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Characterization of Water Quality and Management of Sources in the Uyuca Biological Reserve (RBU), Honduras

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Abstract*– Ensuring the supply of safe water represents a growing challenge in the context of climate change and population growth. This study characterized the availability, quality, and community management of water in six communities supplied by the Uyuca Biological Reserve (RBU) during the 2025 dry season. Flow measurements and sampling were carried out in 26 sources, analyzing physicochemical and microbiological parameters, as well as metals such as iron, aluminum, manganese, copper, and zinc. A correlational analysis among water quality parameters was also conducted. To evaluate community management, focus groups and semi-structured interviews were developed with potable water administrative boards. The results indicate that although most sources present "good" quality according to the Canadian Water Quality Index, there are risks due to the presence of fecal coliforms, acidic pH, and high concentrations of aluminum and iron, associated with geological conditions and deficient management of intake structures. At the organizational level, weaknesses were identified such as lack of legal status, regulations, technical training, and sustainable operation and maintenance plans. Water treatment is limited: few chlorination systems function properly, and knowledge of residual chlorine monitoring is low. The applied tariffs are variable and, in some cases, insufficient to cover operational costs. It is recommended to strengthen the technical and organizational capacities of the boards, promote water treatment, and conduct monitoring during the rainy season to analyze seasonal variations. This study highlights the importance of conserving the RBU as a strategic source and the need for institutional support to ensure safe water and sustainable community management.

Keywords-- Groundwater, water quality, community management.

I. Introduction

In scenarios of climate change and population growth, the Latin American region faces major challenges regarding the supply of safe water for its population. Mountain ranges play a crucial role as the headwaters of watersheds and by promoting infiltration processes to ensure groundwater supplies. Their vegetation cover allows them to stabilize the hydrological functioning of the watershed, facilitating key processes such as runoff and infiltration [1].

Likewise, cloud forests play a fundamental role in global water provision because of their unique capacity to capture and filter water through horizontal precipitation [2]. Their contribution is a relevant factor in the water balance and the potential for water capture [3]. However, different events such as deforestation, population growth, overexploitation of resources, flood and drought disasters, expansion of the agricultural frontier, and other anthropogenic activities have impacted the natural mechanisms of watersheds and their environmental, hydrological, and socioeconomic functions.

Although, 75% of the freshwater destined for consumption is obtained through the natural functioning of watersheds, only 12% of the world's forest area is designated for soil and water conservation, and 30% of forests are used mainly for production [4].

Honduras has 21 watersheds. Due to the region's rainfall, the national demand for potable water represents only 5% of the existing supply [5]. The main water sources supplying the population are found on forest lands and protected areas, which have undergone accelerated degradation of their natural resources [6]. One of these areas—the Uyuca mountain—was established as a Biological Reserve with its protected forest zone under Decree Number 211–85, published in the Official Gazette *La Gaceta* in 1986, and is recognized as an ecosystem of great importance, benefiting various nearby communities with its diversity of ecosystem services, mainly through water production for the municipalities of San Antonio de Oriente and Tatumbla.

The Biological Reserve is part of the National System of Protected Areas of Honduras (SINAPH) under the responsibility of the National Institute for Forest Conservation and Development, Protected Areas and Wildlife and covers 816.9 ha of the Uyuca mountain, of which 237.1 ha correspond to the core zone and 579.8 ha to the buffer zone [7]. To ensure adequate management of these areas and guarantee the secure supply of water in the future, strategic protection activities require information that supports decision-making and validates the importance of conservation actions. It is necessary to periodically update the characterization of the hydric capacities of protected areas, that is, the water supply and demand, and water quality, as well as the territorial spaces (micro-watersheds and direct drainage areas) on which their quantity and quality depend.

