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Hydraulic capacity extension of networks through the water savings and investment analysis approach

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ABSTRACT
This study evaluates the water use efficiency (WUE) implementing under two approaches: i) reduction of water losses and the installation of low-consumption plumbing fixtures, and ii) Water savings analysis including , network Additional capacity, Reduction in per capita water consumption and the Investment (WARI). Hydraulic modeling was performed in the water distribution network of the campus of Universidad de Ibagué using EPANETv2.2, which supplies 5,172 people through 3,499.7 m of pipes during an analysis period of 48 months. The selection process for water-saving plumbing fixtures was carried out using the Analytical Hierarchy Process approach. The results indicate that WUE contributes to reducing water consumption by up to 47.8% and achieving a hydraulic capacity extension of the network of up to 67.0%, which is equivalent to extending pipes life cycle by up to 20 more years. WARI analysis is useful for water resource planners in decision-making processes within an economic and environmental sustainability framework.

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KEYWORDS
Water use efficiency; water consumption reduction; water distribution network; hydraulic capacity extension of networks; analytical hierarchy process

1. INTRODUCTION

Climate change and the increase in global population produce variations in water availability and higher pressure on water bodies. Therefore, water resource management plans have been developed to satisfy the growing demand for water due to its vital importance and multiple and different uses (Makki et al., 2013). Furthermore, the importance of formulating and implementing policies that effectively promote adequate water consumption and mitigate the growing scarcity problem is highlighted (Masserini, Giulia, & Lorenzo, 2018). In this sense, the United Nations Organization (2018), in its sixth sustainable development goal, establishes the need to ensure the availability and sustainable management of water resources through efficient water use in all sectors.

In the context of higher education institutions, university campuses consist of different structural systems that consume significant amounts of water throughout their service period (Alghamdi et al., 2019). These institutions, due to their large size, population, and various activities carried out in their facilities, cause severe direct and indirect damage to the environment (Alshuwaikhat & Abubakar, 2008), and in particular cases, overexploitation of aquifers occur (e.g., Bhakar et al., 2015; Bonnet et al., 2002). Therefore, the water-saving opportunities in this sector that involve strategies such as rainwater harvesting, greywater reuse, and the use of water-saving plumbing fixtures are emphasized (Proença & Ghisi, 2013).

These water-saving measures are usually classified into two types i) structural, focused on the implementation of technologies that modify the supply operation in favor of water consumption reduction (e.g., improvement in the supply network, water-saving plumbing fixtures), and ii) non-structural, focused on modifying user behavior in favor of promoting actions that result in lower water consumption (e.g., economic incentives, regulations, environmental education) (Roccaro, Falciglia, & Vagliasindi, 2011; Soares et al., 2021). Among the structural measures, Da Silva et al. (2014) reported a relationship between water saving and water consumption knowledge through frequent technical inspections of the elements that compose the supply network, adjustment in sanitary equipment flow and monitoring, and the prompt repair of leaks. In addition, F. Gonçalves, Kalbusch, and Henning (2018) found that water consumption is highly related to the physical state of sanitary equipment and its operating conditions. Besides, Cureau and Ghisi (2019) reported great potential to reduce water consumption and its relationship with the discharge characteristics of toilets, especially dual flush toilets that have been used in efficient water

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use programs on university campuses (Gnoatto, Kalbusch, & Henning, 2019). In this sense, Fidar, Memon, and Butler (2016) found that it is possible to reduce water consumption by replacing conventional taps in sinks with electronic taps that limit the supply. Similarly, Meireles et al. (2018) analyzed water consumption behavior when aerators are incorporated into sink faucets. These evaluation techniques are based on describing water consumption behavior by users as the main observation variable (Fidar, Memon, & Butler, 2016). Thus, evaluating efficient water use measures highly depends on user behavior, preferences, and actions (Meireles et al., 2018). Therefore, the efficient use of water can be a powerful strategy to promote the sustainability of university campuses. Likewise, it is also possible to offer technological support that contributes to changing the water consumption behavior of users towards a better relationship between academic activities and the environment (Marinho, Gonçalves, & Kiperstok, 2014). Hence, understanding the water consumption pattern in institutions such as universities is essential because, although daily individual consumption is low, it is necessary to supply a high number of users (Yagoub et al., 2019).

In this context, structural measures face challenges in their implementation, such as reducing the costs of implementing low-consumption sanitary equipment (Velazquez, Munguia, & Ojeda, 2013). Therefore, an incentive from the public sector is usually required for these measures to be economically viable (Kalbusch & Ghisi, 2016) since it is easy to recognize its value when it is possible to reduce consumption and the environmental impact proportionally (Proença & Ghisi, 2013).

Although multiple studies report savings in water consumption after the implementation of structural measures, few articles assess the correlation between water consumption and the number of leaks and failures in the supply network (F. Gonçalves, Kalbusch, & Henning, 2018). Therefore, this last approach represents an opportunity to study the effects of implementing an efficient water use project on the hydraulic capacity extension of water supply networks. For this, it is necessary to implement hydraulic simulation techniques that describe the behavior of distribution networks in changing water consumption environments and the growing number of users who demand the supply (Mabrok et al., 2022). To the best of the authors' knowledge, an analysis that integrates the detection and repair of water leakage in water distribution networks (WDN), the installation of water-saving plumbing fixtures, billing consumption monitoring, and its effect on the WDN in terms of hydraulic capacity extension has not been performed so far. This is essential since, as the population increases, the drinking water supply systems have difficulties meeting the demand increase, given their limited access to water, depending on the characteristics of the supply source (Jeong et al., 2016). In this sense, the hydraulic optimization of the WDN and the implementation of efficient water use projects have great potential to expand the growing population supply without requiring the expansion of the pipe network (Giwa & Dindi, 2017).

This study evaluates the implementation of a WUE strategy on the campus of Universidad de Ibague in Colombia, contrasting the water consumption behavior before and after the implementation of the WUE. In this sense, the study is developed around the following research question: By implementing water-saving plumbing fixtures and reducing water loss through pipe leaks and tank overflow repair, is it possible to increase the hydraulic capacity extension of networks? The analysis includes the hydraulic simulation of WUE implementation scenarios that describe the hydraulic behavior of the WDN using the EPANET 2.2 software application (Rossman et al., 2020). To validate results, an assessment of the billed consumption analysis during the study period and an analysis of *water savings* to extend the *additional capacity of WDN* is proposed through the *reduction of water consumption (%)* by implementing the WUE and the *investment* in different scenarios proposed in the WUE called WARI analysis, which can be useful in investment decision-making processes for water-saving projects in buildings and loss reduction in complex networks such as aqueducts.

