Journal of
Hydroinformatics

Journal of Hydroinformatics Vol 25 No 4, 1329 doi: 10.2166/hydro.2023.206

Rehabilitation of water distribution networks: when and how to rehabilitate

Leandro Alves Evangelista*, Bruno Melo Brentan and Gustavo Meirelles Lima
Engineering School, Federal University of Minas Gerais, Av. Pres. Antônio Carlos, 6627, Pampulha, Belo Horizonte, MG, Brazil
*Corresponding author. E-mail: leandroalves1989@gmail.com

LAE, 0000-0002-4276-3917; BMB, 0000-0003-0616-2281; GML, 0000-0002-1971-3970

ABSTRACT

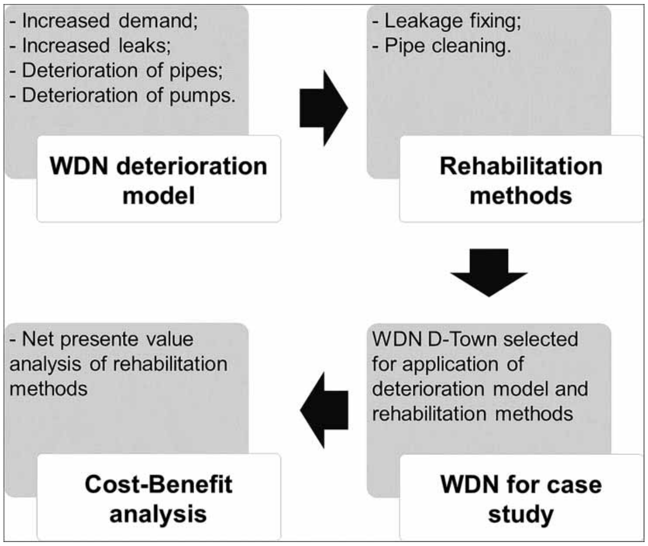
In this paper, a deterioration model is created and used to simulate the life cycle of a water distribution network (WDN). Then, two strategies – leakage fixing and pipe cleaning – are evaluated to rehabilitate its capacity to attend the demand. In order to implement the deterioration model, the following parameters were considered: growth of the consumer population, increase in leakage rate, functional pipe deterioration and reduction of the hydraulic capacity of the pumps. For the leakage fixing, a fixed reduction rate in water losses was considered throughout the entire WDN until a minimum reference value was reached. For pipe rehabilitation, leaning was considered at a rate of 1% of the total length of the network per year. In each of the rehabilitation strategies, a cost–benefit analysis was carried out using the net present value. The results showed that both alternatives can restore the capacity of the WDN, with the pipe cleaning presenting a better economic impact.

Key words: deterioration, energy efficiency, leakage, rehabilitation, water distribution network

HIGHLIGHTS

- This study presents a methodology to understand the impact that the deterioration of a water distribution network (WDN) has on its operation.
- This study brings an estimate of the time when a WDN should be rehabilitated as it deteriorates throughout its useful life.
- This study presents two ways to rehabilitate a WDN and the economic impact of each of these implemented measures.

GRAPHICAL ABSTRACT



INTRODUCTION

The optimal operation of a water distribution network (WDN) can be achieved through the implementation of different strategies or a combination of them. Pump scheduling is commonly combined with the use of tanks and pressure reducing valves (PRVs) to save energy and reduce leakages (Shao *et al.* 2019). In addition, Brentan *et al.* (2018) proposed the use of demand forecasting to improve the reliability of the operation for near real-time operation. District metering area (DMA) creation can also improve the operation of both pumps and valves since smaller districts are easier to manage (Di Nardo *et al.* 2014; Campbell *et al.* 2016). Advanced strategies could also seek the improvement in water quality during the operation (Kang & Lansey 2010; Brentan *et al.* 2021) and energy recovery in PRVs (Hamlehdar *et al.* 2022).

The more efficient the operation, the better the performance of the WDN. As highlighted by Mala-Jetmarova *et al.* (2018), the design of WDNs can take into account, in addition to the implementation costs, several operational parameters, such as water quality and resilience index. Multi-objective optimization and multicriteria procedures are used to contemplate all the relevant aspects of a WDN design and operation and achieve a reliable solution (Farmani *et al.* 2006; Carpitella *et al.* 2019). Even so, considering the long life cycle expected for these infrastructures, the deterioration of its components will constantly reduce the operation efficiency. The rate in which this decline occurs depends on several factors, such as water quality, soil conditions, pipe material, pressure surges and water demand (St. Clair & Sinha 2012). In extreme conditions, this can lead to an intermittent supply, which can lead to economic, social and health problems (Klingel 2012; Simukonda *et al.* 2018). In order to minimize the impacts of intermittent operation, Souza *et al.* (2022) proposed an optimal operation in these conditions, with the rehabilitation of main pipes.

Other problems can arise with the deterioration of WDN and the intermittent operation, such as water contamination due to the intrusion of pathogens through small cracks that appear in the pipes (Mora-Rodríguez *et al.* 2015), and pipe collapse during the filling process (Martins *et al.* 2017). In addition, Liu *et al.* (2016) described the impact of biofilm growth on the pipe wall, potentially reducing water quality for consumers, affecting the taste and smell of water and possibly enhancing bacterial contamination.

Several approaches can be used to rehabilitate a WDN operating under intermittent conditions, such as leakage control, pipe replacement and pumping station reinforcement (Haddad *et al.* 2008; Creaco & Pezzinga 2015). In order to establish the best interventions in the infrastructure of a WDN throughout its life cycle, a cost–benefit analysis is necessary to evaluate the feasibility of each alternative. This is not simple because costs and revenues will occur at different times throughout this period and can significantly vary, as observed for example in energy tariffs. Covelli *et al.* (2016) used a genetic algorithm to propose a methodology to control water losses in a WDN using PRVs. The optimization was performed considering the total costs of acquisition, installation and management of the valves, in addition to the avoided costs with leakages. Creaco & Walski (2017) reinforced this approach with an economic analysis of different pressure control solutions to reduce leaks and pipe bursts. They pointed out that the most appropriate control method should consider the net costs throughout the WDN life cycle, comparing the investment with the leakage reduction economy.