The purpose of this research was to characterize the availability, quality, and community water management for consumption in selected communities supplied by the Uyuca Biological Reserve during the dry season. To the best of our knowledge, this is the first integrated assessment in the Uyuca Biological Reserve evaluating water availability, quality, and community governance under dry-season conditions. The study establishes a comprehensive baseline for rural water security, supporting conservation planning and long-term monitoring in protected mountain ecosystems. To achieve this, the following specific objectives were established:

1) Evaluate the quantity and quality of water from sources for human consumption during the dry season in selected RBU communities.

2) Identify significant relationships among evaluated water quality parameters; and

3) Describe organizational water management in six communities supplied by the RBU.

II. Methodology

A. Study Area

The study was conducted on the southern side of the Uyuca Biological Reserve (RBU), located between the municipalities of San Antonio de Oriente and Tatumbla, Francisco Morazán (Fig. 1). The buffer zone ranges from 1,200 to 1,700 meters above sea level (masl), and the core zone from 1,700 to 2,008 masl. Average total precipitation is 1,200 millimeters (mm), and the mean annual temperature ranges between 12–17 °C [7]. The rainy season in this area usually spans ten months, with March and April contributing the least precipitation, approximately 129 mm.

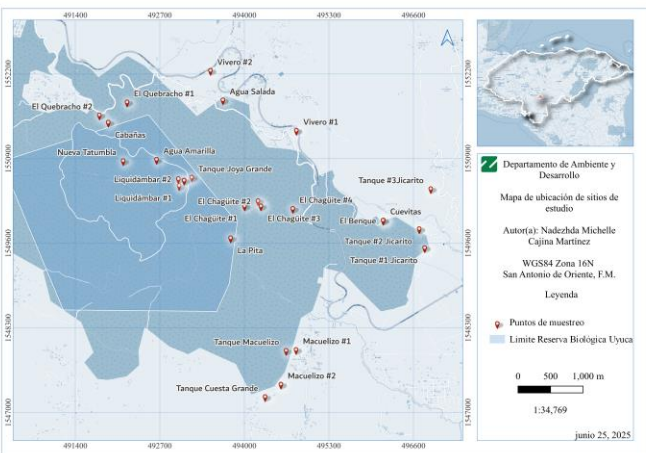

Fig 1. Location map of sampling sites

B. Water Quality Analysis

A single sampling and flow measurement was conducted at water supply sources in the communities of El Jicarito, Nueva Tatumbla, Cuesta Grande, Joya Grande, El Zamorano, and El Chagüite. The sources included: eleven springs, seven storage tanks, four domestic consumption taps, and four streams. Sampling and flow measurements were carried out during the dry season of 2025, from February to April.

Physicochemical parameters were measured in situ using an Oakton® field multiparameter (Table 1). One-liter samples were collected in high-density polyethylene containers for laboratory physicochemical analysis. For bacteriological analyses, samples were collected in sterile 125 mL Whirl-pack™ bags. Subsequently, samples were transported to the Water Quality Laboratory and Environmental Microbiology Laboratory of the Department of Environment and Development at Zamorano for microbiological and physicochemical analysis in a cooler at temperatures < 4 °C. Samples were preserved with sulfuric acid and nitric acid for nutrient and metal determination, respectively. The methods used were in accordance with the twenty-third edition of Standard Methods for the Examination of Wastewater.

TABLE 1
ANALYSIS METHODS USED FOR WATER QUALITY CHARACTERIZATION

Site	Parameter	Method
In Situ	Electrical Conductivity	2510.B Laboratory method
In Situ	Turbidity	2130 B. Nephelometric method
In Situ	Total Dissolve Solids	4500 B. Electrometric method
In Situ	Tempereture	4500 B. Electrometric method
In Situ	pH	4500 B. Electrometric method
IAD Laboratory	Phosphate (PO_4^{3-})	323 Lovibond (4500-P. E. Ascorbic Acid Method)
IAD Laboratory	Nitrates (NO_3^-)	4500-NO3-C. Second Derivate Ultraviolet Spectrophotometric Method
IAD Laboratory	Total Iron (Fe)	3500-Fe B. Phenantroline Method (222 Lovibond)
IAD Laboratory	Manganese (Mn)	8149 Hach PAN Method (242 Lovibond)
IAD Laboratory	Aluminum(Al)	3500-Al B. Eriochrome Cyanine R (40 Lovibond)
IAD Laboratory	Copper (Cu)	3500- Cu C. Bathocuproine Method (153 Lovibond)
IAD Laboratory	Zinc (Zn)	Zinc on Method USEPA (400 Lovibond)
IAD Laboratory	Total coliforms	9222 Membrane filter Technique
IAD Laboratory	Fecal coliforms	9222 Membrane filter Technique

