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Scientific Paper

Development of a database for water supply systems aiming for hydro energy efficiency using R and EPANET

Desenvolvimento de banco de dados para sistemas de abastecimento de água visando eficiência hidroenergética usando R e EPANET

Claudio Abiar Lourenço[1], Fernando das Graças Braga da Silva[1], Alex Takeo Yasumura Lima Silva[1], Matheus David Guimarães Barbedo[1], Sara Maria Marques[1], José Antonio Tosta dos Reis[2]*

ABSTRACT

Currently, many water supply systems collect and monitor data daily, among which we can highlight values of reservoir levels, pressures, and consumption demands, in addition to electrical data. The data generated is transformed into information, providing the necessary knowledge to guide the manager in planning actions and making decisions in general. The R program is a programming language widely used for statistical analysis and, recently, in some R works coupled to EPANET. Thus, this work aimed to evaluate the potential of the R program interconnected to EPANET for the database of water supply systems. For this purpose, the methodology of proposing a simulation in R of a theoretical water distribution network created in EPANET was considered to evaluate the results of daily consumption demand. The proposed network was simulated by varying consumption demands with reservoir levels, obtaining several results in 24 hours. Consequently, it was possible to automate the process of statistical analysis, generating tables and graphs referring to the dispersion of demands, node pressures, and outflows of the stretches arising from each variation in consumption and reservoir levels. The results obtained proved the compatibility and practicality of the mathematical model of the water distribution project in the EPANET program, simulated in R and stored in the SQL SERVER database.

Keywords: statistical analysis; database; EPANET; R software; distribution networks.

RESUMO

Atualmente, muitos sistemas de abastecimento de água coletam e monitoram dados diariamente, com destaque para valores de níveis de reservatórios, pressões e demandas de consumo, além de dados elétricos. Os dados gerados são transformados em informações, proporcionando o conhecimento necessário para direcionar o gestor no planejamento de ações e tomadas de decisão em geral. R é uma linguagem de programação muito utilizada para análises estatísticas e recentemente alguns trabalhos apresentaram o uso do *software* R acoplado ao EPANET. Dessa forma, este trabalho objetivou avaliar a potencialidade do programa R interligado ao EPANET para banco de dados de sistemas de abastecimento de água. Nesse intuito, considerou-se a metodologia em propor uma simulação no R de uma rede de distribuição de água teórica criada no EPANET para avaliar os resultados da demanda de consumo diário. A rede proposta foi simulada variando-se demandas de consumo com os níveis do reservatório, sendo obtidos vários resultados no período de 24 horas. Consequentemente, foi possível automatizar o processo de análises estatísticas gerando tabelas, gráficos referentes à dispersão das demandas, pressões dos nós, vazões dos trechos oriundos de cada variação de consumo e níveis de reservatório. Os resultados obtidos comprovaram a compatibilidade e a praticidade do modelo matemático de distribuição de água projetada no programa EPANET simulada no R e armazenada no banco de dados SQL server.

Palavra-chave: análise estatística; banco de dados; EPANET; software R; redes de distribuição.

[1]Universidade Federal de Itajubá, Instituto de Recursos Naturais – Itajubá (MG), Brazil.
[2]Universidade Federal do Espírito Santo, Departamento de Engenharia Ambiental – Vitória (ES), Brazil.
***Corresponding author:** jatreis@gmail.com
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INTRODUCTION

Access to safe and potable water is a fundamental need for the development and sustainability of communities around the world (GRÖNWALL and DANERT, 2020; ABANYIE *et al.*, 2023; BEKER and KANSAL, 2023). The efficient management of water supply networks plays a crucial role in ensuring access to safe drinking water and promoting sustainability (SMOL, ADAM and PREISNER, 2020; MISHRA *et al.*, 2021; ABDO, NIGUSE and TEKALIGN, 2023).