2. MATERIAL and METHODS

2.1. Study area

The study was carried out in the city of Ibague in Colombia, located at 1,100 m a.s.l., with an average rainfall of 1,000 mm/year and an average temperature of 23.5°C. The campus of Universidad de Ibagué has a total area of 15.35 ha and a built area of 37,367 m^2. It comprises 16 buildings, including classrooms, laboratories, and offices (Figure 1). The buildings have 61 sanitary and water consumption points to meet campus services. In this sense, the university population during the study period comprised, on average, 5,172 people, including undergraduate and graduate students,

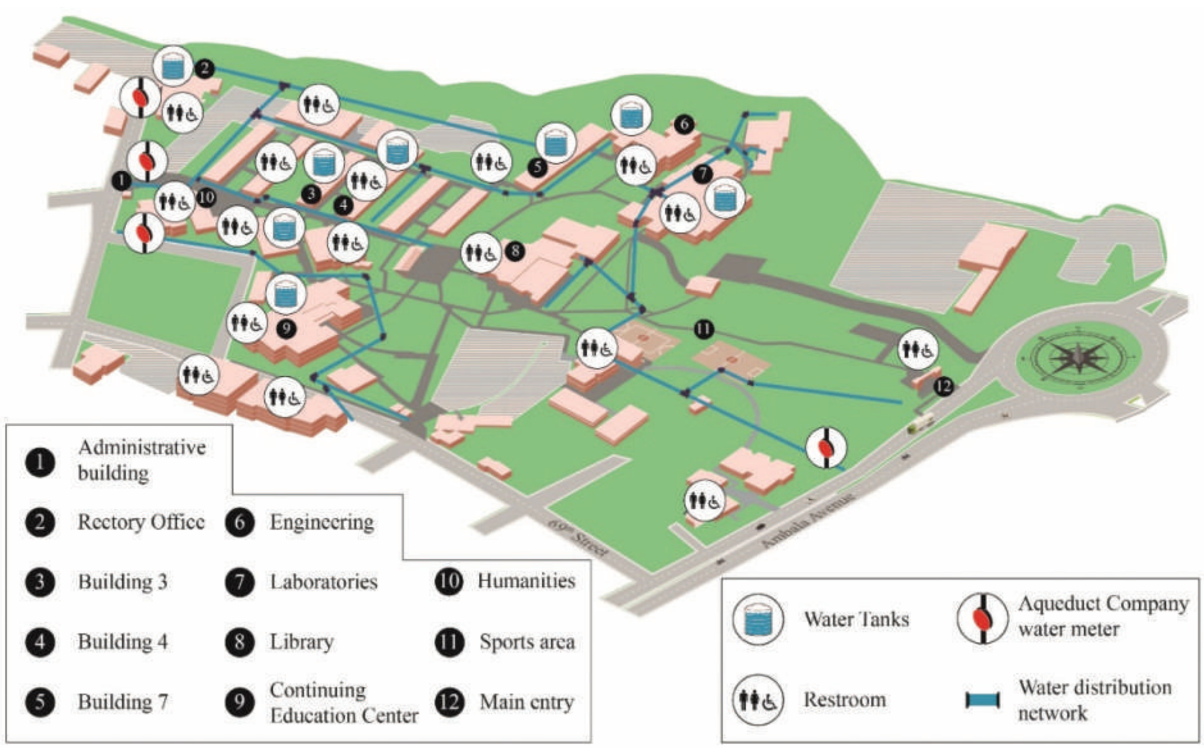

Figure 1. Location of water distribution network elements on the campus of Universidad de Ibagué, Colombia.

professors, and administrators. In addition, an average of 20 visitors per day was recorded. During vacation and inter-semester periods, i.e., June, July, December, and January, the university population is reduced by an average of 88.31%.

2.1.1. Network topology

The university campus is connected to the water system of the city of Ibagué, and given the sloping condition of the campus and the fact that the buildings are less than three stories high, pumping is not required. Therefore, the flow is distributed under pressure by gravity to 12 buildings through a branched PVC pipe network with a length of 3,499.7 m (Figure 1). The main pipe has a diameter of 25 mm, and the average service pressure in the network is 36.4 m varying from 36.5 to 45.6 m at the time of minimum and maximum consumption, respectively. The network operates continuously for 16 h each day, so the average consumption coefficients are 0.90, 1.11, 1.02, 1.12, 0.99, 0.96, 0.90, 1.19, 0.91, 1.05, 1.03, 1.14, 1.00, 0.99, 0.78, and 0.90, from 06:00 to 22:00 hours. Within the network, there are eight storage tanks, each with a capacity of 2.0 m^3, which regulate their level through float valves and correspond to the main water reserve for the bathrooms of the building.

2.2. WUE modeling phase

2.2.1. Field measurements

In this study, the implementation of the WUE strategy was based on two main activities: i) the repair of leaks in pipes and overflows in storage tanks and ii) the installation of sanitary equipment with low water consumption. During this phase, water consumption measurements were obtained on the campus of Universidad de Ibague, concentrated in the sanitary services areas (Figure 2). For this purpose, Contazara Reference CZ3000 micrometers were installed with an error of ±5% in all the sanitary services located in the campus. Thus, an hourly gauging of sanitary services use was carried out for 16 h per day over 1 month, allowing the characterization of the water consumption in the period before the implementation of the WUE. To this end, a discrete variable was randomly sampled for convenience, similar to Horsburgh et al. (2017).

On the other hand, precision tests were carried out on the micrometers from which aqueduct service billing is received (Figure 3(a)). In this case, the measurement error was verified not to exceed 5.0% (Hovany, 2012), related to the apparent or commercial loss of the system (Fontanazza et al., 2014). For this purpose, the flows supplied to the campus network were measured using

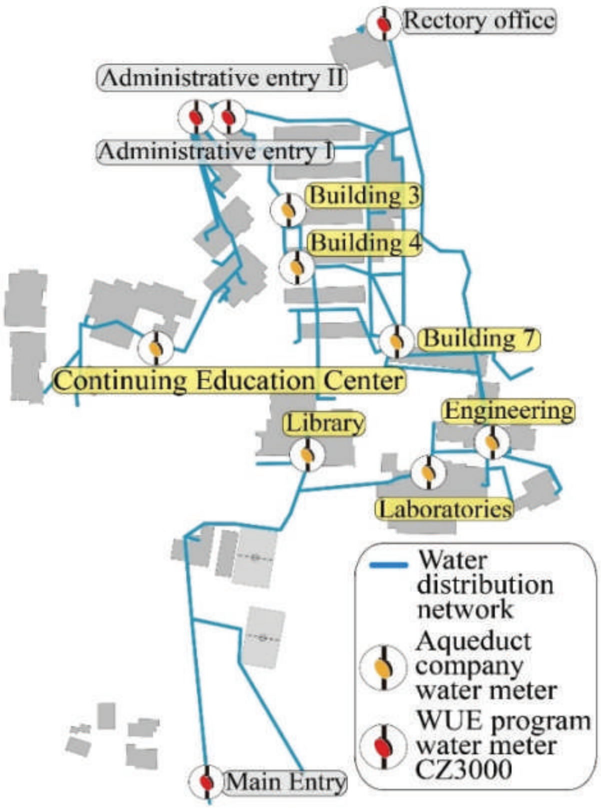

Figure 2. Location of the gauging stations for implementing the water use efficiency (WUE) strategy.

a Dynasonics TFX XP A16A NN series Doppler flow meter with a precision of 3.048E–4 m s^{-1}, according to the manufacturer. Subsequently, leak detection was carried out in pipes using FUJI TECOM HG-10A2 geophones with a sound filtration system. Accordingly, four leaks were detected in pipes with sound frequencies between 800 and 1,200 hz, just as Echeverri (2017) reported. These leaks were repaired after their detection (Figure 3(b)). Likewise, five overflow leaks were found in water storage tanks (Figure 3(b)) due to the poor condition of the float valves, which were replaced, as recommended by Ge et al. (2014).

Before the implementation of the WUE, the network supplied an average of 1,967.6 m^3/month, with losses of 62.3%. Thus, in the hydraulic modeling, the leaks were represented by emitter coefficients described as $q = Cp^{\gamma}$, where the leak flow rate (q) depends on the pressure at the node (p) and factor γ is related to the geometry of the hole that generates the water losses (Rossman et al., 2020).