C. Description of Evaluated Parameters

1) Hydrogen Potential (pH): Consistently acidic values (pH < 5) can affect water quality by increasing metal solubility and promoting the growth of certain microorganisms [8].

2)Electrical Conductivity: High values are interpreted as a potential contamination parameter due to their relation to other elements such as chlorides, magnesium, calcium, sulphate, potassium, among others [9].

3) Turbidity: is caused by suspended or dissolved particles such as clays and organic and inorganic matter [10]. These particles can physically protect microorganisms, making their removal by chemical agents such as chlorine more difficult [11].

4) Total Dissolved Solids (TDS): These correspond to the sum of dissolved minerals, salts, and metals. High levels can affect water palatability [12]. and, if ingested excessively, may cause adverse physiological reactions [13].

5) Phosphate: Phosphorus in water can exist as orthophosphates, polyphosphates, or organic phosphorus, in particulate or dissolved form [14]. High concentrations affect organoleptic characteristics and hinder water treatment processes [15].

6) Aluminium: A structural element of clays, commonly present in soluble form. High concentrations can cause bone, hepatobiliary diseases, anemia, amyotrophic lateral sclerosis, and central nervous system disorders [16].

7) Iron: At pH 4.5–9, iron is in ferrous, soluble form [17]. Its accumulation in non-assimilable concentrations can lead to toxicity through bioaccumulation in tissues and organs [18].

8) Manganese: Abundant in some soils and rocks, it causes changes in taste, color, and odor. In humans, high concentrations affect the central nervous, respiratory, and reproductive systems, and the heart, among others [19]. It also hinders correction in water treatment processes [20].

9) Copper and Zinc: Ingesting water with copper concentrations ≥ 3 mg/L has been associated with gastrointestinal symptoms in humans, such as nausea, vomiting, and abdominal pain [21]. Zinc can be present as salts or organic complexes, generating bitter or metallic tastes [22].

10) Total Coliforms: Total coliforms include Gram-negative bacilli capable of fermenting lactose with gas production within 48 hours at 35 °C. While naturally distributed, their presence indicates inadequate water treatment or contamination [23].

11) Fecal Coliforms: These bacteria can ferment lactose with gas production within 24 hours at 35 °C and inhabit the intestinal tract of warm-blooded organisms. They constitute a potential health risk due to fecal contamination. Some bacteria in this group include *Pseudomonas aeruginosa*, *Escherichia coli*, and *Klebsiella* [23]. Gastrointestinal and infectious diseases are major effects of this contaminant, generating symptoms such as fever, diarrhea, and vomiting, with children under five being most affected [24].

D. Water Quality Index

To express a simplified evaluation of water quality from different potable sources based on compliance with the Honduran Water Quality Technical Standard [25]. the Canadian Water Quality Index (WQI) was applied in this study (Table 2). The index integrates three factors: scope, frequency, and amplitude. Initially, scope (F1) defines the proportion of parameters failing compliance relative to the considered variables (E. Frequency (F2) calculates the ratio of non-compliant values to the total data. Finally, amplitude (F3) measures the deviation in the data [26].

