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HYDRAULIC DESIGN OF A LOOPED WATER SUPPLY NETWORK IN A CRITICAL URBAN AREA USING THE HAZEN-WILLIAMS EQUATION

DIMENSIONAMENTO HIDRÁULICO DE UMA REDE MALHADA DE ABASTECIMENTO DE ÁGUA EM ÁREA URBANA CRÍTICA UTILIZANDO A EQUAÇÃO DE HAZEN-WILLIAMS

DISEÑO HIDRÁULICO DE UNA RED DE SUMINISTRO DE AGUA EN CIRCUITO EN UNA ZONA URBANA CRÍTICA MEDIANTE LA ECUACIÓN DE HAZEN-WILLIAMS

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ABSTRACT

This research aimed at the hydraulic design of a large-scale looped water distribution network, using the Bairro 11 de Novembro (Luanda) as a case study a critical area facing severe deficiencies in its existing system. The methodology integrated water demand determination via assessing apparent needs based on per capita water consumption in Luanda, interviews, and technical consultations with hydraulic analysis using the Hardy-Cross method and the Hazen-Williams equation (C=140), applying iterative corrections (ΔQ) until loop balance was achieved ($\varepsilon \leq 0.01$ m). The OAT sensitivity analysis identified the roughness coefficient (C) as the most critical parameter for head loss ($S \approx 2.6$), while demand coefficients (K_1, K_2) directly impact flow rates ($S \approx 1$). The designed network features flow rates ranging from 125.41 L/s to 5.90 L/s, with diameters from 350 mm to 80 mm, and velocities between 0.6 and 2.9 m/s. Hydraulic balance was achieved with an average of 3.7 iterations per loop and $\Sigma\Delta H=0$ m. The sensitivity analysis identified the roughness coefficient (C) as the most critical parameter for head losses ($S \approx 2.6$). The proposed solution is technically viable and replicable, representing a significant contribution to sanitation engineering in contexts of rapid urban growth, although the results depend on demand estimates and the C coefficient, which require future calibration.

RESUMO

Esta pesquisa objectivou o dimensionamento hidráulico de uma rede malhada de grande porte para abastecimento de água,

Palavras clave:
distribuição de água, dimensionamento do sistema, hardy-croos, rede malhada, perda de carga.

tomando como caso de estudo o Bairro 11 de Novembro (Luanda), uma localidade crítica onde se enfrentam severas deficiências no sistema existente. A metodologia integrou a determinação da demanda hídrica via deção necessidades aparentes pelo consumo de água per capita em Luanda, entrevistas e consultas técnicas com a análise hidráulica pelo método de Hardy-Cross utilizando a equação de Hazen-Williams (C=140), aplicando correções iterativas (ΔQ) até o equilíbrio das malhas (ε ≤ 0,01 m). A análise de sensibilidade OAT identificou o coeficiente de rugosidade (C) como parâmetro mais crítico para perdas de carga (S ≈ 2,6), enquanto os coeficientes de demanda (K_1, K_2) impactam diretamente as vazões (S ≈ 1). A rede dimensionada apresenta vazões entre 125,41 L/s e 5,90 L/s, com diâmetros de 350 mm a 80 mm, velocidades entre 0,6 e 2,9 m/s. O equilíbrio hidráulico foi alcançado com uma média de 3,7 iterações por anel e ΣΔH=0 m. A análise de sensibilidade identificou o coeficiente de rugosidade (C) como o parâmetro mais crítico para as perdas de carga (S ≈ 2,6). A solução proposta é tecnicamente viável e replicável, constituindo uma contribuição significativa para a engenharia de saneamento em contextos de rápido crescimento urbano, embora os resultados dependam de estimativas de demanda e do coeficiente C, que requerem calibração futura.

Resumen

Palabras clave: distribución de agua, dimensionamiento del sistema, hardy-cross, red en bucle, pérdida de carga, análisis de sensibilidad.

Esta investigación tuvo como objetivo el diseño hidráulico de una red de distribución de agua en bucle a gran escala, utilizando el Bairro 11 de Novembro (Luanda) como caso de estudio, un área crítica que enfrenta graves deficiencias en su sistema existente. La metodología integró la determinación de la demanda de agua a través de la evaluación de las necesidades aparentes basadas en el consumo de agua per cápita en Luanda, entrevistas y consultas técnicas con análisis hidráulico utilizando el método de Hardy-Cross y la ecuación de Hazen-Williams (C=140), aplicando correcciones iterativas (ΔQ) hasta lograr el equilibrio del bucle (ε ≤ 0,01 m). El análisis de sensibilidad OAT identificó el coeficiente de rugosidad (C) como el parámetro más crítico para la pérdida de carga (S ≈ 2,6), mientras que los coeficientes de demanda (K_1, K_2) impactan directamente los caudales (S ≈ 1). La red diseñada presenta caudales que oscilan entre 125,41 L/s y 5,90 L/s, con diámetros de 350 mm a 80 mm y velocidades entre 0,6 y 2,9 m/s. Se logró el equilibrio hidráulico con un promedio de 3,7 iteraciones por bucle y ΣΔH=0 m. El análisis de sensibilidad identificó el coeficiente de rugosidad (C) como el parámetro más crítico para las pérdidas de carga (S ≈ 2,6). La solución propuesta es técnicamente viable y replicable, lo que representa una contribución significativa a la ingeniería de saneamiento en contextos de rápido crecimiento urbano, aunque los resultados dependen de las estimaciones de demanda y del coeficiente C, que requieren calibración futura.

Introduction

The supply system is quite complex, and not just in terms of maintenance and operation. This is generally the most costly part of the overall water supply project, requiring considerable attention to *per capita* consumption, system parameters, calculation assumptions, and methodologies in order to develop an efficient project.

Luanda is experiencing population growth, exacerbated by rural exodus. According to EPAL-EP (2021), this situation makes the issue of water supply to the population a critical one. In the 11 de Novembro neighborhood, in the Kima Kieza urban district of the municipality of Cazenga, the drinking water distribution and supply system is unable to adequately serve the entire population and all facilities due to the growth in infrastructure and population. Since this is a critical neighborhood, attention has been focused on including it in this study as a case study, in which we hope to find a solution for a new water distribution and supply network for that community, which has been adversely affected by the system's failure.

