Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X

http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

REVISTA AIDIS

de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica.

USE OF HYDRAULIC SIMULATION AS A TOOL IN DECISION MAKING IN WATER SUPPLY NETWORK: A CASE STUDY IN THE BRAZILIAN CITY OF SÃO GABRIEL, RS

Matheus Rodrigues Martins [1]
Débora Missio Bayer [2]
* Luiza Chiarelli Conte [2]
Luiz Antonio de Brito Bertazzo [3]

Recibido el 8 de diciembre de 2022. Aceptado el 31 de marzo de 2023

Abstract
Population care by water supply networks has evolved in the world but it is still not a reality for the entire population. In the existing systems, almost 40% of the volume of water available does not reach the user. An important variable that influences water losses in the system is the pressure. In this work, part of the water distribution system in the Brazilian city of So Gabriel, in the state of Rio Grande do Sul (RS), was evaluated through hydraulic simulation using [public domain, water distribution system modeling software package developed by the United States Environmental Protection Agencys (EPA) Water Supply and Water Resources Division] EPANET in three different scenarios: maximum, minimum and sustainable water consumption. In the simulations, the pressures and speeds in the distribution system were analyzed, which allowed the proposition of interventions such as: installation of accessories (pump and pressure reducing valves), reducing diameters of some pipe sections, alteration of the operating regime of already existing pumps, system sectorization and estimates of loss reduction resulting from these interventions.

Keywords: water supply network, water losses, pressure.

[1] Universidade Paranaense, Toledo, Paraná, Brazil.
[2] Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brazil.
[3] São Gabriel Saneamento, São Gabriel, Rio Grande do Sul, Brazil.
* *Autor corresponsal:* Departamento de Engenharia Sanitária e Ambiental, Universidade Federal de Santa Maria. Av. Roraima, 1000, Campus, Prédio 10 – Camobi, Santa Maria, Rio Grande do Sul. Brasil. Email: cconteluiza@gmail.com

ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

Introduction

In 2020 only six out of eight people in the world had access to a safe drinking (potable) water system and only three out of five people used adequate sanitation services (WHO, 2021). Indicators from the Brazilian Sanitation Information System (SNIS) point out that in Brazil in 2020 more than 175.5 million people had access to drinking water, accounting for more than 728,000 km of a distribution system (SNIS, 2021). This represents, according to population estimates for 2020 by the Brazilian Institute of Geography and Statistics (IBGE, 2020), a service to about 83% of the Brazilian population.

Brazil has a continental extension with spatial heterogeneity in social, economic and population aspects. Daily water consumption also reflects the country's heterogeneity, since there is a difference of 51.4 L per person between the Southeast region, with the highest per capita daily consumption among the country's regions (171.7 L) and the Northeast region with the smallest (120.3 L) (SNIS, 2021).

Historical data has pointed to a reduction in water consumption but a small increase in water losses. All supply systems undergo some kind of loss (Ganorkar *et al*., 2013) and although some losses are inevitable or compensate very little for their extinction, most of them can be identified and resolved by means of careful analysis (Shabangu *et al*., 2020). The loss index of a system is one of the main indicators of the operation efficiency of a water supply network (Baggio *et al*., 2013). From 2019 to 2020 losses in distribution rose from 39.2% (SNIS, 2020), to 40.1% (SNIS, 2021), that is, in 2020, for every 100 L treated water, only 59.9 L were really billed. Water losses can be divided into apparent losses and real losses and the index mentioned above does not separate them.

Water losses control is part of the decision-making process taking place in the supply system management, the distribution system being an extremely important step in this process (Lima *et al*., 2018; Shabangu *et al*., 2020). There is a potential for reducing water losses in Brazil. For this, the use of tools capable of assisting managers in operationalizing and making decisions in an urban water supply network is essential. NBR (Brazilian standard) ABNT (Brazilian Association of Technical Standards) 12.218 (ABNT, 2017) shows that the global system dimensioning and analysis must be done by means of hydraulic simulation. Hydraulic simulation can also assist managers in making decisions on systems already in place, especially in cases where projects decisions have influenced the system operationalization and are potential generators of water losses. This is the case for a section of the São Gabriel supply system, in the state of Rio Grande do Sul (RS), Brazil. Therefore, in this work this system section is evaluated in terms of proposing improvements in order to meet Brazilian standards and to reduce real water losses.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

Control of leakages can be performed with the control of pressure in the pipeline, active control of leakages and speed and quality in repairs (Lambert & Mckenzie, 2002; Price *et al*., 2022). Due to the increase in water demand caused by the advance of urbanization (SNIS, 2021) it becomes increasingly necessary to improve and better control possible losses that occur in the supply system and with its expansion. Excess pressure is the main reason for leakages in the pipelines (SNIS, 2021). This excess can be caused by project choices or large topographic variation.

