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SENSITIVITY ANALYSIS OF WATER DISTRIBUTION NETWORKS DETERIORATION IN HYDRAULIC AND ECONOMIC PARAMETERS

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Abstract

Water Distribution Networks (WDNs) are responsible for the majority of the costs in a water supply system. Thus, it is reasonable to carefully evaluate the possible interventions to achieve the one with the best cost benefit. Usually, WDN's projects are designed for a life cycle of 20 years, but many systems are already operating longer than this, up to 100 years. Obviously, several maintenance services are necessary during this period, but the knowledge of how the system deteriorate can help the management of these services and keep the operational efficiency high, Therefore, in this work the deterioration of the components of a WDN is evaluated trough the economic losses generated and the pressure deficit. The pipe deterioration is modelled considering the roughness increases at a certain rate. Pumps deterioration are similarly modelled, considering the formation of internal roughness that increases the internal recirculation. Finally, the demand increase is also modelled considering the population growth rate and a minimum leakage flow rate. In addition, pressure dependent leakages are modelled as an orifice, maintaining its characteristics constant during the simulation. The results shown that maintenance services are essential for the efficient operation of WDNs, with leakages representing the most impactful problem.

Keywords

Water distribution networks, energy efficiency, life cycle, maintenance.

1 INTRODUCTION

Water Distribution Networks (WDNs) represent the major cost of the infrastructure of water supply systems. In addition, the performance of the networks directly reflects on operational costs, since pumping stations are designed to attend the consumers demand, in both quantity (flow) and quality (pressure). In addition, leakages are an imperative problem of WDNs, and the leaking flow impacts both in the energy costs of pumping stations as in the treatment of raw water. Therefore, the design of WDNs is one of the most important problems in water supply systems, and different approaches have been proposed to achieve solutions economic and technically feasible.

Firstly, the focuses was on the most cost effective solution, where the pipes diameter were minimized to achieve the lowest cost, while maintaining the minimum required pressure on the network [1]. As good as this approach sounds, as highlighted by different authors [2–4] this strategy can be harmful for other parameters, as water quality and the network resilience. Thus, multiobjective optimization and multicriteria analysis were studied trying to balance operational parameters with a reasonable performance in all aspects. [5] presented a methodology to improve the design of the WDN by increasing the diameter of main pipes to increase the energy recovery potential through a pump operating as turbine, thus reducing the net operational costs.

Even if an optimal solution is achieved, the operation of the WDN can create several conditions that deteriorate the infrastructure during its life cycle. Water quality, soil condition, laying methods, pipe material and pressure surges are just a few parameters that can create failure conditions of the system [6]. As highlighted by [7], age or the remaining life of the infrastructure are a good criterion for the management of the WDN. Although a pipe failure is very harmful to the system, it can also be quickly fixed, since it is easy to identify the problem. On the other hand, leakages can occur in several points of the infrastructure as small holes in pipes, joints and fittings, reservoirs floor and walls and consumers metering [8]. These small leakages are hard to identify, since there is no visual signal, and they tend to increase during the WDN life, as highlighted by [9] and reinforced by the results found by [10], that shown the change of old pipes was more effective for leakage control than pressure management.

When the WDN requires the use of pump stations, the design becomes even more complex. Pipes costs are inversely proportional to the energy costs for pumping, larger diameters reduce the head losses, and consequently, the required power by the pumps. [11] proposes a joint optimization for pipes diameters and pump selection, while [12] also includes the pump location as a problem in the WDN design. As can be expected, pumps also deteriorate during the WDN life, reducing its capacity and efficiency. In addition, its operational point can be drastically affected by the deterioration of other components, as pipes roughness and leakages.

Therefore, in this paper a sensitivity analysis is made to evaluate the energy, hydraulic and economic aspects of the deterioration of a WDN. Pipe deterioration is modelled considering roughness increase at a certain rate, as proposed by [13]. Pumps deterioration are similarly modelled, considering the formation of an internal roughness that increases the internal recirculation [14]. Finally, the demand increase is also modelled considering the population growth rate [15] and a minimum leakage flow rate, economically unfeasible to be fixed. According to the model proposed by [16], the minimum leakage can be calculated using the total length of the WDN and the population. A pressure dependent leakage is also modelled as an orifice. During the simulation time, all orifice features are kept constant. The results show that maintenance services are essential for the efficient operation of WDNs, with leakages representing the most impactful problem.

2 WDN DETERIORATION

2.1 General features of deterioration scenarios

WDNs are subject to deterioration over their lifetime in several ways. Pipes increase internal roughness due to factors such as water quality, pipe diameter, age, and the material [17]. Pipe roughness increases leads to an increase also to the system's head losses, and consequently, the operation characteristics of the system should be changed due to the pressure deficit created. The system's water demand is another important factor to be evaluated. Along the life cycle of the WDN, the water demand of the consuming population in addition to leakage tends to present changes. These changes in demand will directly impact energy consumption, as they can drastically modify the operating point of pumping stations. In addition, the pumps can also deteriorate over time due to misalignment, excessive vibration, and corrosion. As the pumps deteriorates, the hydraulic power provided is compromised and the WDN's overall operating efficiency is harmed.

Thus, this paper proposes to evaluate the parameters that can deteriorate the WDN efficiency over its lifetime. These are the roughness of the pipes, the water demand (consumption and leakages), and the deterioration of the pumps.

