02-007 – Experimental evaluation of pipe roughness for groundwater flow in the Southern Ecuadorian Andes – Evaluación experimental de la rugosidad de tuberías para flujos de agua subterránea al sur de los Andes Ecuatorianos

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English Spanish

Due to the limited and poor quality of surface water, the use of groundwater sources is an alternative; these sources usually contain high concentrations of minerals, which can affect the properties of the pipes by increasing the internal roughness, generating greater load losses and decreasing the hydraulic efficiency, which will increase the operating costs of the drinking water system. The changes in the roughness of pipes of the drinking water system of Guachún in the province of Azuay, Ecuador, where groundwater has high concentrations of minerals, were evaluated. Pipe conduction sections were analyzed by means of experimental tests and pressurized flow banks, considering different operation scenarios. It was observed how changes in the roughness of pipes with different periods of use affected by calcium and magnesium carbonate incrustations influence the hydraulic efficiency of the system, the useful life of the networks and the energy costs of the pumping equipment. Among the main results obtained, a decrease in pipe section of up to 20% with changes in absolute roughness of up to 3 millimeters was observed for pipes with 12 years of use.

Keywords: *Hardness; Absolute roughness; Pressure fluxes*

Ante la escasez y mala calidad de las aguas superficiales, el aprovechamiento de fuentes subterráneas es una alterativa; fuentes que suelen contener altas concentraciones de minerales, lo cual puede afectar a las propiedades de las tuberías al aumentar la rugosidad interna, generando mayores pérdidas de carga y disminuyendo la eficiencia hidráulica que aumentará los cotos de operación del sistema de agua potable. Se evaluaron los cambios en la rugosidad de tuberías del sistema de agua potable de Guachún en la provincia del Azuay, Ecuador; donde las aguas subterráneas presentan altas concentraciones de minerales. Se analizaron dos tramos de conducción de tuberías mediante pruebas experimentales y bancos de flujo presurizado, considerando diferentes escenarios de operación. Se observó como los cambios en la rugosidad de tuberías con diferentes periodos de uso afectadas por incrustaciones de carbonato de calcio y magnesio influye sobre la eficiencia hidráulica del sistema, la vida útil de las redes y los costos energéticos de los equipos de bombeo. Entre los resultados principales obtenidos, se observó una disminución en la sección de la tubería de hasta un 20% con cambios en la rugosidad absoluta de hasta 3 milímetros, para tuberías con 12 años de uso.

Palabras claves: *Dureza; Rugosidad absoluta; Flujos a presión*

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1. Introduction

In many regions of the world, the scarcity of surface water sources has encouraged the use of groundwater, which over time mineralizes the pipes that carry flows with high concentrations of calcium and magnesium (Zektser & Everett, 2004). The term water hardness is related to the amount of calcium and magnesium salts dissolved in the water. These minerals have their origin in calcareous rock formations, and can be found, to a greater or lesser degree, in most natural waters. A limit used to denominate a water as hard considers the solution of minerals higher than 120 mg$CaCO_3$/L (Romo-Toledano & Chilpa-Navarrete, 2017). The surface roughness of water hard-ness wails affects the flow and hence the losses of the head of water. Therefore, it is necessary to determine with adequate precision the geometrical parameters which characterize surface roughness (Lozanskii, 1965).

Shockling et al. (2006) investigated the honed surface roughness in fully developed turbulent pipe flow over the high Reynolds number range with experimental techniques, demonstrating hydraulically smooth, transitionally rough, and fully rough behaviour. Shockling et al. (2006) were found that transitionally rough regime to follow the inflectional behaviour first observed by Nikuradse (1950) in pipes coated with sand grains of a narrow distribution of sizes.

Seifollahi-Aghmiuni et al. (2013) presented an evaluation of the performance of drinking water networks over an operational period, taking into account the uncertainty of pipe roughness generated by probabilistic series of pipe roughness with Monte Carlo simulations, concluding that the analyzed networks have a desirable performance only in the first 10 years. Through energy calculations using the hydraulic model of a large water distribution system, Speight (2014) evaluated the impact of changes in the roughness coefficient associated with pipe rehabilitation, observing energy savings that were highly dependent on the pipes replaced or rehabilitated.

