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Physicochemical Evaluation of Surface Water in the Caplina River Basin, Tacna, Peru, during October 2024: Assessment against Environmental Quality Standards

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Abstract

This study assesses the physicochemical quality of surface water in the Caplina River Basin, Tacna, Peru, during October 2024, comparing the results with the Peruvian Ministry of the Environment's Environmental Quality Standards for Water (ECA-Agua). In situ measurements of temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were conducted at 20 stations distributed along the main river channel and its tributaries, complemented by laboratory analyses following the APHA Standard Methods. The results revealed persistently high EC values (5,085–5,796 µS/cm), far exceeding the reference threshold for irrigation of moderately sensitive crops (1,500 µS/cm), indicating a generalized salinization process. DO levels were critical (<5 mg/L) at 40% of the stations, particularly between P02 and P08, suggesting stress conditions for aquatic biota. pH remained stable (7.39–7.98) within the regulatory range, with no episodes of extreme acidification or alkalinization. The persistence of high salinity and DO deficits, combined with altitudinal gradients and anthropogenic inputs, poses significant challenges for water management in arid–coastal basins. Recommendations include implementing continuous monitoring, optimizing irrigation practices, improving wastewater treatment, and strengthening community engagement in water conservation. These findings provide a technical baseline for the development of adaptive management strategies in response to climate variability and increasing pressure on water resources in the region.

Keywords: Caplina River Basin; Water Quality; Physicochemical Parameters; Dissolved Oxygen; Electrical Conductivity; pH; Environmental Quality Standards; Arid Coastal Basins; Tacna Peru

1. Introduction

The Caplina River Basin is located in the southernmost region of Peru and originates in the Barroso mountain range at approximately 5,300 m a.s.l., flowing through a narrow valley before vanishing into the desert near the city of Tacna [1]. This hydrological system constitutes the primary water source for human consumption, agricultural irrigation, and various industrial uses in the region [2,3].

In arid settings such as Tacna, water availability and quality are strongly influenced by natural scarcity and by increasing demand, which has intensified pressure on water resources [4]. Activities such as intensive agriculture, urban expansion, and mining operations in recharge areas have significantly impacted the hydrological balance, while aquifer overexploitation has promoted processes of seawater intrusion and salinization [5,6].

Several studies have shown that geological variability and the presence of hot springs and geothermal zones naturally enrich the water with elements such as arsenic, boron, iron, aluminum, and sodium, which in certain locations exceed the Environmental Quality Standards for Water established under Peruvian regulations [8]. In Peru, water quality is regulated through the Estándares de Calidad Ambiental para Agua (ECA-Water), which establish maximum permissible limits for multiple uses, including human consumption and recreational activities. These natural contributions are compounded by anthropogenic pollutant loads, mainly from agricultural practices and urban discharges [9].

Recent research conducted in the Caplina Basin has confirmed the presence of arsenic in its various chemical species, as well as boron, at concentrations above regulatory limits [2–5]. This evidence underscores the importance of continuous monitoring and comprehensive assessments to identify areas of greatest vulnerability. In this regard, the measurement of physicochemical parameters such as electrical conductivity, pH, dissolved oxygen (DO), and temperature has become an essential tool for water quality characterization in arid and semi-arid regions [2,3,10].

Within this framework, the present study aims to evaluate the physicochemical quality of surface water in the Caplina River Basin, comparing the results with the values established by the ECA-Water. This analysis seeks to identify potential exceedances, generate updated technical information, and contribute to the sustainable management of water resources in the Tacna region.

2. Materials and Methods

2.1. Study Area

The Caplina River Basin is located in the department of Tacna, Peru, covering an approximate area of 2,627 km² [1]. It extends from the Barroso mountain range, at elevations exceeding 5,000 m a.s.l., to the arid coastal zones of the Pacific Ocean. The climate is predominantly arid to semi-arid, with rainfall concentrated between December and March, and temperatures ranging from sub-zero values in the high Andes to over 25 °C along the coast. The main source of surface water is the Caplina River, which exhibits a seasonal flow regime influenced by Altiplano rainfall and snowmelt [11,12].