In light of this, the study's overall objective was to propose a new mesh-type water distribution and supply network. Specifically, the study sought to: (1) Apply a systematic methodology for the hydraulic design of a large-scale piped network in the 11 de Novembro neighborhood, Kima Kieza District, Luanda; (2) Develop a complete and technically feasible construction design for the aforementioned network, defining a hierarchy of pipe diameters, ensuring balanced flow rates, and guaranteeing the capacity to meet peak demand; (3) Conduct a sensitivity analysis of the designed system, identifying the critical parameters for its long-term sustainability; and (4) Demonstrate the effectiveness and stability of using the Hazen-Williams equation and the Hardy-Cross method in conjunction as a tool for the design of large-scale water distribution networks.

Determining water consumption and flow rates in water distribution systems is a critical step in the proper sizing of this infrastructure. Design flow rates must account for the different types of domestic, commercial, institutional, industrial, and public water use, as well as provide for firefighting needs and compensate for continuous pressure losses (h_f) and any leaks.
The formulas for calculating continuous pressure losses (h_f) establish relationships among the following six main hydraulic variables: pipe length (L), pressure (P), diameter (D), flow rate (Q), head loss (h_f), and internal roughness (Ɛ) (Nogueira & Justino, 2013).

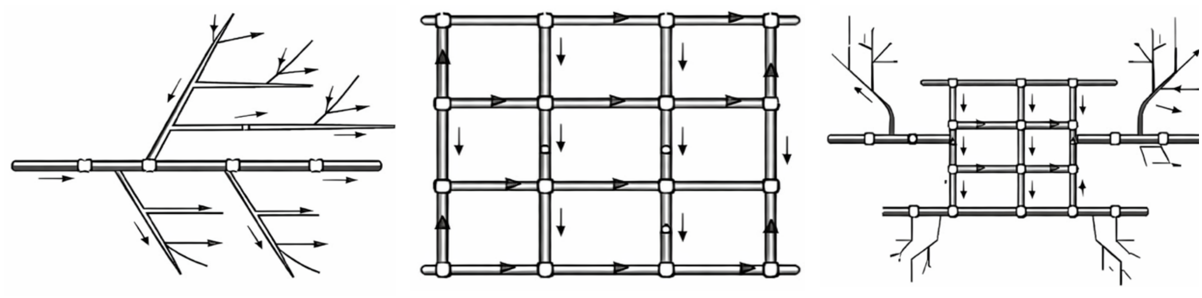
Despite the existence of established standards and methodologies for the design of water supply networks, there is a lack of studies applied to the Angolan context that systematically integrate the determination of local demand, hydraulic design using classical methods, and sensitivity analysis of critical parameters. This shortfall is particularly acute in Luanda's outlying neighborhoods, such as 11 de Novembro, where rapid urban growth has not been accompanied by engineering projects that ensure the system's long-term sustainability and resilience.

Water Distribution Networks

Water distribution networks consist of a series of reservoirs that distribute water to the points of consumption (household connections). There are three types of distribution networks, as shown in the following figure:

Figure 1

(a) Branched network, (b) Mesh network, and (c) Hybrid network



(a) (b) (c)

Note. Adapted from Rossman (2000), Mays (2011), AWWA (2012), and Walski et al. (2003)

A branched network is characterized by a hierarchical, tree-like structure in which water is distributed from a main trunk pipeline that progressively branches into secondary and tertiary pipelines until it reaches the points of consumption. This type of network is simple to design and less expensive to deploy, and is often used in small communities or outlying areas. However, it has low hydraulic redundancy, which can lead to interruptions in water supply in the event of failures or maintenance (Walski et al., 2003; AWWA, 2012).

The meshed network consists of interconnected main pipes that form closed loops or meshes, allowing water to reach any point in the system via multiple routes. This configuration provides greater operational reliability, better pressure distribution, and greater flexibility during maintenance or emergencies. Despite the higher construction costs, it is widely adopted in urban areas with medium and high population densities (Rossman, 2000; Mays, 2011).

A mixed network is the result of combining a branched network and a meshed network, and is the most common solution in real-world water supply systems. Generally, the central and most critical areas of the system use meshed networks, while the outlying regions are served by branch lines. This type of network seeks to strike a balance between cost, reliability, and hydraulic efficiency (AWWA, 2012; Walski et al., 2003).

Hardy-Cross Method

A mixed network is the result of combining a branched network and a meshed network, and is the most common solution in real-world water supply systems. Generally, the central and most critical areas of the system use meshed networks, while the outlying regions are served by branch lines. This type of network seeks to strike a balance between cost, reliability, and hydraulic efficiency (AWWA, 2012; Walski et al., 2003).

It is an iterative method for balancing flow rates in meshed networks, based on the Law of Conservation of Mass (nodes) and the Law of Conservation of Energy (meshes).

The continuous pressure drop in each section is calculated using a formula of the following form:

$$\Delta H\ ou\ h_f = k.Q^n \qquad (1)$$

where:

- To Darcy-Weisbach: $n \approx 2$ (but f it depends on Re and roughness, and may vary with Q)
- To Hazen-Williams: $n = 1{,}852$ e k depends on C (roughness coefficient).

The analysis of the hydraulic balance of water distribution networks is based on the two fundamental laws of fluid mechanics—the law of continuity and the law of energy conservation—as well as on the relationship between flow rate (or velocity) and head loss(or pressure drop) (Munson et al., 2020), established through the Darcy-Weisbach equations (the universal head loss formula) or the Hazen-Williams equation.

Hazen-Williams Equation

The decision to use the Hazen-Williams formula in the design of large-scale networks goes beyond mere numerical efficiency, directly impacting the system's operational reliability and sustainability. The method's fast convergence rate makes it possible to explore more demand and shortage scenarios, thereby optimizing pipe diameters and defining more robust and resilient network configurations (Tsutiya, 2006). This increased efficiency in calculations makes it possible to analyze alternatives that ensure adequate minimum pressures at all points in the network, including during peak periods or in situations of population growth, thereby guaranteeing an equitable water supply—a critical socio-environmental factor (Heller & Pádua, 2006). From an environmental perspective, the careful selection of realistic C coefficients, combined with precise hydraulic sizing, helps reduce leakage losses and minimize the energy required for pumping, thereby promoting energy efficiency and the conservation of water resources (Carrijo, 2012). Therefore, the methodological choice is reflected not only in the network's design but also in its ability to serve society in a fair and environmentally responsible manner.

The choice between the Hazen-Williams and Darcy-Weisbach equations determines the dynamics and efficiency of the iterative hydraulic equilibrium process.