Pressure control in the pipeline, that is, an active control of leakages and speed and quality in repairs, requires detailed monitoring of the supply system functioning (Price *et al*., 2022). The system is complex to manage, which is why it is recommended to split the distribution system into measurement and control districts (DMC), that is, a sectorization of the distribution system. The DMC is a region of the system that can be isolated, thus allowing the control of pressures and flows, the monitoring of the system and consequently a possibility of controlling losses (ABNT, 2017).

Case study

Water distribution network

The water distribution network evaluated in this study belongs to the districts of Bom Fim and Medianeira of the São Gabriel city, RS. The urban population of the city is estimated at 53,292 (IBGE, 2010) inhabitants, and the utility serves 22,924 service connections (SGSSA, 2017). In the districts under study, the network serves 816 service connections, resulting in a population estimate of about 2,000 inhabitants.

The layout and specifications of the pipelines and information on the operation of the system were obtained from the company that manages the city's water supply and sewage system, São Gabriel Saneamento (SGS). It is a private company, belonging to the multinational Solvi group, which started the provision of services in 2012, with a concession for 30 years. The company was not responsible for the design and installation of the network under study.

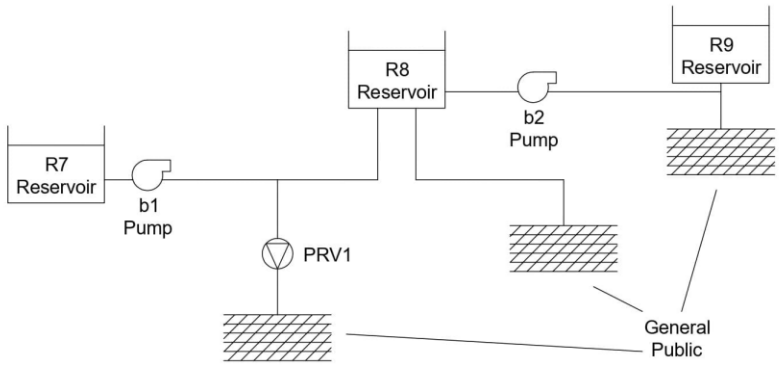
Hydraulic simulation and characteristics of the distribution system under study

To evaluate the system, the EPANET software (Rossman, 2000) was used. It is widely applied in simulation and optimization of water distribution systems, as in Castro and Costa (2004), Barroso and Gastaldini (2010), Vilas-Boas (2008), Moreira (2011), Adachi *et al*. (2014), Mohapatra *et al*. (2014), Bolognesi *et al*. (2014), Farina *et al*. (2014), Saldarriaga and Salcedo (2015), Nagaraj *et al*. (2021) and Price *et al*., 2022.

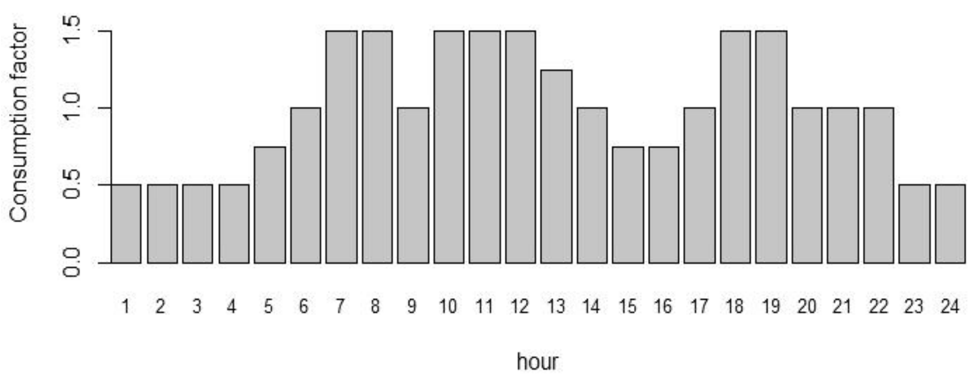
São Gabriel city has six reservoirs in use, of which only three (R7, R8 and R9) belong to the studied system section. The reservoir R7 is located in the center city and receives water from the

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica.
ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

treatment plant, and supplies the different areas of the city. Therefore, this reservoir shall be considered as the starting point of the system under study. In Figure 1(a) a scheme of the studied system section is presented.



(a) Scheme of the water distribution system.