TABLE 2
CLASSIFICATION ACCORDING TO THE CANADIAN WATER QUALITY INDEX

Rate	Rating	Description
95-100	Excellent	Water quality is protected with virtually no threats or damage. Conditions are very close to natural or desired levels.
80-94	Good	quality is protected with some minor threats or damage. Conditions rarely deviate from natural or desired levels.
65-79	Fair	Water quality is usually protected but occasionally threatened or damaged. Conditions sometimes deviate from natural or desired levels.
45-64	Marginal	Water quality is frequently threatened or damaged. Conditions often deviate from natural or desired levels.
0-44	Poor	Water quality is almost always threatened or damaged. Conditions usually deviate from natural or desired levels.

E. Quantification of Water Supply

Volumetric flow measurements were carried out in identified springs using a calibrated container and a stopwatch at each point, applying (1),

$$Q = V/\ T \tag{1}$$

Where:
Q=Flowrate (L/s)
V = Volume (L)
T = Time (s)

For surface water sources, the calculation was carried out using (2),

$$Q = V\ x\ T \tag{2}$$

Where:
Q = Flow rate (m^3/s)
A = Area (m^2)
V = Velocity (m/s)

F. Comparison of Water Supply and Theoretical Demand

The daily available volume for each source was estimated. The total volume, expressed in liters, was divided by the daily per capita allocation established by the National Council for Drinking Water and Sanitation for rural areas in Honduras, which is 160 L per person per day [27]. This water availability was compared with the actual demand of each community based on population size reported by the communities.

G. Statistical Analysis of Relationships Between Water Qualiy Parameter

Statistical analysis was performed using JASP® version 0.19.1.0. Measures of central tendency (mean), dispersion (standard deviation and variance), and minimum and maximum values were calculated. Normality was evaluated using the Shapiro-Wilk test (95% confidence). Relationships between variables were analysed using the non-parametric Spearman rho coefficient [28]. A heat map was created to visualize identified correlations and their significance levels. Additionally, a Principal Component Analysis (PCA) was conducted using standardized data and the correlation matrix to identify dominant patterns among water quality variables. Components with eigenvalues >1.0 were retained and interpreted based on loadings above (0.50).

H. Description of Organizational Water Supply

A focus group was conducted with the Potable Water Administrative Boards of communities supplied by Uyuca mountain sources to evaluate their organizational capacities, operational practices, and administrative processes (Fig 2).

Fig 2. Dimensions analyzed for the institutional description of water boards

1) Organization: Includes the existence and application of plans, regulations, or internal rules that guide the board's functions and objectives [29].

2) Administration: Refers to financial management and service sustainability, generally based on a basic fixed tariff [29].

3) Infrastructure: Analysed the condition of intake works, conduits, storage tanks, and distribution networks, whose quality determines system efficiency.

4) Operational Conditions: The board manages and supervises periodic maintenance tasks, commonly delegated to a trained operator or plumber [29].

5) Water Quality Monitoring: Evaluates compliance with sanitary regulations and the capacity to implement corrective actions in case of deficiencies. Boards must adhere to the guidelines established by the Ministry of Health [30].

III. Results and Discussion

A. Water Quality Analysis

1) Hydrogen Potential (pH): The pH values of the sampled sites were mostly below the recommended range of 6.5–8.5 according to the Honduran Technical Standard for Drinking Water Quality (Fig. 3).

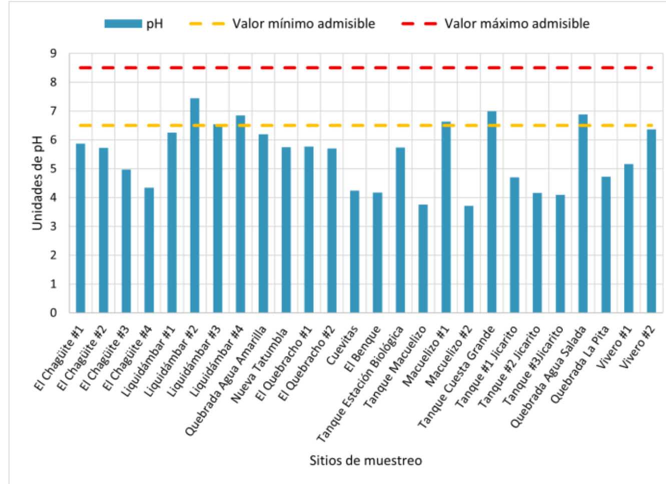

Fig 3. pH values at sampling sites during the dry season and their relationship to permissible limits