Ghabeche et al. (2015) studied the effects of distilled water and dilute hydrochloric acid at different concentrations on the external and internal surfaces of a high-density polyethylene pipe, in this study the pipe roughness showed a substantial increase as a function of increasing concentration of the medium with a consequent decrease in pipe life.

Romero-Sedo et al. (2020) presented the experimental protocol for obtaining the absolute roughness of the material through tests of two pipes of identical material (polypropylene) and geometric characteristics, obtaining the value of the absolute roughness and the Hazen-Williams friction coefficient, in both cases in a uniform and permanent turbulent regime. Furthermore Niazkar & Talebbeydokhti (2020) analyzed explicit and implicit correlations to estimate the roughness coefficient through the application of numerical models to different water distribution networks, highlighting the impact on accuracy and convergence when applying the equation of Colebrook & White (1937).

Taking into account the background presented, the study includes the case of the intake works and drinking water plant of the drinking water system located in the Guachún community (Figure 1), whose source of supply is an aquifer that is in constant con-tact with the geological strata, which causes the water to acquire certain chemical properties of the rocks and soil. This results in a high content of minerals present in the water captured, the most common being iron, calcium and magnesium, with others such as sodium, potassium and sulphate found in lower concentrations.

The objective of the work is to evaluate the changes in pipe roughness produced by the physical-chemical characteristics of the water in two sections of the system piping, located between the intake, the drinking water treatment plant and the potable water storage tank. Experimental laboratory techniques and a pressurized flow test bench will be used to analyze sections with different operation times, which will also allow evaluating the impact of the pumping system's useful life for the water flow with the observed hardness characteristics.

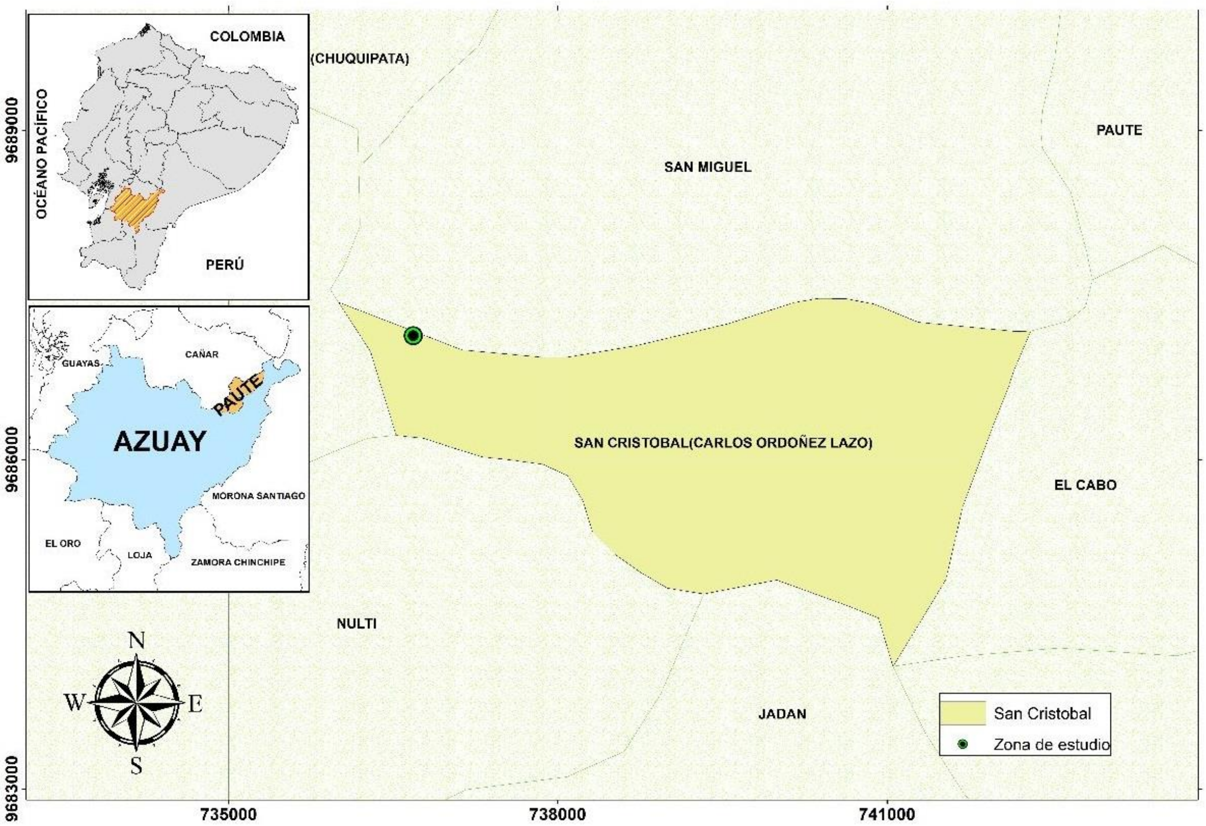
The importance of this analysis lies in the need to determine the quality and efficiency of the impulsion network in order to guarantee an adequate supply of drinking water from the intake to the treatment plant. The information obtained through a study of these characteristics will make it possible to establish guidelines for maintenance and improvements in the infrastructure and equipment, seek to optimize system performance, and determine an adequate design period to guarantee continuous water service without interruptions in this type of water supply (Sarfaraz et al., 2023).