(b) Consumption factor in São Gabriel city.

Figure 1. Scheme representing the water distribution system of the Bom Fim and Medianeira districts and hourly variation in water consumption in the distribution system. In Figure 1(a) PRV1 is a pressure reducing valve.

The Medianeira treated water pumping stations (EEAT) (pump b1) is located just after the reservoir R7. Pump b1 that performs the discharge is the brand MEGANORM, model 050-032-125 GG. The Bom Fim EEAT is located downstream of the reservoir R9 and consists of a pump b2,

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

brand MEGANORM, model 080-050-125 GG. Installed in the tap-changing that supplies the population after the reservoir R7, the pressure reducing valves (PRV1) was not yet in operation and has a valve control parameter of 375 kPa.

The system under study consists of 24,196 m of pipes. The composition of the system is given by 38% of the length of pipes with NPS (nominal pipe size) 50; 4% with NPS 75; 25% with NPS 100 and 13% with NPS 150.

Per capita consumption has been determined using the total monthly flow data for 2017 at the entrance to the study area. Regarding the variations in water consumption that occur by throughout the day, these were adopted as presented in Figure 1(b). The consumption variation temporal pattern was defined by means of the preliminary simulations results in comparisons with real pressure values and together with the SGS Company's technical staff.

Evaluated scenarios

Three scenarios were proposed to verify the adequacy of the distribution system functioning in relation to NBR 12218 (ABNT, 2017). The first is Scenario 1, which corresponds to the maximum water consumption that occurred in March 2017, which was 3.12 L/s (139.25 L/inhabitants/day). Scenario 2 corresponds to minimum consumption in May 2017, that is, 2.52 L/s (112.40 L/inhabitants/day). Scenario 3 seeks to evaluate the effects of introducing sustainable practices in the supply system such as rainwater reuse and/or graywater reuse.

In Scenario 3 consumption was estimated by means of the reuse of 1.34 L/s (about 53% of the minimum consumption) corresponding to uses such as flushing, irrigating gardens, cleaning houses and sidewalks and washing cars. Thus, the consumption used in the simulation was 1.18 L/s since it was evaluated in the situation of minimum consumption.

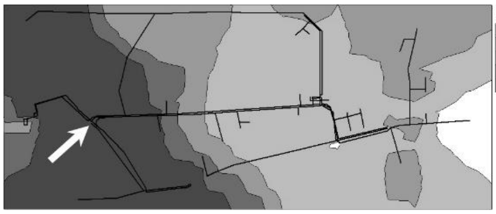
Dynamic simulation of the proposed scenarios

All simulations in present work were carried out for a period of 72 hours, with one-hour interval among the results. To calculate the distributed head loss, the Hazen-Williams equation was used, with a roughness coefficient (C) equal to 130, while the local head loss was considered negligible.

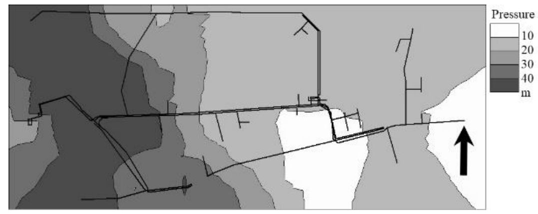
Scenario 1: maximum consumption

According to the hydraulic simulation, the maximum pressure in the system occurs when pump b1 is in operation. This pump is used to maintain the level of the reservoir R8 above 0.65 m (level established as a minimum by the SGS company). The minimum pressure values occur when the R8 water level is close to this minimum level of 0.65 m and the system is being supplied by gravity. In Figure 2 pressure maps for Scenario 1 are shown.

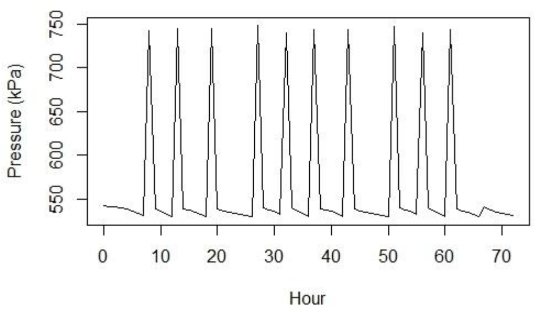
Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica.
ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024



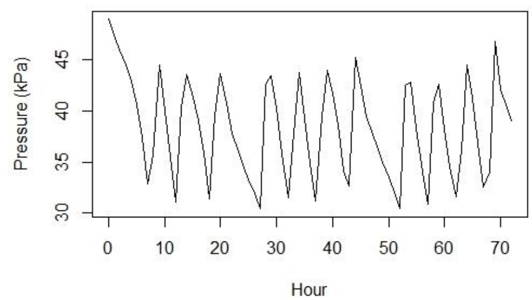
(a) Maximum system pressures



(b) Minimum system pressures.