Despite its practical advantages, the application of the Hazen-Williams equation has limitations that must be made clear. Its validity is recognized for water flow at typical temperatures (around 20°C) under rough turbulent conditions, which are typical in distribution networks. However, for situations involving very small diameters, low velocities (laminar or transitional flow), or fluids with significantly different viscosities, the Darcy-Weisbach equation—because it is theoretically more comprehensive—would be the most appropriate choice (Giles, 2004). In addition, the roughness coefficient 'C' is not constant over the service life of the piping; it decreases due to aging, fouling, and corrosion—a critical aspect that this sensitivity analysis sought to evaluate (Mays, 2000).

While the universal Darcy-Weisbach formula provides a relationship in which the exponent n is approximately 2, but the coefficient f implicitly varies with the Reynolds number and roughness, the Hazen-Williams equation stands out for its structural simplicity, with a fixed exponent $n = 1.852$ and a coefficient k that depends solely on the roughness coefficient C of the material (Azevedo Netto & Alvarez, 2004).

$$\Delta H = \frac{1}{(0{,}2785C)^{1{,}85}} \times \frac{L}{D^{4{,}87}} \times Q^{1{,}85} \qquad (2)$$

This characteristic makes the flow rate–pressure drop relationship explicit and direct, thereby considerably simplifying the calculations within the Hardy-Cross iterative algorithm (Tsutiya, 2006).

For drinking water distribution networks, the choice of the Hazen-Williams formula is amply justified by a number of decisive practical advantages. First, its computational simplicity speeds up the process: with a constant exponent n, the calculation of the flow correction per mesh (ΔQ) becomes more stable and straightforward, without the need to reevaluate a friction factor f that varies with each iteration (Porto, 2004). Consequently, a higher convergence rate is observed, with fewer cycles required to reach equilibrium. This efficiency is complemented by how easy it is to implement in common computer tools, such as spreadsheets. In addition, reference manuals such as those by Azevedo Netto and Tsutiya, which provide standardized tables of the coefficient C, ensure the compatibility and reliability of projects (Tsutiya, 2006). Finally, the applicability of this empirical formula—originally calibrated for these conditions—to the typical flow regime in supply networks characterized by rough turbulence justifies its use.

Limitations of the Hazen-Williams Equation

Despite these considerations, the application of the Darcy-Weisbach equation remains essential in specific scenarios where physical rigor and high precision are imperative. This universal formula should be taken into account when the system operates with fluids whose viscosity differs significantly from that of water at 20°C, such as in cases of extreme temperatures or other liquids (Giles, 2004). It is also necessary in non-turbulent flow regimes, such as in pipes with very small diameters or very low velocities, where laminar or transitional flow regimes may occur, outside the scope of the Hazen-Williams equation. Finally, when the absolute roughness (ϵ) of the material is known with high precision and the designer seeks maximum physical accuracy in the modeling, the Darcy-Weisbach formula, based on fluid mechanics, offers a more comprehensive and accurate representation of the physics of flow under any conditions (Azevedo Netto & Alvarez, 2004).

The evolution of water supply network design builds on classical methods such as the Hardy-Cross method and incorporates contemporary approaches based on optimization and advanced calibration. Johns, Keedwell, and Savić (2014) developed the ALCO-GA genetic algorithm, which improves the efficiency of the search for viable solutions in complex networks. Cui and Kuczera (2025) expanded on this perspective by applying genetic algorithms to the optimization of operational rules, with the aim of minimizing annual costs in systems subject to uncertainty.

In the field of calibration, Rai and Lingayat (2021) validated the use of EPANET by comparing its results with analytical solutions obtained using the Hardy-Cross method. Bas (2026) expanded on this approach by integrating EPANET with statistical indices such as MBE and NSE, demonstrating that models calibrated with field data achieve high reliability in pressure and flow simulations.

This underscores the need to link system sizing to operational control and loss management strategies, as Lusk (2025) points out when discussing the control of actual water losses as a key element in ensuring the sustainability of the water supply.

Method

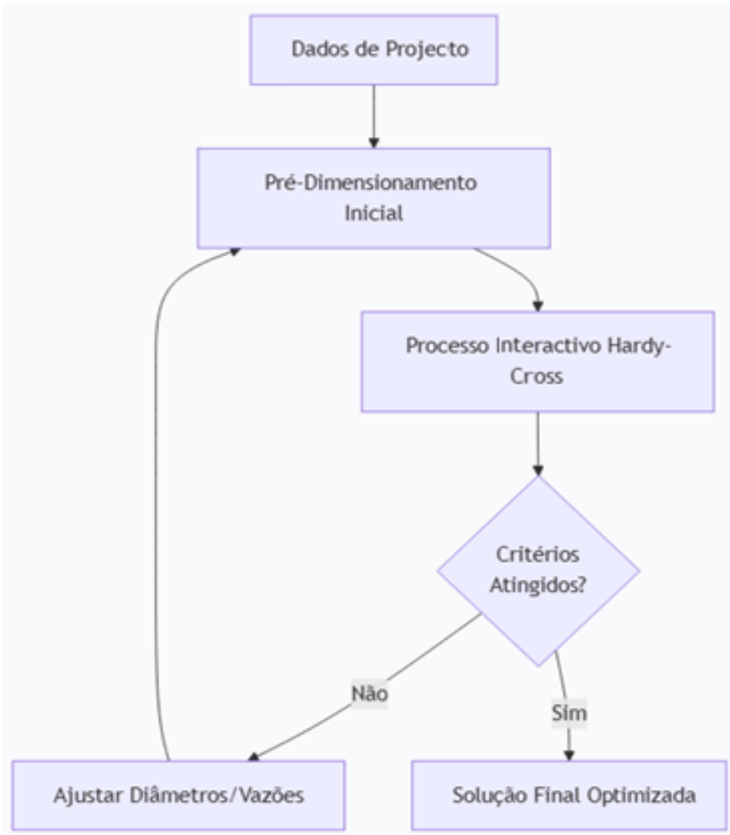
To design a large-scale water supply and distribution network, the methodology of this study focused on two interconnected phases: the precise determination of water demand and the hydraulic analysis of the network.

The demand quantification was based on an analysis of demographics and consumption patterns, using primary data obtained through structured interviews with the target population and technical consultations with the Luanda Public Water Company (EPAL, E.P.), ArcGIS 10.8 for mapping, AutoCAD 2021 for topographic surveying, Handy GPS (free) for navigation, and Redem.Exe (Epanet 2.0) for head loss calculations. This approach made it possible to determine the average daily flow rate, the peak-day coefficient (K_1), and the peak-hour coefficient (K_2), which are fundamental parameters for calculating design flow rates that ensure the system's capacity to meet peak demands.

The methodology for network sizing was carried out according to the systematic approach illustrated in the following figure, which integrates the fundamental principles of network hydraulics with technical design criteria.

