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Assessment of the Performance of a Water Treatment Plant in Ecuador: Hydraulic Resizing of the Treatment Units

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Abstract: Granting access to drinking water has been a challenge because 47% of the worldwide population is not connected to a drinking water distribution network in rural settlements. This study aimed to evaluate the contaminant removal efficiency in a conventional water treatment facility in the Austro region of Ecuador, Paute, to identify the treatment units requiring hydraulic resizing. Water samples were collected from each treatment unit to characterize the physical-chemical and microbiological parameters, and the dimensions of the treatment ponds for hydraulic evaluation purposes. Water hardness, electrical conductivity, SO_4^{2-}, and Fe^{2+} were the main issues found in the water, which failed to comply with Ecuadorian technical guidelines. The treatment units, such as the flocculator, rapid sand filter, and storage tank, were resized to meet the demand of the future population. In addition, the residual free chlorine was measured as insufficient in the community's tap water, showing an unprotected water distribution system to microbiological contamination. No disinfection by-products were found despite the existence of biodegradable organic matter. The findings of this research propose improvements in the deployed treatment practices to provide the community with drinking water in accordance with the Sustainable Development Objectives (SDG 3 and SDG 6).

Keywords: groundwater; conventional water treatment; water quality; hydraulic capacity; resizing

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1. Introduction

Water is essential to sustain life development on the planet. Nevertheless, 800 million people do not have access to a water supply in 2022 [1–3]. Worldwide, fewer than 53% of people living in rural and informal settlements are provided with drinking water [4,5], triggering diseases and limiting their opportunities for economic development [6–9]. The existence of drinking water facilities in rural communities, however, does not guarantee production that complies with drinking water quality criteria and thresholds [10–14]. This highlights the urgency of characterizing the water quality of the catchment bodies and evaluating the performance and operations of drinking water systems to determine the quality of the drinking water supplied to the population [15].

Various methods have been employed to characterize the water quality of surface and groundwater sources [16–21]. For instance, remote sensing technologies have been deployed to provide an estimation of a limited number of physicochemical quality indicators of water bodies through the detection of visible bands obtained via satellite instruments [22]. Elhag et al. [23], identified the colloidal suspension content in the Wadi Baysh Lake in Saudi Arabia. In order to estimate the degree of reliability of the results collected from the remote sensing-reflectance tool, daily turbidity monitoring was performed for a period of two years. A correlation of 0.94 between colloidal content and turbidity was calculated. Similarly, Martins et al. [24], employed the temporal variability of turbidity and water extent of the Sobradinho Dam, monitored over 4 years. It was determined that the unsuitability of the dam for catchment water purposes was due to its poor quality. Nevertheless, the limitation of this approach relies on the analysis of mainly optically active parameters such as those responsible for the color of the water, colloidal matter, and suspended sediments [25–31]. These studies show that experimental measurements are mandatory to validate the results estimated by these evaluation tools.

Other investigations have computed the water quality index (WQI), to judge the potabilization efficiency of rural drinking water treatment plants. The WQI is an algorithm that synthesizes large amounts of water quality characterization data into a single qualitative performance indicator ranging from excellent to poor [17,32–38]. For example, Azzam et al. [33], reported that the WQI of the feed water in various Egyptian drinking water facilities was in a medium category, resulting from its chemical and microbiological quality; namely, high concentrations of organic matter, dissolved oxygen depletion, and the presence of fecal coliforms. The conducted treatment process improved the quality from medium to good. According to Baloitcha et al. [17], the drinking water distribution system in Juja, Kenya ranked as fair, due to the low concentration of residual chlorine, the presence of E. coli, and occurrences of scaling and corrosion in the water mains. On the other hand, in Iraq, the performance of eight treatment plants was evaluated in terms of pollutant removal by comparing the WQI at the plant inlet against the effluent quality [39]. Potabilization efficiencies of 6.0 ± 4.5% were reported due to unforeseen domestic and industrial discharges and saltwater intrusion. This mathematical approach allows a qualitative assessment of water quality. Nonetheless, robust statistics based on the characterization of treated effluent quality require repetitive measurements conducted over a period of time, which represents a significant financial investment for low-income communities, which may not be a feasible option. Furthermore, it does not allow the identification of specific issues in units within the water treatment plants, which is crucial to determine pollutant removal requirements or maintenance needs.

There are few investigations that focused their assessment on the performance of potabilization processes to identify quality issues at an early stage [40–42]. Ali et at. [41], investigated the contaminant removal efficiency of flocculation, sedimentation, filtration, and disinfection units in a conventional treatment plant in Iraq by measuring control variables of a physicochemical nature, e.g., turbidity, pH, electrical conductivity, total dissolved salts, sulfates, calcium hardness, and magnesium. Similarly, Arrieta [42], diagnosed the condition of the treatment ponds of a rural potabilization system in Colombia using field observations and information gathered from surveys of operating and administrative personnel to find hydraulic and sanitary issues. These investigations found that improper selection of the treatment train according to the chemical and microbiological quality of the catchment water, poor operation practices, and the absence of maintenance were critical factors in the potabilization performance. While drawbacks of the treatment processes are evidenced, it is rare to find studies that deploy appropriate assessment mechanisms and present feasible proposals that do not impose economic and technical constraints on the study area.

Commonly, rural drinking water treatment plants are not a priority for local authorities, leading to inadequate investment in essential equipment and monitoring facilities for water quality testing [13]. Additionally, local staff with limited technical training are responsible for making the day-to-day decisions on the operation of the drinking water systems [43–46]. Therefore, control variables employed during the assessment of the performance efficiency of the treatment units must meet the criteria of easiness of measurement and interpretability, and a limited number of quality tests to quickly conclude the operating status of the treatment ponds, the latter serving as a direct indicator of the expenses incurred during the evaluation. Likewise, proposals to improve the potabilization efficiency of the units should consider taking advantage of the existing treatment facilities by recommending better operation and maintenance practices to overcome the "limited technical training" challenge of rural plant operation. The upgrading of the hydraulic capacity of the treatment trains, in cases of poor performance and the inefficiency of treatment units, may be another valid alternative.

In this context, this study aims to individually assess each treatment unit of the El Descanso drinking water treatment plant, in a rural community of Ecuador, using easily measured water quality control parameters, e.g., turbidity, electrical conductivity, pH, dissolved oxygen, and organic content, as well as specific water quality indicators such as Ca^{2+} and Mg^{2+} as $CaCO_3$, residual Cl_2, Fe^{2+}, and SO_4^{2-} to identify common issues in the conventional treatment processes related to improper maintenance and the operation of the units. Likewise, corrective actions are encouraged for the proper functioning of the treatment processes. For example, using optimal dosing of treatment chemicals such as chemical coagulant and chlorine concentrations. The hydraulic capacity of the treatment ponds was evaluated for a design period of 20 years, where the hydraulic parameters of the processes that do not supply the future demand were redesigned. The methodology and the proposed technical solutions presented in this research will provide the technical and timely identification of problems related to the efficiency of the treatment units during the operation of a conventional drinking water treatment plant in low-income communities. This contributes to Sustainable Development Goals No. 3: Health and Well-being and No. 6: Clean Water and Sanitation.

2. Methodology

2.1. Case Study Description

San Cristóbal is a rural community of Paute, located in the northeastern area of Azuay province (Austro-Ecuadorian zone). San Cristóbal has 1712 hectares, primarily used for agricultural, livestock production, and extractive activities, including forestry and aggregate extraction for building materials. The average elevation of San Cristóbal is 2550 m above mean sea level, and the temperature ranges from 12 to 20 °C, with annual rainfall varying between 500 and 750 mm. April and October show the highest and lowest precipitation months, respectively [47].

