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Evaluation of hydraulic behavior of water distribution network varying reservoirs levels, roughness, and diameters with the use of R and EPANET

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ABSTRACT

Disorderly use of water resources has led to depletion, causing environmental and social issues. A relevant aspect to be observed in water supply systems is physical losses which occur during the system's entire operational process. Many different software packages allow simulations of pressures and flow in water networks. The most used is EPANET. The epanet2toolkit is a recently developed R package that performs the interaction between EPANET and R. Based on this tool, a set of functions is developed to study and evaluate a theoretical network. The objective is to find an ideal network configuration (design) mainly for pressure management which simultaneously reduces physical losses. Water network parameters, such as roughness, reservoir levels, and diameters are used as parameters. A Monte Carlo simulation is generated, based on random values of these network parameters. From these, an ideal pressure scenario is found, resulting in a reduction of 11.6% in the occurrence of physical losses concerning the base case.

Keywords: *epane2toolkit*, hydraulic evaluation, water distribution networks.

Avaliação de comportamento hidráulico de rede de distribuição de água variando níveis de reservatórios, rugosidade e diâmetros com o uso do R e EPANET

RESUMO

O uso desordenado dos recursos hídricos tem levado ao esgotamento, resultando no surgimento de questões ambientais e sociais. Um aspecto relevante a ser observado nos sistemas de abastecimento de água são as perdas físicas que ocorrem durante todo o processo operacional do sistema. Muitos pacotes de software diferentes permitem simulações de pressões e fluxos em redes de água. O mais utilizado é o EPANET. O epanet2toolkit é um pacote R recentemente desenvolvido que realiza a interação entre EPANET e R. Com base nesta ferramenta, são desenvolvidos um conjunto de funções para estudar e avaliar uma rede teórica. O objetivo é encontrar uma configuração de rede ideal (projeto) principalmente para gerenciamento de pressão que reduza simultaneamente as perdas físicas. Os elementos da rede hídrica, como rugosidade, níveis dos reservatórios e diâmetros são utilizados como parâmetros. Uma simulação de Monte Carlo é gerada, com base em valores aleatórios dos parâmetros desta rede. A partir destes, é encontrado um cenário de pressão ideal, resultando em uma redução de 11,6% na ocorrência de perdas físicas em relação ao caso base.

Palavras-chave: avaliação hidráulica, *epane2toolkit,* redes de distribuição.

1. INTRODUCTION

Water is a renewable, limited, and extremely important natural resource for human development and its activities. However, the disordered use of water has led to the depletion of springs, causing the emergence of environmental and social issues with the impossibility of supply (Silva Júnior, 2017).

As a result, the sanitation sector has faced problems meeting a growing demand for water as the supply has been decreasing. In addition, they face another important issue: the losses that occur throughout the operation of the system. The greatest losses, however, are found in water distribution networks (Fritz *et al.*, 2020).

This is because water distribution networks are made up of numerous different elements, such as pipes and devices like pumps or pressure reduction valves, interconnected with the function of bringing water in quantity and quality to the points of consumption, thus forming a complex structure (Martinho *et al.*, 2021). For Fontana *et al.* (2012), it is not only its complexity that leads to losses but also the lack of management linked to a deficiency in the effective maintenance of the system, causing the deterioration of the elements that compose it, which leads to an increase in losses. This is because they are underground and, as a result, are forgotten, receiving attention only when they fail (Mutikanga *et al.*, 2013).

These losses, according to Cheung (2004), are determined by the difference between the volume of water that enters the system and the volume accounted for. And they can be of two types, apparent and real. Apparent losses are also called commercial losses and are determined by treated water used without permission (Kanakoudis and Muhammetoglu, 2014; García-Ávila, 2019). On the other hand, the real losses, known as physical losses, are defined by leaks in the pipes and overflow of reservoirs, representing the volume of treated water, but not consumed, that is, that has not reached the end point of consumption (Brasil, 2020).

According to Al-Washali *et al.* (2020), real losses are worrisome due to waste of water, a drop in water quality, increased operation and maintenance costs, factors that lead to a decrease in revenue, and mainly to the waste of water resources. Thus, reducing losses makes it possible to increase the supply available for distribution without the need for new sources of funding, in addition to improving financial performance.

Due to the relevance of the problem, the use of mathematical modeling has shown to be increasingly important for the studies of distribution networks, as it allows the evaluation and solving of problems such as the detection of high-pressure points and those prone to leakage, the evaluation of the quality of water transported in the system, the measurement of expansion capacity and the expansion of service provision in areas above the pressure level, among other things (García-Ávila *et al.*, 2019).