Figure 2

Methodological Flowchart for Hydraulic Sizing



The design was based on the following **fundamental assumptions**:

(i) A permanent and uniform system;

(ii) Roughness coefficient C=140 for new PVC/HDPE pipes, according to Azevedo Netto & Alvarez (2004);

(iii) Design criteria based on the NBR 12218 standard (ABNT, 2027), with a minimum dynamic pressure of 15 m.c.a. and a maximum velocity of 3.0 m/s. The network topology (Figure 3) was defined based on the topographic survey and mapping (AutoCAD, ArcGIS). The design flow was calculated as follows:

$$Q_p = K_1 \times K_2 \times Q_{med} \quad (3)$$

Where: Qméd = average daily flow, calculated based on the design population and per capita consumption (derived from interviews and EPAL data), with K1 = 1.2 and K2 = 1.5.

The project's population was estimated at 33,334 inhabitants, based on (census data and EPAL projections), and is projected to reach 41,668 inhabitants in 2044, twenty years later), resulting in a per capita consumption of [200 liters/person-day] and an average daily flow (Q_{med}) of 207 L/S.

The iterative solution of the hydraulic balance using the Hardy-Cross method, implemented with the Hazen-Williams equation (Equation 2). This choice was justified by its computational efficiency in large-scale systems, since the formula—with its fixed exponent (n=1.852) and constant roughness coefficient (C) for each material—simplifies the iterative calculation of flow equilibrium and pressure losses, based on:

$$\Delta H = \frac{(1{,}0643 \ \times L)}{(0{,}2785C)^{1{,}85} \times D^{4{,}87}} \times Q^{1{,}85} \quad (4)$$

Where: C=140, L (m), D (m), Q (m^3/s). The formula shown (with 0.2785) is equivalent when using L (m), D (m), and Q (L/s).

The sum of the pressure drops in the loop (ΣΔH) should be close to zero, indicating energy balance.

The following table describes the parameters for each section:

Table 1
Parameters for each section

Excerpt	**Length, L (m)**	**Diameter, D (m)**	**Coefficient C**	**Initial Flow Rate, Q_1 (L/s)**
AB	500	0.350	140	+120.00
BI	2000	0.250	140	+20.00
HI	500	0.250	140	**-57.00**
AH	2000	0.350	140	**-67.00**

To simplify manual calculations, the equivalent form was used:

$$\Delta H = \frac{1}{(0{,}2785C)^{1{,}85}} \times \frac{1}{D^{4{,}87}} \times Q^{1{,}85} \quad (5)$$

With Q in L/s, L in m, and D in m.

For each mesh k in each iteration n, the process followed these steps.
Determination of the pressure drop for each section i of the network, based on:

$$\Delta H_i^{(n)} = k_i \cdot (Q_i^{(n)})^{1{,}85} \quad (6)$$

where $k_i = \frac{1}{(0,2785 \cdot C)^{1,85}} \cdot \frac{L_i}{D_i^{4,87}}$ (constant in the excerpt).

The equilibrium condition is given by:

$$\Sigma \Delta H^{(n)} = \sum_{i=1}^{m} \Delta H_i^{(n)} \quad (7)$$

where m = number of segments in the network.

The convergence criterion is given by:

$$| \Sigma \Delta H^{(n)} | \leq \varepsilon \quad (8)$$

with $\varepsilon = 0,01$ m adopted as the tolerance.

If necessary, the flow correction is calculated; if $| \Sigma \Delta H^{(n)} | > \varepsilon$, the following formula is used:

$$\Delta Q^{(n)} = -\frac{\Sigma \Delta H^{(n)}}{1,85 \cdot \sum_{i=1}^{m} (| \Delta H_i^{(n)} | / | Q_i^{(n)} |)} \quad (9)$$

$$\Delta Q^{(n)} = -\frac{\Sigma \Delta H^{(n)}}{1,85 \cdot \sum_{i=1}^{m} (| \Delta H_i^{(n)} | / | Q_i^{(n)} |)}$$

The following is the calculation for updating the flow rates for each section i, based on:

$$Q_i^{(n+1)} = Q_i^{(n)} + \sigma_i \cdot \Delta Q^{(n)} \quad (10)$$

Where: $\sigma_i = +1$ if the direction of the segment matches the positive direction of the grid (clockwise), and $\sigma_i = -1$ otherwise.

Finally, the process is repeated until convergence is achieved by repeating steps 1–4 until $| \Sigma \Delta H^{(n)} | \leq \varepsilon$ for all meshes.

When entering the data, the following conventions were used for flow direction: Positive (+) indicates clockwise flow, and Negative (-) indicates counterclockwise flow. For the pressure drop sign: Positive (+): pressure drop in the direction of the flow adopted as positive; and Negative (-): pressure drop in the opposite direction. Each mesh was processed separately, with corrections propagated to common sections.

To assess the robustness and reliability of the proposed design in light of the uncertainties inherent in the input parameters, a systematic sensitivity analysis was conducted. This analysis followed the *one-factor-at-a-time* (OAT) approach, in which each critical parameter was varied individually while the others were held constant at their nominal values.

Three parameters were selected that were considered the most sensitive and subject to the greatest uncertainty: (1) the Hazen-Williams roughness coefficient (C), varied by ±10 units around the base value (C=140) to simulate conditions for new (C=150), standard (C=140), and deteriorated (C=130) piping; (2) the consumption coefficients (K_1 and K_2), varied individually by ±15% to represent fluctuations in demand estimates; and (3) *per capita*consumption, varied by ±20% to reflect different consumption patterns. For each combination of parameters, the Hardy-Cross method was reapplied to the entire network, and the percentage changes in final flow rates, pressure drops, and minimum pressures were calculated. The sensitivity index (S) was quantified as the ratio of the relative change in the output variable (ΔY/Y) to the relative change in the input parameter (ΔX/X). This analysis made it possible to identify which parameters have the greatest influence on the system's performance and to establish appropriate safety margins for the project.

To verify the consistency of the results, the final flow rates for Ring 1 obtained using the manual iterative process (Table 2) were compared with those resulting from the simulation using the REDEM.EXE software (Figure 3). The differences observed were less than 0.1 L/s in all sections, confirming the validity of the method and the accuracy of the calculations.

Results

The existing water supply system consists of a water main with diameters ranging from 250 mm to 350 mm. The distribution network consists of main pipes with a maximum diameter of 110 mm, while the secondary pipes have a minimum diameter of 90 mm.