"El Descanso," the conventional drinking water treatment plant of San Cristóbal, has been operating for 14 years. This plant treated approximately 175,000 L d^{-1} of groundwater in 2021, which was pumped from a 90 m depth well located 50 m away from the banks of the Burgay River and transported through a polyvinyl chloride pipeline to the treatment facility. This treatment plant was designed to remove colloidal material, hardness, and microbiological agents. The treatment train starts with a pre-oxidation unit, using a slat tray aerator, to remove ferrous iron concentration. Next, water is conveyed to the coagulation-flocculation basin, whereby the colloids increase their density and settle in the sedimentation basin. After that, the outflow of the sedimentation unit is sent to the granular media filters, sand, and activated carbon, to further decrease the concentration of turbidity and organic substances. Later, the softening filter is used to remove hardness. The last step is the disinfection process, where pathogenic agents are inactivated using a chlorine solution so as not to be distributed to the end users. However, the contaminant removal efficiency from conventional water treatment plants is not well documented. Furthermore, the design period of this treatment facility finished in 2021. Therefore, an assessment of the hydraulic capacity of the plant is vital to ensure that the population's water demand is satisfied by acceptable water quality in the next decades.

2.2. Fieldwork

The field inspection was conducted in the dry season (October 2021) where the physical conditions of the treatment units were visually examined, and the basin dimensions and the water flow were measured to assess the hydraulic capacity of the treatment facility. Water samples from the entrance and exit of each treatment unit were collected to analyze the physicochemical and bacteriological parameters. Measurements of pH, electrical conductivity (EC, μS cm^{-1}), Total Dissolved Solids (TDS, mg L^{-1}), Dissolved Oxygen

(DO, mg L^{-1} O_2), and temperature (T, °C) were conducted using a portable analytical probe (HQ40d, HACH) calibrated against standard buffer solutions, and an electrical conductivity probe calibrated against a 1000 µS cm^{-1} NaCl solution. In addition, turbidity was measured using a turbidity meter (2100Q, HACH) that was calibrated against formazin standard solutions of 20, 100, and 800 NTU, and this was verified with a 10 NTU formazin standard solution. The turbidity measurements were useful to identify which treatment units were not working, by computing the efficiency percentage of each process (sedimentation, granular bed filtration stations: sand and activated carbon), accordingly.

Seven sampling points (n = 7) were selected inside the treatment facility as shown in Figure 1: (1) At the plant inlet for evaluating the quality of the raw water; (2) after leaving the aeration process-slat trays aerators; (3) after the sedimentation process once the coagulation-flocculation process was completed to determine turbidity removal; (4) after each of the filtration processes: sand bed filter, and (5) granular activated carbon filter to individually evaluate the removal efficiency of organic matter and turbidity; (6) after the output of the cation resin softening filter to estimate hardness removal due to calcium and magnesium salts; and (7) after the disinfection process by chlorination in the treatment facility to measure the concentration of residual free chlorine and the existence of microbiological contamination.

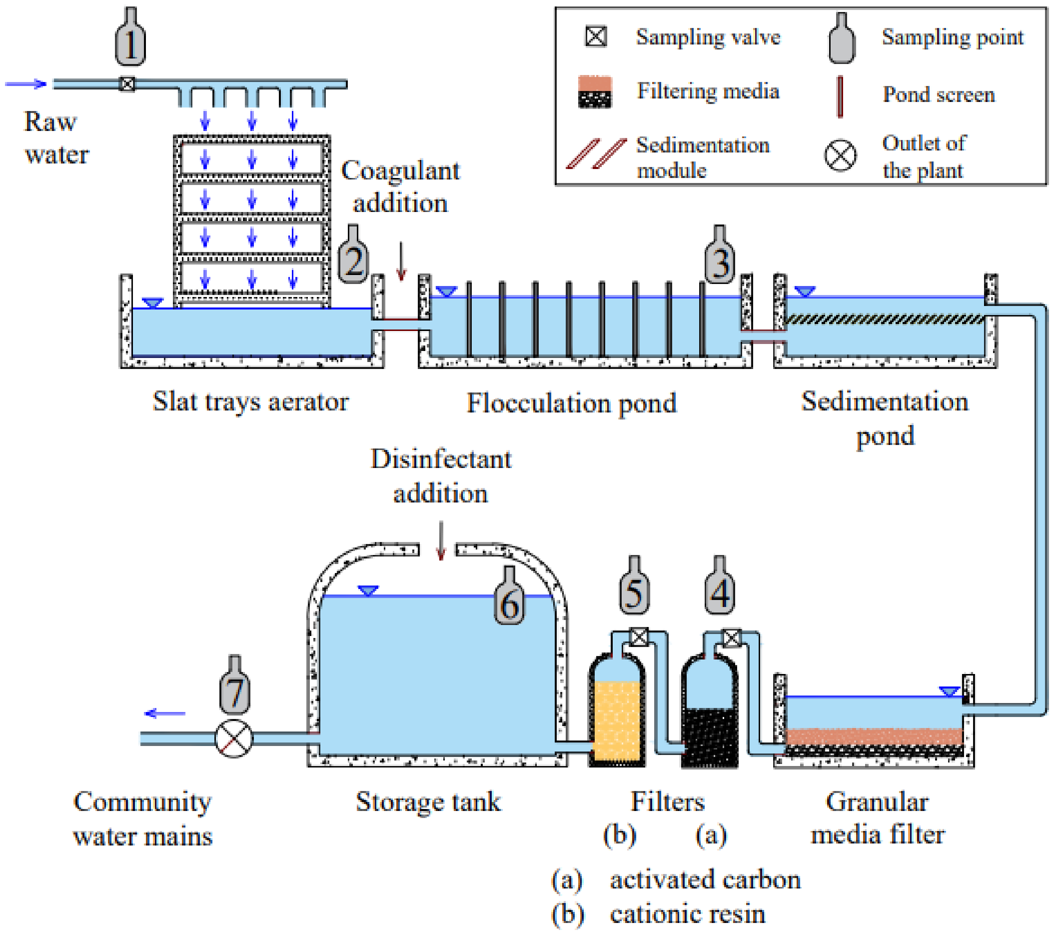


Figure 1. Conventional water treatment units of El Descanso plant showing the selected sampling points (grey bottles).

In addition, the residual effect of the disinfectant reagent (chlorine) was measured in eight random domestic taps (Figure 2) to assess the efficiency of the chlorine dose applied in the storage tank in accordance with the Ecuadorian technical guidelines [48].

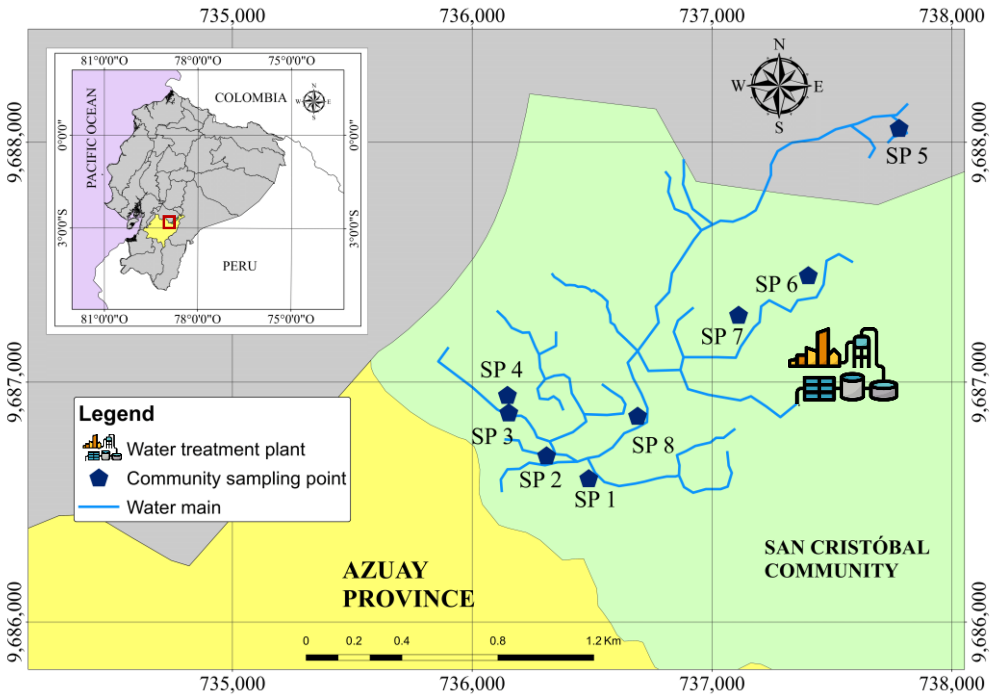


Figure 2. Measurement of the residual free chlorine concentration in the community water main. The eight sampling points were selected from SP1 to SP8. The red frame on the inset shows the study area of San Cristobal community.

