy metals (As, Cd, Cr, and Pb) at most sampling points exceed EQS–Peru standards, which is related to extractive activities and natural erosion. Despite this, the WQI–Pe indicated water quality ranging from regular to excellent, decreasing significantly during the rainy season. The non-carcinogenic risk indicates no adverse effects for most of the metals studied ($HQ_{ing} < 1$), except for As, which greatly exceeded the established limits (RfD 0.0003 mg/kg·day) in all age groups, while Cd and Pb mainly affected infants. $HQ_{derm} > 1$ was reported for Cr in all study areas, indicating high dermatological risk. Carcinogenic risk (ILCR) is high for As and Cr, with greater vulnerability in infants and children. The Monte Carlo simulation indicated a high probability of carcinogenic risk due to As, Cd, and Cr, with up to one expected case per 36 exposed infants and 50% of individuals exceeding the health risk limit. Although the water is generally of good physical, chemical, and microbiological quality, the heavy metal levels pose a chronic health risk, especially to children. These findings are relevant for developing countries with similar hydrogeological and socio-environmental conditions, supporting actions in water resource management, watershed protection, and the development of public health policies for sensitive and vulnerable populations.

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