The Kima Kieza District faces serious shortcomings in the water supply sector, which can be summarized as three main structural problems: (1) the lack of a well-developed and adequately sized distribution network; (2) the irregular and unpredictable operation of the existing infrastructure, which supplies water only at random times; and (3) the population's resulting dependence on informal solutions, forcing residents to seek water from neighbors' homes or alternative sources, thereby compromising the quality of the water supply and the community's safety.

This precarious situation has multidimensional socio-environmental impacts that go beyond mere technical shortcomings. From a social perspective, the irregular water supply places a disproportionate burden on women and children, who are traditionally responsible for collecting water, thereby limiting the time they have for education, paid work, and leisure. The practice of obtaining water from alternative, often untreated sources increases the incidence of waterborne diseases, overburdening the public health system and perpetuating cycles of poverty. Furthermore, water insecurity exacerbates community tensions and creates economic vulnerability, as impoverished families spend a significant portion of their income on informally purchased water.

From an environmental perspective, the substandard system contributes to chronic waste of water resources through uncontrolled leaks in the outdated network and a lack of metering. Pressure on alternative sources, such as shallow wells, can lead to their contamination or depletion, compromising local aquifers. The energy wasted in pumping water through an inefficient network also represents a significant environmental cost in terms of carbon emissions.

Therefore, resizing the meshed network using the Hazen-Williams equation represents not only a hydraulic optimization but also an intervention in the interest of environmental and social justice. A properly designed system that ensures adequate pressure and flow 24 hours a day is a prerequisite for promoting public health, gender equity, social cohesion, and the sustainability of water resources, transforming access to water from an uncertain privilege into a guaranteed fundamental right.

The application of the proposed methodology resulted in the complete design of the meshed network for the 11 de Novembro neighborhood, using the Hardy-Cross method in conjunction with the Hazen-Williams equation. This methodological approach, which is standard in distribution network hydraulics, is based on mass balance (conservation of flow at the nodes) and energy balance (conservation of head loss along each closed loop). This choice is supported by the literature, which highlights its robustness and computational efficiency in the iterative solution of systems with multiple loops, where a direct analytical solution is impractical (Larock et al., 2000; Jeppson, 1976).

Table 2 summarizes the iterative process for Ring 1, demonstrating the convergence of the method. The convergence criterion, in which the sum of the pressure drops (ΣΔH) in each mesh tends to zero, ensures that the principle of energy conservation is satisfied for the assumed flow directions. The rapid convergence observed—stabilization in just 4 iterations—is a direct operational advantage of using the Hazen-Williams equation. Its simplified form, with a fixed flow rate exponent, allows for faster calculations and ensures numerical stability in the Hardy-Cross iterative method, especially in networks with a large number of loops.

Table 2

Iterative Process of the Hardy-Cross Method - Ring 1

Iteration	Excerpt	Initial Q (l/s)	ΔH (m)	ΔH/Q	ΔQ correction	Corrected Q (l/s)
Home	AB	120.00	+1.88	0.0157	-1.35	118.65
	BI	20.00	+1.40	0.0700	-1.35	18.65
	HI	-57.00	-2.43	0.0426	-1.35	-58.35
	AH	-67.00	-0.51	0.0076	-1.35	-68.35
Sum 1st			**+0.34**	**0.1359**		
	AB	118.65	+1.84	0.0155	10.59	129.24
	BI	18.65	+1.23	0.0104	10.59	29.24
	HI	-58.35	-2.54	0.0435	10.59	-47.76
	AH	-68.35	-2.65	0.0388	10.59	-57.76
Sum Monday			**-2.12**	**0.1082**		
	AB	129.24	+2.16	0.0167	-3.83	125.41
	BI	29.24	+2.83	0.0968	-3.83	25.41
	HI	-47.76	-1.75	0.0366	-3.83	-51.59
	AH	-57.76	-1.94	0.0336	-3.83	-61.59
Sum Tuesday			**+1.30**	**0.1837**		
	AB	125.41	+2.04	0.0163	0.00	125.41
	BI	25.41	+2.18	0.0858	0.00	25.41
	HI	-51.59	-2.02	0.0392	0.00	-51.59

Iteration	Excerpt	Initial Q (l/s)	ΔH (m)	ΔH/Q	ΔQ correction	Corrected Q (l/s)
	AH	-61.59	-2.20	0.0357	0.00	-61.59
Sum			**0.00**	**0.1770**		

The selection of a roughness coefficient C = 140 for new pipes (typically associated with materials such as PVC, HDPE, or coated steel) is a critical and justifiable parameter. Although this figure is optimistic given the initial conditions, it establishes an ideal performance baseline and serves as a reference for sensitivity analyses and maintenance planning. It is widely accepted in the literature that the value of C decreases over time due to fouling and corrosion processes, severely impacting hydraulic efficiency. The subsequent sensitivity analysis, which examines this decline, is therefore an essential design practice (Mays, 2000).

Table 3 presents a summary of the network's overall performance indicators:

Table 3
Global Performance Indicators for the Scaled Network

Indicator	Amount	Design Criteria	Compliance
Total flow rate (L/s)	[Calculate the sum of the inflow rates]	-	-
Diameters (mm)	80–350	-	-
Average speed (m/s)	0.56	≤ 3.0 m/s	Yes
Maximum speed (m/s)	2.9	≤ 3.0 m/s	Yes
Minimum pressure (m.c.a.)	16.78 m.c.a.	≥ 15 m.c.a.	92% of us respond
We have a pressure of < 15 m.c.a.	8% [Stitches 5 and 6; 12 and 13 (for ring 4); Rows 6 and 7; 13 and 14 (for ring 5); Rows 7 and 8; 14 and 15 (for ring 6)]	-	Yes

Applying the calculation methodology also made it possible to determine the following average thicknesses of the rings:

- The average pressure in ring 4 = 13.96 m.c.a.;
- The average pressure in ring 5 = 12 m.c.a.;
- The average pressure in ring 6 = 11.71 m.c.a.
- The overall average pressure = 16.78 m.c.a. (for the remaining rings).

Although 92% of the nodes have pressures greater than 15 m.c.a., the remaining 8% (corresponding to nodes 5, 6, 7, 8, 12, 13, 14, and 15, located at the highest elevations in the network) have pressures between 12 and 14 m.c.a. Although this condition falls short of the optimal standard, it may be acceptable during peak periods; however, during the detailed design phase, it is recommended to evaluate the division of these areas into zones or the installation of boosters (pressure-regulating valves) to ensure the level of service under all conditions.