2.2.2. Hydraulic network survey and modeling

The mapping of the hydraulic networks of the campus of Universidad de Ibague was carried out considering criteria associated with pipes, such as the type of joint, material, diameter, length, location, and installation depth (Puust et al., 2010; Sægrov et al., 1999). All the information collected was useful in the process of modeling the hydraulic networks and leak detection. The EPANET v2.2 model of the US Environmental Protection Agency (Rossman et al., 2020) was implemented to describe the hydraulic network behavior. This model has been widely applied to simulate water distribution and consumption in water supply systems (Hossain et al., 2021; Sunela & Puust, 2015; Yousefian & Duchesne, 2021), water losses in pipes (Cobacho et al., 2015; Mashford et al., 2012) and the evaluation of piping systems (Muranho et al., 2014), among many others. In the process of implementing the hydraulic model, six pressure and four flow gauging stations of the hydraulic network were installed (Figure 3(a)), and measurements were registered in an hourly-based resolution for 16 h on the day of maximum water consumption in the WDN. Based on the field measurements mentioned above, demand patterns and emitters were established for various nodes in the WDN. Thus, the implementation of the hydraulic model defined the obtention of the minimum difference between observed and simulated pressure and flow values as a calibration criterion. In this sense, the root mean square error (RMSE) was used to evaluate model calibration performance, applied in similar studies (e.g., Pordal, Noshadi, & Masoudi, 2023). Accordingly, the model was considered calibrated when RMSE values not higher than 0.6 m in pressure and 0.8 L/s in flow were obtained. The hydraulic model allowed the simulation of four water consumption scenarios described in Table 1.

2.3. WUE implementation phase

This phase included repairing leaks in the WDN, changing overflow valves in storage tanks, and installing low-water-consumption appliances at the sanitary service points on the campus, according to the result of the equipment selection process. Therefore, once the flow and water consumption measurements were made in the WDN, the low water consumption equipment was selected in the sanitary service points within the campus. For this purpose, the manufacturer's catalogs for low water consumption toilets, hand-press type sink basins, and waterless urinals were consulted as these have been used in various water use efficiency projects (e.g., Cureau & Ghisi, 2019; Davis, Gutiérrez, & Serrano, 2016; Otaki, Otaki, & Aramaki, 2018; Ramesh Sakthivel et al., 2016). Hence, the selection of this equipment involved the application of the analytical hierarchy process (AHP) approach (Saaty, 2013), widely utilized in

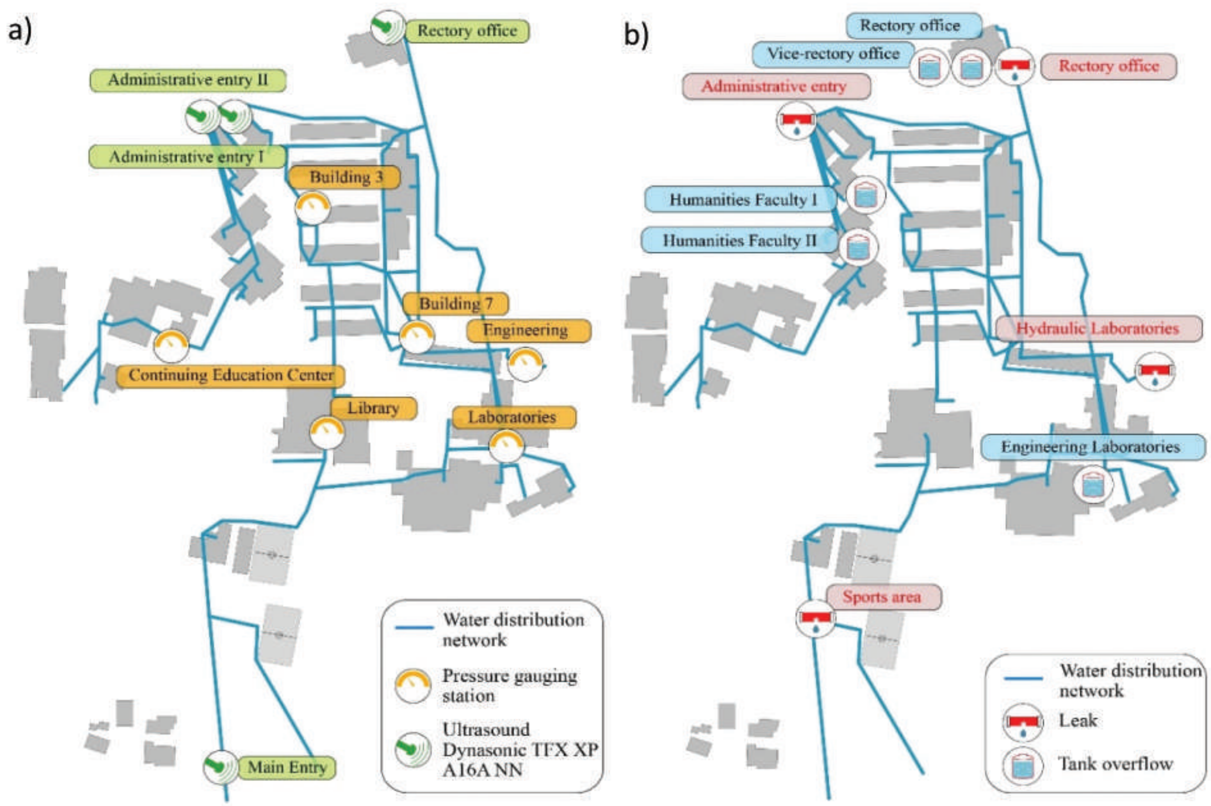

Figure 3. Location measurement stations in the network, a) pressure and flow, and b) leaks and overflow in tanks.

Table 1. Simulation scenarios proposed to evaluate water use efficiency (WUE).

Scenario	Description
S0	Water consumption prior to the implementation of the WUE.
S1	Water consumption when the leaks in pipes have been repaired and overflows in storage tanks have been controlled.
S2	Water consumption when low water consumption equipment has been installed in sanitary service areas without repairing pipe leaks nor installing overflow control valves in storage tanks.
S3	Water consumption when leaks in pipes have been repaired, overflows in storage tanks have been controlled, and low water consumption equipment has been installed in sanitary service areas.

selection processes in water resources and engineering projects (e.g., Peña, Zapata, & Barrios, 2019; Sun, Wang, & Hao, 2017). So, in this study, 18 selection criteria were defined (Table 2), among which the following stand out: water saving, durability, guarantee, price, and user comfort; the latter was essential to include, as it could generate rejection in the implementation of the WUE, as reported by Rodrigues et al. (2020).

2.4. WUE assessment phase

The assessment phase was developed in two parts: i) the simulation effect of implementing the WUE on the hydraulic capacity extension of the network as a strategy to expand the coverage of water users without expanding the existing infrastructure, so water consumption by the university population in the four simulation scenarios defined in this study was projected (Table 1); and ii) the evaluation of the simulated consumption that was contrasted concerning the billed water consumption for 48 months, including the behavior of consumption before, during and after the implementation of the WUE.

In this context, the time between months 01 and 12 corresponds to the period prior to the implementation of the WUE. The WUE implementation phase ranges from months 13 to 25 and the assessment phase from months 13 to 48. The billed consumption record includes months 01 to 48, allowing the quantification of the effect of implementing the WUE on water consumption on the university campus.

In more detail, during month 10, activities to measure water consumption in sanitary services, user count, precision tests for micro-meters, network

Table 2. Criteria for the selection of sanitary equipment with low water consumption.