One of the most used software is EPANET, as it is a free open-source program that allows static and dynamic simulations of pressurized network models, presenting their behavior, thus allowing users to know about the path and destination of water to the point of consumption, in addition to helping to choose the best-operating conditions for the system (Rossman, 2009). R is an open-source statistical analysis computational program, with an integrated language and environment. It has several packages that allow data manipulation, calculations, and graphic presentation that help in the development of hydraulic studies and the most different areas of knowledge, in addition to supporting communication with other software (Oliveira *et al.*, 2018).

With this, we have the development of a package for the R environment, the epanet2toolkit, presented by Arandia and Eck (2018) in "*An R Package for EPANET Simulations*". This tool allows the integration between EPANET and R, through command lines. Together, the interaction of a hydraulic simulation program with a statistical analysis program makes it possible to expand the study and understanding of water systems and distribution.

The application of this tool is presented by Macedo (2020) who studied its use on a theoretical network, with behavior similar to the real network. The modification of the reservoir level, present in the study network, was carried out in three different simulations, statistically analyzing the behavior of the nodes, and comparing them with those established in the NBR 12218/17 standard, which determines the parameters for the water distribution networks for public supply.

Also, according to the author, the use of this tool made it possible to automate the process of analyzing the distribution network, in addition to presenting a satisfactory result about the interaction between the programs and the network (Macedo, 2020).

In the research developed by Barbedo (2022), the coupling tool of R and EPANET software was also presented. In their study, the ability to use the packet for the calibration of a fictitious network, but with the behavior of a real network, was evaluated. The Application was made through the definition of random scenarios of the roughness of network pipes, as it is the parameter that most directly interferes with the pressure.

With that, 10,000 scenarios were created until an optimal scenario was found for network calibration. For this, a comparison was made between base pressure and with pressures of each scenario, finding the relationship that presented the smallest error and, consequently, the best pressure values for the network (Barbedo, 2022).

In this way, this study intends to use this tool to perform the interaction between the two programs, to analyze a theoretical water distribution network that will be elaborated in EPANET and later analyzed in R, to obtain the best scenario of reservoir level, roughness and diameters that generate pressure values suitable for the water distribution system under study and verify if new pressure values found for the network were able to reduce the loss rate since the theoretical network presents a percentage of 48.4%.

2. MATERIALS AND METHODS

The methodology applied in this article was structured in three stages:

- Step 1: Definition of the theoretical study network;
- Step 2: Simulation based on the EPANET of the theoretical network; and
- Step 3: R and EPANET Iteration.

2.1. Step 1: Definition of the theoretical study network.

The Theoretical network developed for this study has a mixed configuration, with parts forming loops and parts with branched sections. It consists of 3 fixed-level reservoirs, 19 nodes, and 20 pipes. It also has an irregular topography, with demand varying between one and two liters per second, as shown in Figure 1.