The specifications of the Ecuadorian technical guidelines (INEN 2169) regarding the sampling, handling, and conservation of samples, were followed during the collection, conservation, and transportation of water samples. These were collected in polypropylene containers for physicochemical analysis, amber glass bottles for organic material analysis, and sterilized plastic containers for the microbiological test. The water samples were labeled, refrigerated, and transported in portable coolers, where the temperature ranged from 0 to 5 °C, until they arrived at the laboratory. Table 1 shows the physicochemical and microbiological analyses carried out at each sampling point at the water treatment plant El Descanso.

Table 1. Physical-chemical and bacteriological parameters measured at the eight sampling points of the treatment plant to evaluate the effectiveness of the conventional treatment units.

	Sampling Point †					
Analytical Parameter	**(1)**	**(2)**	**(3)**	**(4) (5)**	**(6)**	**(7)**
pH	✓	-	✓	-	✓	✓
Electrical conductivity	✓	-	✓	-	✓	✓
Total dissolved solids	-	-	-	-	✓	✓
Dissolved oxygen	✓	-	✓	-	-	✓
Temperature	-	-	✓	-	-	✓
Turbidity	✓	✓	✓	✓	✓	✓
Biochemical Oxygen Demand	✓	-	-	✓	-	✓
Ferrous iron	✓	✓	-	-	-	✓
Calcium hardness	✓	-	✓	-	✓	✓
Magnesium hardness	✓	-	-	-	✓	✓
Sulfate	✓	-	-	-	-	-
Manganese	✓	-	-	-	-	✓
Aluminum	-	-	-	-	-	✓
Total coliforms	✓	-	-	-	-	✓
Free residual chlorine	-	-	-	-	-	✓

† The eight sampling points were collected at: (1) raw water entrance; (2) aeration process; (3) sedimentation basin; (4) sand filter and (5) granular activated carbon filter; (6) softening filter; (7) storage tank.

2.3. Physicochemical and Bacteriological Analyses

The physicochemical and bacteriological analyses were performed at the Sanitary Laboratory of ESPOL Polytechnic University. The Biochemical Oxygen Demand (BOD_5) was measured according to the respirometric method (HACH method 10099) in the BODTrack II, with a range of 0 to 700 mg L^{-1}. These samples were incubated at 20 ± 1 °C in a POLEKO incubator over five days. Fe^{2+} concentration was measured with the Phenanthroline Method (HACH method 8146) with a UV-Vis spectrophotometer ranging from 0.02 to 3.00 mg L^{-1} Fe. Before measurement, the spectrophotometer was calibrated using the standard solution of 2.00 mg L^{-1} Fe^{2+}. The concentration of calcium hardness in the water samples was determined using the ethylenediaminetetraacetic acid (EDTA) titration method (HACH method 8222), ranging from 0 to 25,000 mg L^{-1} as $CaCO_3$. Magnesium concentration Mg^{2+} was computed by the difference after the analysis of total hardness, which was obtained using a similar HACH titration method with EDTA (HACH method 10099). The SO_4^{2-} concentration was measured with the USEPA SulfaVer 4 method (HACH method 8051) with a UV-Vis spectrophotometer ranging from 2 to 70 mg L^{-1} SO_4^{2-}. This measurement was calibrated using the standard solution of 70 mg L^{-1} SO_4^{2-}. Mn and Al concentrations were measured using ion chromatography. For bacteriological analysis, 3M™ Petrifilm™ rapid aerobic count plates were used to estimate the colony-forming units (CFUs) of total coliforms per unit volume in the water. This method used 1 mL of water that was injected in the Petrifilm™ plate and incubated for 24 h at 37 °C. The presence of residual free chlorine (hypochlorous acid and hypochlorite ion) measured in a random water sample was evaluated by the USEPA DPD method (HACH method 10245) using a UV-Vis spectrophotometer and HACH reagents to determine free chlorine, ranging from 0.02 to 2.00 mg L^{-1}.

2.4. Performance of the Conventional Treatment Units

Based on the physicochemical and bacteriological measurements conducted, the removal efficiency of the conventional treatment units was individually computed. The quality of drinking water supplied to the community was assessed by comparing it against the acceptable limits established in the Ecuadorian technical guidelines for drinking water quality, INEN 1108, and by the World Health Organization (WHO) [48].

2.5. Hydraulic Capacity Assessment and Resizing

Based on the information collected in the field inspection stage, the hydraulic capacity of the plant, the design period of which finished in 2021, was evaluated to determine whether the dimensions of the tanks and basins of each process met the criteria for a new design period (until 2041). To estimate the new design flow and sizing criteria for conventional water treatment units, two technical design literature were followed: the Ecuadorian Design Guideline for Drinking Water Supply Systems in rural zones, namely "Norma CO 10.7 602" [49], and the Design Standard issued by the Pan-American Center for Sanitary Engineering and Environmental Sciences (known by the acronym CEPIS, in Spanish) [50].

2.6. Estimation of the Design Flow Rate

The design flow of the treatment plant is crucial for sizing each unit of the treatment process. This flow depends on the estimation of the population growth rate and water consumption data. The water consumption of the future population was determined from the census data collected in the socioeconomic report of the San Cristóbal community, with information regarding the average number of members per household, monthly consumption of fresh water per water meter box, the consumption type, and whether residential, commercial, or institutional, e.g., education facilities and medical centers.

According to the Ecuadorian standard, the population is projected by the geometric projection statistical model with an annual population increase rate calculated using census data from 1992 to 2020, obtained from the Ecuadorian Institute of Statistics and Census [51]. Equation (1) is used to compute the future population using the geometric projection model:

$$P_p = P_i \cdot (1 + r)^n \quad (1)$$

where P_p is the future population; P_i is the population per the recent census; r is the annual population increase rate; n is the number of years of projection.

Equation (2) estimates the average daily water demand; this is a function of the projected population and the data of water allocation:

$$Q_m = \frac{f \cdot P_p \cdot D}{86{,}400}\ [L\ s^{-1}] \quad (2)$$

where f is the leakage factor whose value is 1.20 established by [49] for household connections with more than one tap per house; P_p is the projected population; D is the data for water allocation in liters per capita per day.

Once the average daily water demand was estimated, the design flow was computed to size the water treatment processes. Equation (3) is used to determine the treatment flow rate, also known as the design flow:

$$Q = 1.10 \cdot K \cdot Q_m\ [L\ s^{-1}] \quad (3)$$

where Q is the design flow; the factor 1.10 represents an additional 10% of the water demand due to the maintenance process of the treatment units, such as backwashing and pond cleansing; K is the peak demand coefficient obtained from the daily variation of the water demand of the population in a year of operation, or if no information is available, it is suggested to use the value of 1.25 [49]; and Q_m is the average daily water demand.

2.7. Technical Criteria for the Design of the Drinking Water Treatment Processes

2.7.1. Hydraulic Flocculation System

The criteria for the design of a hydraulic flocculation system were adopted from [50]. The standard suggested designing a 'horizontal' hydraulic flocculation basin for small water treatment plants, a plant with a design flow below 50 L s^{-1}. The design criteria for the sizing of the flocculation tank are shown in Table 2. Since water exhibits high concentrations of hardness, the standard suggests using high-velocity gradient values for the formation of floc during mild agitation.

2.7.2. Clarifier Basin

Regarding the technical aspects of the basin design, the requirements and recommendations established in [50] were applied. Additionally, when selecting the materials for the sedimentation modules, the guidelines published by the World Health Organization (WHO) and the Pan American Health Organization (PAHO) were carefully studied to minimize the risk of using carcinogenic materials. Some of the design criteria for the sizing of the horizontal-flow plate settling basin with flocs based on aluminum sulfate coagulant are shown in Table 2.