(c) Node indicated in Figure 2(a)



(d) Node indicated in Figure 2(b)

Figure 2. Distribution system pressure map for Scenario 1 in (a) and (b), maximum consumption. The arrow in (a) indicates the location of the node whose pressure variation over the 72 hours of simulation is shown in (c) and the arrow in (b) the node of (d).

NBR 12218 (ABNT, 2017) does not establish a maximum dynamic pressure value but the higher this value, the shorter the life of the pipes and the more susceptible they are to cracking and rupture. In Figures 2(a) and 2(b) the pipes contained in the regions in two darker shades of gray have dynamic pressures above 300 kPa (30 meters of water gauge or column - mH2O), values that would be above the recommendation of 250 kPa to 300 kPa for maximum static pressure. In the pipes contained in the white region, the dynamic pressures are below 100 kPa (10 mH2O) established by NBR 12218 (ABNT, 2017) as the minimum dynamic pressure.

Only in the pipes in the regions in the two shades of light gray the pressures would be in ideal operating conditions. In Figures 2(c) and (d) pressure variations are shown at two nodes in the distribution system. The node of Figure 2(c) is located in the first tap-changing after reservoir R7. Pressure peaks occur every time pump b1 is activated, reaching 750 kPa (75 mH2O). The minimum pressure values are always above 530 kPa (53 mH2O) and occur when the system is being supplied by gravity by means of the reservoir R8. This is due to the large difference in topographical projection between the reservoir R8 and the point under analysis,

ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

which is 52.36 m. In this case, for topographic reasons, the node and its surrounding region have high values of dynamic pressure.

The node of Figure 2(d) is located at the furthest point from the beginning of the system in a region that is topographically high in relation to the rest of the distribution system. This point and all its surroundings are supplied by reservoirs R9 and R8 with the aid of pump b2. In this region, the dynamic pressure values are always below 100 kPa (10 mH2O).

Water speed in the distribution system was below 0.50 m/s in many sections. Of the 79 sections of pipe studied, 58% have NPS above 50 mm (about 16,000 m of pipe). Of these, 52% could have their pipes replaced by smaller diameters (about 8,300 m of pipeline) since they had speeds between zero and 0.29 m/s. Reduction of all possible diameters (without preventing the hydraulic simulation) implied the adaptation of the minimum speed with that established by NBR 12218 (ABNT, 2017) in only eight sections (18% of the 52%, about 1,500 m of pipelines). That is, these substitutions would not solve the problem of low speeds in the distribution system. In addition, reductions in diameters have aggravated the situation of the sections where the pressure was less than 100 kPa or very close to that value.

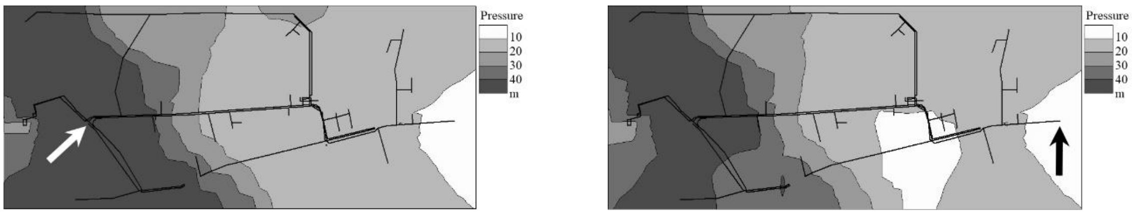
Scenario 2: minimum consumption

The simulated system with minimum consumption values have shown maximum and minimum pressure areas as shown in Figure 3. The high-pressure regions (dark gray and white) are similar to those in Scenario 1 (Figure 2). The white regions remain well delimited, indicating that pressures below 100 kPa remain.