For this, the Matlab R2021 software is used for the elaboration of algorithms, which coupled to the Epanet hydraulic simulator [18] and using the Epanet-Matlab Toolkit developed by [19], performs the hydraulic simulations and the modifications to evaluate the proposed deterioration scenarios. For the analyses, 3 scenarios are prepared, as discussed in the following sections, in which certain parameters are changed over the life cycle of the WDN. In addition, a scenario considered ideal is elaborated to be used as a benchmark for comparison with the data observed in the other scenarios.

Some features used in hydraulic simulations are the same for all scenarios and are summarized as:

- All developed scenarios are simulated in 20-year life cycle periods. As the deterioration processes discussed in this paper occur slowly, hourly hydraulic simulations are performed in a period of 24 hours, and observed data in this period are considered to represent the average of a typical day of the year. In this way, the simulation of the entire life cycle of the WDN is reduced to 20 consecutive daily hydraulic simulations.
- The costs of water losses due to leaks and the costs of electrical energy with the operation of the pumps are considered. For the electricity costs, the tariff differences between on-peak and off-peak hours are considered, observing the current tariffs of the [20]. The costs of leakage are considered through the costs of water production [21].
- In order to evaluate the hydraulic performance of the WDN, with regard to the operating pressures, the critical nodes of the network are analysed for all scenarios. Critical pressure is given as the lowest value observed at any consumption node of the WDN.

2.2 Ideal scenario

In the ideal scenario, the hydraulic components of the WDN remain as the initial characteristics along the entire life cycle. However, the water demand and a given value of minimum leakages (economically unfeasible to be fixed) increase proportionally with population growth, as both features are not manageable through the WDN improvement. The method of demographic components adjusted to a 3rd degree polynomial is used to estimate the population in each year of the simulation. This method is used by the Brazilian Institute of Geography and Statistics and the United Nations [15,22]. The 3rd polynomial used is given by Equation 1, in which the parameters adopted were the values assigned to the state of Minas Gerais in Brazil [15].

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

Where:

Y [n°]: Population;
X: Year; and
a, b, c and d: adjustment coefficients of the polynomial equation (a=0.0000004335; b=-0.0000023355; c=-0.0007653779; d=1.0003835392)

The minimum leakages considered in the WDN are calculated according to Equation 6, described in more detail in section 2.4. This ideal scenario is used as a benchmark for comparison, as this is the best situation among the scenarios evaluated.

2.3 Scenario for evaluation the deterioration of pipes

The process of deterioration of pipes can be classified in two categories: i) structural deterioration, which reduces the ability of pipes to withstand mechanical stress; and ii) functional deterioration, associated with the increase in the roughness of the internal surface of the pipes, reducing their hydraulic capacity [17,23]. Pipes age, material, diameter, the characteristics of the surrounding soil, external load and water quality are among the main factors related to the pipe deterioration rate [17].

Since in this paper the risk of failure is not considered, only the functional deterioration is evaluated. This deterioration relates to the pressure drop in the pipeline Δh, and can be calculated using the Hazen-Williams equation (Equation 2).

$$\Delta h = 10,653\left(\frac{Q}{C}\right)^{1,85} D^{-4,87} L \tag{2}$$

Where:

Q [m^3/s]: is the flow in the pipe;
L [m]: is the length of the pipe;
D [m]: is the diameter of the pipe; and
C: is the Hazen-Williams head loss coefficient.

The increase in pipe roughness changes the head loss of the WDN. This change reduces the available pressure for the consumers and, in critical conditions, can lead to an intermittency in the supply. To maintain the pressures above the minimum required, it is necessary to change the operational rules of the system and increase the hydraulic power by starting more pumps or increasing its speed when variable speed drives are available. In both cases, the adopted measures will reflect in an increase of electric energy consumption.

To consider its impact a new roughness is calculated each year using the methodology presented in [13], where the roughness increase at a constant rate as shown in Equation 3.

$$C = 18,0 - 37,2 \times log\left(\frac{e_0 + at}{D}\right) \tag{3}$$

Where:

C: Hazen-Williams Parameter;
e_0 [mm]: Initial absolute roughness;
a [mm/year]: Roughness increase rate;
t [years]: Time; and
D [m]: pipe diameter.

The values of initial roughness and rate of increase are respectively 0.18 mm and 0.094488 mm/year [13]. However, these values contain many associated uncertainties, due to direct measurement difficulty [17,24]. Thus, as a way to evaluate the uncertainties and the impact of the roughness increase in the WDN operation, different rates re used as shown in Table 1.

Table 1. Rates of increase in the internal roughness of pipes

Rates [mm/year]				
50%	80%	Ref:100%	120%	150%
0.047244	0.07559	0.094488	0.113386	0.141732

2.4 Scenario for evaluating the leakage rate

Water losses correspond to the water volume distributed but not accounted [25]. At WDN, this volume encompass actual losses, such as leakages, and apparent losses, such as clandestine connections. To calculate the flow of water lost through a single leakage, the formulation given by equation 4 is often used [26–28].

$$q = C_d A (2gh)^{0,5} \tag{4}$$

Where:

q [m^3/s]: is the leakage flow;
C_d : is the emission coefficient;
A [m^2]: is the leakage area;
g [m/s^2]: is the gravitational acceleration; and

h [m]: is the pressure load on the leakage.