2.7.3. Rapid Sand Filter

Since the sand filter pond in the water treatment plant was oversized in comparison to the treatment flow, it was resized according to the recommendations of [50] for the design of a rapid sand filtration system. Factors such as the type of filter media, filtration velocity, inlet velocity, and type of suspension according to the physical features of the media (volume, density, and size of the particle), among other variables that influence the filtration process, were considered. The recommendations established in the standard can be found in Table 2.

2.7.4. Storage and Chlorination Tank

The reservoir was intended to fulfill two functions: chlorination and storage. The guidelines established in the Ecuadorian standard [49] were considered, stating that the storage volume of the tank must reach 50% of the future average daily volume of water consumption, and in no circumstances should it undergo less than 10 m^3.

Table 2. Standard parameters for designing conventional water treatment units established by the Pan-American Center for Sanitary Engineering and Environmental Sciences [50].

Hydraulic Flocculator			**Clarifier Basin**			**Rapid Sand Filter**		
Parameter		**Unit**	**Parameter**		**Unit**	**Parameter**		**Unit**
Hydraulic retention time	10–30	min	Surface loading	5–60	$m^3/m^2/d$	Filtration rate	120–360	$m^3/m^2/d$
Water level	1.5–2.0	m	Width/length	1–4, 1–5	-	Sand particle size	0.5–1.2	mm
Flow velocity	0.10–0.8	m s^{-1}	Horizontal-flow velocity	<0.5	cm s^{-1}	Sand bed thickness	0.6–1.8	m
Velocity gradient	200–300	s^{-1}	Number of settling units	2	-	Gravel bed thickness	30	cm

2.8. Chemical Reagent Dosing

2.8.1. Coagulation Test

Coagulation experiments were performed on a flocculation apparatus (7790 PB-950, Phipps & Birds), where rapid agitation was set to 100 rpm for 1 min, followed by a mild agitation of 35 rpm for 20 min. Flocs were allowed to settle for 20 min. The coagulant was prepared by dissolving 5 g of $Al_2(SO_4)_3{\cdot}5H_2O$ in 500 mL of deionized water, e.g., 0.023 M.

The test was conducted with different concentrations of the coagulant, e.g., 10, 20, 30 and 40 mg L^{-1}, to choose a dose of chemical coagulant that reduced calcium hardness concentration and increased turbidity removal efficiency.

2.8.2. Chlorine Demand Curve

The breakpoint curve was constructed with the effluent from the softening process. This water was treated at the lab-bench scale to reduce biodegradable organic content. Thereby, coagulation-flocculation and filtration processes were conducted before chlorination. Water samples were dosed with NaClO as a chlorine source with concentrations from 2.0 to 17.0 mg L^{-1} Cl_2. The contact time was 30 min. Chlorine measurements were performed using a free chlorine portable photometer (HI 96701, HANNA Instruments) by the DPD colorimetric method, with an experimental error of 3%. The instrument had a measurement range from 0.0 to 5.0 mg L^{-1} Cl_2. When the chlorine concentration of the samples went beyond the measurement limit of the equipment, the chlorinated water was diluted 10, 20, and 50 times with deionized water.

3. Results

3.1. Characterization of the Feedwater Quality in the Treatment Plant

A high degree of mineralization was found in the feed flow groundwater of the conventional water treatment plant El Descanso. This may be attributed to the Loyola Fm's marine environment, composed of sandstones and siltstones and stratigraphically located below the Azogues Fm [52]. The groundwater at the catchment source presented an electrical conductivity of 1645 μS cm^{-1}, indicative of appropriate ions content. A total hardness content of 446 mg L^{-1} of $CaCO_3$ was measured, from which 376 mg L^{-1} corresponded to Ca^{2+} as $CaCO_3$, while the remaining amount accounted for Mg^{2+} salts. In addition, a high content of SO_4^{2-} of 490 mg L^{-1} was found in the groundwater catchment, but the maximum acceptable concentration for drinking water is 200 mg L^{-1} [48]. This SO_4^{2-} concentration may occur naturally due to the mineralization of pyrite, chalcopyrite, and sphalerite. In addition, a concentration of BOD_5 of 61 mg L^{-1} O_2 was measured, pointing at biodegradable organic contamination, which could result from anthropogenic activities. This type of contamination seems not to be uncommon, as recent studies have reported organic contamination affecting some Ecuadorian groundwater aquifers such as the Daule aquifer [53], groundwater sources in Loja [54], and the Guayas hydrological basin [55].

Furthermore, a high concentration of Ca^{2+} could tamper with the water distribution pipelines. The presence of SO_4^{2-} could produce digestive disorders in the end-user population [56,57] and also induce corrosion in the water treatment plant facilities. The existence of organic material and sulfate content could be problematic to remove if the treatment facility does not have an installed technical capacity to treat these contaminants.

The groundwater feed had a pH ranging from 6.4 to 8.1, with a low turbidity concentration of 1.3 NTU. The dissolved oxygen level was 2.6 mg L^{-1} O_2 due to limited interaction with the atmosphere. The concentration of Fe^{2+} was 3.6 mg L^{-1}, exceeding the maximum acceptable limit of 0.3 mg L^{-1} Fe^{2+} intended for household use [58]. Notably, a concentration of Mn was measured to be 0.97 mg L^{-1} in the groundwater catchment source, exceeding the admissible concentration of 0.05 mg L^{-1} [59]. High concentrations of Fe^{2+} and Mn might contribute to a metallic or bitter taste in water, staining, scale, and corrosion [60–62]. These findings corresponded well with the unpleasant water organoleptic properties reported by inhabitants of the San Cristóbal community.

3.2. Assessment of the Conventional Drinking Water Treatment Units

3.2.1. Slat Tray Aerators

The objective of the slat tray aerators is oxidizing Fe^{2+} via gas transfer phenomena. The oxidation efficiency of Fe^{2+} in the aeration trays was calculated to be 32.6%. The turbidity was measured as 1.3 NTU at the tray entrance and this increased to 10.6 NTU at the exit of the tray. This may be the result of the lack of maintenance since the trays were rusted where Fe was dissolved into water as colloidal iron [63–65]. Corrosion can be defined as the oxidation of metallic iron, which releases iron in solution and produces iron [66]. Sarin et al. [67] reported that corrosion degrades water quality by causing it to appear rusty-colored, increasing chlorine demand, decreasing dissolved oxygen content, and promoting the presence of biofilm on the pipe surface. The tray treatment method can be inexpensive; however, it may cause turbidity formation [68]. For these reasons, in order to protect water quality, the replacement of the current slat tray aerators is recommended [69].

3.2.2. Alum Coagulation and Floc Sedimentation

It was found that although the turbidity concentration at the exit of the slat tray aerators was 10.6 NTU, the water treatment plant operated a coagulation-flocculation system. There, a concentration of 92.8 mg L^{-1} of $Al_2(SO_4)_3$ as the alum-coagulant source was added. This dose was added by gravity from the coagulant reservoir to the quick-mix spillway for homogenization to occur. Increasing the dose of a coagulant beyond the solubility of the formed metal hydroxides, e.g., $Al(OH)_3$, is known to improve the removal efficiency of the colloidal suspension by increasing the floc density and sedimentation rate [70–72]. However, thick lumps of unknown material were observed floating in the sedimentation basin. In addition, it was reported that a high coagulant concentration might produce foams similar to the agglutinating coagulum formations observed in the coagulation-flocculation basin [73], which may occur in this process due to the unnecessary high concentration of added coagulant, e.g., 92.8 mg L^{-1}.