Sanitary device	Criterion	Description	Criteria
Toilets	Discharge (Q)	Magnitude of discharge required (Liters)	Q ≥ 4 4 < Q < 6 Q ≤ 4
	Comfort (C)	Comfortable height for the user (meters)	C ≤ 0.4 C ≥ 0.5 0.4 < C < 0.5
	Accessories (A)	Requirement of special accessories for installation	Required Not required
	Installation type (I)	Installation of the toilet on the floor or the wall	On the floor On the wall
	Guarantee (G)	Product warranty coverage (years)	G ≤ 2 2 < G < 5 G ≥ 5
	Price (Pt)	Commercial price of the equipment (US dollar)	Pt ≥ 155 145 < Pt < 155 Pt ≤ 145
	Discharge type (T)	Availability of one or two water storages to discharge (ordinal)	T Simple T Double
Urinals	Water operation (W)	Evaluation of the amount of water required for the operation of the equipment (liters per flush – lpf)	W ≥ 3.0 0.0 < W < 3.0 W = 0
	Dimensions (D)	Easy installation in small spaces (categorical)	D = Not D = Yes
	Splashes (S)	The equipment minimizes splashes (categorical)	S = Not S = Yes
	Price (Pu)	Commercial price of the equipment (US dollar)	Pu ≥ 100 40 < Pu < 70 Pu ≤ 70
	Corrosion (Cp)	Equipment ability to prevent pipeline corrosion (categorical)	Cp = Not Cp = Depends on handling Cp = Yes
Faucets	Clasp type (F)	Faucet closure type (categorical)	F = Manual F = Push F = Automatic
	Use degree (U)	Faucet usage level (categorical)	F = Low F = Medium F = high
	Corrosion (Cp)	Equipment ability to prevent pipeline corrosion (categorical)	Cp = Not Cp = Depends on handling Cp = Yes
	Energy (E)	Type of energy required to drive the faucet	E = Battery E = Electricity E = Push
	Pressure (Pr)	Faucet operating pressure (psi)	$p \geq 80$ $20 < p < 80$ $p \leq 20$
	Price (Pf)	Commercial price of the equipment (US dollar)	Pf ≥ 40 30 < Pf < 40 Pf ≤ 30

pressure, and flow measurement campaigns were carried out. During months 11 and 12, the hydraulic model schematization and calibration of the WDN were performed. Between months 13 and 25, the WUE implementation phase took place. In month 13, the leak detection campaign and its respective repairs were done. During months 18 to 23, the review and selection of low-consumption sanitary equipment available in the market and the estimation of installation costs were carried out. This equipment was installed during months 24 and 25, including dual-flush toilets, water-saving taps, and waterless urinals in all the campus restrooms. Finally, invoice consumption monitoring was performed on a monthly basis. Figure 4 presents the methodological process implemented in this study.

3. Results and discussion

3.1. Behavior of water consumption and leaks in the WDN

The WDN of the university campus shows an average service pressure of 27.4 m and daily water consumption before the implementation of the WUE of 55,085.9 L/day on the day of maximum demand in the WDN,

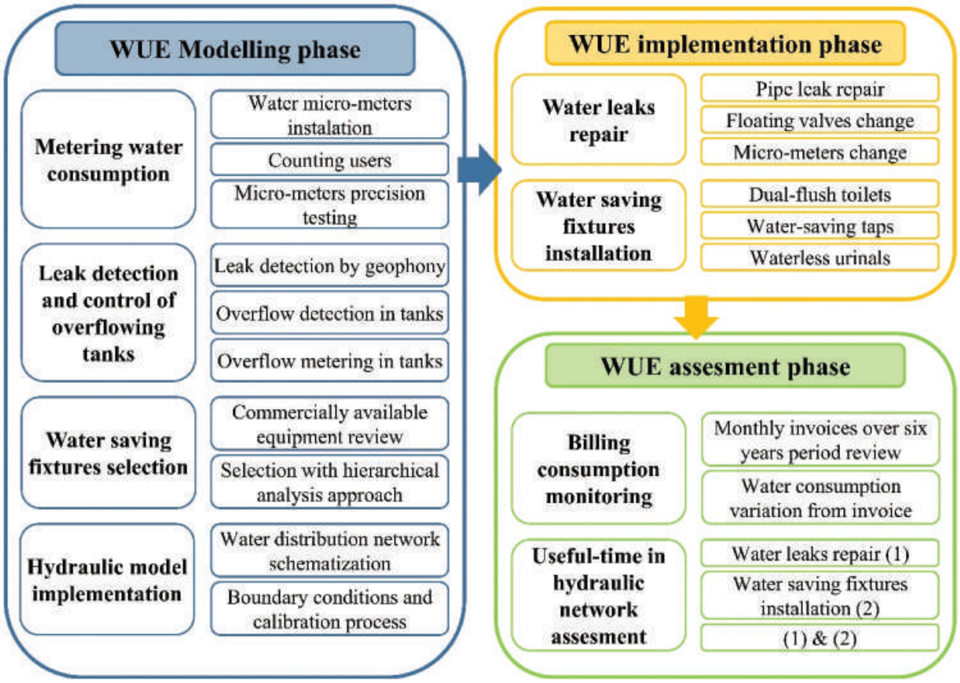

Figure 4. Description of the methodological process implemented.

corresponding to a per capita consumption of 11.9 L/day. Likewise, the highest water consumption was recorded in the buildings corresponding to the library, the continuing education center, and building 7, with daily volumes supplied of 6,744.9, 5,750.6, and 3,557.2 L on the day of maximum demand, respectively. Accordingly, the maximum flows occurred at 18:30, 14:30, and 17:15 hours, respectively (Figure 5).

During the hydraulic network survey, leak detection sessions were carried out, locating four of these in the pipe sections with diameter changes due to improper application of PVC welding to join the fittings (Figure 3(b)). For this purpose, geophones were used, filtering the sound between 900 and 1,200 hz, coinciding with what was reported by Van Arsdel (2017) and Ibrahim et al. (2021). In this process, leaks in pipes were counted by measuring the flow with an ultrasound sensor. Likewise, water leaks due to overflow were identified in five storage tanks (Figure 3(b)), caused by the poor condition of the float valves. These leaks were quantified at 20,943.5 L/day, corresponding to 38.07% of the losses in the distribution network (Table 3). Therefore, after their detection, plumbing fixtures, accessories, and float valves were repaired or changed in pipes at a cost of US$282.41.

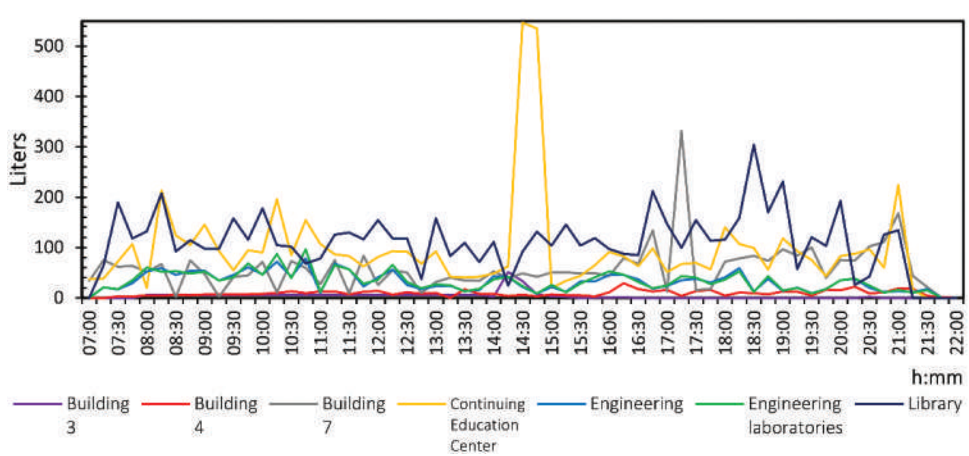

Figure 5. Water consumption measured per building on the day of maximum demand.

Table 3. Water losses detected in the water distribution network (WDN).