This acidity is attributed to the natural characteristics of the soils in the Uyuca Reserve, dominated by ultisols, alfisols, and inceptisols, which enhance metal solubility and geochemical processes that can affect water quality [31, 32]. Additionally, this may cause difficulties in the distribution network due to corrosive effects on operations or water system treatment from the consequent release of metallic ions such as iron and copper [33].

2) Electrical Conductivity: Maximum values of 227 ppm were recorded, within regulatory limits, indicating a low presence of ionized inorganic substances and limited health risk, although there could still be corrosive effects on the distribution network [34].

3) Turbidity: Two springs exceeded the maximum limit of 5 NTU, which may be associated with sediment transport and biofilms in the distribution system, transport of organic matter from the source, and runoff from direct greywater discharge [35]. Increases in turbidity may indicate higher bacterial loads and compromise water disinfection [36].

4) Phosphates: Most sites exceeded the limit of 0.1 mg/L PO_4^{3-} established by the Environmental Protection Agency [37]. Groundwater usually has low phosphorus concentrations due to the low solubility of this element in soil minerals and the soil's capacity to retain phosphates in its structure [38].

5) Aluminum: A total of fourteen sources exceeded the limit of 0.2 mg/L Al; its presence is associated with ultisol soils and natural acidification processes [39]. It has been documented that as carbonic acid increases, aluminium concentrations also increase, showing a strong correlation between the two. This factor implies higher solubility of Al^{3+} cations, released from minerals such as kaolinite and gibbsite, typical of ultisol soils [39].

6) Iron: Ten sources exceeded 0.3 mg/L Fe, mainly due to increased solubility in acidic media and prolonged contact with iron-containing minerals [40]. Factors influencing iron concentration in solution include residence time in the aquifer, presence of organic matter, water percolation rate, and soil composition [40].

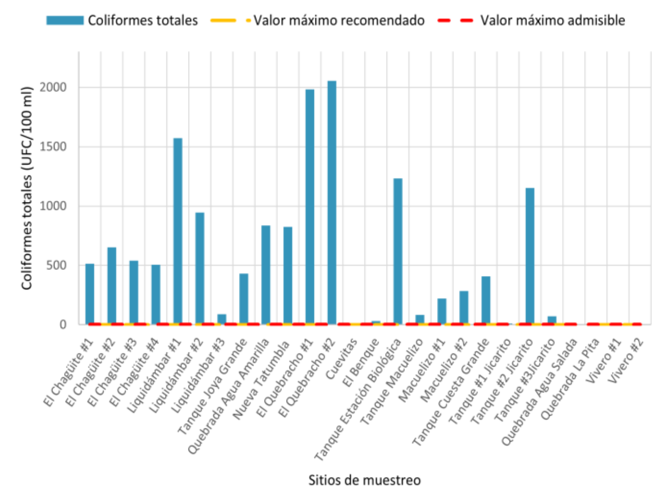

Fig 4. Total coliforms at sampling sites and their relationship to established limits

Additionally, its solubility is favored by carbonic acid conditions, which lower pH. Iron can be released from minerals such as goethite (FeOOH) and hematite (Fe_2O_3), facilitating its dissolution and contributing to the reddish coloration of the water [41].

8) Total Coliforms: Of all sources intended for drinking water, only Cuevitas met the recommended limit of 0 CFU/100 mL for total coliforms (Fig. 4). Other sites exceeded the maximum permissible value of 3 CFU/mL for total coliforms. The presence and quantity in sampled sites can be attributed to these bacteria originating from soil, rocks, and vegetation [42], reaching water intakes by wind action if structures are uncovered or through runoff from surface water flows.