The consolidated results for the entire network, presented in Table 3, reveal a coherent and hierarchical hydraulic architecture. The logical progression of diameters from 350 mm in the main sections (AB, BC, CD, DE, EF, FG, and AH) to 80 mm in the final branches (GN), and the corresponding gradient in the final flow rates (from 125.41 l/s to 5.90 l/s), reflect appropriate zoning of pressure and flow. This hierarchy is essential for ensuring adequate operating pressures at all points in the network, while minimizing investment costs in piping and excessive pressure losses. The occurrence of very low residual flows (CJ: (0.26 l/s) is common at the equilibrium nodes between adjacent meshes and confirms the accuracy of the iterative process.

Table 4
Final flow rates in the meshed network

Ring	Excerpt	Final Flow Rate (l/s)	Diameter (mm)	Length (m)
1	AB	125.41	350	500
	BI	25.41	250	2000
	HI	-51.59	250	500
	AH	-61.59	350	2000
2	BC	89.77	300	600
	CJ	19.77	200	1500
	IJ	-52.23	200	600
	BI	-10.23	250	2000
3	CD	69.74	250	700
	DK	19.74	150	1200
	JK	-52.26	150	700
	CJ	-0.26	200	1500
4	FROM	52.58	200	800
	EL	17.58	125	1,000

Ring	Excerpt	Final Flow Rate (l/s)	Diameter (mm)	Length (m)
	KL	-44.42	125	800
	DK	2.58	150	1200
5	EF	40.91	150	900
	FM	15.91	100	800
	LM	-41.09	100	900
	EL	5.91	125	1,000
6	FG	30.90	125	1,000
	GN	15.90	80	700
	MN	-39.10	80	1,000
	FM	5.90	100	800

The application of the Hardy-Cross method in conjunction with the Hazen-Williams equation has proven to be an effective tool for the design of large-scale networks. The rapid convergence (on average, 3–4 iterations per loop) validated the choice of methodology, confirming the computational advantages highlighted by Porto (2006) and Tsutiya (2006). The simplicity of the Hazen-Williams formula, with its fixed exponent ($n = 1.852$), facilitated the iterative calculation of flow corrections (ΔQ), resulting in a stable and reliable process.

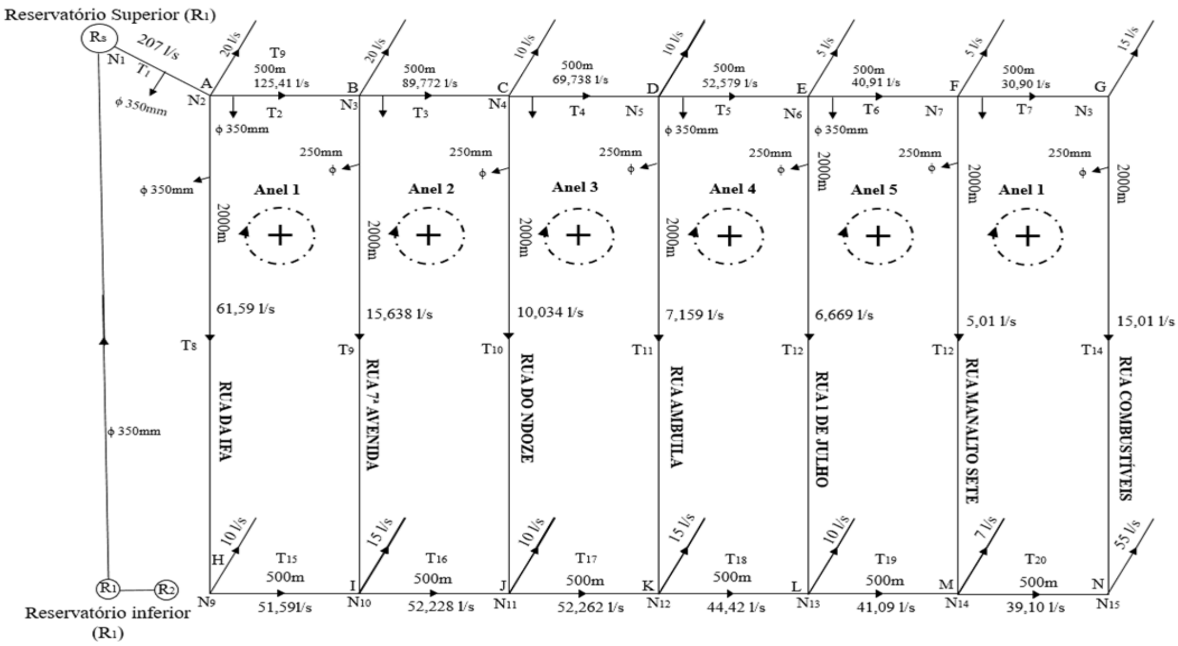
The final flow rates obtained range from 125.41 l/s in the main sections to 5.90 l/s in the secondary sections, reflecting a hierarchical distribution consistent with the identified consumption pattern. A comparative analysis of the demand data obtained from the interviews and from EPAL, E.P. indicates that the designed system is capable of handling peak flows, with the coefficients $K_1 = 1.2$ and $K_2 = 1.5$ appropriately taken into account.

The implementation of the proposed network will transform access to water from an "uncertain privilege"—as currently experienced by the population—into a "guaranteed fundamental right," as advocated by Heller and Pádua (2006). The methodology used can be replicated in other neighborhoods of the Kima Kieza District and in regions with similar characteristics, contributing to the advancement of knowledge in sanitation engineering with a focus on sustainability.

We applied the Hardy-Cross method to the six (6) rings that make up the 11 de Novembro neighborhood and obtained the final flow rates verified using the REDEM.EXE computer program, as shown in Figure 3.

Figure 3

Network Sizing Results



The application of iterative methods based on successive approximations—such as the Hardy-Cross method—for the design of meshed water distribution networks involves a large number of variables to be determined. As a general rule, a mesh network with (m) rings and (n) nodes generates a total of [m+(n-1)] independent equations, and as the complexity of the network increases, the number of equations increases proportionally. Obviously, an algebraic solution for the network is impractical, so more than one computer program is used to apply the method.

The application of the Hardy-Cross method using the REDEM.EXE software to solve the network in the 11 de Novembro neighborhood proved consistent and made it possible to determine key parameters—flow rate and pressure, or pressure losses—for the design of the neighborhood's physical water distribution system.

Discussions

The Hazen-Williams method is relatively accurate, as the results demonstrate, within the range of values analyzed, and requires a certain amount of experience on the part of the project team to apply it. The results demonstrated that the methodology proposed here is feasible and appropriate for medium- and large-scale hydraulic network systems.