In this context, according to Hangan *et al.* (2022) and Wu *et al.* (2023), the use of advanced technologies for data collection, storage, analysis, and visualization, such as databases and hydraulic modeling tools, becomes fundamental. However, efficient management of water supply networks as well as hydro energy efficiency present complex challenges, such as the need to monitor and control flows, pressures, leaks, and water quality in real-time (BELLO *et al.*, 2019; CREACO *et al.*, 2019; SALOMONS and HOUSH, 2020). In this sense, much research is being conducted worldwide to propose innovative and sustainable solutions for the development of database models for water supply networks and even enhancing the existing ones (COSGROVE and LOUCK, 2015; JAFARI *et al.*, 2023).

Sandeep e Rakesh (2011) presented the design of a Database Decision Support System (DSS) that facilitates "on demand" knowledge generation using simulation results from a properly calibrated and validated hydraulic model of an old, existing water network corresponding to emerging water networks or even hypothetical but likely scenarios.

Güngör *et al.* (2019) discussed the methods and tools applied to reduce, control, and monitor leaks in a water distribution system with database integration with an existing supervisory control and data acquisition (SCADA) system, GIS, customer information system (CIS) and district measurement areas (DMAs), and analyzed the results obtained after its application to a real network.

Kabir *et al.* (2019) studied the performance of imputation methods for missing data in water supply network databases and evaluated the simple methods (mean imputation, median imputation, and based on linear regression) and three multiple imputation methods.

Kadhim, Abdulrazzaq and Mohammed (2021) developed a model of geographic information systems to manage the assets of the water distribution networks in the Al-Karada region, Iraq, and evaluated the network geometrically, and based on the results recommended the creation of a comprehensive and updated database to continue.

Gheibi (2022) extracted, classified, and verified the failure data obtained from the database of Preventive Maintenance of Birjand Water Distribution Network in the Southern region of Iran.

Ormsbee *et al.* (2022) assessed the development of a Hydraulic Model Database for Water Distribution Systems Research, specific model inputs, available model building toolkits, general methods for system classification, and general information related to platform and content.

In terms of innovation, integrating R with EPANET for database development offers flexibility and advanced analysis capabilities, allowing the extraction of valuable insights from EPANET simulation data. This approach can be useful for optimization studies, network performance analysis, demand management, and other aspects related to the efficient management of water supply networks.

In addition, we present the functionalities that can be implemented in the database, such as the centralized organization of hydraulic data, automated generation of customized reports, statistical analysis of network parameters, and the creation of interactive graphs for visualization of results.

This article demonstrates a methodology for a database on water supply systems using the R software integrated with the EPANET software. The interface between the programs was designed to analyze a virtual hydraulic network produced in EPANET, using data like a real network. Simulations were produced with the variation of the reservoir level and consumption demands in the 24 hours to statistically analyze the network data. After performing the simulation in the R software, the data were stored in a SQL SERVER database for later consultation.

METHODOLOGY

The methodology applied in this article was structured in three steps, which are presented below:

- Step 1: Definition of the theoretical study network;
- Step 2: Iterations for coupling R and EPANET for database; and
- Step 3: Scenarios simulation and development a database in SQL SERVER.

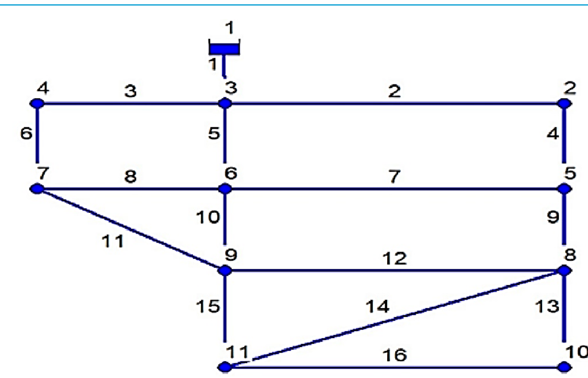
Step 1: definition of the theoretical study network

The theoretical network developed for the study presents a configuration forming meshes. It is composed of one variable level reservoir, ten nodes, and 16 sections. It also has an irregular topography, with demand varying between 0.1 and 2 L/s (liters per second), as shown in Figure 1.