However, for application in real WDN and hydraulic modelling through software, such as EPANET, Equation 4 can be rewritten in a more general way, according to Equation 5 [18,26]. In that case, the values of C_d and y must be calibrated to the WDN under study.

$$q = C_d h^y \tag{5}$$

Where:

C_d : is the emission coefficient; and
y: is the emission exponent.

By default, the EPANET software uses the value of the emission exponent equal to 0.5, often used in the modelling of holes and nozzles. In addition, studies suggest similar values for WDN [26,29]. This leakage modelling is used to represent water losses that can be fixed, as they have a great economic impact. However, small leakages, as observed in domiciliary connections and pipe junctions, are hard to identify, resulting in a cost/benefit relation that is not attractive to fix it. Thus, the proposal given by [16] is used to estimate the minimum losses in the WDN. This formulation considers the network length and the number of consumers to estimate the minimum value of leakages, as shown in Equation 6.

$$q_{min} = 54 + 2.7\,(\frac{N_p}{L_r}) \tag{6}$$

Where:

q_{min} [m^3/km]: is the minimum volume of leakages to be considered;
N_p : is the number of customers served; and
L_r [km]: is the total length of the network pipes.

In the equations proposed for modelling the leakages, it is observed that the volume of leakages changes with the variation of pressure at the node when modelled through Equation 5 (daily variation), and with the variation of the population when modelled by Equation 6 (yearly variation). Finally, as done for the pipe roughness, the emission coefficient is changed to different values to evaluate the sensitivity of the WDN to different water losses percentages, as shown in Table 2.

Table 2. Values used for the emission coefficient

Values used for the C_d				
25%	70%	Ref: 100%	130%	175%
0.125	0.350	0.500	0.650	0.875

2.5 Scenario for evaluating the deterioration of the pump

Pumps used in WDN are subject to deterioration over life cycle, especially if maintenance plans are not carried out properly. Several factors, such as cavitation, corrosion, incrustations, misalignments and excessive vibrations can interfere in this deterioration process, which reflects on the pump performance. [30] suggest that the two main mechanisms lead to pump performance decrease: ii) the development of an internal flow due to gaps; and ii) increase in the roughness of the internal surface of the pumps.

Following the methodology initially proposed by [30], and used by [14], the change in pump head over its life cycle can be calculated according to Equation 7.

$$H'_P = \omega \left(a \left(\frac{Q+R}{\omega}\right)^2 + b \left(\frac{Q+R}{\omega}\right) + c - K_T t \left(\frac{Q}{\omega}\right)^2 \right) \tag{7}$$

Where:

H'_P [m]: Corrected pump head;
ω: relative speed;
a, b and c: Pump curve coefficients;
Q [l/s]: Pump flow;
R [l/s]: Pump internal recirculation flow;
K_T : Internal roughness increase rate; and
t [h]: Cumulative operating time.

The pump internal recirculation flow R, varies with the initial head and with the clearance in the pump impeller wear ring, calculated according to Equation 8.

$$R = 2\gamma D_a H_P^{0,5} \left(\sqrt{\frac{c^3}{75 \times c + L}} - \sqrt{\frac{c_0^3}{75 \times c_0 + L}} \right) \tag{8}$$

Where:

γ [N/m^3]: Specific gravity of water;
D_a [mm]: Wear ring diameter;
H_p [m]: Initial pump head;
L [mm]: Axial length of wear ring;
c [mm]: Wear ring clearance; and
c_0 [mm]: Initial wear ring clearance.

The clearance in the pump impeller wear ring (c) increases with a deterioration parameter β, given according to Equation 9.

$$c = c_0 \times ln(\beta t + e) \tag{9}$$

Where:

c [mm]: Wear ring clearance;
c_0 [mm]: Initial wear ring clearance;
β: Parameter of wear ring deterioration;
t [h]: Cumulative operating time; and
e: Euler number.

There are no reference values for the deterioration parameters K_T and β. Ideally, both should be obtained through calibrations made for each situation. However, in the elaboration of this proposal, the values given by [14], respectively 1.0×10^{-9} and 5.0×10^{-3}, are used as reference. To analyze the impact of severe and mild deteriorations, other rates are used. The rates are changed in values between 10 times lower and 10 times higher than the reference values, as shown in Table 3.

Table 3. Values used in the parameters K_T and β

Parameter change rates K_T and β

coefficient	10%	20%	50%	100%	200%	500%	1000%
$K_T \times 10^{-9}$	0.1	0.2	0.5	1.0	2.0	5.0	10
$\beta \times 10^{-3}$	0.5	1.0	2.5	5.0	10.0	25	50

2.6 Case study

For the development of the case study, the WDN called Anytown is used, conceived by [31], shown in Figure 1. The WDN consists of 40 pipes and 19 nodes supplied by two tanks and a pump station connected to a reservoir used as the only water source for the system.