This coagulation-flocculation basin may be utilized for reducing calcium hardness concentration. In this line, the addition of $Ca(OH)_2$ was investigated to treat the hard water. It was found that 200 mg L^{-1} $Ca(OH)_2$ decreased the calcium hardness concentration from 352 to 114 mg L^{-1} $CaCO_3$; while as a side effect, the turbidity concentration increased from 13.4 to 37.8 NTU. For this reason, the Jar Test experiment was conducted simultaneously by adding $Ca(OH)_2$ for the purpose of hardness removal and alum coagulant to decrease turbidity. Doses of $Al_2(SO_4)_3$, ranging from 10 to 40 mg L^{-1}, removed turbidity from 64 to 79%. The chosen $Al_2(SO_4)_3$ dose was 10 mg L^{-1}, reaching a colloidal suspension removal efficiency of 63.5%. This coagulant concentration was around ten times lower than the actual quantity of added chemicals in the plant and the residual Al content was measured at 0.12 mg L^{-1} in the output flow. Although the Ecuadorian technical guidelines do not monitor this parameter in drinking water, the WHO has established a recommended concentration of 0.2 mg L^{-1}. Table 3 summarizes the results of the Jar Test experiment, dosing alum, where no evidence of pH alteration was observed, though the electrical conductivity increased from 1664 to 1772 μS cm^{-1}, which may have occurred due to the dissociation of the aluminum sulfate to sulfate anions. It is essential to report that the occurrence of SO_4^{2-} in water could deteriorate the coating of the reinforcing steel in the treatment units, damaging the concrete and metal elements [73–75]. By simultaneously performing coagulation and softening processes, with a fixed $Al_2(SO_4)_3$ concentration of 10 mg L^{-1}, and different concentration of $Ca(OH)_2$, an Increase in $Ca(OH)_2$ consumption was observed, e.g., 700 mg L^{-1} to remove 71.3 % of calcium hardness. A similar study [76] reported the simultaneous effect of adding $Al_2(SO_4)_3$, $Ca(OH)_2$, and NaOH to remove total hardness. It was concluded that higher removal efficiencies of total hardness were achieved with a high concentration of $Ca(OH)_2$ when $Al_2(SO_4)_3$ and NaOH were used as coagulants. To exemplify, 30, 90, and 120 mg L^{-1} of $Ca(OH)_2$ resulted in 18.3, 38.1, and 50.0% of removal efficiencies, respectively.

Table 3. Results of the Jar Test experiment for determining the optimal dose of alum-coagulant.

Dose [mg L^{-1}]	T [°C]	pH_o	pH_f	EC_o	EC_f	TU_o	TU_f	Efficiency
				[μS cm^{-1}]		[NTU]		[%]
10	27.3	7.8	7.9	1664	1772	15.4	5.62	63.5
20	27.2	8.0	8.0	1657	1768	15.0	3.19	78.7
30	27.5	8.1	8.1	1656	1774	14.5	3.28	77.4
40	27.2	8.2	8.1	1654	1769	14.9	3.31	77.8

The contaminants removed as sludge through the adsorption capacity of the coagulant [77] were settled in the sedimentation pond and disposed of weekly. However, there was evidence of a decrease in the dissolved oxygen concentration from 6.33 mg L^{-1} O_2, measured at the entrance of the flocculation basin, to 3.04 mg L^{-1} O_2 at the outflow of the sedimentation pond. This decrease in O_2 content may be associated with the degradation and fermentation of the sludge occurring in the sedimentation pond [78–80]. Removing the sludge from the sedimentation pond is recommended as soon as a large volume of coagulation byproducts has accumulated. This removal, however, was not performed immediately at the treatment plant but days later. Therefore, monitoring dissolved oxygen concentration may be a suitable criterion for removing coagulation byproducts [81].

3.2.3. Filtration Units

The granular medium filtration process was carried out in a serial setup starting with sand bed filtration, followed by an activated carbon media filter to further remove suspended solids and organic contaminants. Then, the flow was conveyed to the water softener, where ion exchange occurred. This process aimed to decrease the Ca^{2+} and Mg^{2+} concentrations [82,83].

The rapid filtration unit removed turbidity at a low level. The turbidity of each filtration pond remained reasonably constant, i.e., the sand filter and the activated carbon exhibited a turbidity level of 0.2 NTU, and the colloidal suspension in the effluent from the softening unit was 0.4 NTU. Similar results were highlighted at another water treatment facility, where the rapid filtration process showed a turbidity content removal from 112.3 NTU to 0.71 NTU [84]. The removal efficiency of calcium hardness from granular filtration was 40.68%, with the hardness concentration reduced to 210 mg L^{-1} $CaCO_3$. However, it was found that after water flowed into the cationic exchange softener, the calcium hardness concentration increased to 358 mg L^{-1} $CaCO_3$. This occurred because the softeners did not receive maintenance for over a year. Alternately, this occurrence may be attributed to a lack of Na^+ ions in the softener. The cation exchange softening unit requires an approximate ratio of 3:1 mg of NaCl to remove hardness [85]. Nevertheless, the content of NaCl added to the water softening system was 1.93 mg NaCl, failing to meet this requirement. Furthermore, Fe^{2+} (3.6 mg L^{-1}) and Mn (0.93 mg L^{-1}) concentrations contributed to ineffective hardness removal due to clogging of the resin medium due to the lack of maintenance of the exchange softener [86,87]. When this occurs, acid or sodium bisulfate is recommended to clean the medium and alleviate iron and manganese fouling [88]. At this point of the treatment train, the BOD_5 concentration was measured at 48 mg L^{-1} O_2, 21.3% less than the concentration of the groundwater catchment source.

The maintenance of the water softener was carried out in the water treatment plant around one year later after the initial diagnostic. As a result, the total hardness concentration decreased from 641 mg L^{-1} measured at the plant feed water to 75.6 mg L^{-1} measured at the outflow from the softener. A summary of the main physical-chemical parameters measured after the fully operative softener is shown in Table 4.

Table 4. Comparison of the results of the water quality parameters after the cation exchange softening process.

Analytical Parameter	Units	Raw Water	Outflow from Softener
Electrical conductivity	[μS cm^{-1}]	1611	1946
Total Dissolved Solids	[mg L^{-1}]	1047	1265
pH	-	7.21	7.85
Turbidity	[NTU]	19.2	0.21
Calcium hardness		426	55.7
Magnesium hardness	[mg L^{-1} $CaCO_3$]	215	19.9
Total hardness		641	75.6

3.2.4. Disinfection Stage

During field inspection, it was observed that the dose of disinfectant reagent (sodium hypochlorite) was performed empirically in the storage tank of 125,000 L. No total coliforms were detected, but the existence of other pathogens should not be discarded. The concentration of residual free chlorine was found to be variable from one day to another. For example, free chlorine was measured as 0.6 mg L^{-1} on the first day of monitoring, while the next day, it was 5 mg L^{-1}. Since the addition of NaClO was manually conducted, a proper homogenization of the disinfectant reagent might not occur due to the lack of an agitation mechanism. The absence of agitation in the chlorination tank may result in over-chlorinated areas and others with insufficient chlorine concentration, producing a poor inactivation of pathogens [89]. In addition, the lack of technical knowledge may prevent personnel from dosing the appropriate concentration of NaClO. The free chlorine concentration measured at the community water taps ranged from 0.00 to 0.19 mg L^{-1}, as Table 5 shows, not meeting the Ecuadorian technical guidelines, which established the minimum and maximum free chlorine concentrations as 0.30 and 1.50 mg L^{-1} Cl_2, respectively, to ensure a residual disinfection effect during the water distribution process. Similar results have been found in rural water treatment plants [10]. Surveys conducted in 181 South

African water potabilization facilities reported that 40% of the plants struggled to meet the recommended target range of free chlorine concentration due to technical problems and a lack of water quality monitoring [11].

Table 5. Concentration of the residual free chlorine measured in the tap water of households in the community of Paute.