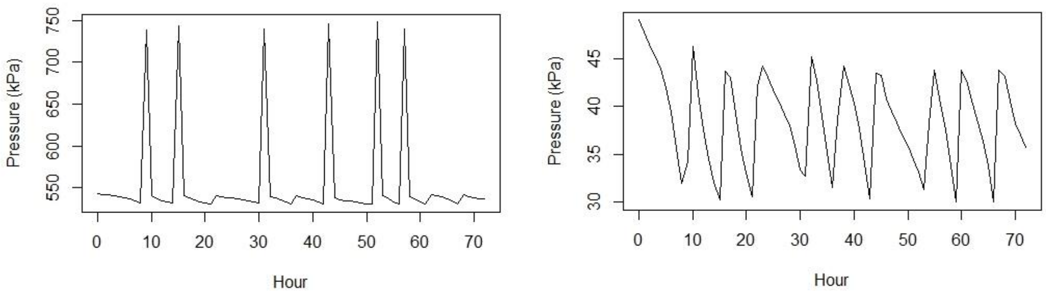
In Figures 3(c) and 3(d) pressure variations are presented in the same nodes as Figure 2(c) and 2(d), respectively. The most significant change in relation to Scenario 1 occurs when comparing the high-pressure region, Figure 2(c) with Figure 3(c). It is observed that the reduction in consumption implied a decrease in the number of pump b1 operations, resulting in a lower number of pressure peaks. In the low pressure region there was little impact due to reduced consumption, as can be seen in the comparison between Figure 2(d) and Figure 3(d). This is because this region is supplied by gravity, with the water coming mostly from the reservoir R9, with the existing pressure head being only the reservoir level.

With the decrease in consumption in Scenario 2, the system speeds were 50% lower than in Scenario 1. Simple reduction of diameters would not be enough to increase the speed. However, if associated with other measures it can be advantageous for the system management. A second measure that could assist in the system management would be its sectorization, dividing it into DMCs, presented in Item 2.3.4.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica.
ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024



(a) Maximum system pressures (b) Minimum system pressures.



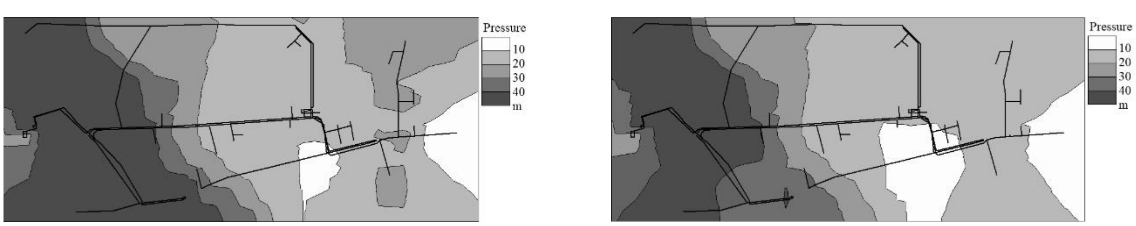
(c) Node indicated in Figure 3(a). (d) Node indicated in Figure 3(b).

Figure 3. Distribution system pressure map for Scenario 2 in (a) and (b), minimum consumption. The arrow in (a) indicates the location of the node whose pressure variation over the 72 hours of simulation is shown in (c) and the arrow in (b) the node of (d).

Scenario 3: sustainable consumption

The implementation of Scenario 3 would give rise to pressure values slightly higher than those presented in the Scenario 2 simulations. In the region where the pressures are lowest, that is, the white region in Figure 4(a), the increase would be about 2%, which would not result in adaptation to the minimum value established by the standard. In this region, the average pressure was 38.6±8.8 kPa, still below the minimum value of 100 kPa.

In relation to the speed in the pipes, these were lower than those obtained for Scenario 2. Speeds ranged from 0.09 to zero in some sections. The average speed in the scenario was 0.011 m/s, thus disagreeing with NBR 12218 (ABNT, 2017).



(a) Maximum system pressures (b) Minimum system pressures.

Figure 4. Distribution system pressure map for Scenario 3, sustainable consumption.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

Distribution system sectorization

In a distribution system with large pressure ranges sectorization is interesting. In the Figure 5 a proposal for sectorization of the distribution system is presented. Sector 1 (S1) would encompass the region with the highest-pressure values. This sector starts at PRV1, already installed, but still inoperative. The start of PRV1 operation for a control parameter of 375 kPa is essential to reduce the pressure in this sector, which can reach values of up to 750 kPa. In addition, it is suggested that pump b1 has its control parameter changed so that its speed is 40% of the current operating speed value. In this way, its operation, that is, the filling of the reservoir R8, would be slower but there would be no sharp spikes in flow and pressure.