2. Methods and Materials

2.1 Study Area Definition

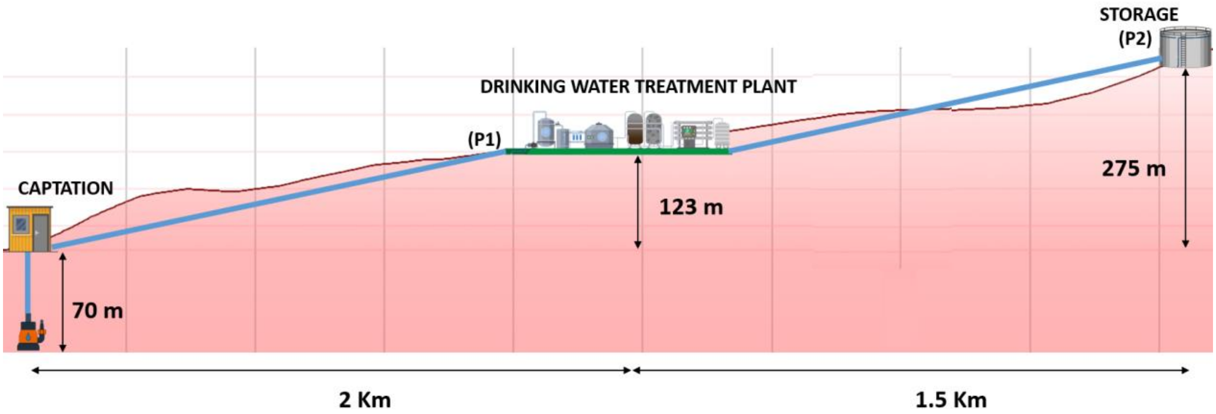
The study area is located in the San Cristobal sector of the Paute canton in the province of Azuay, Ecuador, in the area known as Guachún (Figure 1). The GAD Provincial del Azuay conducted research in the area known as El Descanso and found a subway aquifer on the banks of the Burgay River, at a depth of 70 meters. Five years after discovering the natural source, a potable water project was developed, for which a deep well was drilled and a pumping system was installed to extract the water and then transport it to the San Cristóbal potable water treatment plant through a 110-millimeter PVC pipe.

Figure 1: Study Area.



In the El Descanso sector, there is a pumping house where water is collected from the well, located at an altitude of 2320 m.a.s.l. The water is piped from this location to the treatment plant in the Guachún sector. From this location, the water is piped to the treatment plant in the Guachún sector. Due to the mountainous and rugged topography of the area, the treatment plant is located at an altitude of 2443 m.a.s.l. The water is treated in the Guachún sector. Here, the necessary treatment is carried out to ensure that the water is fit for human consumption. Once treated, the water is stored in a 90 m3 tank before being pumped to another storage tank of equal capacity, located in the La Chala sector, at an altitude of 2595 m.a.s.l. (Figure 2).

Figure 2: Water Development Scheme.



The storage tank shown in the diagram in Figure 2 is intended to provide water to the sectors in need that do not have this vital liquid. The previously treated water is pumped through a 110-millimeter PVC pipe up a 152-meter drop from the treatment plant to the storage tank, located at a distance of 1.5 kilometers.

