2nd International Joint Conference on Water Distribution
Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14132

THE USE OF RESILIENCE METRICS TO SUPPORT DECISION MAKING IN DRINKING WATER SYSTEMS

Joana Carneiro[1], Dália Loureiro[2] and Dídia Covas[3]

[1,3]CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001, Lisboa, Portugal
[2]Urban Water Unit, Hydraulics and Environment Department, Laboratório Nacional de Engenharia Civil, Av. Do Brasil 101, 1700-066 Lisboa, Portugal

[1]*joana.carneiro@tecnico.ulisboa.pt,*
[2]*dloureiro@lnec.pt,* [3]*didia.covas@tecnico.ulisboa.pt*

Abstract

Performance assessment is essential for effectively managing drinking water systems. It allows to understand the system's behaviour, identify critical components and subsystems, and help with the decision analysis of measures to improve economic, infrastructural and water and energy resources. The current paper proposes an updated methodology for diagnosing drinking water networks, considering different perspectives: water and energy efficiency, infrastructural sustainability, and the quality of service provided, including resilience and redundancy concepts. Several performance indicators and indexes, including Resilience index and Entropy, are recommended to describe each perspective. The methodology is applied to a real-life network, and the attained results are discussed. The status quo situation for the network area is assessed, and the main problems are identified (i.e., high friction losses, inefficient pump operation, old pump equipment). Different improvement solutions are considered (e.g., pipe replacement with higher diameter, pump operation improvement, pump replacement). These interventions are considered individually or combined. Using the resilience-based perspective with other performance assessment criteria has provided a broader assessment. The resilience index has proven sensitive to the different alternatives, endorsing the system's efficiency. Smaller values of the resilience index indicate that a small amount of energy in excess is available as surplus energy in the consumption nodes, being dissipated, either as pumping inefficiencies, water losses, or friction and singular head losses. The Entropy metric is sensitive to the network layout and is helpful in alternatives that consider flow path alterations to prevent the impact of pipe failure. The best improvement alternative achieves a considerable enhancement in energy efficiency, maintains a good quality of service, improves the system's infrastructural sustainability, and corresponds to the highest resilience index value.

Keywords
Drinking water systems, resilience, performance metrics, system diagnosis, alternative comparison.

1 INTRODUCTION

Drinking water systems are crucial infrastructures worldwide and are managed by water utilities that have the mission to continuously and efficiently deliver water in the desired amount and with good quality to all consumers. Therefore, it is of the utmost importance that drinking water systems perform well and respond adequately to future challenges. As water utilities look to incorporate sustainable and improvement measures in their daily practices, performance assessment has become essential for managing drinking water systems. It is a tool capable of identifying critical components and prioritising subsystems within the water system.

In the last couple of decades, different approaches were developed to assess different performance aspects of water systems. A comprehensive effort to analyse and quantify the technical performance of water networks was developed by [1]. Based on the quantified evaluation of system behaviour as a function of pre-defined objectives, this approach can be applied to assess hydraulic and water quality performance (i.e. pressure, water age).

Performance assessment frameworks have been developed using performance indicators to monitor the effectiveness and efficiency of water utilities in different aspects, such as water losses [2], infrastructure asset management [3,4], energy efficiency [5,6], among others. These frameworks were developed to evaluate a specific aspect of the system, neglecting a broader vision. Additionally, most of these indicators are not dependent on the hydraulic and water quality network model, lacking a more detailed analysis that allows the identification of specific problems.

In recent years, resilience has become a more noticeable topic in the water sector. A broader definition describes resilience as "the ability to absorb local failures, quickly recover and maintain the essential service functions, and adapt to long-term changes in the environment and uncertainty disturbances" [7]. Several metrics have been used to assess resilience in the literature, classified into two main groups: hydraulic and topological [8]. Hydraulic resilience measures the hydraulic capacity to maintain supply under failure or uncertain demand conditions, being the resilience index [9] one of the most commonly used metrics. Topological reliability considers the graphical linkage among nodes in water distribution systems, most used graph-theory metrics [10] and flow-entropy measures [11,12]. In Portugal, a Security and Resilience index was proposed in the 4th edition of the "Guide for the Assessment of the Quality of Service in Water and Waste Services" [13]. The index assess the water utility by its concern and measures planned in terms of water security, safety, draught and flood contingency and emergency management and response. To the authors' knowledge, resilience metrics have not yet been used to support diagnosis and decision analysis in drinking water systems.