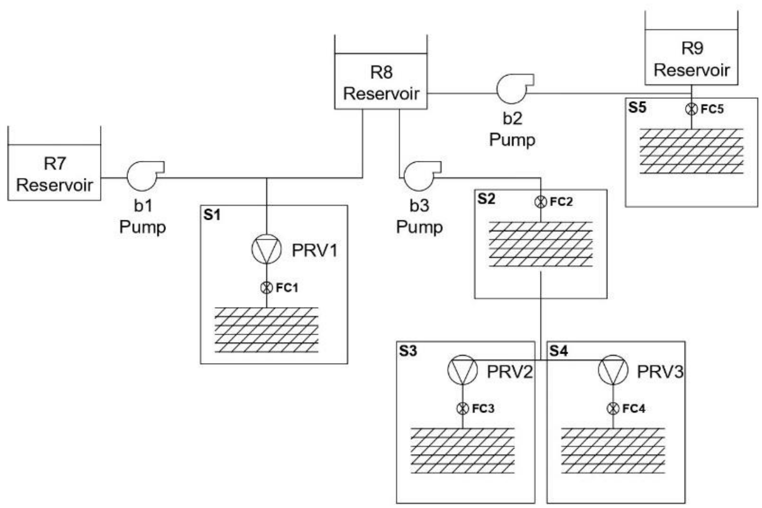


Figure 5. Proposed sectorization for the distribution system. FC are flow meters, and S are sectors.

Sector 2 (S2) starts downstream of the reservoir R8 and is the largest sector proposed. The simulations indicate that in this sector there are no problems in relation to the maximum pressures. However, there are small sections where the minimum pressures are below 100 kPa. In this region, it is recommended to install a pressure gauge at the most unfavorable point (highest topographical projection) of the system. In addition, installing a pump (b3) identical to pump b2 after reservoir R8 is suggested in order to guarantee that these zones have the pressure above the minimum value established by NBR12218 (ABNT, 2017).

Sectors 3 (S3) and 4 (S4) are downstream from S2. In these sectors (S3 and S4) high pressure values occur and installing PRVs is recommended. PRVs would need to be configured for control parameters of 375 kPa and 175 kPa in S3 and S4, respectively. In these sectors, at points with the lowest topographical projections, installing pressure gauges is recommended.

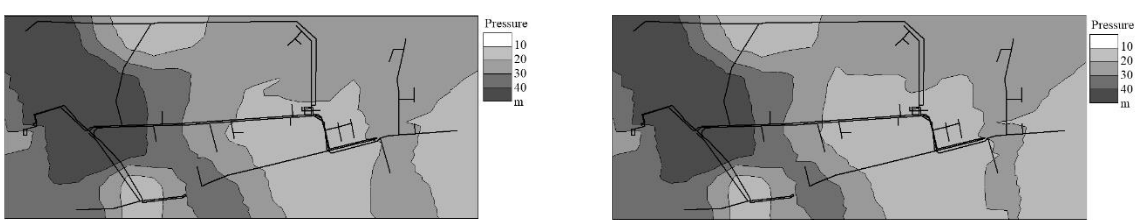
Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

Sector 5 (S5) would include the system downstream of reservoir R9. Pump b2 injects water directly into this system, indicating a change in its operation control, increasing its speed 93% in relation to the current speed. This increase would imply an improvement in service in the region with low pressure values (white region on the right in Figures 2(a), 2(b), 3(a), 3(b), 4(a) and 4(b)). In addition, installing pressure gauges at the high points of the system is recommended since this region have pressures below 100 kPa. To allow monitoring of possible leakages and control of the sector, installing flow meters (FC) at the entrance of each sector is recommended as indicated in Figure 5.

To verify the suitability of the proposed interventions, Scenario 3 was simulated again, as it is the most critical in relation to the maximum pressures. However, considering the changes in the operation of pumps b1 and b2, the inclusion of pump b3 in S2, the beginning of the PRV1 operation, the inclusion of PRVs in S3 and S4. In Figure 6 the pressure map is displayed for the situation of maximum and minimum pressures in the system.

Under these conditions the system is almost completely compliant with NBR 12218 (ABNT, 2017), except for the dark gray region. However, even if the maximum pressure value in these conditions is 577.4 kPa (57.74 mH2O), it is about 23% lower than the maximum pressure value acting in Scenario 2, with minimum consumption and without changes.

The simulations indicate that although the system continues to have low speed values, only 6% of the sections reached the minimum value of 0.5 m/s of NBR 12218 (ABNT, 2017), in general there is an increase of up to 25% in speed values in relation to Scenario 3.



(a) Maximum system pressures (b) Minimum system pressures.

Figure 6. Distribution system pressure map for Scenario 3, sustainable consumption considering the proposed changes in the distribution system functioning.