Even in reliable WDN, economic analyses are necessary to try to improve the operation of pump stations (Brentan *et al.* 2018; Briceño-León *et al.* 2023) or even to recover the excess energy in gravity systems (Meirelles *et al.* 2017). Finally, as highlighted by Tscheikner-Gratl *et al.* (2016), a maintenance schedule is also required to preserve the WDN conditions through its life cycle.

In this paper, a deterioration model is used to identify the optimal period to start investing in rehabilitation strategies and avoid water shortages. The model is composed of four algorithms to simulate pipe encrustation, population growth, leakage behaviour and pump deterioration. Each parameter is set with a specific deterioration rate, and 20 years of operation are simulated. A typical operation week is used to calculate the yearly costs, and after each year, the deteriorated parameters are updated. With the simulated life cycle, it is possible to identify at which period the WDN began to have problems. At this point, two strategies for rehabilitation are studied separately: leakage fixing and pipe cleaning. The D-Town network is used as a case study, and the results have shown that both strategies for rehabilitation are successful, with pipe cleaning having a better economic impact.

WDN DETERIORATION MODEL

The deterioration model is composed of four different algorithms to describe the behaviour of four parameters that can significantly affect the WDN performance. The first one refers to the increase in water demand as a function of population growth. The method of demographic components is used to estimate the population in each year of the simulation (IBGE 2018). A third-degree polynomial was adjusted using a Brazilian state as a reference, as shown in Equation (1). The same average consumption observed in the first year is adopted for new consumers: 150 L/hab/day.

$$Y = aX^3 + bX^2 + cX + d \tag{1}$$

where Y is population; X is year and a, b, c, d are adjustment coefficients of the polynomial equation ($a = 0.0000004335$; $b = -0.0000023355$; $c = -0.0007653779$; $d = 1.0003835392$).

The second component of the WDN deterioration is the leakage, composed of two parts: a minimum value that is economically unfeasible to fix, described by Equation (2) (Ahopelto & Vahala 2020), and a variable value that depends on the operation pressure of the network, calculated by Equation (3) (Boian *et al.* 2019). The minimum leakage is equally distributed in all nodes as an additional demand, and increases during the years, as it is related to the number of consumers. In contrast, the emitter coefficient and exponent of Equation (3) are previously calibrated to create a water loss of around 20–30% during the first year, a typical value in WDNs, and then maintained constant during the life cycle simulation. Although the emitter coefficient is expected to grow as time goes by, in this paper a constant value is adopted. This approach tries to replicate the constant appearance of new leakages and the fixing of the visible ones. Thus, the adopted constant value represents an average of cracks during the WDN life cycle:

$$q_{\min} = 54 + 2.7\left(\frac{N_p}{L_r}\right) \tag{2}$$

$$q = C_e h^y \tag{3}$$

where $q_{\min}$ (m³/km) is the minimum volume of leakages to be considered; N_p is the number of customers served; L_r (km) is the total length of the network pipes; C_e is the emission coefficient and y is the emission exponent.

The third component expresses the deterioration of pipes during the WDN life cycle. This deterioration can be divided into structural – which describes the reduction of pipe resistance to mechanical stress, and functional – which describes the reduction of its hydraulic capacity, i.e., the increase in pipe roughness. As important as the structural deterioration is, the models require a great amount of data and have high uncertainties. In addition, the conditions to cause a pipe failure are usually observed during transient events, which are not considered here. Thus, only the functional deterioration is simulated, using Equation (4) proposed by Sharp & Walski (1988):

$$C = 18.0 - 37.2 \times \log\left(\frac{e_0 + at}{D}\right) \tag{4}$$

where C is Hazen-Williams coefficient; e_0 (mm) is the initial absolute roughness; a (mm/year) is the roughness increase rate; t (years) is the time and D (m) is the pipe diameter.

Finally, pump deterioration is modelled according to Equation (5), proposed by Nault & Papa (2015). This equation describes the reduction of the hydraulic power supplied by the pump due to the increase in internal roughness and internal flow through gaps. As for the pipes, structural deterioration is also observed in pumps, mainly caused by cavitation, corrosion, misalignments and vibration. Even if a pump failure is more serious than a pipe failure, this risk is also not taken into account in the modelling:

$$H'_P = \omega\left(a\left(\frac{Q_p + R}{\omega}\right)^2 + b\left(\frac{Q_p + R}{\omega}\right) + c - K_T t\left(\frac{Q_p}{\omega}\right)^2\right) \tag{5}$$

where H'_P (m) is the corrected pump head; ω is the relative speed; a, b and c are pump characteristic curve coefficients; Q_p (l/s) is the pump flow; R (l/s) is the pump internal recirculation flow; K_T is the internal roughness increase rate and t (h) is the cumulative operating time.

REHABILITATION METHODS

Leakage fixing

Fixing leakages in a WDN affect the whole water production chain: less water needs to be withdrawn from natural sources and treated, and less energy is consumed in pumping stations, as the system will require lower flows and consequently lower hydraulic grade, as the head losses are also reduced. However, despite its great benefit, it is not easy to detect and locate leakages in a WDN (Li *et al.* 2015). According to Zaman *et al.* (2020), two main methods can be used to identify leakages: (i) direct, which requires field inspection using specific equipment such as acoustic devices, that rely on the detection of vibration or noise signal created by leakages and (ii) indirect, which uses hydraulic models or data mining techniques to identify anomalies in the monitoring data. The major drawback of the direct method is the related cost, whereas, for the indirect methods, the uncertainties are high for the existing techniques.

In this paper, it is considered that any method can be used to detect and locate leakage. Therefore, an average value of 7.27 R$/m³/year of water loss reduction is used (European Commission 2013). The applied investment strategy in this case is reducing 10% of the actual water losses each year until this index reaches the benchmark value of 10%. It is important to highlight that, to maintain the new index level, the investment must be maintained for each of the following years. This leakage reduction is modelled by reducing the emission coefficient C_e in all nodes by the same amount. Thus, no geographical influence of leakages can be observed in this study, i.e., there is no prioritization to fix high pressure zones, where leakage rates are higher.

Pipe cleaning

The rehabilitation of pipes can be done simply by cleaning their wall, aiming to restore, or at least improve, its hydraulic capacity by reducing its roughness. Another alternative is to replace part or the entire length of the pipe. In addition to the roughness reduction, this alternative allows us to improve the pipe capacity by increasing its diameter, and, indirectly, it is possible to fix existing leakages that are not detected. The drawback of this alternative is its elevated cost. In this paper, only the cleaning strategy is studied, with a cost of 9.13 R$/m (CASAN 2021). Therefore, each rehabilitated pipe remains with the same diameter and the same leakage rates. Thus, the only benefit considered is roughness reduction.