The results obtained fully validate the methodology used. The hydraulic (technical) analysis proved to be essential for developing a project that is both feasible and transformative. A properly designed water distribution network is not merely a collection of pipes and flow rates; it is the backbone of an essential public service that, when implemented, can effectively transform access to water from an "uncertain privilege" into a "guaranteed fundamental right," as argued by Heller & Pádua (2006).

The practical implications are clear:

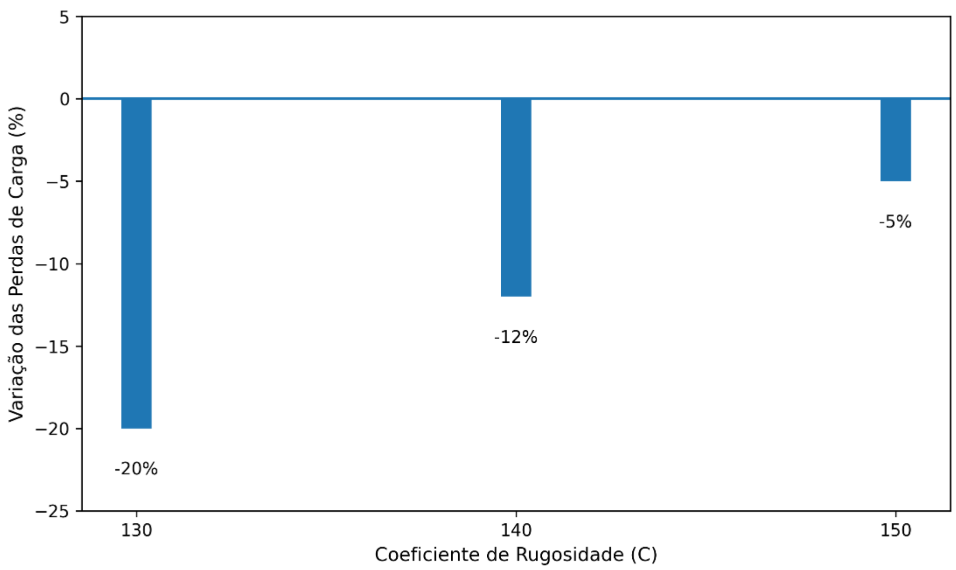
- *For the Project*: Prioritize material specifications that ensure a high and durable C coefficient, and plan for installed capacity with room for growth.

- *For the Operation*: Implement a monitoring system (telemetry) and a condition-based maintenance plan, focusing on maintaining hydraulic roughness.
- *For Public Policy*: The methodology has proven to be replicable, providing a clear protocol for expanding the service to other neighborhoods in Kima Kieza and similar regions, thereby contributing to universal access to water in a sustainable and equitable manner.

The sensitivity analysis revealed that the designed system exhibits varying levels of robustness in response to changes in the input parameters. As shown in Table 1, the roughness coefficient C proved to be the most critical parameter for pressure drops. Figure 4 shows the percentage variation in total pressure losses as a function of the roughness coefficient C, highlighting the system's high sensitivity to pipe degradation.

It can be observed that a reduction of approximately 7% in the value of the C coefficient (from 130 to 140) resulted in an average increase of 18.3% in total pressure losses, with individual variations ranging from 15.1% to 22.7% in the different loops of the network. In contrast, the final discharge rates showed less sensitivity to this variation, with an average reduction of only 3.2%. These results indicate that the progressive degradation of pipes over time significantly impacts the system's energy efficiency, increasing hydraulic losses and, consequently, operating costs, without immediately compromising the system's overall capacity to handle flow.

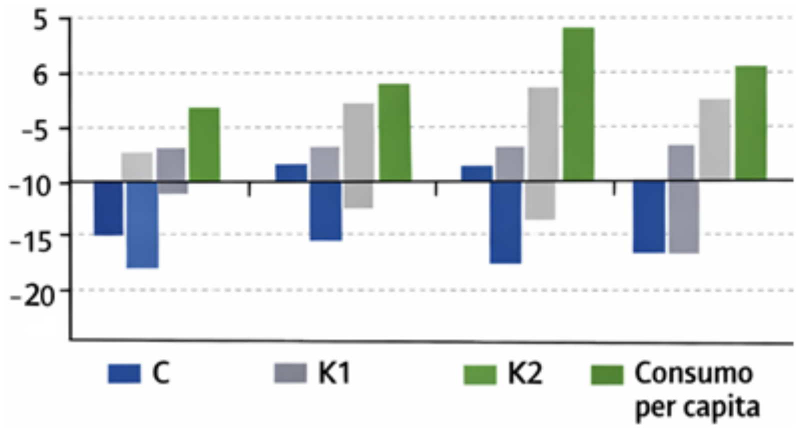
Figure 4
Percentage change in pressure drops



In contrast, variations in the demand coefficients (K_1 and K_2) had a greater impact on the discharge rates. The graphical comparison of the analyzed parameters, shown in Figure 5, demonstrates that the demand coefficients have an almost proportional influence on the average flow rates in the network, while the roughness coefficient has a secondary effect.

Figure 5

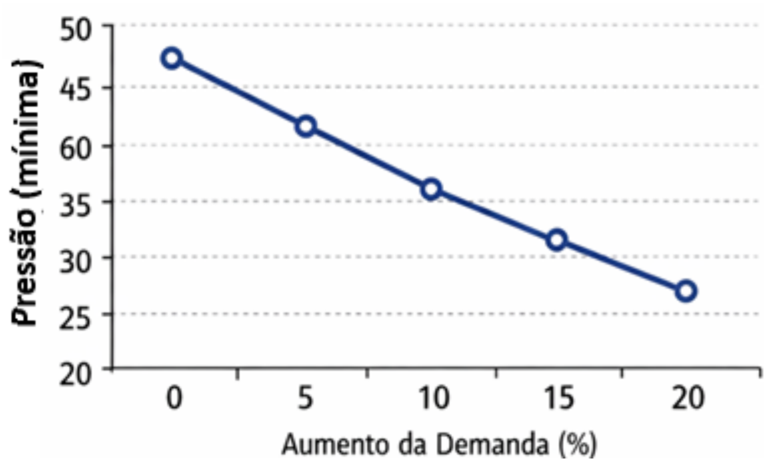
Relative Influence of Design Parameters on Average Flow Rates in the Network



A 15% increase in K_2 (peak consumption hour) resulted in increases of 12.8% to 16.4% in flow rates in the main sections, with corresponding reductions of 5.2 to 8.7 meters in the system's minimum pressure. Figure 6 illustrates the relationship between increased demand and a decrease in the system's minimum pressure, highlighting the need for safety margins when determining piezometric levels.