Leak type	ID	Location	Water supplied (L/day)	Measured leaks (L/day)	Network leaks (%)
Pipes	1	Rectory office	55,085.9	3,196.8	5.80
	2	Administrative staff entry		3,196.8	5.80
	3	Hydraulic laboratories		3,369.6	6.12
	4	Sports area		3,628.8	6.59
	Leaks in pipes			***13,392.0***	***24.31***
Overflow in tanks	1	Rectory office		6,744.9	12.24
	2	Engineering laboratories		5,750.6	10.44
	3	Vice-Rector office		3,523.2	6.40
	4	Humanities Faculty I		3,000.0	5.45
	5	Humanities Faculty II		1,924.7	3.49
		Overflow losses		***20,943.5***	***38.02***
Total network losses				34,335.5	62.33

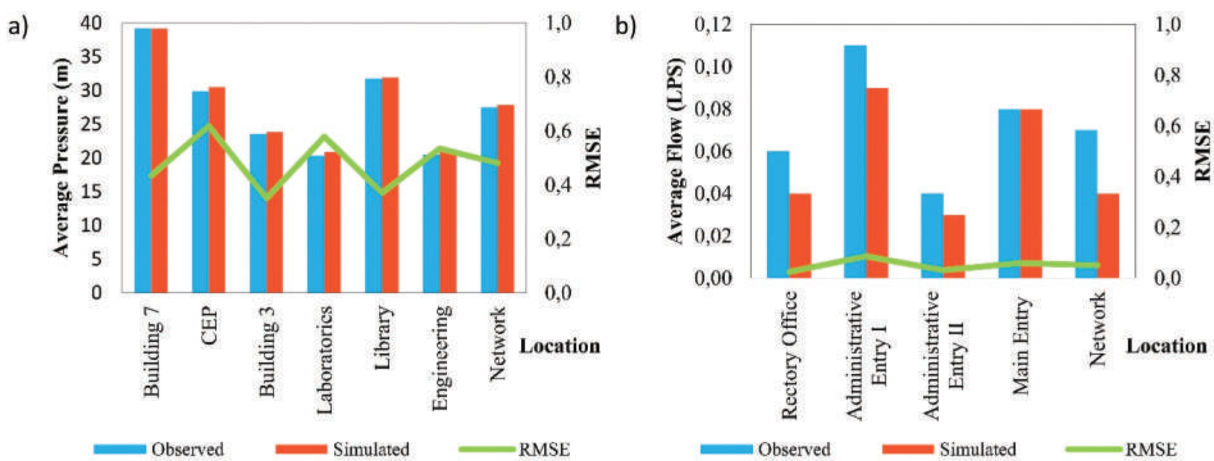

Figure 6. Hydraulic model calibration for a) average pressure in the water distribution network (WDN) and b) average flow in the WDN during the simulated period.

3.2. Calibration of the hydraulic model

Based on the results of the measurement campaign at the six pressure and four flow gauging stations, the differences between the observed and simulated values were obtained from 07:00 to 22:00, corresponding to the daily duty period of the campus. Figure 6 shows the average results obtained from calibrating the pipe pressure and flow over the 16-h period. The RMSE values obtained can be contrasted with those of Sharu and Ab Razak (2020), who concluded that a pressure RMSE around 0.60 m shows that the model has a good performance. Similarly, the RMSE for pipe flow was lower than that obtained by Pordal et al. (2023), who modeled the drinking water in a WDN and obtained errors higher than 0.80 L/s, indicating the excellent performance of the hydraulic model. On the other hand, when observing pressure behavior, the lowest pressures were recorded at 17:00 with a minimum value of 17.53 m. In this study, the minimum required pressure of service was 15 m, corresponding to that adopted in similar studies (e.g., Meirelles Lima, Brentan, and Luvizotto (2018), p. 10 m; Paluszczyszyn, Skworcow, and Ulanicki (2013), p. 16 m; Soltanjalili, Bozorg-Haddad, and Mariño (2011): between 0 and 30 m).

3.3. Selection of low water consumption appliances through the AHP

In this study, 18 criteria were defined for selecting low-water consumption appliances (Table 2). These were qualified using the qualification matrix proposed by Saaty (2013) so that the AHP approach allows integrating specific information on sanitary appliances with analytical judgments issued by a group of experts, in this case, including professors from Universidad de Ibagué, so that a peer evaluation was carried out to determine the weights between variables (Table 4), as reported by Peña, Zapata, and Barrios (2019).

Table 4. Criteria for the selection of sanitary equipment with low water consumption.

			Toilets							Urinals					Faucets						AHP-based
Device	Variable	Criterion	Q	C	A	I	G	Pt	T	W	D	S	Pu	Cp	F	U	Cp	E	Pr	Pf	weights (%)
Toilets	Q	Discharge	1	9	9	9	9	7	7												35.28
	C	Comfort	1/9	1	1/3	1/3	1/5	5	1/3												4.80
	A	Accessories	1/9	3	1	1/7	1/5	1/7	1/7												3.28
	I	Installation type	4/9	3	7	1	1/7	7	7												18.01
	G	Guarantee	1/9	5	5	7	1	7	7												20.25
	Pt	Price	1/7	1/5	7	1/7	1/7	1	1/9												5.73
	T	Discharge type	1/7	3	7	1/7	1/7	9	1												12.64
Urinals	W	Water operation								1	1/5	7	5	1/7							16.53
	D	Dimensions								5	1	7	7	1/7							25.42
	S	Splashes								1/7	1/7	1	5	1/9							8.94
	Pu	Price								1/5	1/5	1/5	1	1/7							3.34
	Cp	Corrosion								7	7	9	7	1							45.76
Faucets	F	Clasp type													1	5	1/7	1/5	1/7	7	11.37
	U	Use degree													1/5	1	1/7	1/5	1/7	5	5.72
	Cp	Corrosion													7	7	1	7	7	9	37.34
	E	Energy													5	5	1/7	1	1/7	9	17.02
	Pr	Pressure													7	7	1/7	7	1	9	26.67
	Pf	Price													1/7	1/5	1/9	1/9	1/9	1	1.89

AHP: analytical hierarchy process. Scores from 1 to 9 where: 1 Equally important, 3 Slightly more important, 5 Significantly more important, 7 Demonstrably more important, and 9 Absolutely more important (Saaty, 2013).

On the other hand, it is essential to consider that implementing water-saving equipment contributes to reducing CO_2 emissions and environmental impact, but within its life cycle, processes such as manufacturing and disposal generate new impacts (Gnoatto, Kalbusch, & Henning, 2019). However, the use phase generates environmental benefits due to water savings, which can be at least 15,000 times higher than the impacts caused during production (Berger et al., 2017). In this sense, it has been shown that installing flush valves allows a reduction of around 26.97% in water consumption in toilets (Gnoatto, Kalbusch, & Henning, 2019) and does not produce an overall increase in environmental impact when its replacement considers an average useful life of 20 years (Shimizu, 2013). Likewise, water-saving faucets reduce water consumption, energy, human toxicity, global warming, and ozone layer depletion by 26.2%, 4.6%, 14.8%, and 15.8%, respectively (Kalbusch & Ghisi, 2016). Thus, in this study, sanitary fixtures that had a service time of more than 35 years, such as toilets with 10 liter flushes, urinals and faucets of manual flushing, and plastic float valves in storage tanks, were replaced in month 25 of the study implementation process by: i) Five bronze float valves with a diameter of 25 mm and maximum closing pressure of 88 m; ii) 90 double flush toilets of 3–6 liters per flush (lpf), with operating pressure range of 18–88 m, siphon diameter of 5.1 cm, and they meet disability user requirements and criteria of the Environmental Protection Agency (EPA) for equipment that uses water efficiently; iii) 40 waterless urinals, which meet the requirements for reduced mobility users of the Americans with Disabilities Act (ADA); and iv) 94 retrofit taps with working pressure between 14 and 56 m, 0.33–0.49 lpf with automatic timed closing between 5 and 9 seconds. The investment made was US$42,519.13. These devices and the investments made are similar to those reported in various studies (e.g., Chipako & Randall, 2019; Meireles et al., 2018; Torrijos, Soto, & Calvo Dopico, 2020).