9) Fecal Coliforms: According to technical water quality standards, the recommended and maximum allowable value for fecal coliforms is 0 CFU/100 mL. Sites exceeding this limit were those located at higher altitudes in the reserve. Since there are no human settlements in this area, risk factors for fecal contamination in groundwater sources may include inappropriate design, poor construction, or insufficient maintenance of intake areas, as these pathogens are transmitted only by warm-blooded organisms [43].

B. *Water Quality Index (WQI)*

According to the Canadian Water Quality Index, all communities fall into the "good quality" category, with Cuevitas and Macuelizo standing out for meeting most regulatory parameters.

Although most sources were classified as "Good" under the Canadian Water Quality Index, this may mask specific risks such as fecal coliform contamination, highlighting the need for parameter-specific assessments. The association between iron and aluminum suggests a shared geological origin, while the inverse relationship between pH and manganese reflects greater metal solubility under acidic conditions. Although concentrations mainly exceeded aesthetic and operational thresholds, they may affect water acceptability and treatment efficiency, reinforcing the need for periodic monitoring.

C. *Quantification of Water Supply*

The springs with the highest supply were El Benque, Tank #3 in Jicarito, and Liquidámbar #2, while Quebrada Agua Amarilla had the lowest flow (0.02 L/s) (Fig. 6). Comparing supply and population demand, communities face water deficits during the dry season, with El Jicarito and El Macuelizo supplying only about 60% of the theoretical per capita demand of 160 L/day [27].

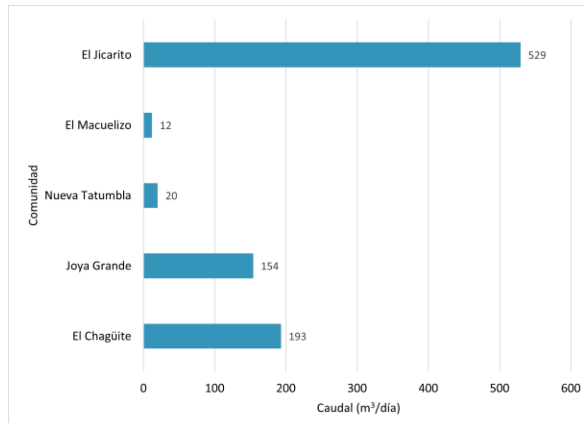

Fig 5. Daily volume available in communities supplied by RBU sources during the dry season

This pattern is repeated across the evaluated communities, where water availability falls below what is required for adequate coverage. Consequently, there is widespread vulnerability during the dry season, reflecting a structural problem in resource distribution and equitable access.

D. *Spearman Rho Correlation Test*

Spearman correlation coefficients identified significant relationships between parameters: pH–manganese, iron–aluminum, turbidity–iron, turbidity–aluminum, TDS–total coliforms. A moderate negative correlation was observed between pH and Mn ($\rho = -0.666$, $p < 0.05$), indicating that lower pH can correspond to higher manganese concentrations. This aligns with manganese's property of being reduced in acidic environments from insoluble forms (Mn^{4+} oxides) to soluble forms (Mn^{2+}) [40].