Sampling Point	Free Residual Chlorine Content [mg L^{-1} Cl_2]	Distance from the Treatment Plant [m]
SP1	0.05	1554
SP2	0.19	1631
SP3	0.10	1872
SP4	0.00	1923
SP5	0.00	2692
SP6	0.01	1452
SP7	0.01	1048
SP8	0.02	1154

The BOD_5 content was measured at the entrance (61 mg L^{-1}) and the exit of the plant (48 mg L^{-1}). Since organic matter reacting with NaClO may induce the formation of disinfection byproducts (DBPs) [90], one water sample was collected from the storage tank to analyze if the formation of some DBPs (bromoform, bromodichloromethane, dibromochloromethane, and chloroform) occurred after the disinfection process was conducted in the treatment plant. It was found that although BOD_5 > 48 mg L^{-1}, the concentration of bromoform, bromodichloromethane, and dibromochloromethane were < 0.002 mg L^{-1}, and the concentration of chloroform was < 0.01 mg L^{-1}. The Ecuadorian technical guidelines (INEN 1108) has established a bromodichloromethane concentration not higher than 0.06 mg L^{-1} and a chloroform content not higher than 0.3 mg L^{-1} for drinking water. This is a positive result, as the concentration of bromodichloromethane and chloroform did not exceed the levels determined by the Ecuadorian technical guidelines. Nonetheless, monitoring the DBPs precursors, such as organic matter and turbidity, is encouraged before performing chlorination, as seasonal variation in the concentration of trihalomethanes (THMs) has been identified in studies [91,92]. For example, the pre-chlorination and filtration units were reported to perform negatively, regarding the removal of seasonally influenced organic content, at a water treatment plant in northern China. Over a one-year-long period, the formation of DBPs were evidenced [93]. Pre-chlorination was not recommended in some studies, since it promotes the occurrence of THMs [94,95].

The demand curve at the breakpoint was constructed to establish the optimal dose of disinfectant, as Figure 3 shows. Different concentrations of NaClO were added to filtered-coagulated water. From the linear equation of the free chlorine demand curve (see inset in Figure 3), a dose of 8.6 mg L^{-1} was computed to be optimal at a pH of 8.02. The ideal pH should be acidic or neutral since better conditions for the hypochlorous acid formation occurred [96–98]. Therefore, pH monitoring is important during the disinfection process, but it is not conducted due to the lack of equipment handling training at the treatment plant. Local operators of the drinking water treatment plant added ~3.0 mg L^{-1} of NaClO in the storage tank, empirically. Because this concentration was below the optimal dose, the absence of DBPs after the chlorination process may be understood.

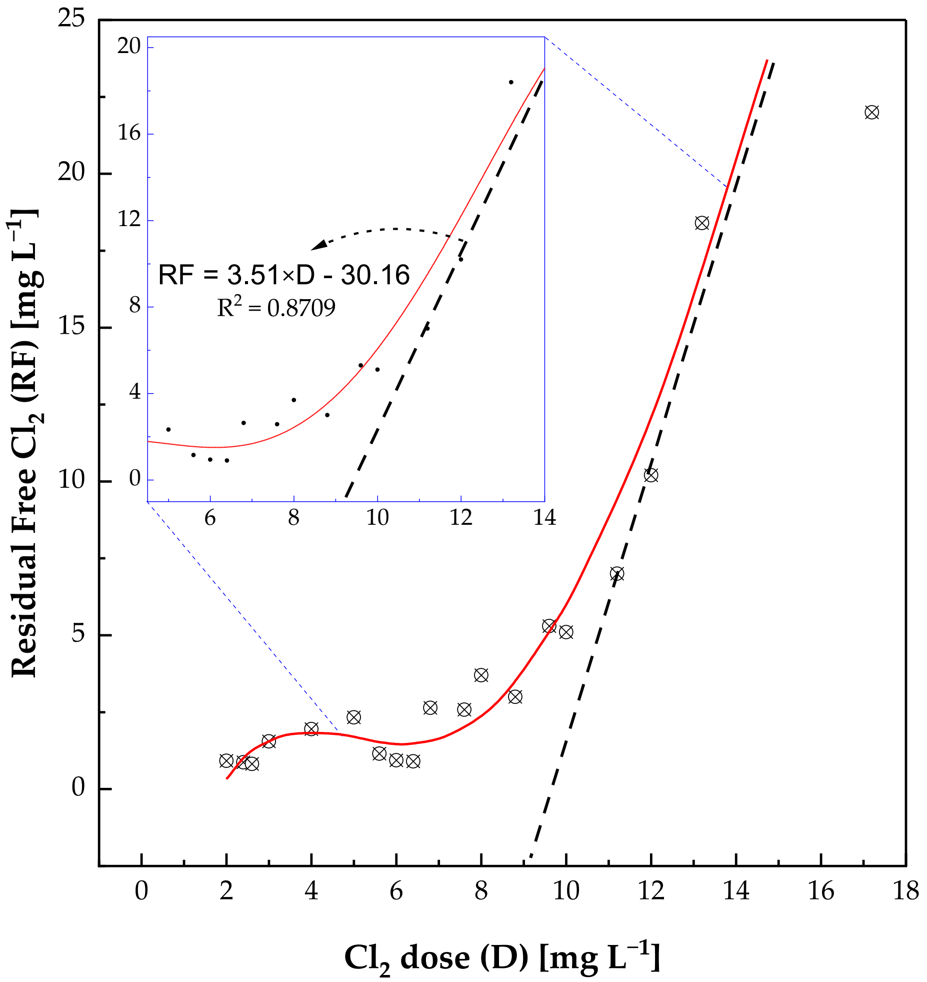


Figure 3. Constructed chlorine demand curve to determine the optimal dose of disinfectant reagent at the breakpoint. The dash line represents the best linear fit to determine this optimal dose.

In summary, Figure 4 shows real pictures of each of the drinking water treatment units, where some issues were easily identified by visual inspection. To exemplify, the pumping station was surrounded by solid waste (Figure 4a), corrosion of slat tray aerators is visible (Figure 4b), and the hydraulic flocculator pond presents thick lumps on the water surface due to overdosing of the coagulant (Figure 4d), as discussed earlier. The remaining units of the drinking water treatment train are presented, although treatment problems were not readily detected.

Figure 4. Individual units of the conventional drinking water treatment facility El Descanso. (**a**) Pumping station; (**b**) Slat tray aerators; (**c**) Quick mix spillway; (**d**) Flocculation pond; (**e**) Sedimentation pond; (**f**) Filtration basin; (**g**) Activated carbon and cationic resin filters; and (**h**) Storage tank.

The water quality indicators estimated in the treatment outflow, such as total water hardness, BOD_5, and free residual chlorine concentrations, did not comply with the local and international water quality standards for water consumption, as shown in Table 6. Although the water hardness meets the recommended threshold established by the WHO, it does not qualify according to the Ecuadorian technical guidelines. Water hardness does not represent a health problem for the population; however, it can degrade the condition of the distribution systems and fittings. The low concentration of free residual chlorine poses a potential threat to the microbiological safety of the water in the distribution network [99].

Table 6. Comparison of the water quality parameters of the treatment outflow against the Ecuadorian technical guidelines and World Health Organization standards.

Water Quality Indicator	Value	INEN 1108	WHO
pH	8.0	6.5–8.5	-
Electrical conductivity ($\mu S\ cm^{-1}$)	1946	-	800
Total dissolved solids ($mg\ L^{-1}$)	1265	1000	1000
Dissolved oxygen ($mg\ L^{-1}\ O_2$)	5.7	6.0	-
Temperature (°C)	25	20–30	-
Turbidity (NTU)	0.2	5.0	5.0
Biochemical Oxygen Demand ($mg\ L^{-1}\ BOD_5$)	48	-	-
Ferrous iron ($mg\ L^{-1}\ Fe^{2+}$)	3.6	0.5	0.3
Total hardness * ($mg\ L^{-1}\ CaCO_3$)	484	300	500
Manganese ($mg\ L^{-1}$ Mn)	0.97	0.40	0.50
Aluminum ($mg\ L^{-1}$)	0.12	-	0.20
Total coliforms	Absence	Absence	Absence
Free chlorine ($mg\ L^{-1}\ Cl_2$)	0.05	0.30–1.50	0.30–1.50

* Measurement performed when the water softener was not operating.