Two main aspects should be considered for the pipe replacement strategy: which pipes are more suitable for replacement and which replacement rate should be used. To select the pipes for replacement, the proposal of Campbell *et al.* (2015) to identify the trunk network was used, in which the WDN is modelled as a graph to identify the shortest path between each node and the water source. As these pipes transport higher flow rate and are connected to a higher number of nodes, it is expected that by reducing their headlosses, the pressure in the entire WDN will improve. For the rate of replacement, 1% of the length of the WDN is replaced each year, following the recommendations of the European Commission (2013). It is important to highlight that, as the mains pipes are replaced, they start the deterioration process again, and could be reconsidered for replacement in the following year if their headlosses significantly increase again.

Cost–benefit analysis

To evaluate the economic attractiveness of each rehabilitation alternative, the net present value (NPV) is used, as it estimates the return on investment with future cash flows according to Equation (6) (Hartman 2000):

$$\mathrm{NPV} = \sum_{t=1}^{N_t} \frac{\mathrm{CF}_t}{(1+i)^t} \tag{6}$$

where NPV (R$) is the net present value; N_t is the number of years with benefits; CF_t (R$) is the cash flow in year t and i (%) is the discount rate.

The cash flow is calculated by the difference between energy and water production costs with and without rehabilitation. For each period, Equation (7) is used to calculate these costs. The energy tariff varies and is 0.4698 R$/kWh between 05:00 and 08:00 PM, and 0.3395 for the remainder of the day (CEMIG 2021), while the water production cost is constant, set as

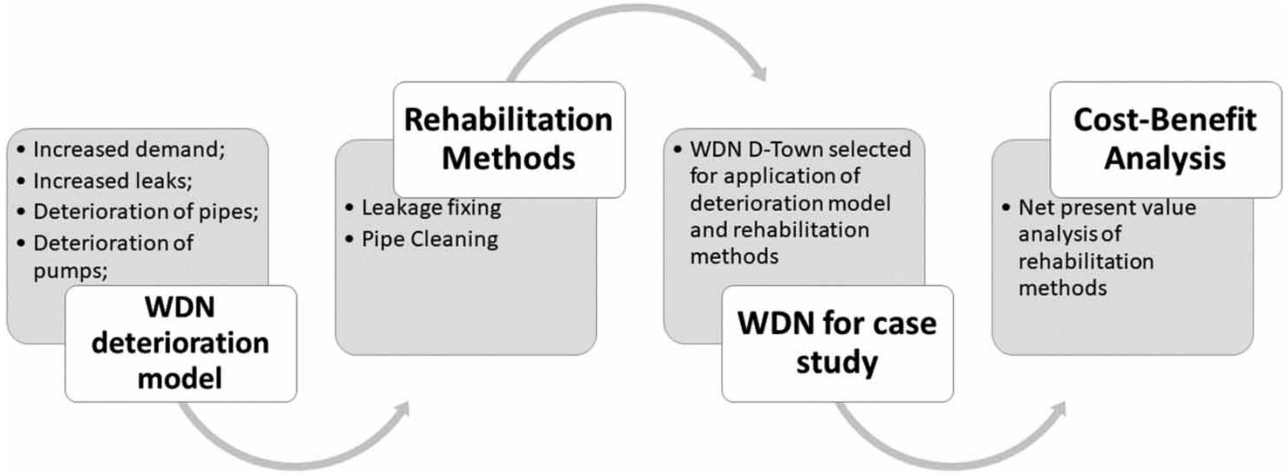


Figure 1 | Flowchart summarizing the methodology.

0.30 R$/m³ (SNIS 2019):

$$\mathrm{TC} = \sum_{i=1}^{N_s} \mathrm{CE}_i \cdot \mathrm{TE}_i + \mathrm{CW}_i \cdot \mathrm{TW}_i \tag{7}$$

where TC (R$) is the total operational cost; CE_i (kWH) is the energy consumed in period i; TE_i (R$/kWH) is the energy tariff in period i; CW_i (m³) is the volume of water losses in period i and TW_i (R$/m³) is the water production cost in period i.

The efficiency of the WDN is measured by the specific energy consumption (SEC) calculated by Equation (8). Although this indicator is not recommended for comparison among different WDNs, it is well suited to observe the evolution of a specific system:

$$\mathrm{SEC} = \sum_{i=1}^{N_s} \frac{\mathrm{CE}_i}{V_i} \tag{8}$$

where SEC (kWh/m³) is the specific energy consumption; N_s is the number of simulation periods; CE_i (kWH) is the energy consumed in period i and V_i (m³) is the water volume distributed (including leakages) in period i.

The flowchart in Figure 1 presents the synthesized steps of the entire methodology adopted in this paper.

RESULTS

Case study

The D-Town network (Marchi *et al.* 2014) is used as a case study. This WDN is composed of 399 nodes, 443 pipes, 7 tanks, 5 valves and 11 pumps divided into 5 pumping stations, as shown in Figure 2. As mentioned in Item 2, the emission coefficient for all nodes was calibrated with the same value, $C_e = 0.03$, creating a water loss of 28%. The initial daily consumption is 159,617 m³, which, considering the base consumption *per capita* of 150 L/hab/day, refers to 1.06 million habitants.

Figure 3 presents the operational costs and critical pressures observed over the 20-year life cycle for the D-town network. The total cost presented is the sum of the costs during a year of operation, whereas the pressures are the minimum value observed in each year, which can be from different nodes and periods of a day. It is clear that from the ninth year of operation onwards that the WDN no longer meets the consumer demand as pressures are well below the minimum necessary of 10 m for supply. The negative pressures result from the demand-driven model used for hydraulic simulation. Although the values obtained do not have physical relevance, it shows how large the gap to a feasible operation is when the WDN is deteriorated. Finally, observing the costs, it is noticeable that they are constantly increasing, which creates a more difficult management of the system as the economic resources are diminished.