However, the previously treated water generates problems in the conduction due to the high levels of hardness present. For this reason, the inhabitants of this area have experienced water shortages due to clogging in the impulsion pipes, as the obstructions in the network pipes are caused by the physical and chemical properties of the groundwater when it is extracted, since the raw water needs to be propelled to a height of approximately 123 meters until it reaches the treatment plant, where it will be treated. During transport through the impulsion network, the lack of prior water treatment causes the formation of deposits on the pipe walls, which implies an increase in head losses in the system, which generates a greater demand for pump operating time to maintain the volume of consumption necessary for the population and obstruction in the conduction pipes.

2.2 Pipe Roughness Coefficient

The drag coefficient, often referred to as the friction factor, is a dimensionless parameter used in fluid dynamics to calculate the energy losses caused by pipe friction. It is closely related to the Reynolds number and its value varies with pipe diameter and average flow velocity. This coefficient measures the resistance to movement (dynamic friction) or the resistance to movement itself (static friction) (Mott et al., 2006).

Conveying capacity losses in a pressurized piping system are due to the friction of the fluids with the internal walls of the pipelines. This energy loss is converted into heat and affects the efficiency of the system. The magnitude of these losses depends on factors such as the roughness of the pipe, the material used, the type of fluid and its characteristics. To calculate these losses accurately, the Darcy-Weisbach formulation (1) is used (Saldarriaga, 2019).

$$hf = f * \frac{L}{D} * \frac{V^2}{2g} \quad (1)$$

Where: hf is the head loss or energy, f is the coefficient of friction, D is the pipe diameter, L is the pipe length, V is the average flow velocity in the pipe and g is gravity.

There are two types of friction for turbulent flow in pipes; the first is associated with smooth pipe, where the effects of viscosity predominate and the friction factor depends only on the Reynolds number; the second type refers to rough pipes, where the effects of viscosity and roughness affect the flow, and the friction factor also depends on the Reynolds number and relative roughness. In order to consider all the friction behavior of turbulent flow with the walls of closed ducts, the following equation can be applied (Saldarriaga, 2019).

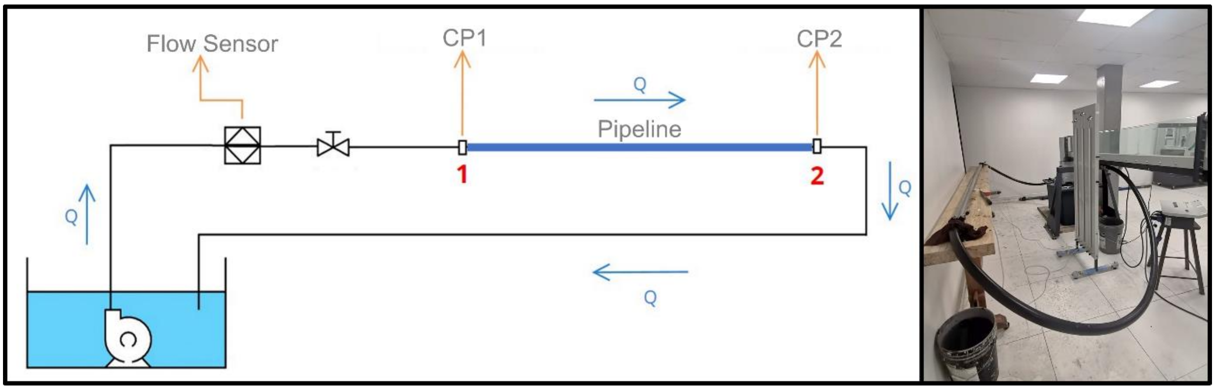
$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \quad (2)$$

Where: ε is the absolute roughness of the pipe y Re is the Reynolds number of the flow that relates the inertia forces to the viscous forces ($Re = \frac{V*D}{\nu}$) and ν is the fluid kinematic viscosity (Saldarriaga, 2019).

2.3 Experimental Methodology

For the experimental part of the research, the determination of roughness in different pipes was carried out, for which a hydraulic bench was built using the previously mentioned materials. This hydraulic bench operated by means of a hydraulic pump that propelled water from a reservoir to a butterfly valve, which was used to control the flow of water entering the pipe (Figure 3).