To determine the pipe inlet parameters, diameters between 50 ~ 150 mm were defined, with pipes close to the reservoirs having larger diameters than pipes further downstream. The length of the pipes varied between 700~1200 m with a dimensionless roughness of 150. Table 1 presents all the values that were defined for the pipes of the network under study. Table 2 presents all the values that were defined for the nodes of the study network.

Step 2: Iterations for coupling R and EPANET for database

Once the EPANET and R software packages have been installed, the following steps can be used to perform an integrated simulation for database, as show in Figure 2.



Source: the authors (2022).

Figure 1 – Theoretical study network.

Step 3: Scenarios simulation and development a database in SQL SERVER

The following flowchart (Figure 3) shows how this phase of interaction between R and EPANET was performed.

Table 1 – Data from pipes of the theoretical study network.

Pipe ID	Length (m)	Diameter (mm)	Roughness (without unit)
Pipe 01	1,000	150	150
Pipe 02	1,200	100	150
Pipe 04	990	100	150
Pipe 05	1,100	75	150
Pipe 06	1,100	100	150
Pipe 07	1,200	75	150
Pipe 08	990	50	150
Pipe 09	830	75	150
Pipe 10	830	100	150
Pipe 11	1,000	75	150
Pipe 12	1,200	50	150
Pipe 13	700	50	150
Pipe 14	1,300	50	150
Pipe 15	700	50	150
Pipe 16	1,200	50	150

Source: the authors (2022).

Table 2 – Data from nodes of the theoretical study network.

Node ID	Level (m)
Reservoir 01	985-990
Node 02	970
Node 03	970
Node 04	965
Node 05	949
Node 06	935
Node 07	945
Node 08	925
Node 09	920
Node10	990
Node11	995

Source: the authors (2022).

The water network was elaborated using the EPANET and R software for the integrated simulation. For the coupling between EPANET and R, the packages epanetRead, epanet2toolkit, tidyverse, ggplot2 and dplyr, developed for the interface between EPANET and R were used. Once installed, the package was saved in the R memory. The file was imported from EPANET, then it was created in compatible R. In this way, it was possible to produce the program with the desired functions.

In this mesh network, consumption demand values per node ranging from 0.1 ~ 2.0 L/s and reservoir level ranging from 985 ~ 990 m were proposed, choosing the values of the physical parameters of the nodes and sections so that the pressures generated in the simulation were always positive and did not exceed 100 mca.

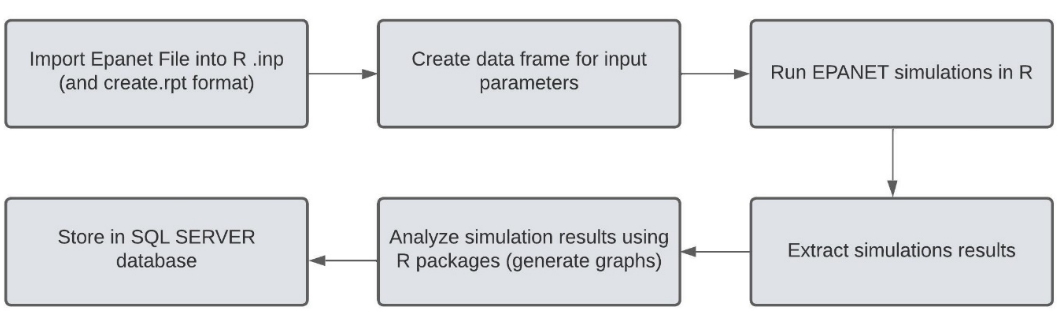
When choosing a database to support the modeling of water supply networks using R and EPANET, SQL Server, managed by Microsoft®, stands out as a superior choice to other database management systems, due to its advantages in performance, data management, security, scalability, integration, and technical support. The powerful combination of R and EPANET with the robust capabilities of SQL Server not only optimizes the modeling process, but also provides a solid basis for better-informed decision-making by water managers in the field of water resources management.