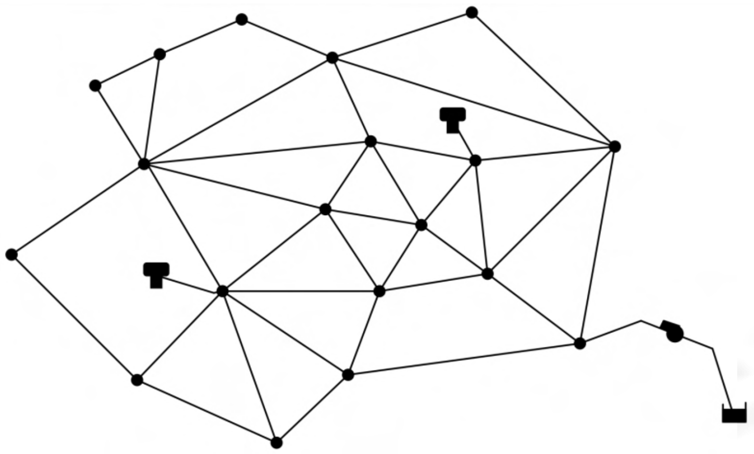

Figure 1. Water distribution network Anytown

All proposed scenarios and their respective variations are applied to this WDN. The annual total costs are calculated according to Equation 10. In addition, for each year of operation the minimum hourly pressure of the network is determined.

$$C_{year} = C_{typical} \times D_{year} \tag{10}$$

Where:
C_{year} [R$]: is the total cost during the year of operation;
$C_{typical}$ [R$]: is the cost during a typical day of the year of operation; and
D_{year}: is the number of days in the year.

Typical day costs are calculated as the sum of electricity costs during the day of operation, summed to the costs related to leakage during the same period, according to Equation 11.

$$C_{typical} = (D_{ener} \times P_{max}) + \sum_{i=1}^{24} (P_{(i)} \times C_{ener(i)}) + (Vol_{(i)} \times C_{vol(i)}) \tag{11}$$

Where:
$C_{typical}$ [R$]: is the total cost during the typical day;
$P_{(i)}$ [kwh]: is the energy consumed in the hour *i*;
$C_{ener(i)}$ [R$/kwh]: is the cost of electricity in the hour *i*;
D_{ener} [R$/kW]: is the cost with electrical energy demand;
P_{max} [kW]: is the maximum power achieved in the period considered;
$Vol_{(i)}$ [m^3]: is the volume of water lost in the hour *i*; and
$C_{vol(i)}$ [R$/m^3]: is the cost of producing water in the hour *i*.

For electricity costs, power demand and energy tariffs were considered at peak times (period between 5 and 7 PM), where tariffs are more expensive, and at off-peak times, when tariffs are cheaper, according to the current rates of the Energy Company of Minas Gerais in Brazil [32]. Leakage costs are calculated as the product of the cost of water production and the volume of water lost [21]. Table 2.4 summarizes the costs considered.

Table 4 – Values used to calculate total costs

Off-peak times		Peak times		Water production cost [$/m^3]
Electricity [$/Kwh]	Demand [$]	Electricity [$/Kwh]	Demand [$]	
0.35666	13.95	0.53425	43.85	0.30

3 RESULTS

3.1 Pipe deterioration

Figure 2 shows the total annual costs, for each rate of increase in the internal roughness of the pipes evaluated. The overlap of the lines indicates that the different rates of increase in roughness do not cause direct changes in operating costs, since the pump operating point is not altered by changes in roughness. This occurs because the modeling of the WDN is demand driven, so the water consumption remains the same despite any pressure variation.

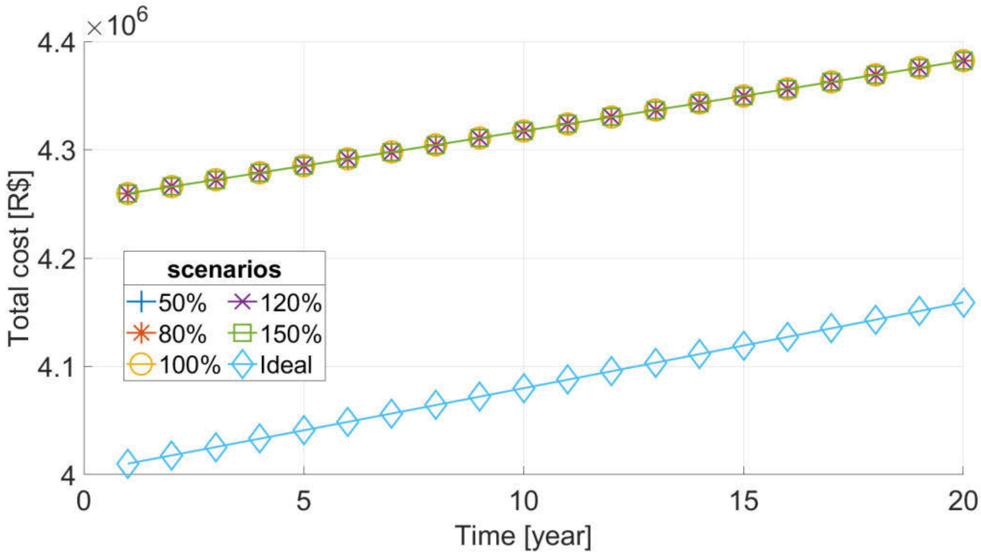

Figure 2. Total costs for each roughness increase rate

However, the operating pressures of the WDN are constantly reducing, as shown in Figure 3, both due to population growth (water demand) and the increase in pipe roughness, which increase the head losses. Thus, to maintain a minimum pressure required, it would be necessary to change the operating point of the pump, or add another one, which would change the operating costs. It's worth noticing in Figure 2 that, compared to the ideal scenario, the operating costs are 6.2% higher in every year, result of the addition of the minimum leakage.