Figure 3: Diagram of the hydraulic bench.



Downstream of the regulating valve, a flow sensor was installed to measure the amount of water entering the pipeline (Figure 3). Polytube was used to connect the flow sensor to the pipe, and a half-inch borehole was drilled at the pipe entry point. In this borehole, a collar and a coupling were placed that allowed connecting by means of catheter hoses to the piezometer. The same procedure was repeated in the final section of the pipe.

At the outlet of the pipeline, polytube was again used to conduct the water to the reservoir, resulting in a hermetically sealed circuit in which the water flows continuously. This design of the hydraulic bench made it possible to simulate the real conditions of water flow in the pipeline and facilitated the necessary tests and measurements. For data collection on the hydraulic bench shown in Figure 3, the flow rate at which the fluid entered through the pipes was varied. Piezometer readings were recorded at the first control point (CP1), and the same procedure was followed for the second control point (CP2). In total, approximately 12 different flow rates were experimented for each pipe, the results of which will be presented below.

Within a process of calibration and configuration of the hydraulic bench prior to the measurements performed, the accuracy of the flow sensor of the hydraulic bench was verified by comparing the readings with respect to the manual measurements using a volumetric container and a stopwatch. Also, the tightness of the closed circuit was checked and air bubbles were eliminated by continuous circulation prior to the tests. Regarding the piezometers that were installed, the readings obtained were evaluated on the basis of a new PVC pipe with an absolute roughness in the order of $1.5x10^{-6}$ meters, verifying that under these conditions, the head losses observed have values similar to those calculated by applying equations (1) and (2).

3. Results

3.1 Water Quality Characterization

For the characterization of the water quality parameters, two control points were considered at the entrance to the San Cristóbal drinking water treatment plant (P1) and the reservoir where the treated water is located before entering the distribution system (P2) (Figure 2). On-site measurements were made with a HACH-HQ30D multiparameter probe and samples were taken for testing at the Water Quality Laboratory of the Center for Research, Innovation and Technology Transfer (CITT) of the Catholic University of Cuenca. The results obtained in the corresponding characterization are presented in Table 1.

Table 1: Water quality characterization.

PARAMETERS	UNITS	P1	P2	Allowable
TURBIDITY	UNT	22.9	1.1	5*
APPARENT COLOR	Pt Co	100	0	15*
CONDUCTIVITY	microsiemens/cm	8.17	7.53	-
TOTAL DISSOLVED SOLIDS	mg/l	851	830	250**
pH	U	7.26	7.65	6.5-8.5**
ALKALINITY	mg/l $CaCO_3$	524	512	-
TOTAL HARDNESS	mg/l $CaCO_3$	515	460	200***
Ca^{++}	mg/l	160	162	-
Mg^{++}	mg/l	355	298	-
DISSOLVED OXYGEN	mg/l	6.32	5.21	-
CHLORIDE	mg/l	525	700	250***
NITRITES	mg/l	1	0	0.2*
NITRATES	mg/l	1.8	4.4	50*

* NTE INEN 1108 (2011)

** CPE INEN 005-9-1 (1992)

***WHO (2022)

Table 1 shows that both dissolved solids and total hardness of the water before and after the treatment plant are above the norm. Sediment accumulation in the distribution systems can be caused by hardness levels present in the water when it is higher than 200 mg/L, depending on other factors such as pH and alkalinity. Sediments damage domestic and industrial distribution networks are mostly caused by a thermal process that breaks down the soluble calcium and magnesium bicarbonates present in the drinking water when it is heated to remove carbon dioxide, causing the precipitation of carbonates ($CaCO_3$), which are formed when the concentration of calcium and carbonate in the water exceeds its capacity to remain in solution. These carbonates, being insoluble, deposit and settle on the internal surfaces of the material that transports them. The main components of scale are mostly calcite and to a lesser extent dragonite, and they belong to calcium carbonates with identical chemical compositions. However, the incrustation capacity of calcite exceeds that of dragonite, since it is much more soluble, which allows it to adhere more easily to the pipe walls (Neira Gutiérrez, 2006). Figure 4 shows the variation of surface roughness inside the pipe analyzed over different years of operation.

Figure 4: Variation of roughness in the study pipes over time.