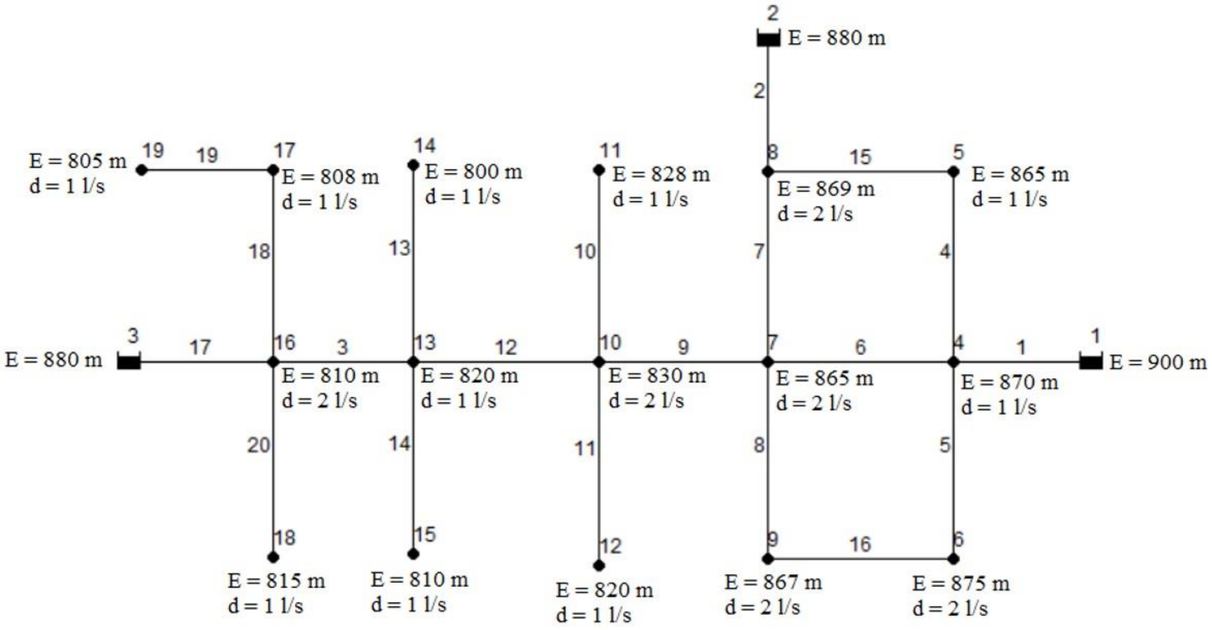

Figure 1. Theoretical network in EPANET.

To determine pipe input parameters, diameters between 50 and 200 mm were defined, with pipes close to the reservoirs having larger diameters compared to pipes further downstream. The length of the pipes varied between 100 and 150 meters so that they were close to the dimensions presented by the blocks of real subdivisions. The material chosen for all pipes was PVC, which has an average roughness of 0.06 defined based on Porto (2006), which specifies for PVC pipes a roughness value range from 0.0015 to 0.010, with the average value of this interval used in the network. Table 1 presents all the values that were defined for the pipes of the study network.

Table 1. Data from theoretical study network sections.

Pipe identifier	Length (m)	Diameter (mm)	Roughness
Pipe 01	200	200	0.06
Pipe 02	300	200	0.06
Pipe 04	150	100	0.06
Pipe 05	150	100	0.06
Pipe 06	150	100	0.06
Pipe 07	150	100	0.06
Pipe 08	150	100	0.06
Pipe 09	100	100	0.06
Pipe 10	100	100	0.06
Pipe 11	100	100	0.06
Pipe 12	150	75	0.06
Pipe 13	100	50	0.06
Pipe 14	100	50	0.06
Pipe 15	150	100	0.06
Pipe 16	150	100	0.06
Pipe 03	100	100	0.06
Pipe 17	200	200	0.06
Pipe 18	150	75	0.06
Pipe 19	100	50	0.06
Pipe 20	100	50	0.06

2.2. Step 2: Simulation based on the EPANET of the theoretical network

With input parameters defined, a hydraulic simulation of the network was performed for the static period, in the EPANET program, to verify if the speed and flow were following the parameters established for the network.

In this simulation, network pressures were also verified, and the values found are unfavorable for the system, as there are points with very low pressures, close to 10 m.w.c. and points with high pressures, with a value of 80 m.w.c.

Due to these pressures, the system is prone to ruptures and consequently water losses. With this, it is possible to justify the study of this network with the use of R and EPANET software, seeking to find a scenario in which the pressures can be equalized.

2.3. Step 3: R and EPANET Iteration

The following flowchart (Figure 2) shows how this step of interaction between R and EPANET was performed.