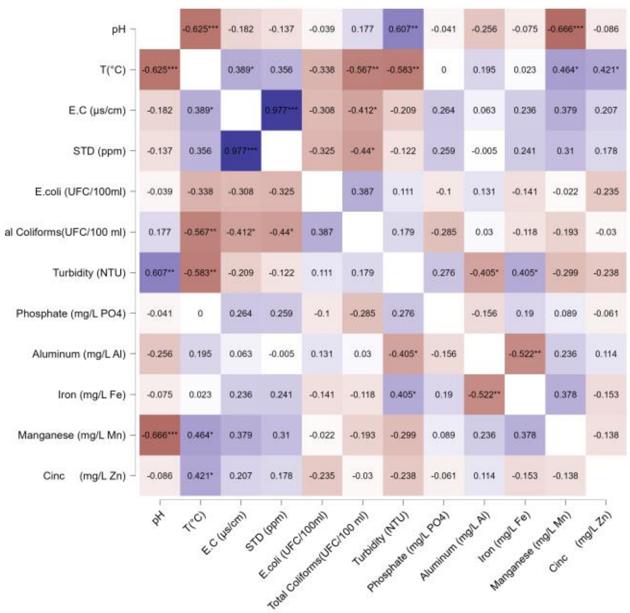

Fig 6. Heat map of Spearman's correlation coefficient rho

Additionally, the heat map revealed a moderate negative correlation ($\rho = -0.522$, $p < 0.01$) between iron and aluminum (Fig. 7). Both metals are structural components of soil particles, and the release or solubilization of ions varies according to physicochemical properties such as pH and the presence of organic acids [44].

E. Principal Component Analysis

The PCA retained two components explaining 54.4% of total variance, confirmed by parallel analysis and the scree plot (Fig. 8). PC1 (32.5%) grouped CE, TDS, temperature, manganese, total coliforms, and E. coli (positive loadings) with pH (negative loading), representing a mineralisation and general contamination gradient consistent with geochemical dissolution processes in the ultisol soils of the RBU [31,32]. PC2 (21.9%) grouped turbidity, iron, aluminum, and zinc, representing a metallic load and turbidity gradient associated with colloidal metal transport in acidic recharge zones [40,44]. Together, both components reinforce the Spearman findings and suggest that geology is the primary driver of water quality variation at these sources. Phosphates were excluded due to near-zero communality (uniqueness = 0.97).

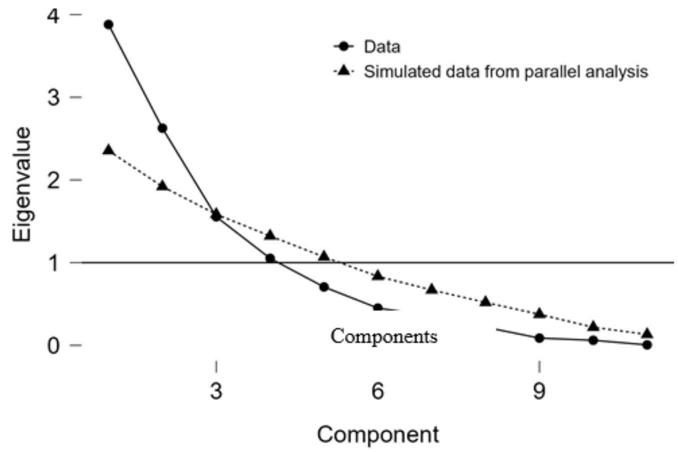

Fig 7. Scree plot of the Principal Component Analysis.

F. Organizational Water Management Description

1) Organization: Analysis of the water boards shows notable heterogeneity in legal formalization, internal organization, and institutional recognition. While some, such as El Chagüite and Joya Grande, have clear operational structures and some experience, others like Nueva Tatumbla or Cuesta Grande show marked weaknesses in legal and organizational aspects. Although several have internal regulations, many are not integrated into collaboration networks nor possess active legal status, limiting their management and sustainability capacity.

2) Financial Administration: Some boards set tariffs through assemblies and apply penalties, while others operate more centrally. Service frequency is variable and affected by water availability in the dry season, generally insufficient to meet community demand. While most maintain maintenance funds and keep the community informed, gaps persist in managing delinquency and tariffs that do not reflect operational realities or future investment needs. Lack of adequate collection mechanisms often leads to financial imbalances and instability, limiting the ability to maintain a community fund [45].

3) Infrastructure: Protection and technical management conditions of water systems vary considerably among communities. While most perform maintenance and recharge zone activities, weaknesses remain such as lack of fencing at intakes and absence of permanent technical staff. These limitations increase system vulnerability and affect sustainability. Variability in storage capacity and lack of household practice data further complicate comprehensive and efficient resource management.