The range of roughness of the analyzed pipes varied from a completely smooth pipe, with no visible scale inside, to the last pipe exhibiting an abundant layer of clearly visible scale and an extremely rough surface, as can be seen in Figure 4. To determine the losses, present in the different pipe prototypes, the constructed experimental bench (Figure 3) was used with a progressive variation of the flow rate in order to record the pressure differences along the pipe, to obtain, based on the formulation presented in section 2.2, the range of absolute roughness presented in Table 2.

Table 2: Summary of experimental results.

Pipeline	Q (m^3/s)	D (m)	L (m)	V (m/s)	Re	hf (m)	$f_{average}$	$\varepsilon_{average}$ (m)
0 years	0.0003 - 0.000648	0.045	3	0.189 - 0.407	7381 - 15943	0.0041 - 0.0155	0.0293	0.00000423
2 years	0.00019 - 0.00064	0.045	3	0.119 - 0.402	4675 - 15746	0.0019 - 0.0155	0.0327	0.00003139
4 years	0.000205 - 0.00063	0.045	3	0.129 - 0.396	5044 - 15500	0.0023 - 0.0193	0.0375	0.00020284
6 years	0.00019 - 0.000625	0.045	3	0.119 - 0.393	4675 - 15377	0.0026- 0.0242	0.0479	0.00067150
8 years	0.00023 - 0.000605	0.045	3	0.145 - 0.38	5659 - 14885	0.0046- 0.0326	0.0649	0.00165470
12 years	0.00016 - 0.00063	0.045	3	0.101 - 0.396	3937 - 15500	0.0031 - 0.0452	0.0847	0.00301097

The absolute roughness (ε) was determined by combining Eq. 1 and Eq. 2, applying the Nonlinear Generalized Reduced Gradient (GRG nonlinear) solution method, which related the hydrodynamics of the flow with the head losses observed in the installed piezometers (see Figure 3). It may be noted that the values obtained for the roughness in pipeline of 0 years are in the order of $1.5x10^{-6}$ meters, a value characteristic of a PVC pipe (Saldarriaga, 2019). Figure 5 shows the relationship between the absolute roughness of the pipe with the friction factor obtained.

Figure 5: Estimated absolute roughness and coefficient of friction.

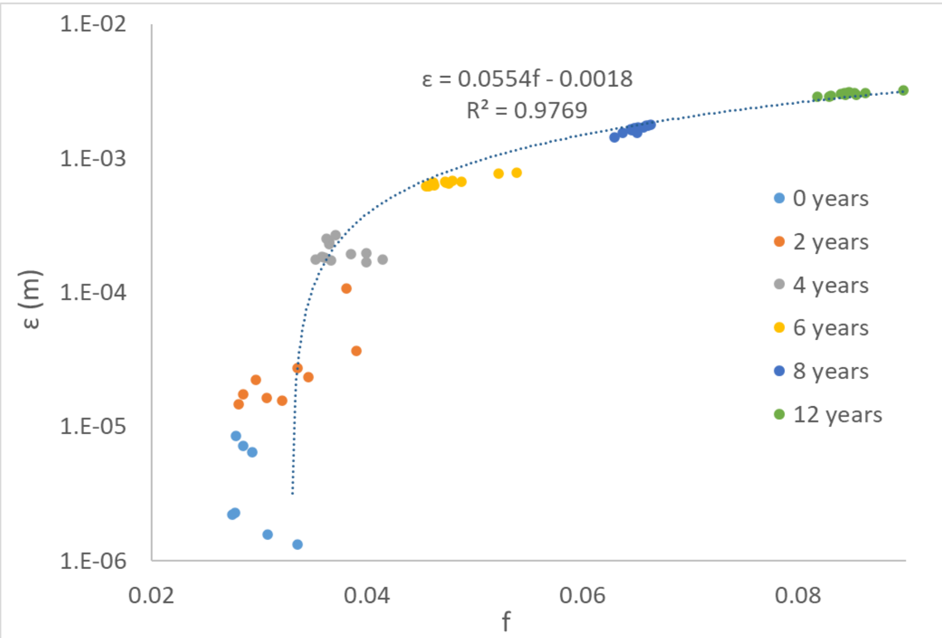


Figure 5 shows a linear relationship of the absolute roughness with respect to the friction factor with a correlation coefficient R^2 close to 1. Also, it can be observed how the absolute roughness in the pipes increases in relation to the years of conduction, up to two orders of magnitude higher than the initial roughness of the PVC estimated for the new pipe. Figure 6 shows a graph of the average friction factor in the tests carried out in each of the pipes.