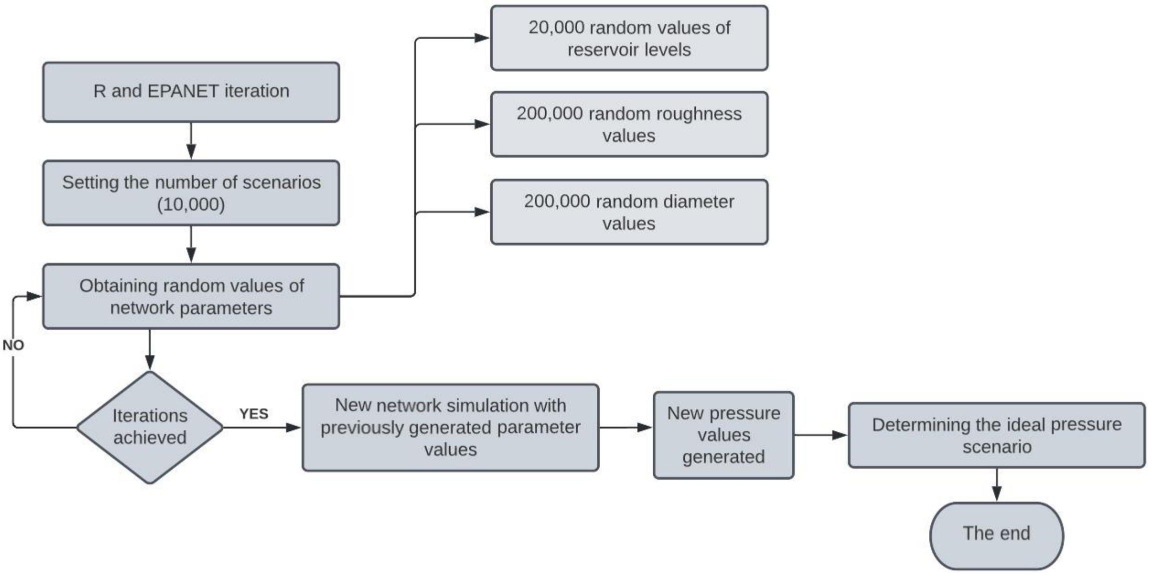

Figure 2. Study flowchart of the theoretical network.

After defining the network input parameters and performing the first static simulation in EPANET, a function in R was created to find an ideal scenario in which the network pressures are between 10 and 50 m.w.c. These values are established by the NBR 12218 technical standard, which deals with water distribution network projects for public supply (ABNT, 2017).

For this, it was first necessary to define the number of iterations that would be needed to find the ideal scenario of network pressures, and then it was defined by the value of 10,000 iterations. Then, random values were generated for reservoir levels, roughness and diameters parameters that can be changed in this network so that the pressures are also changed, thus seeking the ideal pressures. For values of these parameters, the maximum and minimum limits were established based on the initial data of the network and its behavior. These values are shown in Table 2.

Table 2. Maximum and minimum limits established for the network.

	Reservoirs (m)	Roughness	Diameter (mm)
Minimum	830	0.04	50
Maximum	930	2	200

The number of random values generated for reservoir levels, roughness, and diameter, was 20,000, 200,000, and 200,000, respectively. These values are defined by multiplying the number of elements by the number of iterations defined.

Then, a function was developed to generate the pressure values for all nodes of the study network based on the random data found for the parameters, in the previously described function. The pressure obtained is the same as the number of iterations, 10,000.

From these obtained pressure values, through a new command in R, the ideal scenario was selected, that is, the iteration number in which the pressures of all nodes were in the range established by the norm. However, it was decided to find a scenario of pressures, in which the values were equalized because a system with equal or equalized pressures is less likely to suffer losses due to ruptures. Thus, the established range was from 20 to 45 m.w.c. According to this scenario, the values of roughness, diameter, and reservoir level that generated these pressures of the ideal scenario were also found.

The loss value was also obtained in this ideal scenario, based on the equation of Tucciarelli *et al.* (1999), where the water loss at each node is given by the average pressure raised to an exponent of value 0.5. The value of the loss is given in percentage (%). Equation 1 is presented below:

$$\sum_{i=1}^{nodes} = P_{mean}^{0,5} * 7{,}27 \quad (1)$$

In addition to the loss value of the ideal canary, the same equation was also used to find the loss that the original network has. This value will serve as a base of comparison with the so-called ideal scenario as a way of verifying if the network with the new pressure values was able to reduce system loss.

3. RESULTS AND DISCUSSION

With the pressure data obtained in R, a scenario was found with pressure values within the established range. Table 3 presents pressure data obtained in the ideal scenario and the nodes corresponding to them, in addition to the base pressure.

Table 3. Comparison of ideal scenario and base scenario pressure values.

	Ideal scenario - 7142 (m.w.c)	**Base scenario (m.w.c)**
Pressure node 4	25.92	27.81
Pressure node 5	30.57	24.10
Pressure node 6	20.14	21.46
Pressure node 7	30.24	20.87
Pressure node 8	26.26	12.24
Pressure node 9	28.22	28.72
Pressure node 10	20.10	54.20
Pressure node 11	22.09	56.18
Pressure node 12	30.09	64.18
Pressure node 13	22.55	60.17
Pressure node 14	42.49	79.45
Pressure node 15	32.52	69.45
Pressure node 16	32.54	69.99
Pressure node 17	34.53	71.47
Pressure node 18	27.54	64.27
Pressure node 19	37.50	73.774

Comparing the pressures obtained by the best scenario with the original pressures of the network, it is possible to observe that there was practically an equalization of pressures, which are within a range of 20 to 40 m.w.c. In addition, the most critical points, such as nodes 8 and 14, which had very extreme pressures, being 12.24 and 79.45 m.w.c respectively, now had pressures of 28.22 m.w.c for nodes 8 and 42.49 m.w.c. m.w.c for node 14. With this, there was a 56.19% increase in pressure for node 8 and a 46.70% reduction in pressure for node 14. Thus, the operation of the system becomes more favorable, as there is a significant reduction in the probability of losses occurring because it will not suffer from pressure variations, as occurred in the original network.