3.4. WUE implementation evaluation

The expected decrease in total water consumption on campus was used to evaluate water consumption in the four simulation scenarios defined in this project (Table 1), according to the results obtained from the hydraulic simulation. In scenario S1, a decrease in consumption was calculated at 62.33% (Table 3). For the S2 scenario, a 22.00% decrease in water consumption was considered, corresponding to those reported in multiple studies as a decrease achieved after the installation of water-saving sanitary equipment (e.g., Kalbusch & Ghisi, 2016; Meireles et al., 2018; Proença & Ghisi, 2013; Roccaro, Falciglia, & Vagliasindi, 2011). Finally, for the S3 scenario, a decrease of 70.62% was projected as an expected value after implementing the WUE. Figure 7(a) shows the evolution of water consumption on the day of maximum demand in 15-min intervals registered in the gauging stations. The water supplied in S0 was 55,085.9 L. In the same way, in S1, S2, and S3, 20750.4, 50520.8, and 16,185.3 L were supplied, respectively (Figure 7(b)). Finally, Figure 7(c) shows water saving values obtained in each of the scenarios highlighting that in S2, a maximum simulated reduction of

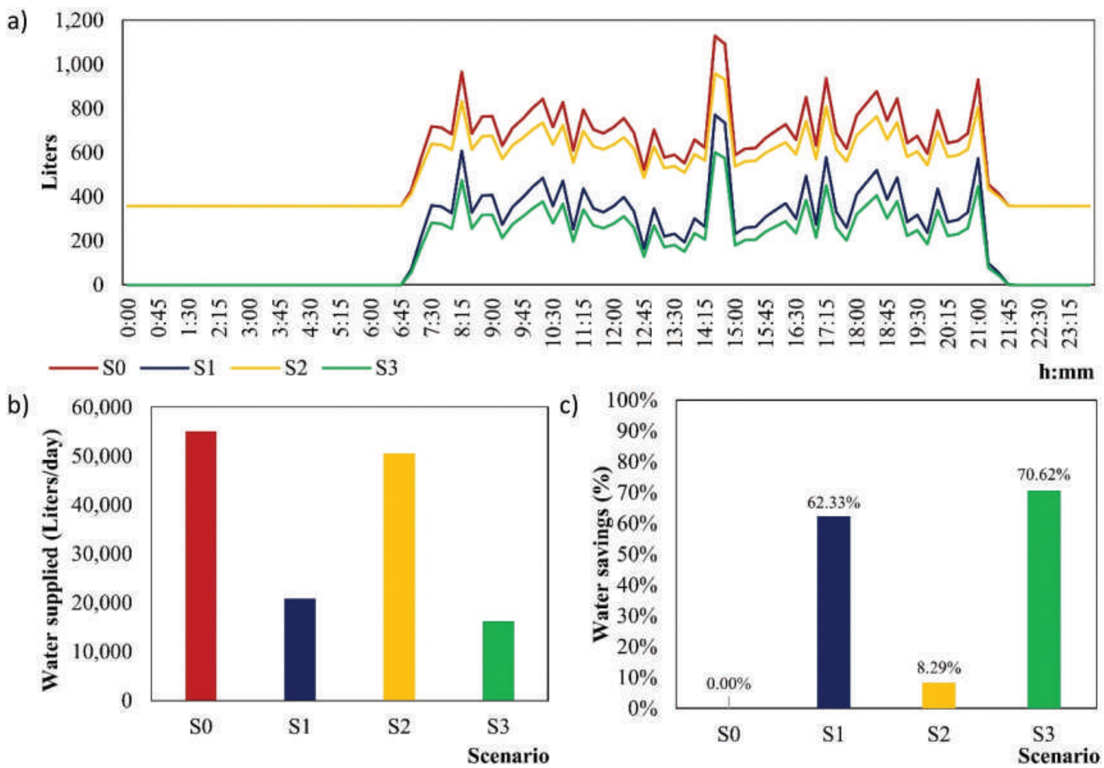

Figure 7. Water consumption reduction scenarios in the water distribution network: a) water consumption behavior on the day of maximum demand, b) daily volume supplied, and c) water supply reduction per water use efficiency (WUE) scenario.

8.29% was achieved. However, a reduction of 22.00% was expected due to installing low-water consumption sanitary equipment.

3.5. Billing consumption monitoring and analysis

As part of the validation process, the aqueduct billing service was analyzed each month for 48 months to evaluate the effect of the implementation of the WUE on the university campus, registering the monthly water consumption on the campus before, during, and after the implementation of the WUE (Figure 8). Thus, the billed water consumption in months 01 to 12 registered a total of 23,611 m^3 and a total cost/billed value of US$ 3,734.37 with a university population between 4,503 and 4,745 people and corresponded to the period prior to implementing the WUE. Similarly, months 13 to 24 correspond to the water leaks repair period with a cost

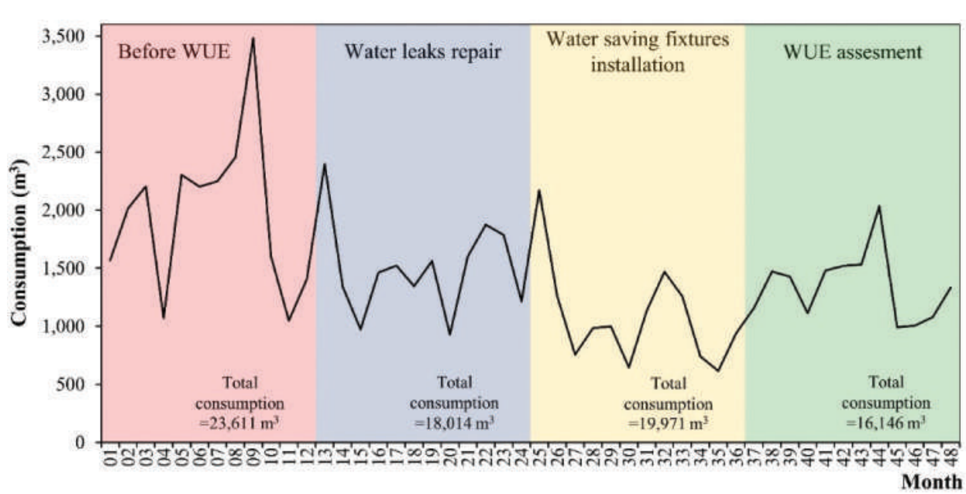

Figure 8. Evolution of water consumption concerning water use efficiency (WUE).

of US$31.95 and US$250.46 to change float valves, with a total consumption of 18,014 m^3 for US$ 2,898.0 with a population ranging between 4,980 and 5,009 people. In months 25 to 36, corresponding to the period in which water-saving plumbing fixtures were installed with a cost of US$42,519.13 and water leaks were repaired, total consumption was 12,971 m^3 with a total cost of US$ 1,622.0 and with a population between 5,248 and 5,350 people. Finally, from months 37 to 48, corresponding to the WUE assessment period, a total consumption of 16,146 m^3 was registered with a total cost of US$ 2,857.0 and a population between 5,742 and 5,797 people.

The results indicate that water consumption behavior shows minimum values in each period, mainly associated with the months when the students are on vacation. Similar behaviors have been reported by Meireles and Sousa (2020) and Yagoub et al. (2019). Likewise, odd semesters tend to have more students than even semesters in the context of this study. Therefore, Figure 9(a) presents the university population of the campus, and Figure 9(b) shows the per capita consumption in each semester. Similarly, Figure 9(a) reports total consumption savings registered each semester so that the consumption recorded before WUE is identified. Likewise, it is observed that after repairing leaks in the network, a decrease in consumption was achieved by 23.39% in semester III and 24.02% in semester IV. On the other hand, semesters V and VI show the savings obtained due to the joint performance of repairing leaks in the network and installing low-consumption sanitary equipment, which is 21.36%. These results are similar to those reported by Proença and Ghisi (2013), who obtained water savings from 21.6% to 57.4%. In the same way, Freitas et al. (2019) recorded a reduction between 21.72% and 24.17% when implementing low-consumption sanitary equipment. Finally, in the VII and VIII semesters that correspond to the WUE assessment period, where it is possible to evaluate the effect of the complete implementation of the WUE, savings of 30.79% and 32.45% were registered. Simultaneously, Figure 9(b) shows the savings recorded in per capita consumption per semester compared to the two semesters in the period before WUE, showing a range of 28.46% to 54.42%.