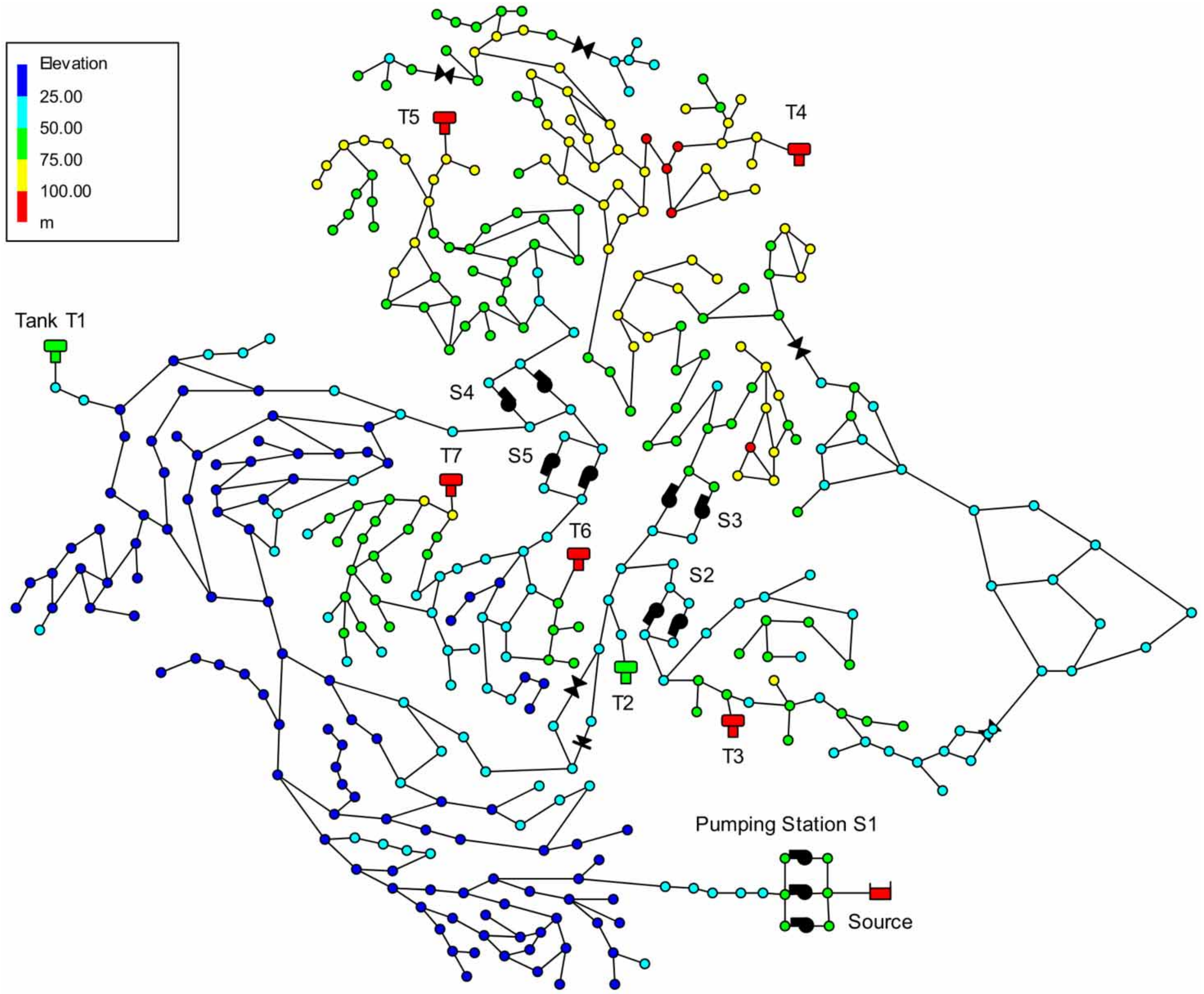


Figure 2 | D-town network.

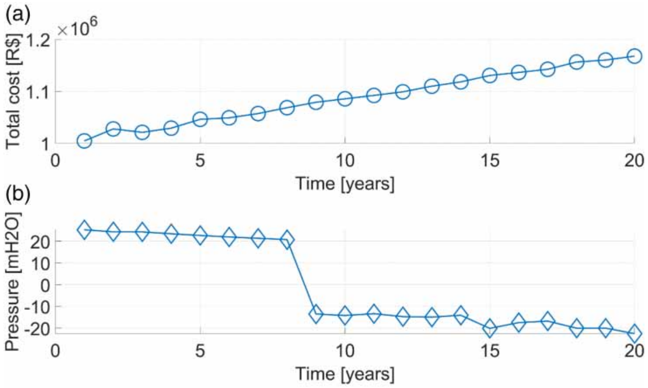


Figure 3 | D-town life cycle operation: (a) total costs and (b) minimum pressure.

Leakage fixing

Figure 4 presents the economic benefits resulting from the leakage fixing rehabilitation from the ninth year of operation. The reduction of operational costs is around 16% each year, whereas the reduction in SEC reached 42%. It is also noticeable that the strategy controlled the rise in costs, as the curve trend got smoother. Regarding the pressure, Figure 5 shows the improvement obtained, especially in the northern region. It is important to highlight that, with this rehabilitation, the operation was able to achieve the minimum required pressure in all years, although some nodes presented excessive values, which could be reduced with an optimized operation of pumping stations.

Finally, Figure 6 presents the cash flow resulting from the leakage fixing. The high costs for leakage fixing resulted in an unfeasible investment, with a negative NPV of R$ 47,705.10. Only for the final 4 years of the life cycle considered did the benefits surpass the necessary investment. However, it is important to highlight that the benefit considered regards only the economy in energy and water production costs. The reestablishment of supply conditions, guaranteeing a minimum pressure on the network, would also represent revenue due to the maintenance of demand. Despite that, a social and health benefit is also achieved, and is not economically measurable.

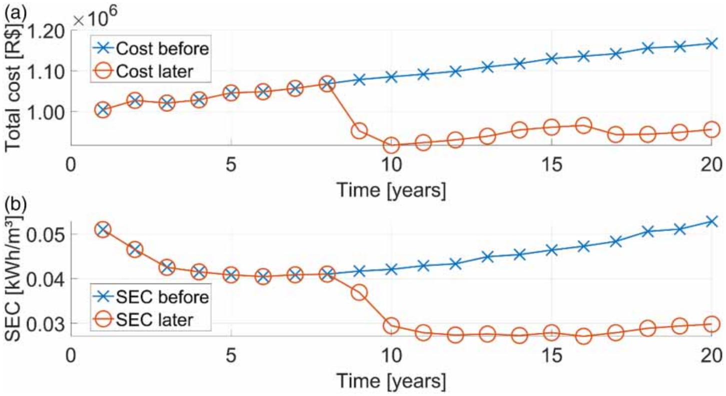


Figure 4 | Economic benefits for the leakage fixing: (a) total costs and (b) specific energy consumption.