With the best scenario already established based on pressure, it was possible to find the values of network parameters, such as reservoir levels, roughness, and diameters corresponding to this scenario. Data referring to these network elements for the ideal scenario are presented in Figure 3.

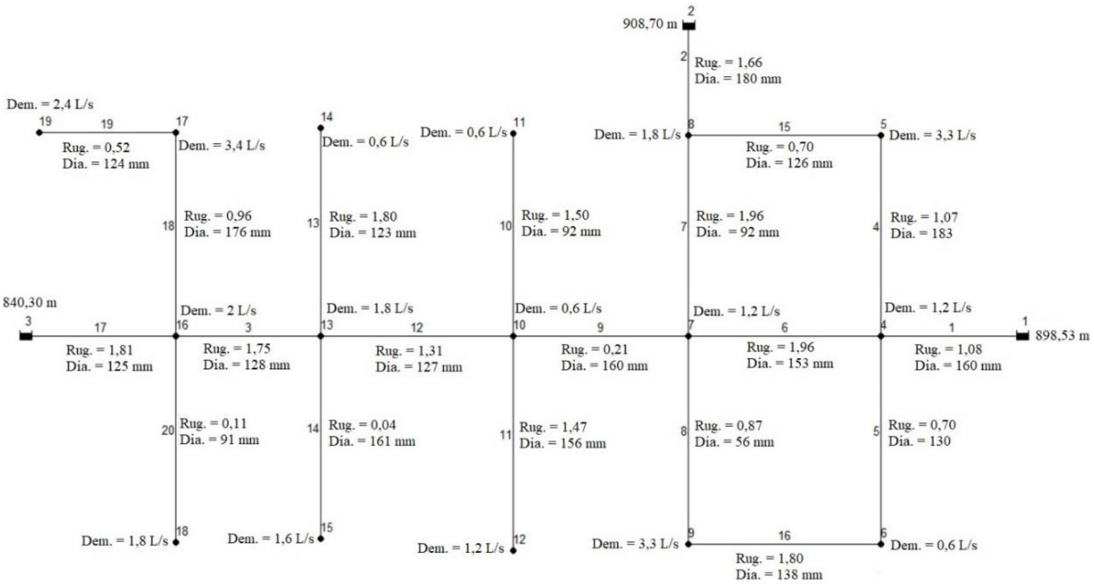

Figure 3. Roughness, diameter, and level of the network reservoirs for the ideal scenario.

Based on the new scenario, the percentage of losses was also determined and the equation of Tucciarelli *et al.* (1999), uses the average pressure to determine the percentage. The loss value found for the ideal scenario found in the R and EPANET iteration, the loss value was 36.9%. When compared to the loss value of the original network, which has a significant loss of 48.4%, there was a reduction of 11.5%.

As a result, the use of the modeling applied to the network was favorable, as it allowed, in a way, an equalization of pressures, in addition to allowing a reduction in the percentage of losses, even if some network parameters are above the initial values.

4. CONCLUSIONS

Obtaining optimal scenarios for the operation of a water network is important not only for the reduction of physical losses, leading to a reduction in revenue losses but also for the reduction of energy consumption in pumping, since it allows the network to operate with lower pressures, avoiding waste such as those generated by the need to pressurize the network too much and with the unnecessary use of valves, dissipating the energy consumed by pressurization.

Thus, the application of the developed algorithm proved to be effective for the system, as it allowed an almost equalized pressure range, with values ranging from 20 to 40 m.w.c, obtaining a significant improvement in critical nodes, as is the case of nodes 8 and 14 which presented pressures very close to the limits established by NBR 12218. In addition, the percentage of losses that the network presented, which was 48.4% in its initial configuration, went to 36.9%, thus having a reduction of 11.5% in the percentage of losses for the theoretical study network.

Thus, the tool used proved to be effective for the present study; however, other studies need to be carried out in more complex networks, with the presence of more active elements such as pumps and valves, in addition to real ones, so that the model can be validated under other conditions.

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