On the other hand, the payback period investment (PI) for leak repair and water-saving devices was estimated by calculating the accumulated water consumption value (C_{cum}) in a period of n years represented as $C_{cum} = \sum_{1}^{n}[(C_{w0} - C_i)*1 + (I_{wi}*Ip_i)]$, where C_{w0} is the water consumption value in the initial year, C_i is the water consumption value in year i, I_{wi} corresponds to the rate increase in year i, and Ip_i is the population increase each year. So, in this study, $PI = 430.7e^{0.3173*n}$ is the initial investment, and it was established as $PI = 14.5$ years. Reported PI values in similar studies correspond to 7, 10, 15, and more years (e.g., Ahmed, Alazazmeh, & Asif, 2023; Jacque et al., 2024; Sousa, Silva, & Meireles, 2019). In this sense, 15 years is considered the standard period for replacing water-saving devices (Tam & Brohier, 2013). In this context, researchers discuss contradictions between environmental and economic criteria for the implementation of water-efficient projects (J. M. Gonçalves et al., 2011), and therefore, economic incentives from governments are necessary to achieve a balance between economic and environmental benefits.

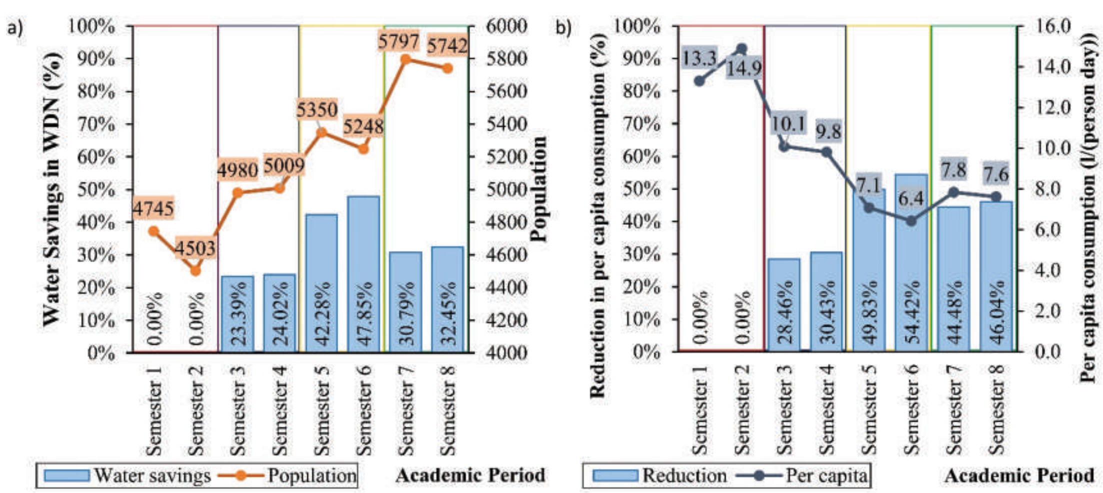

Figure 9. a) water savings in total consumption and university population per semester, and b) reduction in per capita consumption and per capita consumption per semester.

3.6. Hydraulic capacity extension simulation in the WDN

Based on the calibrated hydraulic model, the S0, S1, S2, and S3 scenarios were simulated, and with the water consumption billed by the water company on the campus, the estimation of the hydraulic capacity extension in the network, which represents an approximation to determine the number of additional users that could theoretically be served with the infrastructure existing on the campus, was obtained. The hydraulic option 'Demand Multiplier' offered by EPANET was used for this. It is a global multiplier applied to adjust all the values of baseline demands for all junctions and all demand categories to make total system consumption vary up or down by a fixed amount (Rossman et al., 2020), which represents the increase in base demand at each node, according to the population increase. Therefore, for each scenario proposed in this study (Table 1), the Demand Multiplier was increased until at least one of the network nodes did not reach the minimum service pressure of 15 m. Therefore, in this study, the additional population to which water could be supplied was projected by varying the existing population factor prior to the implementation period of the WUE program. This corresponds to a theoretical demand projection exercise since it is important to consider that college enrollment in higher education institutions has declined globally, as reported by Juszkiewicz (2020). However, this is part of a simulation exercise considering that network capacity could supply a larger population with the installed hydraulic infrastructure.

Based on what was previously shown, billed water consumption and the hydraulic simulation indicate that in the S0 scenario 55,110.6 L/day are supplied, which, when compared to the one measured in the system (55,085.9 L/day; Table 3), indicates a high descriptive capacity of the model to represent the hydraulic behavior of the real-scale system. Therefore, comparing the results projected by hydraulic simulation and those measured by billing consumption in the distribution network was possible. In the case of S1, the emitters of the hydraulic network were eliminated, and a supply of 42,256.8 L/day was obtained, representing a water-saving value in the WDN of 23.29% compared to S0. In the same way, in S2, the demand patterns were all reduced by 58.74% to obtain a supply of 43,372.4 L/day and a water-saving value in the WDN of 21.26%. This result is consistent with what was obtained in section 3.5 *Billing consumption monitoring and analysis*. Finally, S3 consisted of the combination of the previous scenarios, where a supply of 36,976.0 L/day was obtained, which meant water saving in the WDN of 32.88%.

Once the hydraulic models of each scenario were obtained, their respective Demand Multiplier was obtained, which led to the minimum required service pressure in the WDN. The results were 1.52, 1.31, and 1.67 for S1, S2, and S3, respectively. The periods before implementing the efficient water use program (Semesters 1 and 2) had a population of 4,745 and 4,503 people, respectively. The average was used to estimate the theoretical additional capacity of users that the current hydraulic network can offer. Therefore, based on the Demand Multiplier obtained, it was estimated that S1 could supply an additional population of 2,404 users, and S2 and S3 could supply 1,433 and 3,098 users. This is equivalent to extending the service time of the pipes in the WDN for each scenario by 10, 16, and 20 years, respectively. Thus, taking as a reference point Semester 1 of this study (Figure 9), the analyzed network was installed 35 years ago. However, it is possible to extend its service time for 20 more years by implementing scenario S3, considering a linear growth of water users on the university campus. This allows achieving a balance between energy expenditure and the life cycle of the pipes, which, according to Filion, MacLean, and Karney (2004), is achieved over 50 years. However, the pipes can be reused in other networks, contributing to sustainability (Dixit, 2019).