Quantification of water losses and economic viability of PRVs

With the inclusion and operation of PRVs and a more efficient and rational pumping, a reduction in water losses is expected due to the decrease in pressure to which the system is subjected. The estimate of water losses was carried out considering that the size of the leakage hole varies according to the pressure in the system (Lambert, 2001),

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X

http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

$$Q_1 = Q_0 \left(\frac{P_1}{P_0}\right)^{N_1} \qquad \textbf{Equation (1)}$$

where Q_0 is the the initial leakage flow (L/h) which occurs with pressure P_0 (mH2O), Q_1 is the final leakage flow (L/h) which occurs with pressure P_1 (mH2O) and N_1 is a dimensionless coefficient that varies depending on the material of the pipe. As the pipes in the studied system are made of PVC (polyvinyl chloride), the value of $N_1 = 0.5$ has been used (Greyvenstein & Zyl, 2007).

In this stage, a comparison was made among the system pressures without interventions (real system) with the system with the proposed interventions. In the original system, it was considered that the existing pressures would cause water losses due to leakage of about 30% of the total system losses (Araujo *et al*., 2006). Total losses are estimated at 31%, according to the SGS Company.

In S1 the pressure reduction in the system would prevent loss of about 28 thousand liters of water monthly (Equation 1). According to the SGS tariff table, the price per cubic meter of water in the residential category is BRL 4.94 (US$ 0.93), which would represent BRL 1,659.84 (US$ 312.59) of annual return for the company.

In sectors S3 and S4 the installation of PRVs would prevent losses of about 38.88 L/year and 72.36 L/year, respectively. These would not have such an expressive return, BRL 192.07 (US$ 36.17) per year and BRL 357.46 (US$ 67.32) per year to S3 and S4 respectively. This low return, even in the long run, would indicate a possible financial infeasibility in the installation of these PRVs. Pipes could be replaced more frequency instead of PRV installation since they shall have their life reduced by the excess pressure to which they are subjected. These values are less expressive than the return value of S1 because there is a lesser reduction in pressure in sectors S3 and S4 of 12% and 10%, respectively, compared to 31% reduction in pressure values in S1.

Discussions and conclusions

Water supply networks are essential for society. Taking water to consumers means taking it safely and guaranteeing its quality. In this sense, it is also essential to be careful with the water losses in the system and to comply with current regulations. Economic analysis of how feasible and desirable water losses control is, as well as the monitoring of how much of the loss that occurs in the system is real loss and not measurement error or billing error, is crucial in the water supply system management.

To combat real losses, the main tools available are pressure control and active leakage control. Pressure control can be performed by means of using equipment such as pumps and PRVs, and by means of this control, the supply system rationalization is sought.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

For an efficient analysis of supply systems, NBR 12218 proposes the adoption of the use of hydraulic simulations in new projects (ABNT, 2017). However, for existing systems its use can be a facilitator in making operational decisions.

Investment in accessories in a distribution system may not be, many times, financially viable and may not have technical improvement justifying such an intervention. In the case evaluated in this work, specific interventions such as change in the operation regime of pumps b1 and b2 and the start of the PRV1 operation would bring a favorable result to the system without the need for new investments.

Acquisition and installation of new PRVs would represent a significant initial investment and technical gain, although existing might not be enough to justify them. Pump b3, in spite of needing a considerable initial investment for acquisition and maintenance costs, would bring technical suitability to the S5 sector since its use would allow the water supply service within the molds provided for in the NBR 12.218 standard. However, further analysis would be necessary to evaluate the influence or possible occurrence of water hammer in the system due to the addition of this pump.

Taking into account several uncertainties associated with the study, implementation of water reuse and the use of rainwater would result in a significant drop in water consumption from the concessionaire and consequently a reduction in revenue. These issues need to be evaluated in order to guarantee the maintenance of the quality of services. In general, sectorization of this section of the system is necessary since it is divided into different piezometric zones, which makes management difficult as a whole.

Acknowledgements

We thank the company São Gabriel Saneamento for providing the operating water supply system data, and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001 for the financial support.

References

ABNT (Ed.) (2017) NBR12.218 *Projeto de rede de distribuição de água para abastecimento público*.

Adachi S, Takahashi S, Kurisu H and Tadokoro H (2014) Estimating area leakage in water networks based on hydraulic model and asset information. *Procedia Engineering* **89**, 278–285.

Araujo LS, Ramos H and Coelho ST (2006) Pressure control for leakage minimisation in water distribution systems management. *Water Resources Management* **20**, 133-149.