Figure 6: Average friction factor along time.

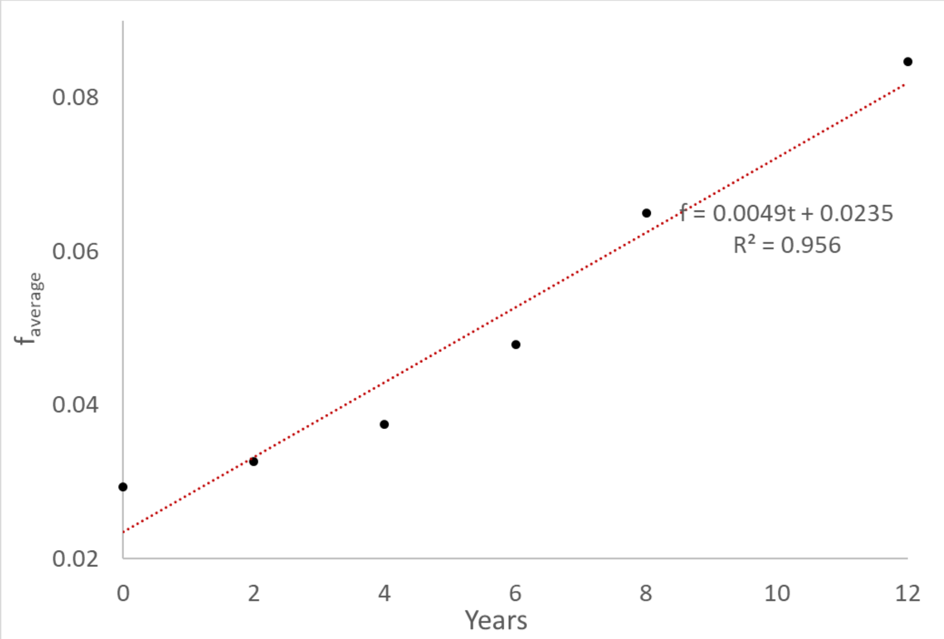


Figure 6 shows the constant increase in the friction factor as a function of the years of operation of the pipelines, this due to calcium carbonate incrustations from the flow with high hardness above 400 mg/l CaCO3 according to the quality tests carried out (Table 1). On this point is important that techniques to improve water quality and reduce the total hardness in the water catchment of the utilization are proposed and analyzed.

The application of the appropriate treatment to ensure the elimination of salts that may be detrimental to a given application depends mainly on the characteristics of the extracted water and its intended use. There are several options for softening water, ranging from total demineralization, which is achieved by applying some of the resins used in ion exchange, to partial demineralization, which consists of removing only part of the ions responsible for the hardness (Neira Gutiérrez, 2006).

The evaporation-condensation process is based on a heat treatment in which water is heated to boiling point. The resulting vapor is then collected in a condenser to produce hardness-free water. As the water in the solution evaporates and the liquid becomes more concentrated, a point is reached where the dissolving power of the salt overcomes it, resulting in precipitation. This precipitation often takes the form of scale that adheres to heat transfer surfaces as the water evaporates. These incrustations constitute in calcium, magnesium, and silica salts (Vera Saltos & Noles Aguilar, 2018). This procedure is recommended mainly for domestic use.

The cal-carbonate process allows the removal of a portion of the calcium and magnesium compounds, resulting in the reduction of the hardness present in the water to a predetermined value that is consistent with the prevention of corrosion, the control of scale formation and other factors that contribute to adequate water quality. Usually, it is necessary to add two types of reagents to this process: one is hydrated lime to remove temporary hardness caused by bicarbonates, calcium and magnesium carbonates, and the other is calcium carbonate to remove permanent hardness caused mainly by calcium sulfate (Neira Gutierrez, 2006). The main drawback of this process is the production of residues such as sludge that must be treated and disposed of properly.