4. Discussion

4.1. Estimation of the Design Flow

The community of San Cristóbal reported a population of 2764 people in 2021, and the statistical projection of the future population showed a growth rate of 1.01% [51]. Using Equation (1), the number of residents of the community was estimated to increase to 3406 inhabitants by 2041, which means 20 years of design time. Data collected from the socioeconomic report revealed that 'residential use' was the only water consumption category recorded in 2021. The monthly water intake records were extracted from this report and are summarized in Table 7. The maximum allocation rate of water was reached in August; therefore, a water allocation rate of 130 L/capita/d was chosen as it satisfies the required water allocation range in Ecuador for rural communities in mild weather; 130–160 L/capita/d [49].

Table 7. Monthly residential water consumption of the San Cristóbal community to determine the water allocation of the population.

Months	Water Meter Records	Monthly Water Consumption [m^3]	Water Allocation [L/capita/d]
January	210	3374	107
February	225	4052	120
March	248	4081	110
April	252	4204	111
May	242	4190	115
June	243	3784	104

July	226	2854	84
August	269	5233	130
September	247	3458	93
October	248	3347	90
November	262	4078	104
December	230	3591	104

The end-use water consumption in residential categories involves personal hygiene, housekeeping, toilet use, irrigation, and leaks [100]. In other parts of the world, the water allocation is estimated as 168.1 L/capita/d [101], similar to the one calculated for the San Cristóbal community. It was identified that the highest percentage of water use was associated with personal hygiene at 27%, laundry at 24%, and irrigation in fifth place with only 8% [101]. These percentages are different in Australia and the United States of America, where irrigation ranks first between 25 and 54% of the water consumption [102–104]. Watering the garden with potable water is common in these countries; therefore, the demand for water allocation is higher, ranging from 225–335 L/capita/d.

Using the data of future population and water consumption, the average daily water demand was computed from Equation (2) to be 6.15 L s^{-1}, corresponding to the average flow required to supply a population of 3406 inhabitants. However, the water consumption patterns were not uniform throughout the day [105]. Therefore, the peak demand coefficient was estimated to regulate the daily variation of water consumption by considering the ratio between the highest consumption in a year of operation versus the monthly average daily consumption. As a result, a peak demand coefficient of 36% was obtained, as Figure 5 shows. Using Equation (3), the design flow rate was calculated to be 9.2 L s^{-1}, which is a parameter applied in evaluating the hydraulic capacity and resizing of the treatment units.

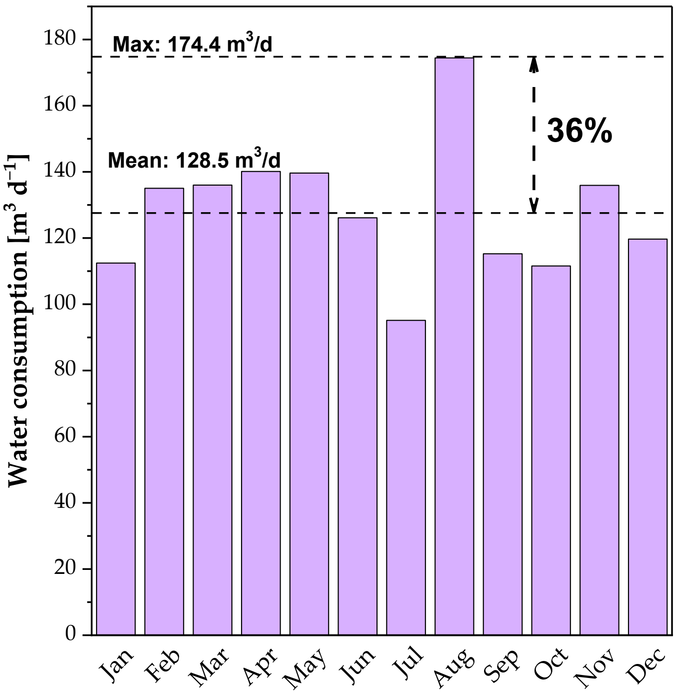


Figure 5. Estimation of the peak water demand coefficient. The graph plots the daily average water consumption data in a year of operation.

4.2. Hydraulic Capacity and Resizing

The current capacity of each treatment unit was evaluated to ascertain if the future population demand could be reached until 2041. Considering that the hydraulic parameters, dimensions of the basins, and distribution of the accessories did not comply with the design standards requested in [49,50], the treatment unit basins were resized.

The flocculation system consists of two tanks in series. Each flocculation tank is 3.0 m in width and 4.6 m in length, corresponding to a total volume of 28,000 L. Screens 2.5 m long were arranged every 0.2 m, creating channels within the tank, allowing the development of a horizontal flow along a 112 m length. According to the standard [50], the recommended design criteria for the hydraulic detention time ranged from 10 to 30 min for a hydraulic flocculation basin and a velocity gradient between 200 and 300 s^{-1}. However, the average velocity gradient for this system was found to be 12 s^{-1}, with a detention time of 12 min, resulting in a low flow velocity of 0.08 m s^{-1}. Flow velocities below 0.10 m s^{-1} do not allow the binding of colloidal particles, while velocities above 0.80 m s^{-1} might break the flocs, preventing the removal of colloidal matter. Nonetheless, the reduction of the floc size might be caused by the rate of turbulence dissipation attained at velocities greater than 1.5 m s^{-1} [106].

A horizontal flow hydraulic flocculation setup was assessed, comprising of two pools in series, with a total volume of 38,000 L, as shown in Figure 6a,b. Each pond is 3.04 m in width and 9.02 m in length. These optimized dimensions, combined with an increase in screen spacing from 0.20 m to 0.25 m in the second pond, resulted in a flow length of 120 m with a hydraulic detention time of 10 min. Consequently, the velocity gradient of this process is 226 rpm, associated with a flow velocity of 0.20 m s^{-1}, fulfilling the technical design specifications.

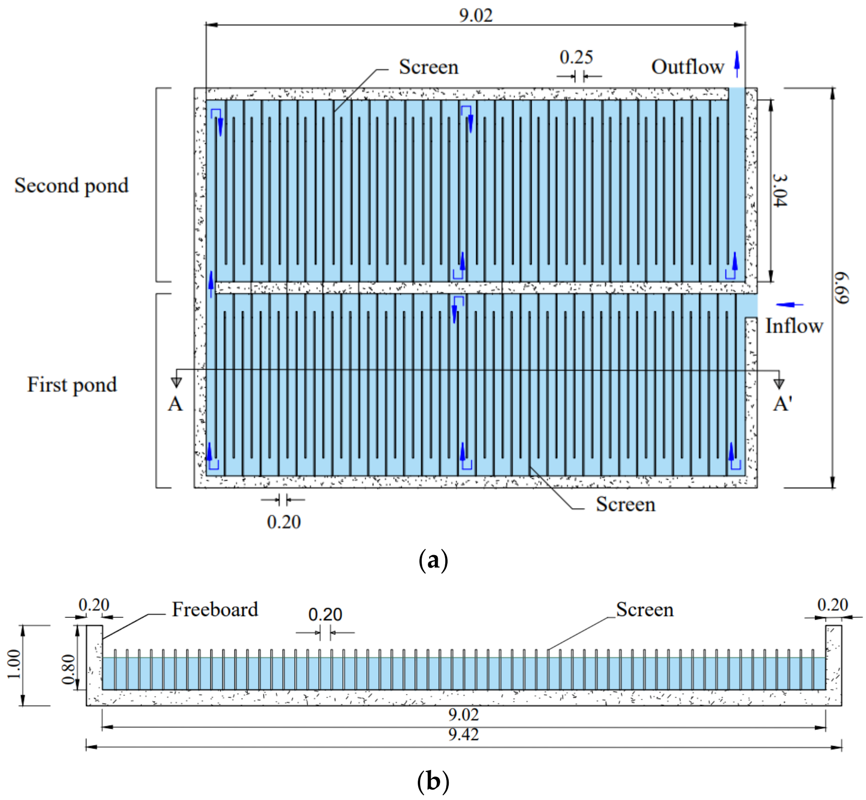
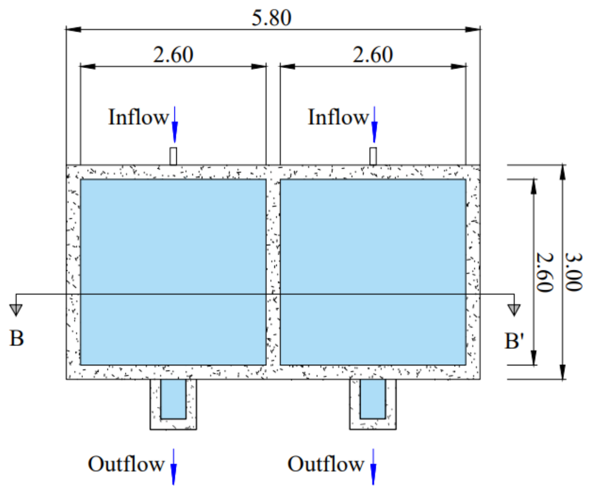