The current paper proposes an updated methodology for diagnosing drinking water systems and assessing improvement measures considering different perspectives. The paper's main novelty is considering resilience metrics together with hydraulic, energy efficiency, water losses, infrastructural condition, and water quality in the performance assessment system. The methodology is applied to a real-life network, and the attained results are discussed, mainly the importance of attending to different dimensions of drinking water networks and considering resilience.

2 METHODOLOGY

2.1 Approach Overview

A methodology to assess the performance of a drinking water system, attending different dimensions of analysis, is described herein. The energy efficiency performance assessment [5], in the scope of the Portuguese peer-to-peer innovation project "Assessment of energy efficiency and sustainability in urban water system – Avaler+", and the decision-making approach developed by [4] was improved in this study.

Avaler+ project first developed a performance assessment framework, including indicators capable of assessing the system's energy efficiency and effectiveness [5]. This approach calculates the indicators using historical information gathered annually by the water utility, without hydraulic modelling. Energy efficiency was assessed for drinking water systems by calculating Standardised energy consumption and Energy in excess per unit of authorised consumption. Non-revenue water and Infrastructure value index were selected to assess the system's effectiveness. The diagnosis phase is carried out for a reference year and allows the prioritization of subsystems for further analysis and intervention to improve energy efficiency.

In the present methodology, other indicators and assessment methods that require the modelling of the system are introduced for more comprehensive performance analysis. The setting of the assessment framework is composed of three main stages: (i) identifying the relevant dimensions for performance analysis in drinking water systems, including resilience, (ii) selecting a set of metrics to assess each dimension and (iii) identification of reference values for each metric. This framework is used to assess the priority subsystem for the reference year and applied to each alternative identified as improvement measures. This study assumes that measures are implemented in the year following the reference year, and the improvement impact is immediately reflected. Further analysis is recommended to compare long-term alternatives and consider different scenarios.

2.2 Framework for Performance Assessment

The first dimension under scope is Energy efficiency using the same metrics those used in Avaler+ project [5]. Standardized energy consumption [13] allows assessing pumping energy efficiency. Energy in excess per unit of authorised consumption, calculated through the energy balance [6], represents the theoretical potential for energy reduction per volume of authorised consumption since energy in excess is calculated as the total input energy into the system minus the minimum energy required to supply the consumers. The energy balance can be calculated by a top-bottom approach requiring minimum data, has in the Avaler+ project, or by a bottom-up approach requiring a calibrated hydraulic model of the network providing a detailed assessment of energy consumption in every component of the balance, used in the present work, according to work developed in [6].

The second dimension is Infrastructural sustainability. From the Avaler+ project [5], Infrastructure value index [4] assess the infrastructure's age. Non-revenue water is replaced by Real water losses [13] in this study, as the later reflects the network leaks that directly impact energy consumption, and the former also considers apparent losses due to theft or metering inaccuracies. Infrastructural sustainability can be in jeopardize if a system has elevated pressures, significant pressure fluctuations and high flow velocities in pipes. Therefore, performance assessment includes Maximum pressure, Pressure fluctuation and Maximum velocity, following the methodology developed by [1] and considering the modifications in the performance scale proposed by [14]. This methodology is based on applying a penalty function over the results of the variable under analysis. The penalty function relates the variable value and a scale of performance for each network element. A generalising function, weighted average, is used to extend the element-level calculation to the network. The network performance is assessed for 24h simulations, and the results are in the form of extended-period performance graphs showing the system performance and 25% percentiles bands of the network elements. In the present study, penalty and generalising functions for Maximum pressure, Pressure fluctuation and Maximum velocity are the same as [14]. The system's performance for a specific aspect is calculated as the average of the system performance over the 24h. As an example, Pressure fluctuation performance is optimal if a node is always kept at constant pressure and starts dropping linearly until it reaches the threshold of nodal head fluctuation of 30 m.c.a. (normal water utility establishment), corresponding to a performance of 25 %, meaning that it has poor performance with no service interruption. The penalty function for pressure fluctuation is presented in Figure 1. Once the penalty function is applied to node results, nodal performance is generalised by the weighted average in terms of demand, to obtain the system global performance.