2.2. Sampling Design

Monitoring was conducted at 12 strategically distributed stations along the basin, covering upper, middle, and lower zones, as well as tributaries and critical points identified by the National Water Authority (ANA) due to agricultural, urban, and mining activities [11]. Field campaigns took place in October 2024 during the dry season, aiming to capture the spatial variability of water quality parameters under low-flow conditions.

2.3. Parameters Analyzed

Physicochemical parameters were assessed both in situ and in the laboratory. In situ measurements included:

- **Water temperature (°C):** measured with a multiparameter digital thermometer (±0.1 °C).
- **pH:** determined using a calibrated portable potentiometer (±0.01 pH units).
- **Electrical conductivity (µS/cm):** measured with a calibrated conductivity probe (±1%).
- **Dissolved oxygen (mg/L):** determined using a digital oxymeter with a polarographic sensor (±0.1 mg/L).

Water samples for laboratory analysis were collected in polyethylene bottles pre-washed with acid and rinsed with distilled water, then preserved at 4 °C during transport. Analyses followed the *Standard Methods for the Examination of Water and Wastewater* of the American Public Health Association (APHA, 23rd ed., 2017) [13], and results were compared against the Environmental Quality Standards for Water (ECA-Water) established by the Peruvian Ministry of the Environment [8].

2.4. Data Analysis

Data were organized and processed using Microsoft Excel® and statistically analyzed with R software (version 4.3.1). Descriptive statistics (mean, median, standard deviation, and range) were calculated for each parameter. In this study, the term ECA-Water refers to the Estándares de Calidad Ambiental para Agua established by the Peruvian Ministry of the Environment (Ministerio del Ambiente, MINAM), which set maximum permissible limits for various physical, chemical, and biological parameters according to water use categories. For international readers, these values correspond to Peru’s national Environmental Quality Standards for Water. Compliance with the maximum permissible limits established by the ECA-Water, Category 1: Population and Recreational Use [8,14], was also assessed. The official cartography of the National Geographic Institute (IGN) [15] was used for site location mapping.

3. Results

3.1. General Characterization of Physicochemical Parameters

During the monitoring campaign conducted in October 2024, 20 sampling stations (P01–P20) were evaluated along the main axis of the Caplina River Basin. The altitudinal range extended from the Andean headwater zone to the lower coastal area, allowing for the assessment of spatial variability in parameters under the combined influence of natural factors and anthropogenic activities.

The values obtained for temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) are presented in Table 1. Overall, EC remained consistently high across all stations, ranging from 5,085 to 5,796 µS/cm, indicating a high concentration of dissolved salts throughout the river course.

Temperature values were relatively homogeneous, ranging from 22.68 to 25.71 °C, with a slight increasing trend toward the lower basin. DO showed greater variability, with values ranging from 3.77 to 6.13 mg/L, falling below the ecological threshold of 5 mg/L at 40% of the stations, particularly in the initial segment (P01–P08).

pH remained stable within a narrow range (7.39–7.98), within the limits established by the national Environmental Quality Standards for Water (ECA-Water), indicating the absence of significant acidification or alkalinization events during the sampling period.

Table 1. Table 1. Physicochemical parameters measured in the Caplina River Basin (October 2024).