Figure 3 shows the critical pressures of the WDN each year during its life cycle. The pressure observed in the initial year is the same for all scenarios, however for the different rates of increase in roughness there is a significant deviation in the behavior of pressures over time. In the scenario where the average rate (0.09448 mm/year) is used, the critical pressure in the WDN decreases until the value of 20 m (minimum required pressure according to [13]) in the 11th year and 10 m (minimum required pressure according to the [33]) in the 20th year of operation. When the roughness increase rate is 50% higher than the average value (0.141732 mm/year), the worst case scenario considered, the pressure of 20 m is reached in the 8th year and the 10 m in the 15th year of operation, earlier compared to the average scenario. In the case of the best scenario, with the roughness increase rate 50% lower than the average value (0.047244 mm/year), the pressure of 20 m is reached only in the 18th year of operation and the pressure of 10 m is always satisfied.

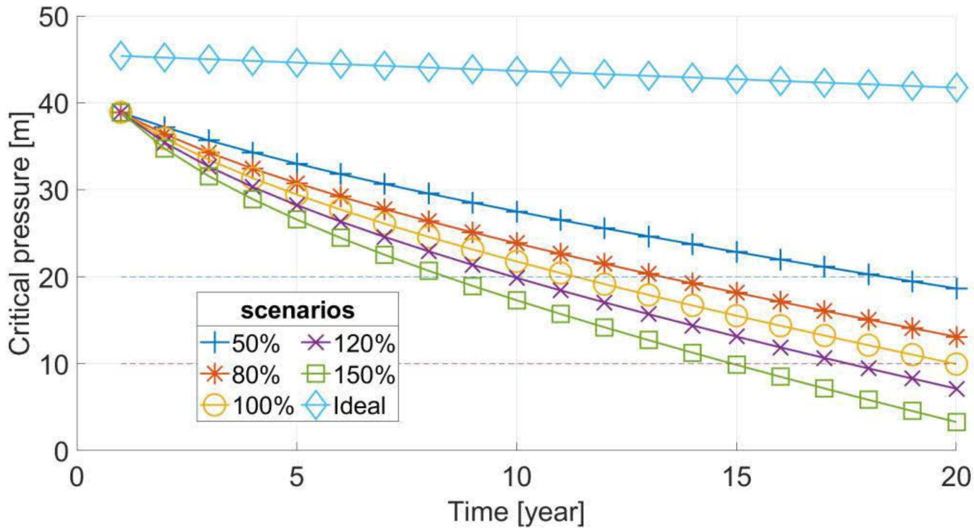

Figure 3. Critical pressures for each roughness increase rate

With the roughness increase rate 50% higher than the average value, the critical pressure at the end of the WDN lifecycle is 67.1% lower than the average rate scenario. When the roughness increase rate is 50% less than the average value, the critical pressure at the end of the WDN life cycle is 86.5% greater than the average rate scenario. The critical pressure values presented show how harmful the pipe deterioration can be for the WDN operation. On the other hand, when the deterioration is not severe, the pipe roughness has a very small impact, which shows the importance of the knowledge of system characteristics, especially water quality parameters, pipe material and soil characteristics, which can be an indicative of potential problems. Table 5 presents the critical pressures and the percentages in relation to the ideal scenario, for the pressure value at the beginning and end of the WDN life cycle.

Table 5. Critical pressures at the beginning and end of the life cycle for each roughness increase rate and for the ideal scenario

	Scenarios					
Scenarios	Ideal	50%	80%	Ref: 100%	120%	150%
Rates [mm/year]	-	0.047244	0.07559	0.094488	0.113386	0.141732
Pressure at the beginning of the life cycle [m]	45.4	38.9	38.9	38.9	38.9	38.9
End of life pressure [m]	41.8	18.7	13.1	10.0	7.1	3.3
Difference in relation to the ideal	-	-55.3%	-68.7%	-76.1%	-83.0%	-92.1%

3.2 Leakages

Figure 4 shows the total costs for each year when only changes in the emission coefficient were evaluated. Operating costs are significantly impacted by leakages, with the highest total values observed among all the scenarios evaluated in this work. This because, in addition to increasing the costs of water lost through the modelled orifices, the pump operation point is considerably altered due to the greater volume pumped to meet the demand for leakages.