3.7. WARI relationship for the evaluation of the service period of the distribution network

Based on the results obtained from the hydraulic simulation and the analysis of billed water consumption, the relationship analysis among the variables measured in each of the WUE scenarios (Table 1) – called WARI – is constructed (Figure 10). These variables include i) **W**ater savings in the WDN (%) referring to the decrease in the water supply in the entire water distribution network and was obtained by comparing the consumption registered in the water billing consumption with respect to the previous implementation period of the WUE; ii) theoretical **A**dditional capacity (users) regarding the additional population that can be supplied by the current water distribution network, according to the results of the hydraulic simulation in the implementation scenarios of the WUE program (Table 1); iii) **R**eduction in per capita water consumption (%), representing the decrease or percentage change in per capita consumption compared to the period before the implementation of the WUE program. The per capita consumption

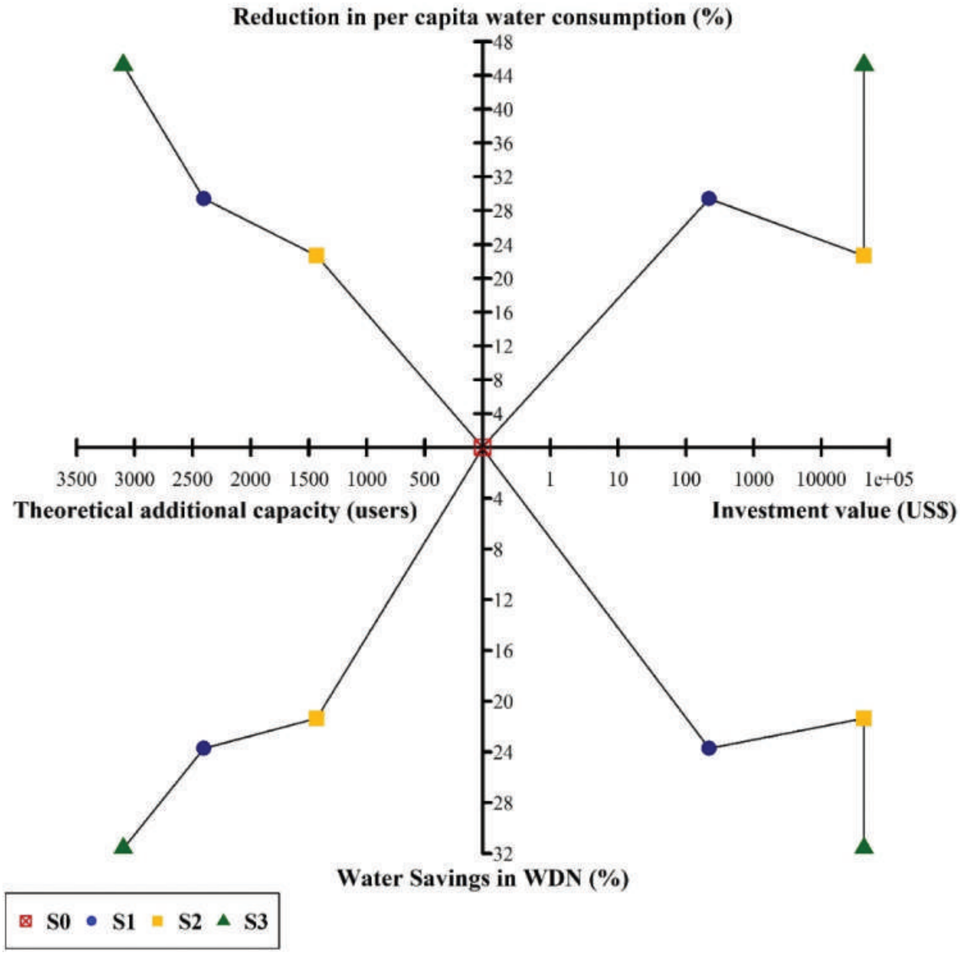

Figure 10. Relationship of the water use efficiency (WUE) variables and scenarios.

considered changes in the population and a decrease in water consumption registered in the invoice (bill); iv) **I**nvestments (US$) were the applied measure costs of the WUE program. In this sense, S0 corresponds to the base scenario in the period prior to the implementation of the WUE program. Therefore, the values in this scenario corresponded to 0.0 for each variable. For the water savings in the WDN variable, the S1, S2, and S3 scenarios recorded values of 23.71%, 21.36%, and 31.62%, respectively. Similarly, the theoretical additional capacity variable showed 2,404 additional users for S1, 1,433 new users for S2, and 3,098 extra users for S3. Subsequently, the variable reduction in per capita water consumption reported values of 29.43%, 22.69%, and 45.24% for S1, S2, and S3, respectively. Finally, the investment made to execute the different scenarios in the WUE program was US$ 220.8, 42519.1, and 42,740.0 for scenarios S1, S2, and S3, respectively. In this way, Figure 10 presents the relationships between the four variables analyzed in the framework of the WUE implementation and corresponds to the conceptual proposal for evaluating efficient water use projects.

In this context, the proposed methodology can be implemented not only in buildings but also in complex network systems, such as aqueduct systems, which can be part of the water loss management plans in distribution networks that incorporate campaigns to locate and repair leaks in pipes, since this contributes to reducing the leak rate and operating costs (Ananda, 2019). It also favors access to water for new users and increases the service time of the pipes, thus contributing to reducing the costs of their replacement in economic and environmental terms (Berhanu et al., 2017). Likewise, it is possible to estimate and project the decrease in water consumption involved in implementing WUE in buildings based on the reported water-saving values in the technical sheets of low-consumption sanitary equipment, as proposed by Shimizu (2013). Hence, although the reduction of water consumption has a positive return in economic and environmental terms, the development of public policies that promote and provide incentives for the implementation of WUE projects is also required, as proposed by Gnoatto, Kalbusch, and Henning (2019), which can contribute to improving the resilience of water supply in cities in scarcity scenarios (Daloğlu Çetinkaya et al., 2022; Grecksch, 2018).

4. LIMITATIONS and SCOPE

In this study, although metrics were not included to identify the possible rejection/acceptance of low water consumption equipment by users, criteria such as comfort and compliance with standards that favor use by populations with disabilities or reduced mobility were incorporated into the selection process. However, it has been reported that water users are willing to undertake sustainable actions due to well-known global environmental problems (Willis et al., 2011). Likewise, the analysis focused on the evaluation of water savings and leak repair concerning their implications in the extension of the hydraulic capacity of the distribution network as a strategy to extend the service period of pipes, which can be useful not only in buildings but in more complex networks such as water supply systems, are emphasized. Additionally, in this study, the return period of the investment in the implementation of the WUE was estimated at 14.5 years, which is based on the projection of population growth and the increase in the water supply service rate, consistent with what has been reported by other authors. However, this value may vary depending on changes in the water rate in each region, which, in turn, are affected by variables such as climatic conditions that define water scarcity in each region, among others.

5. CONCLUSIONS

By implementing a water use efficiency (WUE) management strategy, reducing the water volume distributed in the network and the per capita water consumption on the campus of Universidad de Ibague is possible. Thus, the results indicate that extending the hydraulic capacity of the distribution network by up to 67% is possible, which means that the service period and life cycle of the pipes can be extended for up to 20 years. In this sense, activities such as locating and repairing leaks significantly impact water supply reduction to the network. Likewise, integrating this activity with the installation of low-water consumption sanitary equipment allows for water savings of up to 33% in the context of this study.

Hence, integrating variables in the WARI analysis facilitates the projection of relationships between the projected consumption under investment scenarios that represent the implementation of actions to repair leaks in pipes and low-water consumption equipment. This is useful in planning and decision-making processes. In this sense, researchers working in the area of water resources are encouraged to explore the implementation of WARI to assess the potential impact of implementing a loss reduction and efficient water use project, not only in academic settings but also in industry networks and on larger-scale water distribution networks in aqueducts, so that the relationship between the variables proposed in this study, i.e., water saving in WDN (%), theoretical additional capacity (users), reduction in per capita water consumption (%), and investment (US$), provide valuable information for decision-makers in water resources planning processes.

Finally, the implementation of the WUE in this study contributes to improving three main aspects: i) the environmental, by extending the capacity of the pipelines, which contributes to extending their life cycle; ii) the social, through the decrease in consumption to improve access to water by other communities; iii) the technical, since it is possible to extend the period of service of the distribution networks, and iv) the economical. By decreasing water consumption, it is possible to reduce the billed value of the aqueduct service in buildings, as well as extend the period for the restoration of pipes in large-scale networks, which contributes to achieving a balance between economic and environmental sustainability.

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Disclosure statement

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Data availability statement

All data, models, and codes that support the findings of this study are available from the corresponding author upon reasonable request.

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