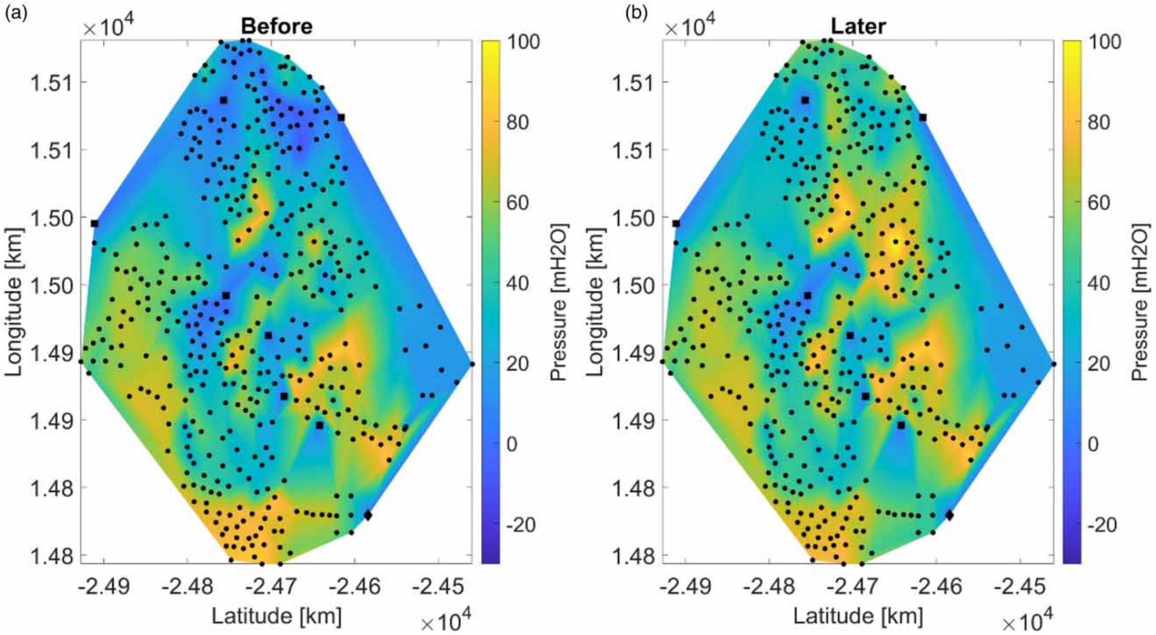


Figure 5 | Operating pressure for the maximum consumption period in the 10th year of operation: (a) deteriorated network and (b) rehabilitated network with leakage fixing.

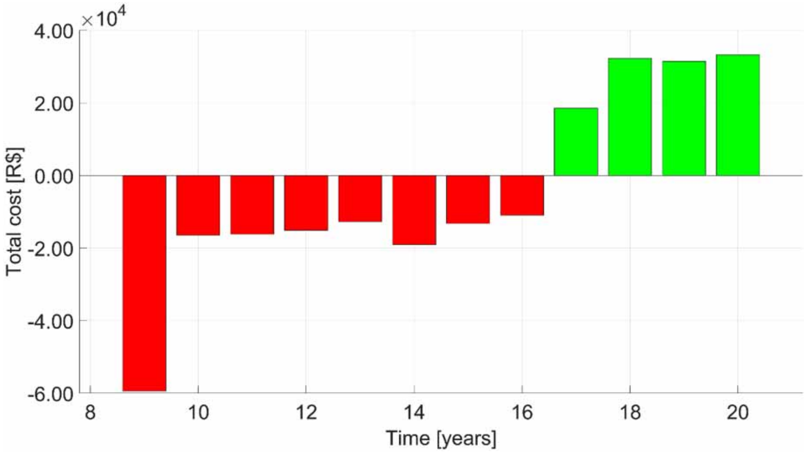


Figure 6 | Cash flow for the leakage fixing rehabilitation.

Pipe cleaning

As for the leakage fixing, the pipe cleaning started in the ninth year of operation, when the minimum pressure dropped below the required value. For the following 12 years of operation, 1% of the pipes have been cleaned every year, following the schedule presented in Figure 7.

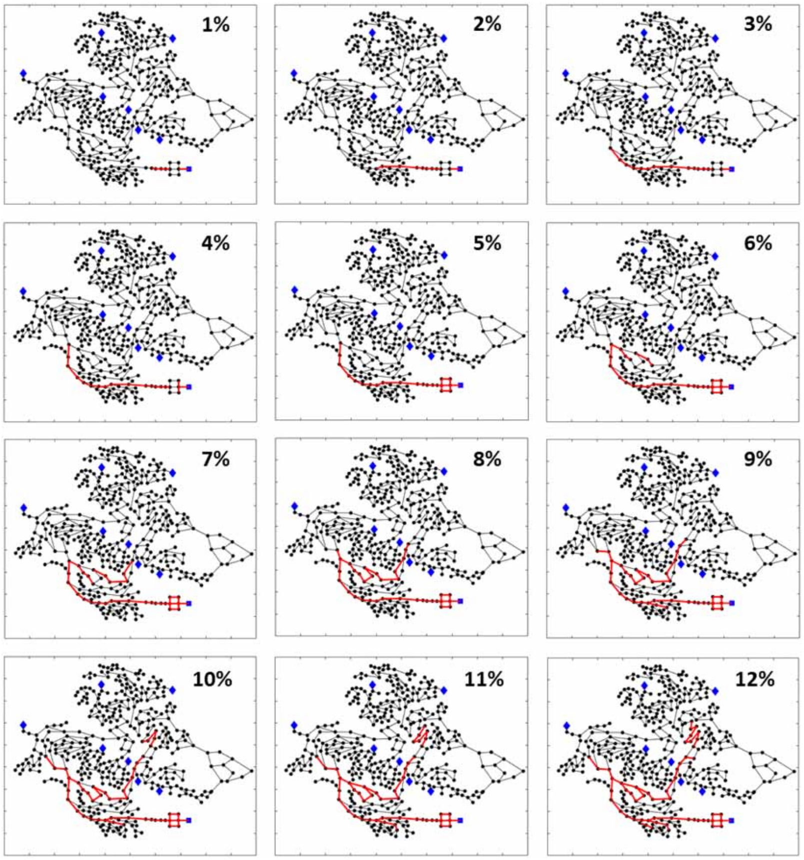


Figure 7 | Cleaning priority for each year of rehabilitation.