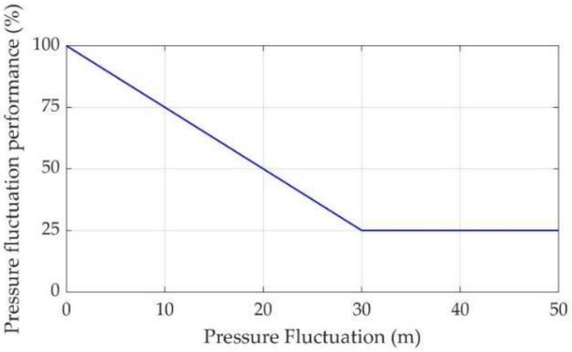


Figure 1. Penalty curve for pressure fluctuation (based on [14]*).*

The third dimension under analysis is the service provided, in both quantity and quality. In this dimension, the capacity of the system to provide water is assessed through the Minimum pressure performance and the Todini's Resilience index [9]. Resilience index requires hydraulic simulation and measures the amount of energy available at each end-use point, evaluating the capacity of the system to continue the provision of water, ranging from 0 to 1. Comparing the Resilience index equation with the energy in excess (obtained through the energy balance [6]), this resilience metric is a measure of surplus energy over energy in excess. Surplus energy refers to the energy supplied to the end-use points minus the minimum energy required to supply the consumers.

Water quality is assessed through Minimum velocity and Water age performance, as these are related to the time of water inside the system. Minimum pressure performance and water quality metrics are calculated with the same procedure as [1] and exemplified for Pressure fluctuation performance. For Minimum pressure and Minimum velocity, penalty and generalising functions are the same as in [14] while for Water age are the same as in [1].

Another metric evaluated is the Entropy of the system [12]. This metric measures flow uncertainty inside the network and considers flow path redundancy. This metric is important as it accounts network layout and the respective capacity for successfully surpassing any link failure in the network.

The metrics selected to assess each dimension are summarised in Table 1, along with a brief description and the respective reference values that allows the classification of the metrics as good (represented by 🟢), fair (represented by 🟡) or poor (represented by 🔴). The metrics requiring hydraulic simulations were calculated in Matlab via Epanet-Matlab-toolkit [15], except entropy calculated through the Water Network Tool for Resilience (WNTR)[16]. As the entropy and resilience metrics do not have reference values, the performance assessment for these metrics is performed by a comparison between the results of the diagnosis and the assessment of alternatives, as improve (↗), stay the same (→) and decrease (↘).

Table 1. Performance indicators for diagnosis and improvement alternative assessment, description and reference values

Dimension	**Metric**	**Description**	**Reference values** 🔴 (poor), 🟡 (fair), 🟢 (good)
Energy Efficiency	Standardised energy consumption [kWh/(m^3.100m)] [13]	Energy consumption for pumping/Sum of the volume elevated multiplied by the pump head/100	🟢 [0.27; 0.40] 🟡]0.40; 0.54] 🔴]0.54; 5.00]
	Energy in excess per unit of authorised consumption [kWh/m^3] [4]	(Energy supplied to the system - Minimum energy necessary)/Volume of authorised consumption	🟢]0.0; 0.15] 🟡]0.15; 0.30] 🔴]0.30; +∞[
Infrastructural Sustainability	Real water losses [l/(connection·day)] [13]	Average daily volume lost/Number of connections	🟢 [0.0; 100] 🟡]100; 150] 🔴]150; +∞[
	Infrastructure value index [-] [4, 13] *	Current value of the infrastructure/Replacement cost of the infrastructure	🟢]0.6; 1.0] 🟡 [0.4; 0.6] 🔴]0.0; 0.4[
	Maximum pressure performance in network nodes [%] [1, 14] **	Average of the 24h system maximum pressure performance	🟢]75; 100] 🟡]50; 75] 🔴 [0; 50]
	Pressure fluctuation performance in network nodes[%] [1, 14] **	Average of the 24h system pressure fluctuation performance	🟢]75; 100] 🟡]50; 75] 🔴 [0; 50]
	Maximum velocity performance in network links [%] [1, 14] **	Average of the 24h system maximum velocity performance	🟢]75; 100] 🟡]50; 75] 🔴 [0; 50]
Service Provided	Minimum pressure performance in network nodes [%] [1, 14] **	Average of the 24h system minimum pressure performance	🟢]75; 100] 🟡]50; 75] 🔴 [0; 50]
	Resilience index [-] [9]	Surplus energy / energy in excess	***
	Water Age performance [%] [1]	Average of the 24h system water age velocity performance	🟢]75; 100] 🟡]50; 75] 🔴 [0; 50]
	Minimum velocity performance in network links [%] [1,14] ***	Average of the 24h system minimum velocity performance	🟢]75; 100] 🟡]50; 75] 🔴 [0; 50]
	Entropy [-] [12]	Uncertainty in the flow of the network pipes	***