Baggio M, ao AG, Rosito CA, Tardelli J and Ajzenberg M (2013) Perdas em Sistemas de Abastecimento de Água: Diagnóstico, Potencial de Ganhos com sua Redução e Propostas de Medidas para o Combate. Technical report, *Associação Brasileira de Engenharia Sanitária e Ambiental*.

http://dx.doi.org/10.22201/iingen.0718378xe.17.1.84270
Vol. 17, No.1, 81-93
Abril 2024

Barroso LB and Gastaldini MCC (2010) Redução de Vazamentos em um Setor de Distribuição de Água de Santa Maria-RS. *Revista Brasileira de Recursos Hídricos* **15**(2), 27–36.

Bolognesi A, Bragalli C, Lenzi C and Artina S (2014) Energy efficiency optimization in water distribution systems. *Procedia Engineering* **70**, 181–190.

Castro MAH and Costa LHM (2004) Otimização de redes de distribuição de água usando a metodologia de Morgan e o EPANET. *In IV Seminário Hispano-Brasileiro sobre Sistemas de Abastecimento Urbano de Água*.

Farina G, Creaco E and Franchini M (2014) Using epanet for modelling water distribution systems with users along the pipes. *Civil Engineering and Environmental Systems* **31**(1), 36–50.

Ganorkar RA, Rode PI, Deshmukh SA and Dhoble RM (2013) Water audit a tool for assessment of water losses. *International Journal of Computional Engineering Research* **3**(3), 252–256.

Greyvenstein B and Zyl JEV (2007) An experimental investigation into the pressure-leakage relationship of some failed water pipes. *Journal of Water Supply Research and Technology* **56**(2), 117–124.

IBGE (2010) *Moradores em domicilios particulares permanentes em áreas urbanas com ordenamento regular (Pessoas) – ANO 2010.* Accessed on 20 Mar. 2023. Available at: https://sidra.ibge.gov.br/tabela/3359#resultado

IBGE (2020) *Estimativas da população residente no Brasil e unidades da federação com data de referência em 1 de julho de 2019*. Accessed on 25 Nov. 2022. Available at: https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao.html?edicao=16985&t=resultados

Lambert A (2001) What do we know about pressure: leakage relationships in distribution systems? In *IWA Conference on System Approach in Leakage Control and Water Distribution Systems Management*, p. 8p.

Lambert A and Mckenzie R (2002) Practical experience in using the infrastructure leakage index. In *Proceedings of IWA Conference Leakage Management: A practical approach in Lemesos*, cyprus.

Lima, Gustavo Meirelles, Luvizotto, Edevar, Brentan, Bruno Melo and Ramos, Helena M. (2018) Leakage Control and Energy Recovery Using Variable Speed Pumps as Turbines. *Journal of Water Resources Planning and Management* **144** (1).

Mohapatra S, Sargaonkar A and Labhasetwar PK (2014) Distribution network assessment using EPANET for intermittent and continuous water supply. *Water Resources Management* **28**, 3745–3759.

Moreira TOM (2011) *Gestão de perdas em redes de abastecimento de água assistida pelo simulador EPANET*. mathesis, Universidade do Porto.

Nagaraj A, Kotamreddy GR, Choudhary P, Katiyar R and Botre BA (2021) Leak detection in smart water grids using EPANET and machine learning techniques. *IETE Journal of Education* **62**(2), 71–79.

Price, Eyal, Abhijith, Gopinathan R. and Ostfeld, Avi (2022) Pressure management in water distribution systems through PRVs optimal placement and settings. *Water Research* **226**.

Rossman LA (2000) EPANET 2 user's manual. EPA/600/R-00/057. *National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency*, Cincinnati, 200p.

Saldarriaga J and Salcedo CA (2015) Determination of optimal location and setting of pressure reducing valves in water distribution networks for minimizing water losses. *Procedia Engineering* **119**, 973–983.

SGSSA (2017) *Acervo particular São Gabriel Saneamento*.

Shabangu, Thabane H., Hamam, Yskandar, Adedeji, Kazeem B. (2020) Decision support systems for leak control in urban water supply systems: A literature synopsis, *Procedia CIRP* **90**, 579-583.

SNIS (2020) Diagnóstico Temático dos Serviços de Água e Esgotos 2019. Technical report, *Sistema Nacional De Informaes Sobre Saneamento*.

SNIS (2021) Diagnóstico Temático dos Serviços de Água e Esgotos 2020. Techreport, *Sistema Nacional De Informaes Sobre Saneamento*.

Vilas-Boas PR (2008) *Modelação de uma rede de distribuição de água*. Master thesis, Universidade do Porto.

WHO (2021*) Progress on Household Drinking Water, Sanitation and Hygiene: 2000-2020 Five Years into the SDGs*. Technical report, Geneva: World Health Organization (WHO) and the United Nations Childrens Fund (UNICEF).