Evaluating Figure 8, it is noted that the reduction in operational costs was lower when compared with the leakage fixing, varying between 2 and 6%. The reduction in specific consumption is also lower, reaching a maximum of 16% in the final year. A higher value is also observed in the 11th year of operation, which could be due to changes in tank conditions, as the operation is not optimized. Regarding the pressure, the improvement rate is also worse, but the minimum required value is achieved for the final years as shown in Figure 9.

The lower benefits are already expected, as pipe cleaning influences only the head required at pumping stations, whereas leakage fixing, in addition to the head, affects the pump flow and water production. However, the necessary investment is much lower and the benefits quickly surpassed the investments, as shown in the cash flow presented in Figure 10. This

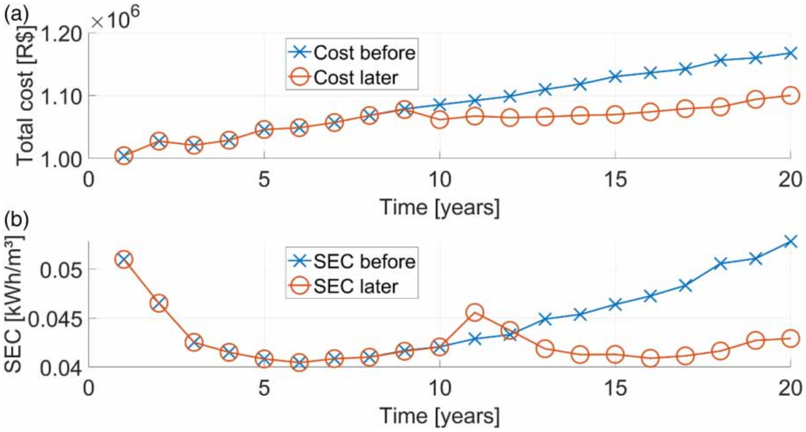


Figure 8 | Economic benefits for pipe cleaning: (a) total costs and (b) specific energy consumption.

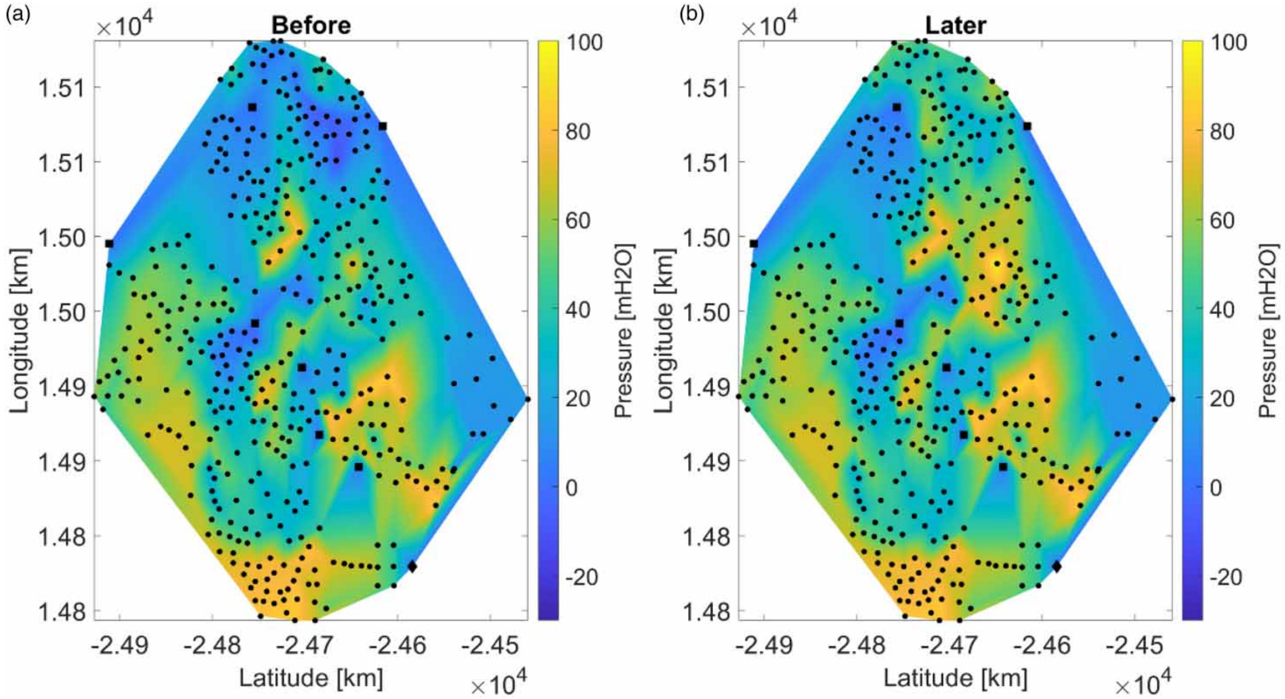


Figure 9 | Operating pressure for the maximum consumption period in the 10th year of operation: (a) deteriorated network and (b) rehabilitated network with pipe cleaning.