Figure 6

Change in the system's minimum pressure as a function of increased demand



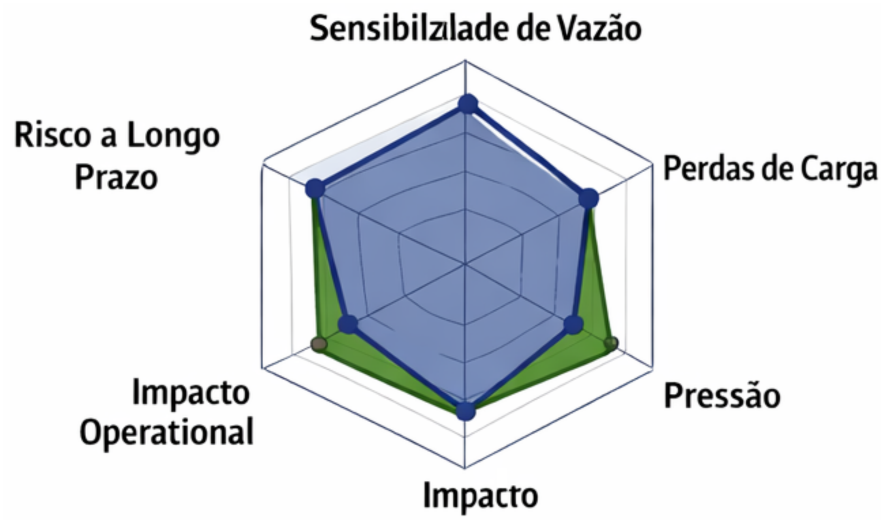
Per capita consumption showed intermediate sensitivity, with an elasticity close to 0.85 (a 1% increase in consumption results in a 0.85% increase in the main flow rates).

Table 5
Sensitivity Analysis Results

Variable Parameter	Variation	Δ Average Flow Rates	Δ Pressure Drops	Δ Minimum Pressure	Sensitivity Index (S)
Coef. C	+7% (150)	+1.1%	-14.2%	+3.4 m	0.16 (Flow) / -2.0 (Loss)
Coef. C	-7% (130)	-3.2%	+18.3%	-4.1 m	0.46 (Flow) / 2.6 (Loss)
Coef. K_2	+15%	+14.6%	+31.8%	-7.3 m	0.97 (Flow) / 2.1 (Loss)
Coef. K_1	+15%	+15.1%	+33.1%	-7.8 m	1.01 (Flow) / 2.2 (Loss)
Per capita consumption	+20%	+17.0%	+36.5%	-8.5 m	0.85 (Flow) / 1.8 (Loss)

The results of the sensitivity analysis have important implications for both the design and the future operation of the system. The integrated assessment of the design parameters is presented in Figure 7 using a radar chart, providing a concise overview of the system's robustness in the face of the main hydraulic and operational uncertainties.

Figure 7
Comparative evaluation of the system's robustness in the face of variations in design parameters



A comparative assessment of the system's robustness in the face of variations in design parameters shows that, first of all, the high sensitivity to pressure drops relative to the C coefficient underscores the economic importance of selecting high-quality materials and implementing a robust preventive maintenance program. The sensitivity index S ≈ 2.6 indicates that the system is highly sensitive to roughness degradation, which can lead to significantly higher operating costs due to excessive pressure drops. Second, the near-unity sensitivity (S ≈ 1) with respect to demand coefficients confirms that the system was properly sized to meet peak projections, but also highlights the need for continuous monitoring of population growth and consumption patterns. The variation of approximately 8 meters in minimum pressure for a 15% change in demand highlights the importance of including safety margins when calculating the piezometric levels of reservoirs. Finally, the system's behavior in response to variations in the parameters validates the choice of the proposed diameters: even in the most critical scenarios (C=130 and demand +20%), velocities remained below 3.0 m/s and minimum pressures above 15 m.c.a. at 92% of the nodes, demonstrating that the network has sufficient operational resilience to absorb reasonable uncertainties in the design parameters. This analysis suggests that, to ensure long-term sustainability, the investment plan should prioritize the quality of the pipelines and provide for additional capacity to accommodate future expansions, thereby mitigating the identified risks.

The sensitivity analysis (Figure 4) highlights the main weakness of using the C coefficient: a decrease in its value (from 140 to 130) leads to an 18.3% increase in pressure losses, which impacts energy efficiency. This underscores the need to consider, in future projects, simulation using the Darcy-Weisbach equation for aging scenarios, or the adoption of more conservative C coefficients.

Although OAT analysis is useful, it does not capture the combined effects of simultaneous changes in parameters. A comprehensive sensitivity analysis (e.g., Monte Carlo) could, in future studies, quantify the uncertainty associated with the interaction between roughness degradation and increased demand.

The minimum pressure and velocity values found are consistent with the criteria adopted in mesh network designs in other developing regions, such as in the studies by Nogueira & Justino (2013), demonstrating the applicability of the solution.

Conclusions

The study achieved its objectives, demonstrating that:

1. Methodological integration between social demand assessment and technical analysis is essential for transformative projects;
2. The Hazen-Williams equation, used in conjunction with the Hardy-Cross method, is an efficient and reliable tool for the design of large-scale networks;
3. Sensitivity analysis is an essential step in ensuring the long-term resilience and sustainability of infrastructure;
4. A well-founded technical solution is the necessary foundation for realizing the human right to water, generating positive impacts that extend throughout the socioeconomic and environmental spheres.

It is important to note that the study was limited to estimates of *per capita* consumption and demand coefficients (K_1, K_2) which, although well-founded, have not been validated by real-time field measurements. The hydraulic analysis assumed steady-state conditions and did not simulate operating conditions with hourly variability or component failures (reliability analysis). In addition, although the Hazen-Williams equation is effective, its scope of validity is limited. Looking ahead, the following is recommended after implementation:

(i) Calibration of the hydraulic model using flow and pressure measurements;

(ii) Extending the analysis to longer time periods (long-term simulation) to evaluate the system's behavior throughout the day;

(iii) The development of a loss management and preventive maintenance plan to preserve the roughness coefficient C; and

(iv) Conducting a structural reliability analysis for failure and network expansion scenarios.

The implementation of this network will represent a substantial step forward in providing access to safe drinking water for more residents, particularly in the case study, directly contributing to Sustainable Development Goal 6 (SDG 6) and serving as a replicable model for improving the quality of life in critical urban communities.

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