Sample ID	Conductivity (µS/cm)	pH	Dissolved Oxygen (mg/L)	Temperature (°C)
P01-102024	5594	7.41	3.79	25.69
P02-102024	5592	7.39	3.77	25.62
P03-102024	5596	7.42	3.81	25.66
P04-102024	5591	7.40	3.80	25.71
P05-102024	5089	7.72	4.65	25.04
P06-102024	5088	7.71	4.61	25.06
P07-102024	5085	7.69	4.63	25.11
P08-102024	5089	7.65	4.66	25.15
P09-102024	5639	7.93	6.05	22.7
P10-102024	5633	7.91	6.01	22.81
P11-102024	5631	7.94	6.09	22.74
P12-102024	5637	7.98	6.13	22.68
P13-102024	5764	7.87	4.97	23.47
P14-102024	5766	7.81	4.99	23.51
P15-102024	5768	7.83	4.87	23.54
P16-102024	5769	7.85	4.86	23.42
P17-102024	5710	7.9	5.13	23.49
P18-102024	5708	7.89	5.12	23.44
P19-102024	5711	7.93	5.17	23.38
P20-102024	5713	7.92	5.10	23.45

3.2. Comparison with the Environmental Quality Standards for Water (ECA-Water)

The measured **values** were assessed against the ECA-Water, Category 1: Population and Recreational Use [8], yielding the following results:

pH: Across all stations, pH values remained within the permissible range (6.5–8.5), varying from 7.39 to 7.98. **This** indicates chemically stable conditions, with no evidence of acidification or pronounced alkalinization events.

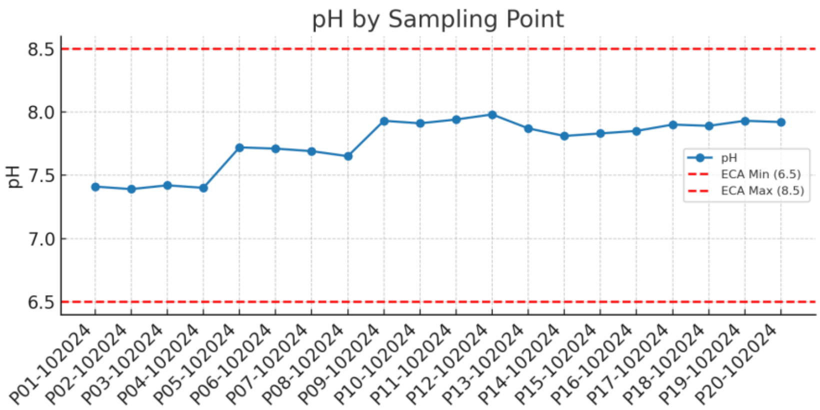

Figure 1. pH by Sampling Point.

Dissolved Oxygen (DO): Stations P01–P08 exhibited DO concentrations below 5 mg/L, the minimum threshold recommended to sustain aquatic life. This deficit may be associated with elevated conductivity, potential organic matter input, and reduced flow rates.

Temperature: While the ECA-Water does not establish a maximum permissible temperature, all stations recorded values between 22.68 and 25.71 °C. Such thermal conditions can promote DO depletion and disrupt ecological balance.

Electrical Conductivity (EC): All stations exceeded the 1,500 µS/cm reference value, with readings between 5,085 and 5,796 µS/cm. These consistently high values reflect elevated dissolved salt concentrations, potentially constraining water suitability for irrigation of moderately sensitive crops.

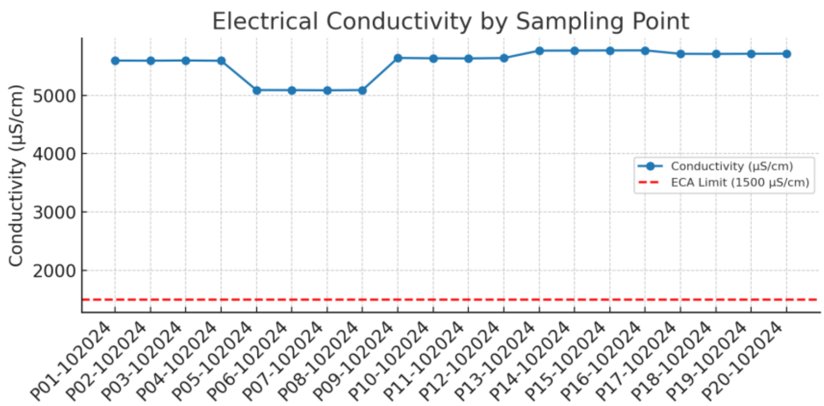

Figure 2. Electrical Conductivity by Sampling Point.