Note: *Reference values obtained in [13]; ** Reference values obtained in [14]; ***Reference values not found in literature

doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14132

3 CASE STUDY

The case study is a drinking water system located in the Algarve region (Portugal) and is one of the systems analysed in Avaler+ project. The drinking water system comprises five subsystems (S1 to S5) and receives water from three inlet delivery point provided by Águas do Algarve. It comprises five storage tanks, eight pumping stations, approximately 130 km of pipes and 5730 service connections. In the reference year of 2018, the system supplied ca. 4 Mm^3 of water to the consumers. Figure 2 presents the drinking water network, identifying subsystems S1 to S5.

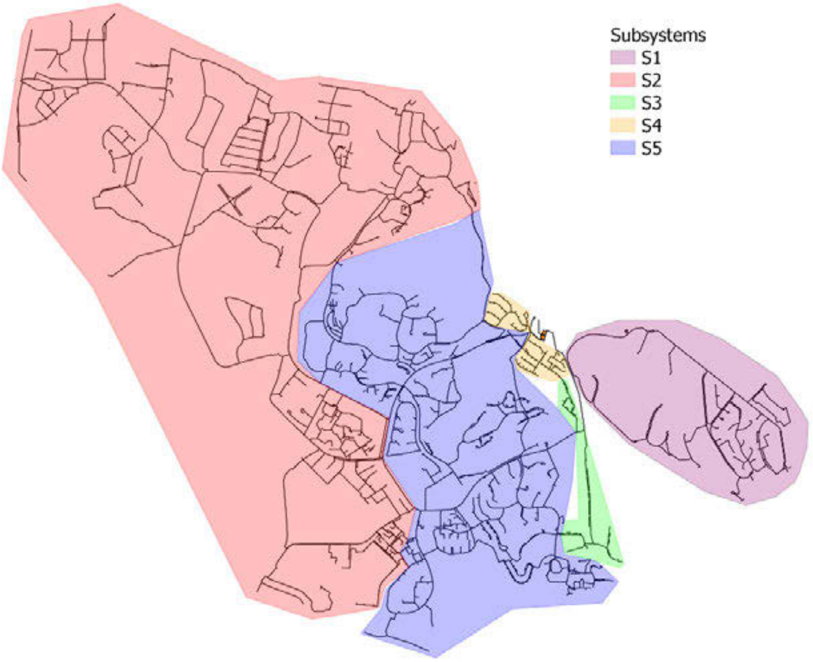


Figure 2. Subsystems of the drinking water distribution system

The updated performance assessment was implemented in the subsystem identified as the priority (S3) as explained in section 4.1. This subsystem is composed of approximately 3 km of pipes in asbestos cement (78 %) and polyvinyl chloride (22 %), with nominal diameters ranging from 80 to 110 mm, 276 service connections and 15 % of annual water losses. The subsystem is supplied by a storage tank with 53 m of water level and has a pumping station downstream needed to pump water to the highest elevation area (ca. 43 m), assuring the minimum required pressure-head (20 m). This pumping station has four pump groups installed in parallel, each with a nominal flow rate of 16 m^3/h and a nominal head of 58.4 m, with a total hydraulic power of 7.63 kW.

The water utility provided two hydraulic models of the network developed in EPANET [17], set to 24h simulation period, corresponding to the summer and winter seasons with a total water supply of 775 947 l/day and 109 433 l/day, respectively. The performance assessment falls on the summer model, as it requires higher hydraulic capacity from the network due to higher demands (demand is five times higher in the summer season). Water losses were simulated as emitters in EPANET and calculated as the pressure-driven method described in [18], with leak coefficient constant c=1.2×10^{-5} l/(s.m.m$^{1.18}$) and pressure exponent of 1.18. Data was provided for the reference year 2018, and the alternatives are implemented and assessed in year 2019.