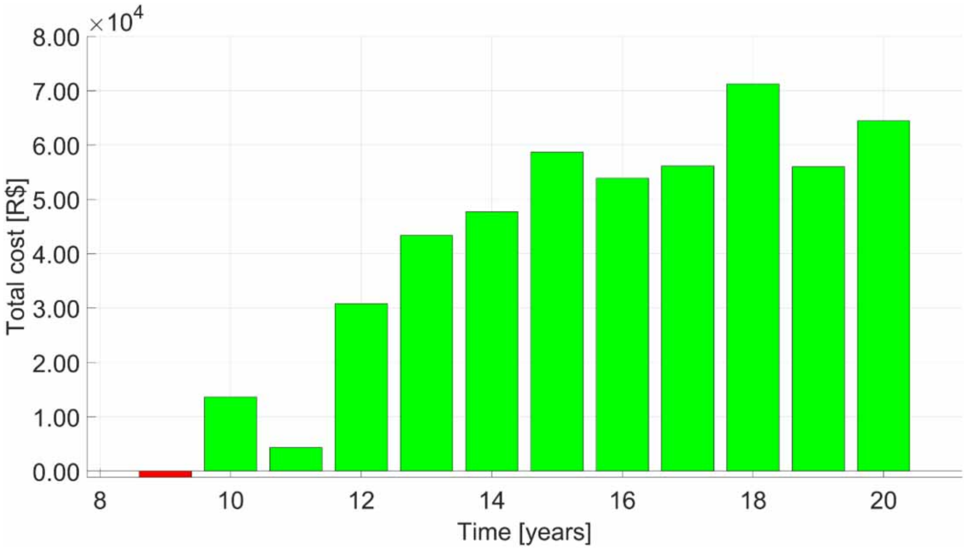


Figure 10 | Cash flow for pipe cleaning rehabilitation.

resulted in an attractive strategy, with a positive NPV of R$ 499,110.76. In addition to the greater economic benefit, pipe cleaning (or replacement) is much easier to be effectively implemented, as the maintenance can be easily scheduled according to the pipe lifetime and relevance to the WDN.

CONCLUSIONS

The paper presented two different strategies for the rehabilitation of a deteriorated WDN. Pipes incrustation, leakage increase and pump deterioration were considered to model the WDN conditions during its life cycle. In addition, the water demand increase was also considered, using an estimation of the population growth. For the D-town case study, a significant increase in operational costs was observed when compared to the ideal situation of no deterioration. More important, after the ninth year of operation, the minimum pressure dropped below the required value. Thus, if no maintenance is made, the WDN would operate under intermittency or be unable to supply some consumers for half of its life cycle. Pressure management could be an important strategy to improve the water supply conditions at this point. However, this is not a direct rehabilitation of the network, since the orifices of leakages remain and the water losses are just better controlled. Thus, the real problem was not effectively solved, only postponed. Both strategies for rehabilitation studied – leakage fixing and pipe cleaning – were capable of reestablishing the required pressure conditions. From the hydraulic point of view, fixing leakage is more attractive, as it reduces both pump flow and head, and also the water production volume. This is clearly observed when the operational costs and SEC of the two strategies are compared, with leakage fixing significantly better. However, the investment necessary for leakage fixing is much higher, and by using the NPV as an economic indicator, it was observed that pipe cleaning resulted in a much better option. In addition, it is much easier to effectively implement a maintenance schedule of pipe cleaning according to its lifetime and relevance to the WDN compared to fixing leakages, which can be hard to identify – especially the small ones. It is important to note that the case study presented here contains two singular aspects, namely its design, with pipe diameters capable to attend the population growth, and five pump stations, capable to adjust the schedule to operate during more hours per day, also assisting the demand increase. In other case studies, with poorer hydraulic conditions, a pipe replacement strategy may be required for rehabilitation.

FUNDING

The authors acknowledge the financial support from the National Council for Scientific and Technological Development (CNPq) through the Productivity Scholarship PQ-2 (CNPQ N° 305256/2021-1) and Universal Demand Project (CNPQ N. 404605/2021-4), and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) through the project APQ-01320-21.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Ahopelto, S. & Vahala, R. 2020 Cost–benefit analysis of leakage reduction methods in water supply networks. *Water* **12** (1), 195.

Boian, R. F., Macedo, D. O., Oliveira, P. J. A. D. & Janzen, J. G. 2019 Comparison between FAVAD and general equations to evaluate the leakage lost flow in urban water distribution systems. *Engenharia Sanitaria e Ambiental* **24**, 1073–1080 (in Portuguese).

Brentan, B., Meirelles, G., Luvizotto Jr, E. & Izquierdo, J. 2018 Joint operation of pressure-reducing valves and pumps for improving the efficiency of water distribution systems. *Journal of Water Resources Planning and Management* **144** (9), 04018055.

Brentan, B., Monteiro, L., Carneiro, J. & Covas, D. 2021 Improving water age in distribution systems by optimal valve operation. *Journal of Water Resources Planning and Management* **147** (8), 04021046.

Briceño-León, C. X., Iglesias-Rey, P. L., Martínez-Solano, F. J. & Creaco, E. 2023 Integrating demand variability and technical, environmental, and economic criteria in design of pumping stations serving closed distribution networks. *Journal of Water Resources Planning and Management* **149** (3), 04023002.

Campbell, E., Izquierdo, J., Montalvo, I., Ilaya-Ayza, A., Perez-Garcia, R. & Tavera, M. 2015 A flexible methodology to sectorize water supply networks based on social network theory concepts and multi-objective optimization. *Journal of Hydroinformatics* **18** (1), 62–76.

Campbell, E., Izquierdo, J., Montalvo, I. & Pérez-García, R. 2016 A novel water supply network sectorization methodology based on a complete economic analysis, including uncertainties. *Water* **8** (5), 179.

Carpitella, S., Brentan, B., Montalvo, I., Izquierdo, J. & Certa, A. 2019 Multi-criteria analysis applied to multi-objective optimal pump scheduling in water systems. *Water Supply* **19** (8), 2338–2346.

CASAN 2021 *Santa Catarina State Water and Sanitation Company – Civil Works Price List*. https://www.casan.com.br/.

CEMIG 2021 Available in: https://www.cemig.com.br/atendimento/valores-de-tarifas-e-servicos (accessed 8 October 2021).

Covelli, C., Cimorelli, L., Cozzolino, L., Della Morte, R. & Pianese, D. 2016 Reduction in water losses in water distribution systems using pressure reduction valves. *Water Supply* **16** (4), 1033–1045.

Creaco, E. & Pezzinga, G. 2015 Multiobjective optimization of pipe replacements and control valve installations for leakage attenuation in water distribution networks. *Journal of Water Resources Planning and Management* **141** (3), 04014059.

Creaco, E. & Walski, T. 2017 Economic analysis of pressure control for leakage and pipe burst reduction. *Journal of Water Resources Planning and Management* **143** (12), 04017074.