3.3. Spatial Patterns

The analysis of the data shows that the monitoring points share a common pattern of high salinity and temperature with low DO in several stations:

Stations P01–P04: Highest EC (≈5,591–5,596 µS/cm) and lowest DO (≈3.77–3.81 mg/L), suggesting salinity stress and potential oxygen depletion.

Stations P05–P08: Slightly lower EC (≈5,085–5,089 µS/cm) and improved DO (≈4.61–4.66 mg/L), yet still under the ecological threshold.

Stations P09–P12: EC between 5,631 and 5,639 µS/cm, with DO levels around 6.01–6.13 mg/L, showing partial recovery.

Stations P13–P20: EC remains high (5,708–5,796 µS/cm) with DO between 4.86 and 5.17 mg/L, indicating that although oxygen levels slightly improve in some points, salinity remains critical.

3.4. Relevant Trends and Observations

EC values are consistently high across all stations, suggesting a persistent source of salinity, possibly from groundwater discharge, rock-water interaction, or anthropogenic inputs.

- DO is below the recommended threshold in 40% of the stations, indicating potential ecological stress.
- The stable pH values indicate effective natural neutralization processes.
- Stations P01–P08 represent critical points in terms of oxygen deficit and require targeted monitoring.

3.5. Statistical Analysis

The descriptive statistics for each parameter (mean ± standard deviation) across the 20 stations were:

- **Temperature:** 24.03 ± 1.04 °C
- **pH:** 7.76 ± 0.17
- **EC:** 5,616 ± 244 µS/cm
- **DO:** 4.91 ± 0.73 mg/L

The coefficients of variation indicate that EC has the lowest spatial variability (CV ≈ 4.3%) because all stations are consistently high, while DO shows moderate variability (CV ≈ 14.9%). pH (2.19%) and temperature (4.33%) are the most stable parameters. This confirms that DO is the most sensitive parameter to environmental changes in this dataset.

4. Discussion

The results obtained indicate that, during October 2024, the Caplina River basin exhibited physicochemical conditions characterized by elevated salinity and variable dissolved oxygen (DO) concentrations, within a context of stable pH. These patterns can be explained by the interaction between natural processes typical of an arid–coastal system and anthropogenic inputs.

4.1. Dissolved Oxygen (DO) and Thermal Dynamics

The DO deficit recorded at stations P02–P08, with values ranging from 3.77 to 4.66 mg/L, suggests potential stress for aquatic biota, as these levels fall below the ecological threshold of 5 mg/L recommended for the preservation of fluvial ecosystems. This phenomenon is associated with relatively high temperatures (25.04–25.71 °C) and possible organic loads that increase biochemical oxygen demand. Studies conducted in arid and semi-arid basins have reported that even moderate temperature increases reduce oxygen solubility and accelerate microbial respiration processes, thereby amplifying oxygen depletion [2,19,20].

The observed pattern suggests that low-flow hydrological conditions during the dry season, combined with agricultural and urban influences, intensify DO reduction, particularly in the upper–middle reaches of the river.

4.2. Electrical Conductivity (EC) and Persistent Salinization

The EC values recorded (5,085–5,796 µS/cm) greatly exceed the 1,500 µS/cm limit cited for the irrigation of moderately sensitive crops. The low spatial variability (CV ≈ 4.3%) indicates that the salinity problem is generalized throughout the basin, rather than being **concentrated** at a single discharge point. This suggests a combination of factors, including groundwater discharges with high mineral content, evaporation under arid conditions, and return flows from irrigation containing dissolved salts.