4) Operation and Maintenance: Although domestic consumption is prioritized in all communities, only some have active chlorination systems, often based on estimates. Technical staff salaries vary widely, and in most cases proper protective equipment is lacking. This highlights the need to standardize treatment and improve labor and safety conditions. Data indicate that rural systems with informal, untrained personnel have operational failure rates up to three times higher than models with defined preventive maintenance [46].

5) Water Quality Monitoring: Significant diversity exists in practices, capacities, and information levels among community boards. Only some have received formal training in drinking water treatment, notably Joya Grande and Macuelizo. These communities also conduct periodic water quality analyses, often with external institutional support, and take corrective actions when problems are identified. In contrast, communities such as El Jicarito, Chagüite, Cuesta Grande, and Nueva Tatumbla lack technical training and face limitations in quality analysis or systematic application of corrective measures (Table 3). This represents a technical gap directly affecting consumer safety, as it prevents informed decision-making due to lack of contamination indicators [47].

In addition, during the information gathering process, each water board was provided with a report of the results according to the sources in each community, as well as an opportunity to explain each parameter and clarify any questions.

TABLE 3
SUMMARY OF ASPECTS RELATED TO WATER QUALITY IN THE SYSTEMS EVALUATED

Aspects	El Jicarito	Joya Grande	El Chagüite	El Macuelizo	Cuesta Grande	Nueva Tatumbla
The Water Board has received training in drinking water treatment	No	Yes	No	No	No	No
They conduct water quality analyses	Yes	No	No	Yes	No	No
Analysis frequency	Trimestral	Semestral	-	Occasional	-	-
Entity that performs the analyses	El Jicarito Health Center	External institution	-	External instituion	-	-
Corrective actions are taken when quality problems are detected	Sí	Sí	No	Sí	During winter	-
Changes in water quality perceived in recent years	No	Sí	No	Sí	No	No
Residual chlorine level in the tank is known	No	-	No	No	No	-

The six communities evaluated depend directly on the Uyuca Biological Reserve for domestic water supply, representing a critical ecosystem service for rural livelihoods. Sources affected by contamination sources and insufficient dry-season flow place local populations at risk of reduced access to water, particularly during peak scarcity months. Beyond household consumption, these deficits may affect hygiene practices, institutional operations, and community resilience under climate variability.

Based on these findings, priority actions for water security improvement should focus first on public health through quarterly chlorination and residual chlorine monitoring in all community systems to reduce microbiological risks. In the medium term, intake structures should be upgraded with protective roofing, perimeter fencing, and sediment barriers to improve source protection, while annual technical training should strengthen water boards in maintenance, financial management, and water quality surveillance. Over the long term, a seasonal monitoring framework covering both dry and rainy seasons should be established to support adaptive watershed management.

IV. CONCLUSIONS

The water sources studied showed differences in both quantity and quality. Water availability is low for most communities during the dry season, which affects supply. Most sources can be considered of "Good Quality"; however, the presence of fecal contamination indicators represents a potential health threat that requires prevention and treatment strategies.

The correlation analysis revealed strong relationships between certain parameters, highlighting associations between pH and manganese, iron and aluminum, as well as between turbidity and iron, and turbidity and aluminium. These patterns suggest a common origin for these elements, predominantly associated with the geology of the area, specifically the composition of rocks present in the recharge zone.

The characterization of water management in the communities revealed weaknesses in organizational structure, technical and administrative capacities, and water quality management. Although all communities have a water board or committee, only some possess legal status, implemented internal regulations, trained personnel, or tariffs that ensure the sustainability of the systems. Despite these challenges, low water availability during the dry season is identified as the main obstacle in community water management.

STUDY LIMITATIONS

This research was conducted during a single hydrological period corresponding to the 2025 dry season. Therefore, the results represent seasonal conditions rather than annual variability. Water quality and flow may differ substantially during the rainy season due to increased runoff, sediment transport, and dilution processes. Resource and logistical constraints limited repeated sampling across seasons. Consequently, the findings should be interpreted as a dry-season baseline, and future monitoring should incorporate multi-season campaigns to capture temporal dynamics and improve long-term management decisions.

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