Di Nardo, A., Di Natale, M., Santonastaso, G. F., Tzatchkov, V. G. & Alcocer-Yamanaka, V. H. 2014 Water network sectorization based on graph theory and energy performance indices. *Journal of Water Resources Planning and Management* **140** (5), 620–629.

European Commission 2013 *Resource and Economic Efficiency of Water Distribution Networks in the EU*.

Farmani, R., Walters, G. & Savic, D. 2006 Evolutionary multi-objective optimization of the design and operation of water distribution network: total cost vs. reliability vs. water quality. *Journal of Hydroinformatics* **8** (3), 165–179.

Haddad, O. B., Adams, B. J. & Marino, M. A. 2008 Optimum rehabilitation strategy of water distribution systems using the HBMO algorithm. *Journal of Water Supply: Research and Technology – AQUA* **57** (5), 337–350.

Hamlehdar, M., Yousefi, H., Noorollahi, Y. & Mohammadi, M. 2022 Energy recovery from water distribution networks using micro hydropower: a case study in Iran. *Energy* **252**, 124024.

Hartman, J. C. 2000 On the equivalence of net present value and market value added as measures of a project's economic worth. *The Engineering Economist* **45** (2), 158–165.

IBGE (Org.) 2018 *Population projections: Brazil and units of the Federation, revision 2018*, 2nd edition. IBGE, Brazilian Institute of Geography and Statistics, Minas Gerais.

Kang, D. & Lansey, K. 2010 Real-time optimal valve operation and booster disinfection for water quality in water distribution systems. *Journal of Water Resources Planning and Management* **136** (4), 463–473.

Klingel, P. 2012 Technical causes and impacts of intermittent water distribution. *Water Science and Technology: Water Supply* **12** (4), 504–512.

Li, R., Huang, H., Xin, K. & Tao, T. 2015 A review of methods for burst/leakage detection and location in water distribution systems. *Water Science and Technology: Water Supply* **15** (3), 429–441.

Liu, S., Gunawan, C., Barraud, N., Rice, S. A., Harry, E. J. & Amal, R. 2016 Understanding, monitoring, and controlling biofilm growth in drinking water distribution systems. *Environmental Science & Technology* **50** (17), 8954–8976.

Mala-Jetmarova, H., Sultanova, N. & Savic, D. 2018 Lost in optimisation of water distribution systems? A literature review of system design. *Water* **10** (3), 307.

Marchi, A., Salomons, E., Ostfeld, A., Kapelan, Z., Simpson, A. R., Zecchin, A. C., Maier, H. R., Wu, Z. Y., Elsayed, S. M., Song, Y., Walski, T., Stokes, C., Wu, W., Dandy, G. C., Alvisi, S., Creaco, E., Franchini, M., Saldarriaga, J., Páez, D., Hernández, D., Bohórquez, J., Bent, R., Coffrin, C., Judi, D., McPherson, T., van Hentenryck, P., Matos, J. P., Monteiro, A. J., Matias, N., Yoo, D. G., Lee, H. M., Kim, J. H., Iglesias-Rey, P. L., Martínez-Solano, F.J., Mora-Meliá, D., Ribelles-Aguilar, J. V., Guidolin, M., Fu, G., Reed, P., Wang, Q., Liu, H., McClymont, K., Johns, M., Keedwell, E., Kandiah, V., Jasper, M. N., Drake, K., Shafiee, E., Barandouzi, M. A., Berglund, A. D, Brill, D., Mahinthakumar, G., Ranjithan, R., Zechman, E. M., Morley, M. S., Tricarico, C., de Marinis, G., Tolson, B. A., Khedr, A. & Asadzadeh, M. 2014 Battle of the water networks II. *Journal of Water Resources Planning and Management* **140** (7), 04014009.

Martins, N. M., Delgado, J. N., Ramos, H. M. & Covas, D. I. 2017 Maximum transient pressures in a rapidly filling pipeline with entrapped air using a CFD model. *Journal of Hydraulic Research* **55** (4), 506–519.

Meirelles, G., Junior, E. L. & Brentan, B. M. 2017 Selection and location of pumps as turbines substituting pressure reducing valves. *Renewable Energy* **109**, 392–405.

Mora-Rodríguez, J., Delgado-Galván, X., Ortiz-Medel, J., Ramos, H. M., Fuertes-Miquel, V. S. & López-Jiménez, P. A. 2015 Pathogen intrusion flows in water distribution systems: according to orifice equations. *Journal of Water Supply: Research and Technology – AQUA* **64** (8), 857–869.

Nault, J. & Papa, F. 2015 Lifecycle assessment of a water distribution system pump. *Journal of Water Resources Planning and Management* **141** (12), A4015004 (in Portuguese).

Shao, Y., Yu, Y., Yu, T., Chu, S. & Liu, X. 2019 Leakage control and energy consumption optimization in the water distribution network based on joint scheduling of pumps and valves. *Energies* **12** (15), 2969.

Sharp, W. W. & Walski, T. M. 1988 Predicting internal roughness in water mains. *Journal-American Water Works Association* **80** (11), 34–40.

Simukonda, K., Farmani, R. & Butler, D. 2018 Intermittent water supply systems: causal factors, problems and solution options. *Urban Water Journal* **15** (5), 488–500.

SNIS 2019 National System of Sanitation Information (Water and Sewerage Services Diagnosis N° 25; p. 183). Ministry of Regional Development. Available from: http://www.snis.gov.br/diagnosticos.

Souza, R. G., Meirelles, G., Brentan, B. & Izquierdo, J. 2022 Rehabilitation in intermittent water distribution networks for optimal operation. *Water* **14** (1), 88.

St. Clair, A. M. & Sinha, S. 2012 State-of-the-technology review on water pipe condition, deterioration and failure rate prediction models!. *Urban Water Journal* **9** (2), 85–112.

Tscheikner-Gratl, F., Sitzenfrei, R., Rauch, W. & Kleidorfer, M. 2016 Enhancement of limited water supply network data for deterioration modelling and determination of rehabilitation rate. *Structure and Infrastructure Engineering* **12** (3), 366–380.

Zaman, D., Tiwari, M. K., Gupta, A. K. & Sen, D. 2020 A review of leakage detection strategies for pressurised pipeline in steady-state. *Engineering Failure Analysis* **109**, 104264.

First received 1 December 2022; accepted in revised form 29 May 2023. Available online 7 June 2023