In Tacna's agricultural context, this condition poses a risk to irrigation sustainability and crop productivity, as the progressive accumulation of salts in soils reduces their capacity to retain water and nutrients, ultimately affecting yields.

4.3. pH and Chemical Stability

The pH remained stable within a narrow range (7.39–7.98), complying with ECA-Water standards. This behavior reflects a strong chemical buffering capacity in the system, likely associated with the presence of carbonates and bicarbonates in the local geology. Although the observed stability is favorable for aquatic life preservation, a slight shift toward alkalinity in the lower basin stations may be linked to increased photosynthetic activity and carbonate precipitation processes.

4.4. Comparison with Previous Studies

The findings are consistent with previous research conducted in the Caplina River basin and in neighboring fluvial systems such as the Locumba River, where the combination of high salinity and DO deficits has been a recurrent pattern [3,4,17,19]. Likewise, the records of stable pH but elevated EC corroborate the influence of both natural and anthropogenic salinization processes, as previously reported in studies on arsenic, boron, and other metalloids in the region [2–5].

4.5. Implications for Water Resource Management

The magnitude and persistence of salinity, together with the presence of critical zones with oxygen deficits, highlight the need for targeted management measures:

1. Implement continuous monitoring of physicochemical parameters and specific contaminants.
2. Optimize irrigation and fertilization practices to reduce saline return flows.

3. Incorporate treatment technologies for agricultural and urban wastewater.
4. Design conservation measures for river reaches with low oxygen concentrations, prioritizing the protection of aquatic refugia.

4.6. Relevance to Arid Basin Contexts

The case of the Caplina River represents a characteristic example of arid and semi-arid coastal basins, where the combined pressure of climate variability, water overexploitation, and intensive agricultural use leads to sustained water quality degradation. The findings provide a valuable baseline for assessing the effectiveness of public policies and adaptive management strategies in the face of climate change.

5. Conclusions

The results of this study demonstrate that the physicochemical quality of water in the Caplina River basin exhibits marked spatial variability, influenced by altitudinal gradients and the combined effects of natural processes and anthropogenic activities. The main findings are summarized as follows:

1. Dissolved oxygen (DO) shows a progressive decline from the upper to the lower basin, reaching critical values (<5 mg/L) at several stations—particularly between P02 and P08—indicating stress conditions for aquatic biota.
2. Electrical conductivity (EC) remains persistently high throughout the river course (5,085–5,796 µS/cm), far exceeding the reference value of 1,500 µS/cm for the irrigation of moderately sensitive crops, evidencing a generalized salinization process.
3. pH remained within the acceptable range (7.39–7.98), with no evidence of extreme acidification or alkalinization, although a slight alkaline tendency was observed in the lower basin.
4. The recorded patterns are consistent with previous research in the basin and other arid–coastal fluvial systems, confirming that the lower reaches are more vulnerable to water quality degradation due to urban and agricultural discharges, as well as hydroclimatic factors inherent to arid environments.

6. Recommendations

1. Continuous and Expanded Monitoring: Implement a permanent monitoring program that includes physicochemical, biological, and priority contaminant parameters (nutrients, metals, and metalloids), with particular focus on the most vulnerable areas.
2. Control of Pollutant Inputs: Optimize the treatment of domestic wastewater and agricultural return flows prior to discharge, applying technologies adapted to local conditions.
3. Irrigation Management: Promote efficient irrigation techniques to reduce saline return flows and encourage agricultural practices that prevent salt accumulation in soils.

4. Community Education and Participation: Develop training and awareness programs for farmers, local authorities, and communities aimed at conserving water quality.
5. Integrated Planning: Incorporate the results of this study into regional water resource planning and the formulation of public policies that consider the impacts of climate change and hydrological variability.

These results and recommendations provide a sound basis for decision-making and the design of adaptive management strategies to ensure the sustainability of water resources in the Caplina River basin and in similar coastal basins.

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