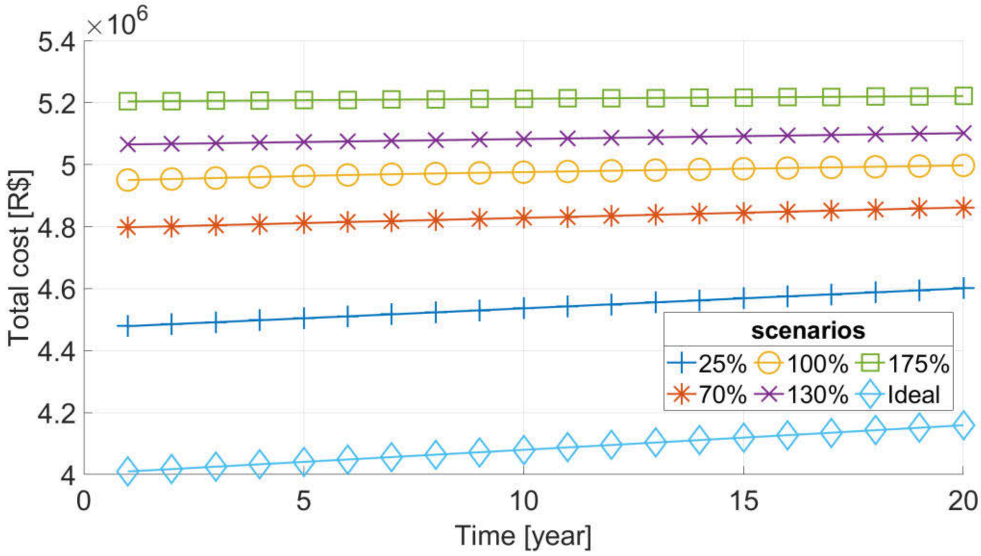

Figure 4. Total for different emission coefficients

When the emission coefficient is 75% higher than the average value (0.875), the total costs in the final year of the WDN life cycle are 4.5% higher, and when the emission coefficient is 75% lower (0.125), the total costs is 7.9% lower. Compared to the ideal scenario, the operating costs for the different leakage percentages are always higher as can be seen in Figure 4. Table 6 presents the total costs for the end of life cycle of the WDN and the percentage relationship with the ideal scenario.

Table 6. Total costs in the final year of the WDN life cycle for each emission coefficient compared to the ideal scenario

Scenarios	Ideal	25%	70%	Ref: 100%	130%	175%
Coefficients	0	0.125	0.350	0.500	0.650	0.875
Leakage index	0	9.0%	14.4%	18.9%	21.8%	25.5%
Cost [R$]	4,159,130	4,600,970	4,861,670	4,997,300	5,101,350	5,220,960
Difference in relation to the ideal	-	+10.6%	+16.9%	+20.2%	+22.7%	+25.5%

Critical pressures in this scenario vary for each emission coefficient considered, as shown in Figure 5. With the emission coefficient equal to 0.125, the critical pressure is 56.0% greater than the average value at the end of the life cycle. With the emission coefficient equal to 0.875, the critical pressure is 42.5% lower than the average value. The critical pressures in the initial year vary from 14.4 m to 34.6 m, respectively being the worst and best cases evaluated.

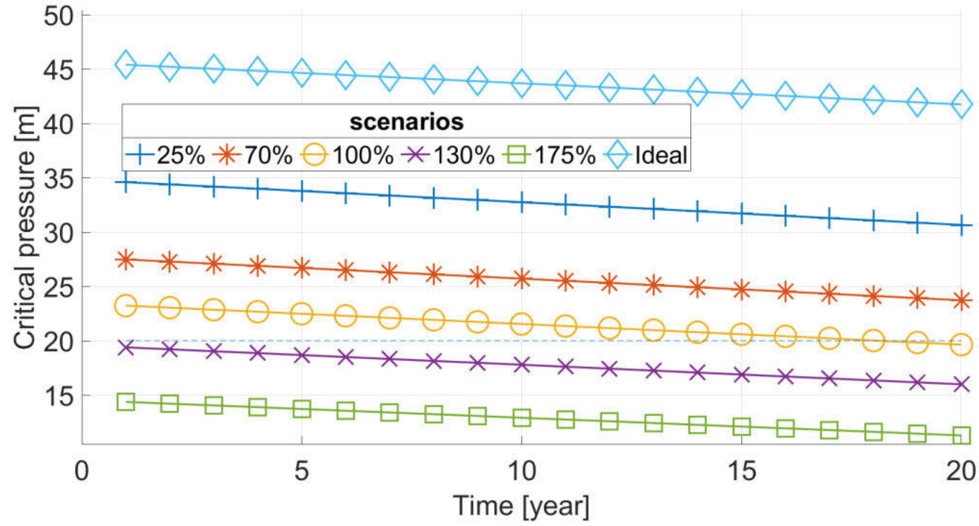

Figure 5. Critical pressures each year for the different emission coefficients

When the pressure of these scenarios is compared with the ideal scenario, it is observed that it is always lower within the evaluated life cycle. The higher the emission coefficient, the worse it is.

It is also worth mentioning that the leakage percentages observed in the simulations are still lower than those observed in Brazil, which presents an average of 39.2 %, but with cities operating with values well above [21]. This corroborates the importance of leakage control strategies in WDN.

3.3 Pump deterioration

Figure 6 shows the total costs each year over the life cycle of the WDN, for each pump deterioration rate. Contrary to what would be intuitively expected, as pump deterioration rates increase, operating costs decrease. A maximum increase of 1.3% is observed in the final year of the life cycle of the WDN.