RESULTS AND DISCUSSION

The daily demand program was simulated in R using the same network as the previous items considering the demand, total flow (total consumption of the network), flow per section, reservoir level, and pressure in the 24 hours. Scenario 1 demonstrated in Figure 4 represents the behavior of dispersion by nodes of the consumption demand of a supply system.

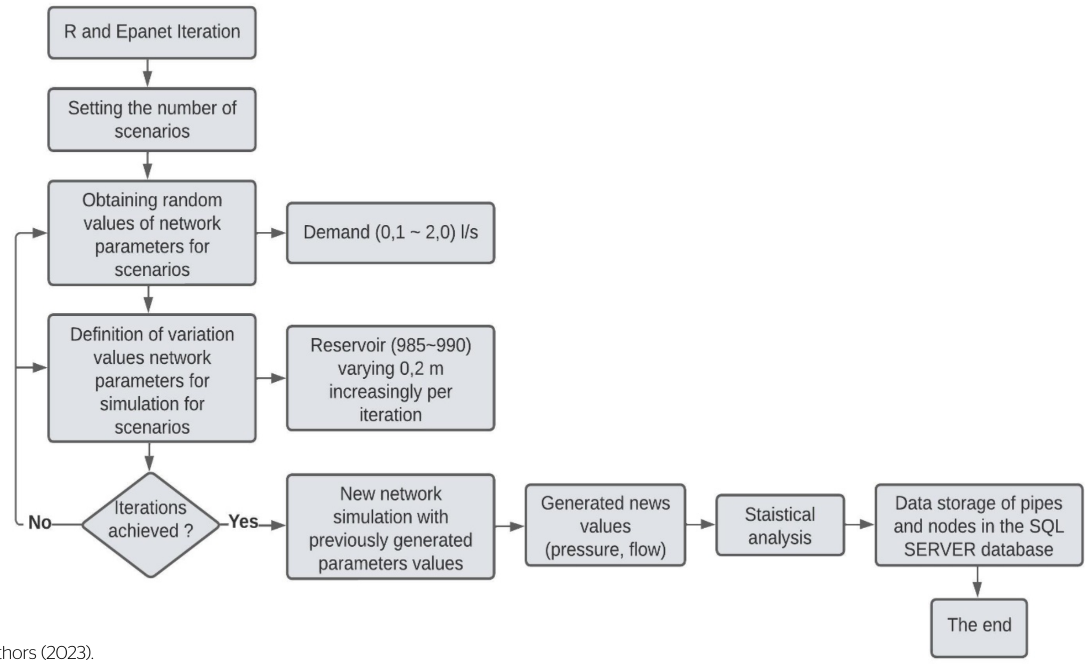
Figure 5 demonstrates Scenario 2, the behavior of the total consumption demand of the supply system, which shows higher consumption during the day and decreases throughout the night, reaching lows at dawn. This behavior is conventional at water distribution networks and predicted in Tsutiya (2006), although with small variations according to the locality.

Figure 6 demonstrates Scenario 3, the behavior of the total consumption demand of the supply system, which shows higher consumption during the day and decreases throughout the night, reaching lows at dawn. This behavior is conventional at water distribution networks and predicted in Tsutiya (2006), although with small variations according to the locality.