4 METHODOLOGY APPLICATION AND RESULTS

4.1 Subsystem #3 diagnosis

Avaler+ performance assessment framework [5] requires data gathered by the water utility that was not provided. A simpler version of the assessment was carried out for the diagnosis phase considering Energy consumption, Standardised energy consumption, Energy in excess per unit of authorised consumption, Non-revenue water and Infrastructure value index. The diagnosis results carried out during the Avaler+ project are presented in Table 2, and subsystem S3 was identified as a priority to implement energy efficiency improvement measures.

Table 2. Avaler+ diagnosis results for subsystem prioritisation (reference year)

Performance Indicator	**Subsystems**				
	S1	**S2**	**S3**	**S4**	**S5**
Energy consumption (%)	19	8	15	8	49
Standardised energy consumption [kWh/(m³.100m)]	0.48 🟡	0.84 🔴	1.13 🔴	0.53 🟡	0.41 🟡
Energy in excess per unit of authorised consumption [kWh/m³]	0.15 🟢	0.12 🟢	0.40 🔴	0.21 🟡	0.16 🟡
Non-revenue water [%]*	2.4 🟢	15.0 🟢	15.0 🟢	15.0 🟢	15.8 🟢
Infrastructure value index [-]	0.15 🔴	0.12 🔴	0.15 🔴	0.00 🔴	0.00 🔴

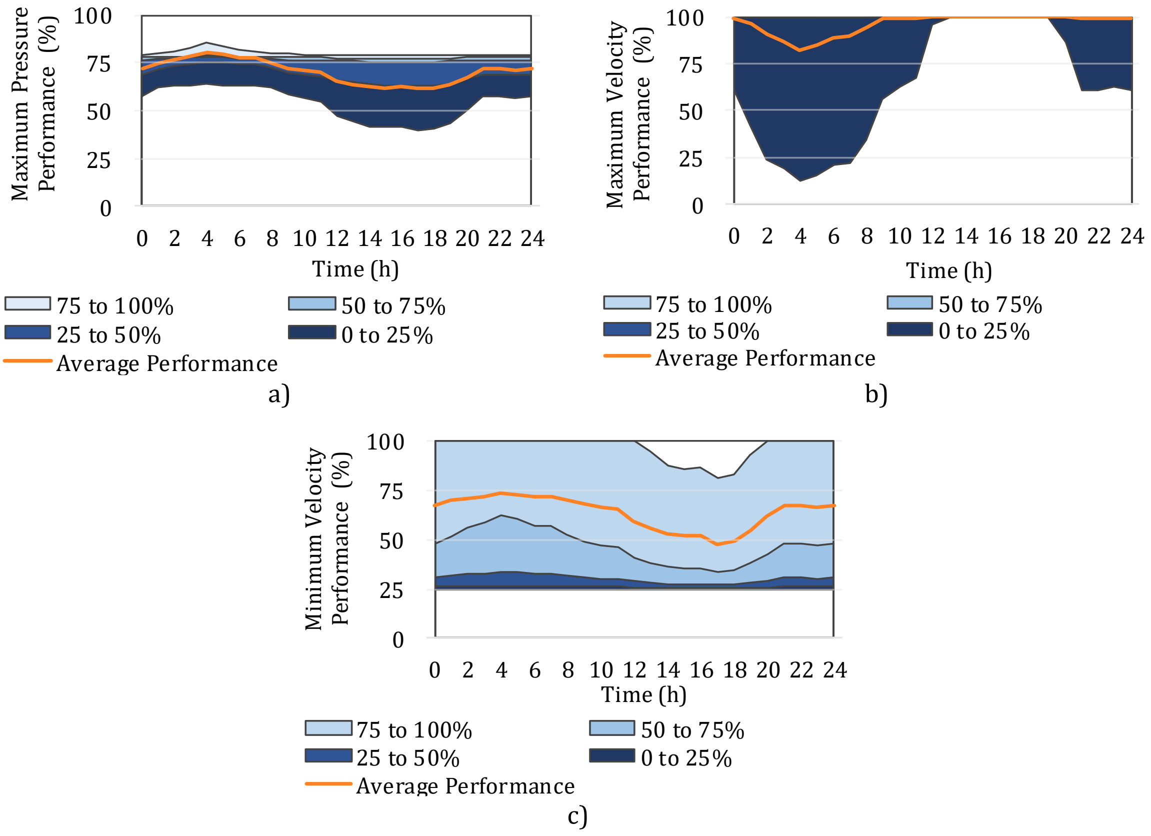
Note: *Reference values obtained in [13].