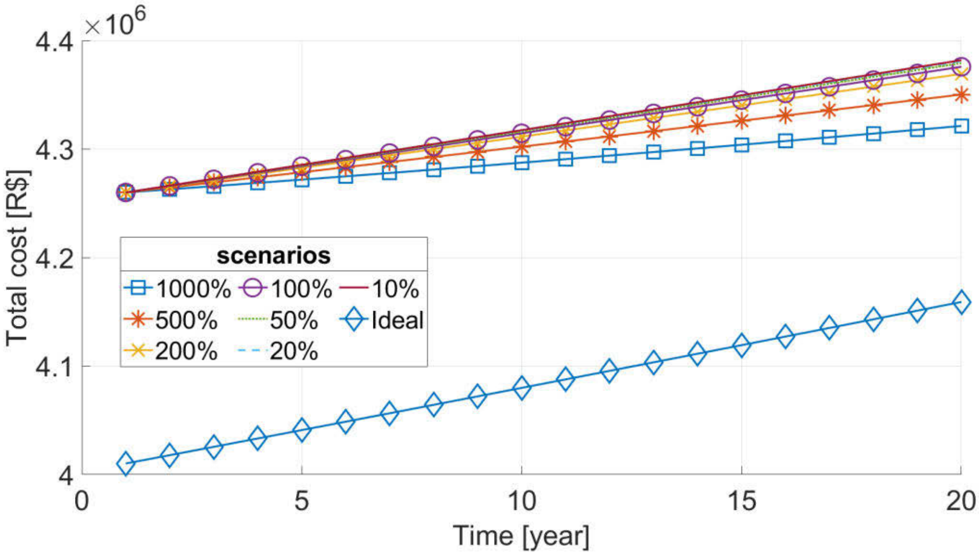

Figure 6. Total costs each year for different pump deterioration rates

This because, as the rate of deterioration of the pump increases, the head decrease according to the formulation used. Once again, as the model is demand driven, the power required to deliver water to the consumers is lower, as the head for the same flow is now lower. This behaviour reflects on the pressure of the WDN as will be following shown. However, it is important to emphasize that in this case the operating costs should not be evaluated individually, as the deterioration of the pump can also lead to supply failures due to mechanical problems resulting from the deterioration of the pump.

Figure 7 shows the critical pressures each year in the WDN, for each pump deterioration rate. Critical pressures decrease in all scenarios over time, but the decrease is more pronounced as the rate of deterioration increases. When the pump deterioration rate is 10 times the average value, the critical pressure at the end of the WDN life is 3.5% lower. When the pump deterioration rate is 10 times lower than the average rate, the system pressure remains practically the same. Although these scenarios present variations in critical pressures, with the methodology and rates adopted for the pump deterioration scenarios in this work, the values suggest that these changes are not very expressive for the time considered. Thus, if the pumps are capable to deliver the required flow with a minimum pressure, they should not be the main focus for the system improvement, since, as already seen in items 3.1 and 3.2, pipes deterioration and leakages have a greater impact in the operation. However, it is emphasized that maintenance plans must take place to avoid sudden shortages caused by mechanical failures, which can become more frequent due to the deterioration process.

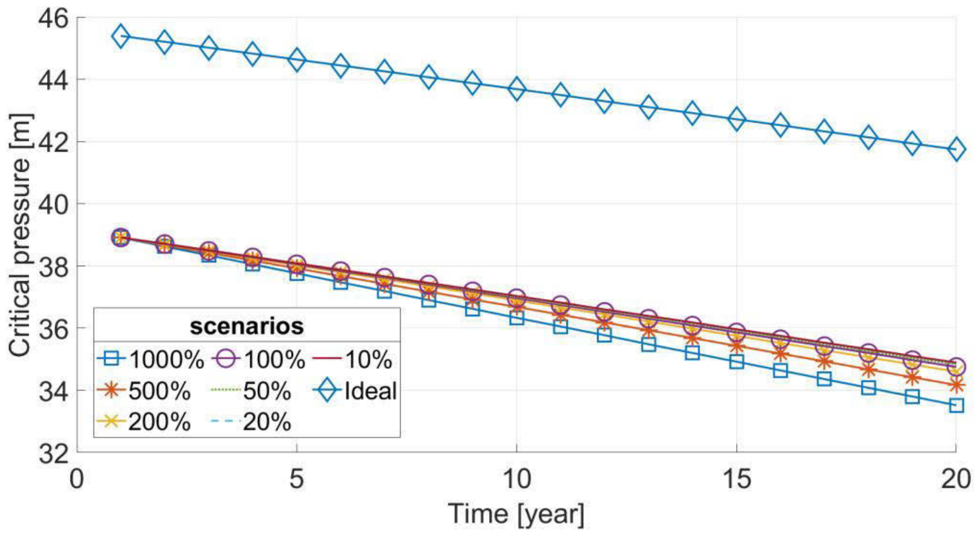

Figure 7. Critical pressures for each rate of deterioration increase

3.4 Evaluation between the average scenarios

Figure 8 shows the total annual costs for the three average scenarios evaluated. In addition, it shows the ideal scenario, presented earlier, and a new intermediate scenario. In this intermediate scenario all three average parameters analyzed were considered simultaneously. The main impact on total costs is clearly caused by leakage, as seen by the different amplitude in the curves. Relative to the ideal scenario, the total costs each year are 23.4% higher in the leakage scenario and 6.2% higher in the pump deterioration and roughness change scenarios. The growth of total costs in each of the scenarios follows a similar rate, given by the slope of the curve, which is related to the population growth rate. The intermediate scenario presents total costs close to the values observed in the leakage scenario. This is because in the intermediate scenario, leakage is also considered in the simulations, in addition to the other parameters.