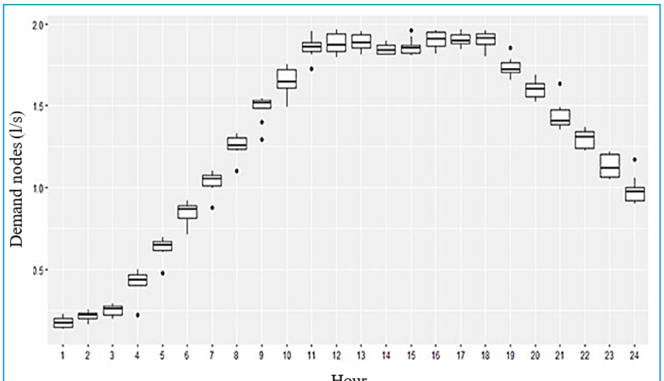
Source: the authors (2023)

Figure 2 – Flowchart of the coupling steps.



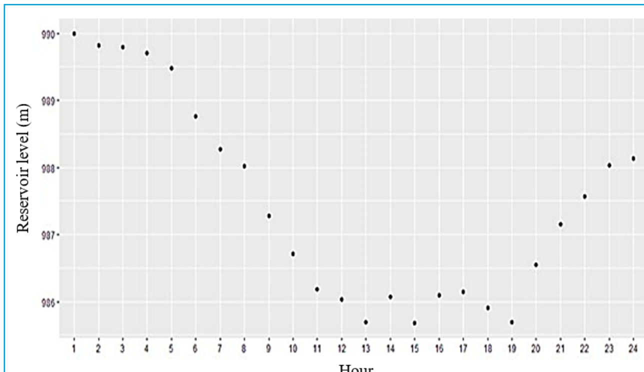
Source: the authors (2023).

Figure 3 – Flowchart of the simulations.



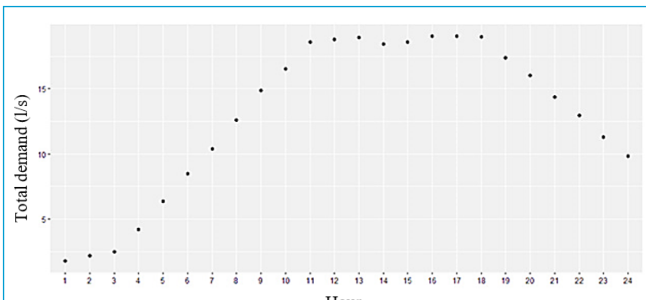
Source: the authors (2022).

Figure 4 – Demand nodes × hour.



Source: the authors (2022).

Figure 6 – Reservoir level × hour.



Source: the authors (2022).

Figure 5 – Total demand × hour.

The behavior of the reservoir level related to the variation in consumption: when the consumption demand increases, the reservoir level tends to decrease; when the consumption demand decreases, the level tends to increase, as expected in water distribution systems.

Figure 7 demonstrates Scenario 4, the flow dispersion behavior by tubulations with its flow varying directly with the consumption demand per node. As expected, flows oscillate at consumption peak hours, since higher consumption increases flow, leading to pressure reduction as shown in Figure 7. It is possible to see great uncertainty during the higher consumption hours, which shows a possible instability in the network.

Figure 8 demonstrates Scenario 5, the behavior of pressure dispersion by nodes, where it is possible to see a reduction due to higher consumption. Pressure varies inversely with consumer demand, as expected, since consumption relieves pressure on the network.

The statistical analysis of the simulation results (daily demand) is shown in Tables 3 and 4.

These simulations can be used to assess the impact of different actions on network performance. With the input parameters defined, a hydraulic simulation of the network was carried out in the EPANET program, to verify that the pressure and flow were following the established goals.

During the simulation of the R program for the daily demand, the network pressures were verified with some values found unfavorable for the system, since there are points with pressures below 10 mca, and points with high pressures, with a value above 90 mca. Due to these pressures, the system is subject to ruptures and, consequently, water losses. Other studies have also found that pressure problems are common in water distribution networks. For example, a study by Ghorbanian, Karney and Guo (2016) found that more than 20% of water distribution networks in the United States have pressure problems.

Ideally, network pressures are between 10 and 50 mca. These values are established by the Brazilian Technical Norm NBR 12218 standard, which deals with water distribution network projects for public supply (ABNT, 1994).