Subsystem S3 represents 15% of the water utility's energy consumption in drinking water transport and distribution. The subsystem has poor performance in both energy efficiency performance indicators, indicating low efficiency of the pumping equipment. Additionally, the Infrastructure value index has poor performance, indicating assets with low residual life. In terms of Non-revenue water, all subsystems have good performance.

Identified as the subsystem with higher priority for intervention, subsystem S3 was selected for a more detailed diagnosis in this paper, and the results are presented in Table 3. Figure 3 presents the extended-period performance simulation graphs to understand the dynamic of subsystem S3 in 24h.

Table 3. S3 performance metrics results for diagnosis (reference year). Complementary metrics are shaded

Dimension	**Performance Metrics**	**Value**
Energy efficiency	Standardised energy consumption [kWh/(m³.100m)]	1.13 🔴
	Energy in excess per unit of authorised consumption [kWh/m³]	0.39 🔴
Infrastructural sustainability	Real water losses [l/(connection·day)]	227 🔴
	Infrastructure value index [-]	0.15 🔴
	Maximum pressure performance [%]	90.6 🟡
	Pressure fluctuation performance [%]	77.0 🟢
	Maximum velocity performance [%]	96.4 🟢
Service provided	Minimum pressure performance [%]	100.0 🟢
	Resilience Index [-]	0.16
	Minimum velocity performance [%]	63.8 🟡
	Water age performance [%]	100 🟢
	Entropy [-]	2.65



a) b) c)

Figure 3. Subsystem S3 extended-period performance assessment for: a) maximum pressure, b) maximum velocity, c) minimum velocity

In addition to the poor performance in energy efficiency, infrastructural sustainability needs improvement since the system has poor performance in Real water losses and Infrastructural value index and fair performance in Maximum pressure. Looking at the extended-period performance simulation graphs for Maximum pressure (Figure 3a), in the higher pressure period (from 12h to 20h) the system has fair performance (average maximum pressure between 50% and 75%). Moreover, less than 25% of the network nodes have poor performance (25th percentile of maximum pressure below 50%). At 4h time instant, Maximum pressure performance increases while Maximum velocity performance decreases (Figure 3b). This instant corresponds to the peak demand, with nodes' pressure decreasing and pipes' velocity increasing. Note that in the Maximum velocity performance (Figure 3b), for less than 25% of the network's pipes, velocity significantly increases with the increase in the demand, suggesting the existence of pipes with high head losses, identified as critical assets according with EPANET simulation.

In terms of quality of the provided service, Minimum velocity has fair performance (Table 3). In the extended-period performance simulation graph for minimum velocity (Figure 3c), over 50% of the network pipes have poor performance throughout the 24h, potentially leading to high water retention time. However, Water age has good performance staying in the range of 100% for all nodes, emphasising the importance of looking at different dimensions of analysis for diagnosis. From the results obtained, it can be inferred that subsystem S3 has a good performance in terms of water quality.

The minimum pressure required by the utility is always met, and the performance is 100% in terms of quantity. The resilience index result of 0.15 is close to 0 and indicates that the denominator is considerably higher than the numerator, which means that from the energy in excess present in the system, only a small part is available at nodes as surplus energy. On the other side, the performance is poor in terms of Energy in excess per unit of authorised consumption, Standardised energy consumption and real water losses (Table 3). Therefore, we can infer that energy in excess, is mainly due to pumping inefficiencies, water losses and possible high head losses in some pipes.

4.2 Alternative Assessment

From the diagnosis phase, it was possible to identify priority assets that require measures to improve the system's performance in terms of energy efficiency. For that, along with the prediction of the *status quo* situation, several improvement measures were selected as follows:

- Alternative A0: *Status quo*, not considering interventions;
- Alternative A1: Replacement of the pump groups with the same rated characteristics (like-for-like replacement);
- Alternative A2: Replacement of the pump groups properly designed, considering the opportunity to improve the operating points of the pump groups;
- Alternative A3: Replacement of ca 900 m of water pipes properly designed, considering appropriate nominal diameters;
- Alternative A4: a combination of alternatives A1 and A3;
- Alternative A5: a combination of alternatives A2 and A3.

The capital costs, obtained as in [4], for each alternative are presented in Table 4.