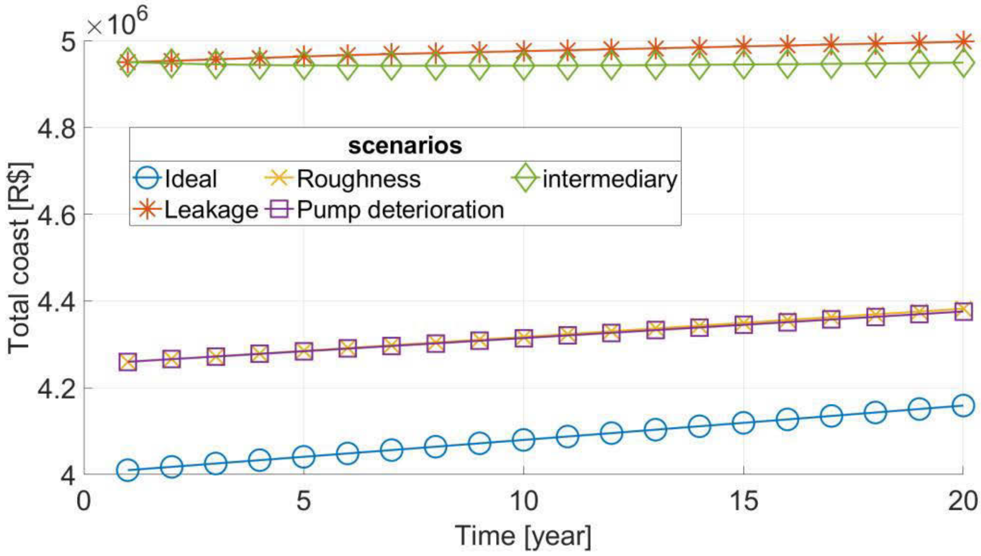

Figure 8. Total costs for each year of the evaluated scenarios

Figure 9 shows the critical pressures for the three average scenarios evaluated above, in addition to the ideal scenario and intermediary. Until the middle of the WDN life cycle, the scenario with the lowest critical pressures is observed in the leakage scenario. However, from the 10th year onwards, the pressures are lower in the scenario where the roughness of the pipes changes. The increase in the roughness of the pipes with the adopted rate causes the pressures to decrease significantly with time. When associated with the additional demand over the years, due to population growth, the head losses observed in the WDN significantly increase, reaching levels where intervention would be necessary for the WDN to continue operating satisfactorily. In relation to the ideal scenario, the pressures of the roughness change scenario are 4.2 times lower at the end of the life cycle. In the leak and pump deterioration scenarios, the pressures are 2.1 and 1.2 times lower, respectively.

When the increase in the roughness of the pipes is added to the other parameters evaluated, in the intermediate case, we observe the worst scenario in terms of pressure in the network. In this case, the pressure is always lower than all the scenarios evaluated, reaching values that would require intervention in the first years of operation.

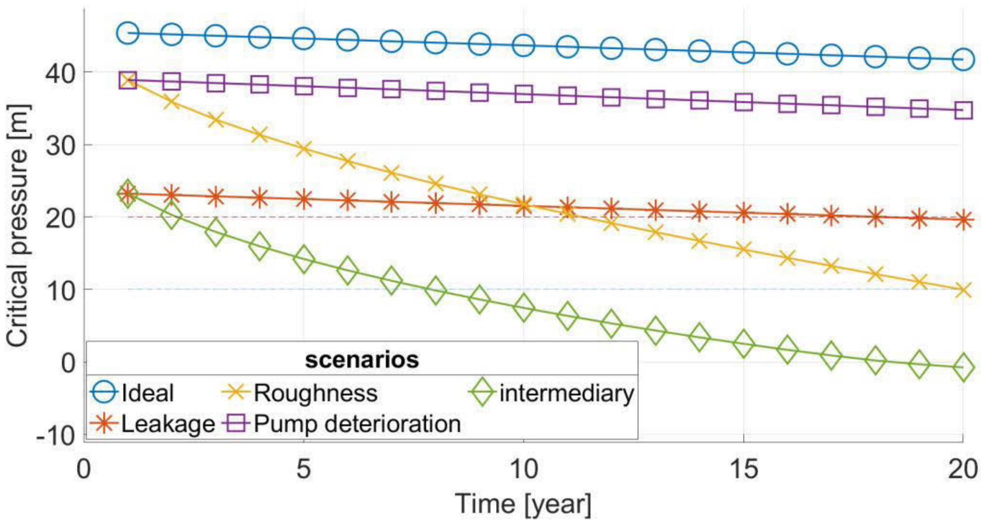

Figure 9. Critical pressures each year for the evaluated scenarios

The individual results shown are for evaluating the sensitivity of each parameter. However, in real systems the deterioration of the parameters occurs simultaneously, as in the intermediate scenario, and can cause significant impacts. Decisions about network maintenance and rehabilitation plans need to be made based on the impact (cost/benefit) of each of the parameter, to keep the WDN operating according to the standards.

4 CONCLUSIONS

In this paper, it was evaluated how the deterioration of the WDN, through the alteration of the internal roughness of the pipes, the deterioration of the pump and the change in the volume of leakages, impacted the WDN throughout its life cycle, in terms of operating costs and operating pressures. With the scenarios evaluated, the following conclusions could be drawn:

- The results show that the deterioration of the network has significant impacts on its performance, which corroborates what is observed in practice. This shows the importance of monitoring the functioning of the WDN to verify its efficiency, in addition to assisting in decision-making on the implementation of rehabilitation plans.
- In terms of total costs, leakages were the main responsible for the direct impacts on cost growth. The increase in water demand due to leakages significantly alters the operating point of the pumping station, consequently increasing the energy consumption. In addition, a large percentage of the water produced is wasted.
- WDN operating pressures are significantly altered by increasing pipe roughness. The observed decrease is a consequence of the increase in the head losses of the system. Considering that WDN work for life cycles many times longer than 20 years, the rehabilitation or replacement of pipe sections must be properly planned in order to maintain efficiency in the network operation.

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