The hydraulic simulation results presented in the article are generally in line with the findings of other studies. For example, a study by Jun, Jung and Lansey (2021) found that pressure and flow in a water distribution network can vary significantly throughout the day, depending on consumption demand.

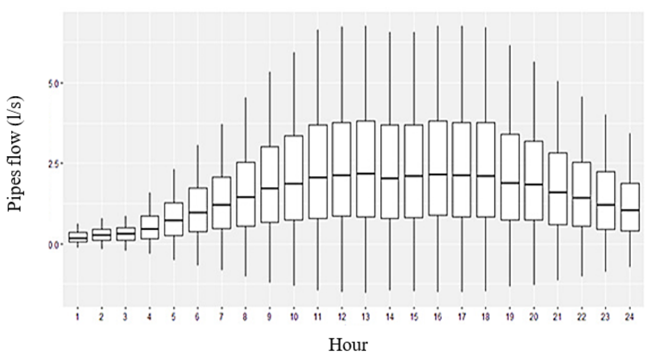
Node number (11) has the highest-pressure result of 94.56 mca; suggestion: put a pressure reducer. Node number (2) has the lowest pressure result of 4.15 mca. Pipe (5) had the highest flow rate of 6.77 L/s; suggestion: increase the pipe diameter from 75 to 100 mm. Other studies have also found that pressure reducers and pipe resizing are effective ways of improving pressure distribution in water distribution networks (VICENTE *et al.* 2016; GARCÍA-ÁVILLA *et al.* 2019; BIDERIS-DAVOS and VOVOS, 2023).

In the statistical analysis of the results of the daily simulations, the consumption demand is indirectly related to the pressure dispersion by nodes and directly to the flow by sections (pipes). The reservoir level is directly related to the pressure dispersion behavior in the nodes. Pressure presented a higher standard deviation index due to the variation in the reservoir level and the variation in consumption demand. It was possible to graphically and didactically visualize the behavior of a supply network in the 24-hour cycle. The statistical analysis identified pressure problems in the network, such as points with pressure below the recommended range and points with pressure above the recommended range, according to a study by Dawidowicz (2017), which approximately 16,3% of the nodes were within the recommended range.

Node data were saved in xlsx (excel) format files using the command (writexl::) and exported to a SQL SERVER database, where they were stored as illustrated in Figure 9.

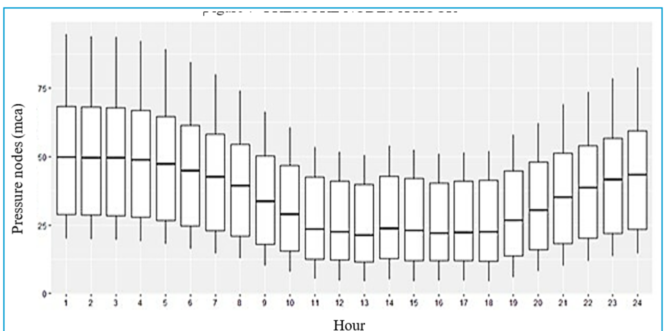
The tubes (pipes) were saved in files in xlsx (excel) format using the command (writexl::) and exported to a SQL SERVER database, where they were stored as shown in Figure 10.

The database management can be used to simulate different scenarios, such as changes in demand or pipe failures, generating management reports that summarize the results of the hydraulic simulation, as in the work of Rathnayaka *et al.* (2016), who proposed a methodology to integrate the results of these simulations into a water utility asset management database to improve pipeline failure prediction. These reports can be used to track



Source: the authors (2022).

Figure 7 – Pipes flow × hour.



Source: the authors (2022).

Figure 8 – Pressure nodes × hour.

Table 3 – Result of the scenario (daily demand).