Table 4. Capital cost of each analysed alternative

Alternatives	A0	A1	A2	A3	A4	A5
Investment (€)	- €	13 700 €	12 896 €	38 835 €	52 535 €	51 731 €

Like-for-like replacement of pump group alternatives (A1 and A4) are slightly more expensive than adequately designed new pump groups (A2 and A5), because the installed pumping groups are overdesigned, with the operating point far from the maximum efficiency point. The new, properly designed pump groups were selected to have 5 m over the minimum pressure required by the water utility (20 m). The detailed performance assessment results for each alternative are presented in Table 5.

Alternatives involving pump replacement, either like-for-like (A1 and A4) or properly designed (A2 and A5), promote an improvement in metrics that depend on pump efficiency, such as Standardised energy consumption, Energy in excess per unit of authorised consumption and Resilience index metric (Table 5). The replacement of properly designed pump groups (A2 and A5) directly impacts metrics that depend on pressure results, particularly on the Maximum pressure performance and Real water losses. The replacement of water pipes properly designed (A3, A4 and A5) decrease the head loss in the pipes, promoting a better Pressure fluctuation performance, Maximum velocity performance and Resilience index. It can also be noted that the replacement of water pipes has a smaller impact in the Resilience index than the pump replacement.

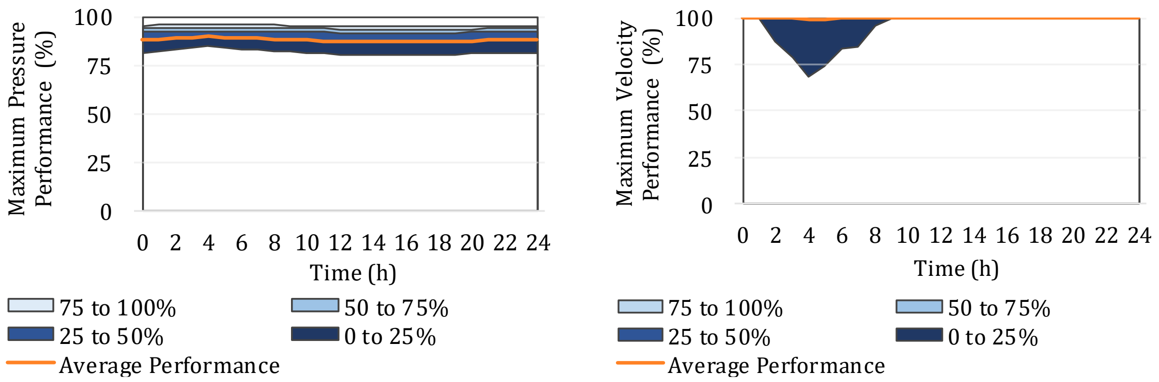
The proposed alternatives do not contemplate the improvement of network redundancy (i.e., installing new pipes to create new paths to support the supply of the branched part of the network). As such, the flow paths remain the same for all alternatives and the Entropy index, which is why the Entropy index is not shown in Table 5. A more exploratory analysis of this metric is presented in the next section.

Overall, alternative A5 has a higher performance in the different dimensions and is the one that should be implemented by the water utility, even though it requires the second-highest investment (Table 4). This alternative combines different measures that improve pump efficiency, decrease high head losses in critical pipes and decrease the pressure input into the system, maintaining the necessary pressure to provide a good service to the consumers.

Table 5. S3 performance metrics results for alternatives (implementation year). Complementary metrics are shaded.

Dim.	**Performance Indicator**	**Analysed alternatives**					
		A0	**A1**	**A2**	**A3**	**A4**	**A5**
Energy efficiency	Standardised energy consumption [kWh/(m³.100m)]	1.18 🔴	0.54 🔴	0.48 🟡	1.13 🔴	0.54 🔴	0.48 🟡
	Energy in excess per unit of authorised consumption [kWh/m³]	0.41 🔴	0.18 🟡	0.09 🟢	0.39 🔴	0.19 🟡	0.07 🟢
Infrastructural sustainability	Real water losses [l/(connection·day)]	227 🔴	227 🔴	153 🔴	239 🔴	239 🔴	147 🟡
	Infrastructure value index [-]	0.1 🔴	0.3 🔴	0.3 🔴	0.5 🟡	0.7 🟢	0.7 🟢
	Maximum pressure performance [%]	70.6 🟡	70.6 🟡	87.5 🟢	64.4 🟡	64.4 🟡	88.0 🟢
	Pressure fluctuation performance [%]	77.0 🟢	77.0 🟢	77.2 🟢	91.4 🟢	91.4 🟢	91.7 🟢
	Maximum velocity performance [%]	96.4 🟢	96.4 🟢	96.6 🟢	99.9 🟢	99.9 🟢	99.9 🟢
Service provided	Minimum pressure performance [%]	100 🟢	100 🟢	100 🟢	100 🟢	100 🟢	100 🟢
	Resilience Index [-]	0.16	0.34 ↗	0.32 ↗	0.19 ↗	0.38 ↗	0.39 ↗
	Minimum velocity performance [%]	63.8 🟡	63.8 🟡	63.1 🟡	62.7 🟡	62.7 🟡	61.8 🟡
	Water age performance [%]	100 🟢	100 🟢	100 🟢	100 🟢	100 🟢	100 🟢