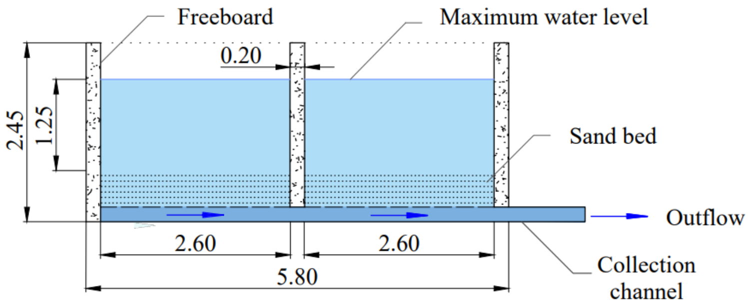
Figure 6. Resized horizontal hydraulic flocculation ponds set in series. (**a**) Top view of the flocculation ponds, and (**b**) Section A-A′ of the flocculation pond.

The high-rate settling system, operating under laminar flow conditions (Re < 500), consisted of two pools installed in parallel, treating a daily flow rate of 795,000 L d^{-1}. The current settler dimensions provide a capacity of 22,500 L for a detention time of approximately 8.2 min. The settling ponds were 1.5 m in width, 3.0 m in length, and 2.5 m in height, with a freeboard of 0.2 m. In addition, the system had plate-accelerated sedimentation modules with an inclination of 45°, allowing a sedimentation rate of suspended particles of 0.10 m s^{-1}. Under the conditions mentioned above, the surface load of the high-rate settler was 9.25 m^3/m^2/day, complying with the design criteria [50]. Thus, it was not necessary to resize this unit. Still, it is recommended to change the current sedimentation modules from plates of asbestos cement to 'acrylonitrile butadiene styrene accelerated plates' of Glass Fiber Reinforced Polyethylene (GRP). The GRP plates inclined at 45°, with technical characteristics of 0.5 m height and 1.5 m long, a free spacing of 0.04 m and a thickness of 10 mm would reduce the suspension velocity, improving the sedimentation effectiveness while avoiding the use of carcinogenic material [107,108].

The treatment plant has two rapid granular media filters operating in parallel. The filters were designed for a downward flow that benefits from the action of gravity as a hydraulic gradient to transport the water across the filter media. The porous media is stratified, placing the sand in the upper layer with a thickness of 0.6 m and a uniformity coefficient of 2.90, while the gravel acts as a support bed, with a thickness of 0.3 m. The inflow velocity is 0.10 m s^{-1} while the water permeates the bed with an infiltration rate of 14.6 m^3/m^2/day. This infiltration rate does not suit the recommended range from 120 to 360 m^3/m^2/day [50]. Furthermore, the dimensions of the pool are large (7.6 m long and 7.2 m wide) compared to the treatment flow rate, making it impossible to reach the necessary hydraulic gradient to overcome the 1.7 m friction loss head. For enhancing the hydraulic capacity of the filtration unit, the dimensions of the basins are suggested to be 2.60 m wide and 2.60 m long, as Figure 7a,b shows. Thus, the flow would present a filtration rate of 150 m^3/m^2/day, maintaining the initial thicknesses of the filter media, e.g., 0.60 m. Unfortunately, the media filter has not been changed since the plant started its operation. Therefore, changing the filter bed is highly recommended, selecting the filtration media that minimizes friction losses [109]. For this type of rapid filters, it is also recommended to monitor a simple parameter, such as turbidity, as an indicator to change the filter media, and backwashing should be carried out between 24 and 72 h of operation.



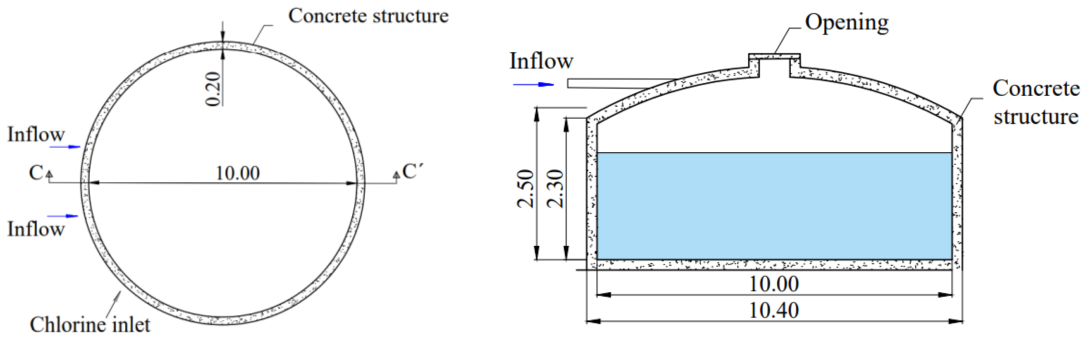
(**a**)



(**b**)

Figure 7. Resized sand filter. (**a**) Top view of the filtering basin set in parallel, and (**b**) Section B-B′ of the filtering basins.

The volume of the storage tank is 250,000 L, corresponding to a treatment flow of 5.35 L s^{-1}. However, this volume will not satisfy the future demand of the community. Hence, it is estimated that the storage tank should increase the volume by double, e.g., ~400,000 L, corresponding to two tanks, each with an inner diameter of 10.0 m and a height of 2.5 m, as Figure 8a,b shows.



(**a**) (**b**)

Figure 8. Resized storage tank to supply the increased population demand. (**a**) Top view of the storage tank, and (**b**) Cross-sectional view of the storage tank, section C-C′.

5. Conclusions

The inadequate operation and maintenance of water treatment units have posed significant challenges in rural settlements in Latin America, limiting the efficiency of the treatment train to supply contaminant-free water, and reducing the useful lifetime of the treatment system. These issues also trigger inequality of opportunities, affecting the socioeconomic development and well-being of vulnerable social groups. The findings of this study demonstrate deficiencies in the operations of a conventional treatment facility in Ecuador that led to the insufficient removal of Fe^{2+}, SO_4^{2-}, Ca^{2+}, and organic content of a biodegradable nature. The main water quality problems were mostly attributed to poor maintenance of the pools and treatment equipment, inadequate empirical dosing of treatment chemicals, leading to overdosage of coagulant (92.8 mg L^{-1} $Al_2(SO_4)_3$), and deficiencies in the dose of disinfectant.

This research recommends improvements in the dosages of treatment reagents, to further optimize chemical use while ensuring the removal of pollutants and the presence of residual disinfection effects, to improve the quality of the drinking water for end users. Moreover, the assessment and resizing of the treatment units were proposed for a projected flow until 2041. The redesign presented will serve a population of 3406 people. Nonetheless, this resizing proposal is not only applicable to communities with a low population index; this model can be scalable to a larger population following the methodology presented in this study by selecting the water allocation in accordance with the demands of the community.

The evaluation of contaminant removal efficiencies and the monitoring of contaminant concentrations should be a common practice before the construction of a drinking water treatment plant and during its operation, to ensure that its functioning, and the distribution of drinking water, complies with both international and national drinking water requirements. The methodology presented in this study cannot only be deployed to monitor the operation of drinking water facilities, but also wastewater treatment systems. This may allow the improvement of maintenance practices, and thereby, the performance of these facilities.

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