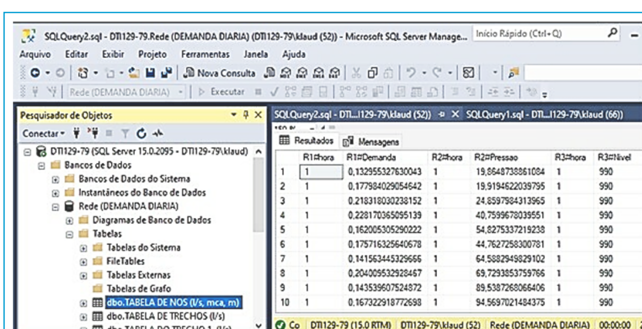
Network	Values
Level (max.) (m)	90
Level (min.) (m)	85.67
Pressure (min.) node (mca)	4.17
Pressure (max.) node (mca)	94.56
Demand (min) node (L/s)	0.13
Demand (max.) node (L/s)	1.96
Demand (max.) pipe (L/s)	6.77
Demand (min.) pipe 1 (L/s), full exit	1.75
Demand (max.) pipe 1 (L/s), full exit	19.05

Source: the authors (2022).

Table 4 – Standard deviation of daily demand.

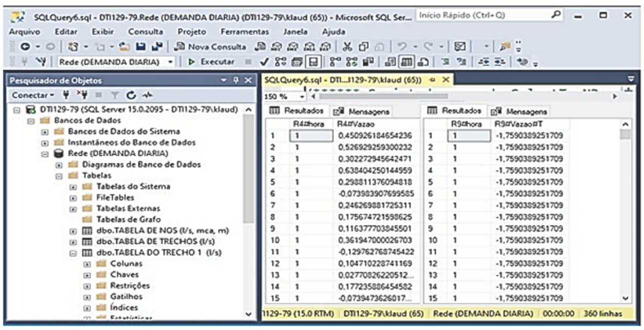
Standard deviation demand per node	Standard deviation pressure per node	Level standard deviation
1,30 ± 0,59	36,92 ± 22,44	87,44 ± 1,48

Source: the authors (2022).



Source: the authors (2022).

Figure 9 – SQL server database (node).



Source: the authors (2022).

Figure 10 – SQL server database (pipes).

network performance and identify potential problems. In addition, the database can be used to identify opportunities for optimizing the network, such as reducing water losses or increasing energy efficiency, as in the work of Ramos *et al.* (2019), who suggested that smart cities will have water network data guaranteed by the database.

CONCLUSIONS

In the study, the feasibility of a database methodology was evaluated by associating the EPANET and R tools. Simulations were performed using resources of EPANET and R-coupled software, through the packages epanetReader, epanet2toolkit, tidyverse, ggplot2, dplyr.

The tools were chosen for carrying out hydraulic simulations (in the EPANET case) and for the potential of statistical analysis, in the case of R. The results obtained demonstrated the viability of these tools for data analysis in a water supply system, considering the amount of daily information that can be generated.

The hydraulic simulations of scenarios generated by EPANET represent day-to-day situations and R helps in the statistical treatment of the data. Such functionality contributes to the stage that precedes subsidies for the manager of water and energy systems to make decisions.

Therefore, about the management of hydropower resources, the knowledge produced through this scientific research could become quite useful, since it presents an intelligent and efficient tool for automating the processes of simulation, analysis, and statistics of supply systems. In this way, the tool developed and tested showed great potential to add benefits to the organization, as it helps in planning, avoiding waste of water, and energy.

Finally, the structure of the routine is presented in the form of a flowchart, but if you are interested in making the code available, we are at your disposal.

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AUTHORS' CONTRIBUTIONS

Lourenço, C.A.: Conceptualization, Data Curation, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Software, Validation. Silva, F.G.B.: Conceptualization, Investigation, Methodology, Project Administration, Supervision. Silva, A. T.Y.L.: Formal Analysis. Barbedo: M.D.G.: Writing – Original Draft, Writing – Review & Editing. Marques, S.M.: Writing – Original Draft, Writing – Review & Editing. Reis, J.A.T.: Investigation, Methodology, Visualization.

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