The ion exchange process removes undesirable ions from a raw water by sending them to a solid substance called an ion exchanger, which accepts them in exchange for an equivalent number of desirable ions that are present in the ion exchanger matrix. The cation resin is one of the main ion exchangers that can be seen today and its main function is to make calcium and magnesium ions exchange places with sodium or potassium ions when water moves through the cation resin. In this way, the cation resin softens the water by lowering the concentration of calcium and magnesium ions that cause hardness in the water. The treated water is then available for use with lower concentrations of calcium and magnesium ions (Neira Gutiérrez, 2006).

The treatment of hard water by membrane separation consists of subjecting the water to a process in which it passes through a force-driven membrane, leaving behind a portion of the original concentrated impurities. The two most commonly used membrane techniques are reverse osmosis and nanofiltration. Membrane softening brings great benefits, since it is a continuous process that does not use chemicals and can achieve high efficiency in removing mainly calcium and magnesium. However, the quality of the incoming water must be considered since it should not have a large amount of sediment as it can become clogged, the maintenance of the membranes and the associated costs must be taken into account before implementing this type of treatment system (Vera Saltos & Noles Aguilar, 2018).

The effect of the magnetic field with a device that is placed inside the pipe through which the water flows. This device has permanent or electromagnetic magnets that create a magnetic field in the water. Changes in the structure and behavior of the calcium and magnesium ions responsible for the “hardness” occur when the water passes through this magnetic field. It is believed that the magnetic field affects the way calcium and magnesium ions clump together, preventing scaling and adhesion to the surface. In addition, it is argued that the magnetic field can affect the precipitation of heavy minerals, making them less likely to form deposits (Vera Saltos & Noles Aguilar, 2018).

Taking into account the previous paragraphs and the fact that the total hardness of groundwater in the Guachún sector exceeds 400 mg/l $CaCO_3$, when the regulations recommend values of less than 200 mg/l $CaCO_3$, the best option in terms of cost-benefit and efficiency is ion exchange, since it allows a significant reduction in hardness with a medium investment ($500-$1500 USD/m^3/day) and manageable operating costs ($0.8-$3 USD/m^3). The cal-carbonate process is also viable because of its lower investment ($100-$300 USD/m^3/day), but it may not achieve sufficient hardness reduction and generates sludge that requires disposal. If maximum efficiency is sought, reverse osmosis is the best alternative, but with high installation costs ($1500-$3500 USD/m^3/day installation and $1-$4 USD/m^3 operation). Methods such as evaporation-condensation and magnetic field are not recommended due to the high hardness of the analyzed source.

4. Conclusions

The study conducted in the supply system with source in the Guachún sector showed that the hardness of the groundwater extracted exceeds 400 mg/l CaCO3, which generates significant problems in conduction due to the accumulation of incrustations in the impulsion pipes. This accumulation of calcium and magnesium carbonates causes a progressive reduction of the conduction capacity, increasing the head and operating losses of the pumps, which negatively impacts the efficiency of the drinking water distribution system.

Through experimental tests in a hydraulic bench, it was determined that the absolute roughness of new PVC pipes is in the order of 1.5×10^{-6} m, but over the years, due to the accumulation of incrustations, this roughness increases up to two orders of magnitude. As a consequence, the coefficient of friction in the pipes progressively increases, compromising the performance of the hydraulic system and requiring water treatment solutions to mitigate this effect.

The ion exchange process is the best option evaluated in terms of cost-benefit and efficiency, allowing a significant reduction in hardness with a manageable investment and operating costs. The cal-carbonate process is viable as a lower-cost alternative, but has the disadvantage of generating solid waste that requires proper disposal. On the other hand, reverse osmosis offers the highest hardness removal efficiency, although its installation and operating costs are high. Methods such as evaporation-condensation and magnetic field treatment are not recommended due to the high hardness of the water analyzed.

One of the limitations of the study was that the seasonal variation of water quality was not considered to obtain a more accurate relationship of the estimated absolute roughness with respect to the flow characteristics, for example, as a function of the seasonal variation of flow hardness in the pipes of the supply system analyzed. The integration of continuous water quality monitoring technologies is recommended for future work to be able to evaluate seasonal variations in water quality and the impact on the sections of the pipeline system.

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Use of Generative Artificial Intelligence

No generative artificial intelligence was used in preparing this communication.

Communication aligned with the Sustainable Development Goals