Comparing the extended-period performance simulation graph for alternative A5 (Figure 4) and the diagnosis (Figure 3), it can be concluded that the maximum pressure performance has improved to good performance in all network nodes. The replacement of the under-designed pipes decreases unit head loss from 15 m/km in diagnosis to 5 m/km in alternative A5, corresponding to a reduction of 32%. This replacement promotes a significant improvement of the subsystem pressure fluctuation performance (Table 5) and is also responsible for the improvement shown in alternative A5 of maximum velocity performance (Figure 4b), where no pipes have poor performance, as opposed to the diagnosis assessment (Figure 3b).



a) b)

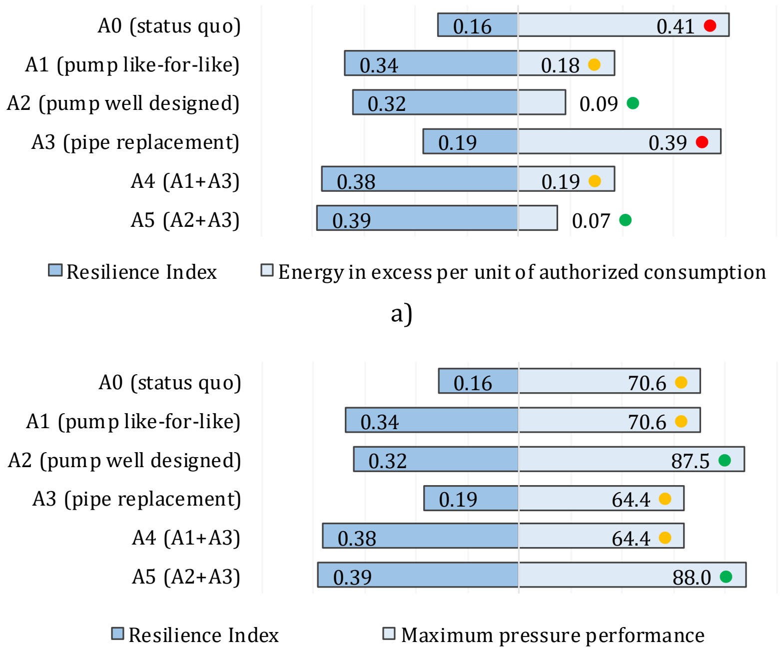
Figure 4. Alternative 5 extended-period performance simulation for: a) maximum pressure, b) maximum velocity.

The best alternative (A5) demonstrates a good compromise between energy efficiency and maintaining a good quality of service, providing the required quantity of water with sufficient pressure and good quality while improving the infrastructural sustainability of the system.

4.3 Resilience metrics exploratory analysis

The introduction of resilience indexes brought new information to the assessment of the system. Comparing Resilience index and Energy in excess per unit of authorised consumption (Figure 5a), both increase their performance with the implementation of improvement measures and are more sensitive to pump replacement (A1, A2, A4 and A5) than under-designed pipes replacement (A3). For alternatives considering pump replacement, like-for-like alternatives (A1 and A4) have similar Resilience index results as properly designed alternatives (A2 and A5) while Energy in excess per unit of authorised consumption have better results for properly designed alternatives (A2 and A5) than like-for-like alternatives (A1 and A4). This infers that the Resilience index is not very sensitive to implementing adequately dimensioned pumping groups as opposed to Energy in excess per unit of authorised consumption.

Comparing the equivalent alternatives without and with pipe replacement (A0 and A3, A1 and A4, A2 and A5), it is observed that the replacement of under-designed pipes has a more positively impact in Resilience index than in the Energy in excess per unit of authorised consumption. Both the Maximum pressure performance and the Resilience Index provide different information (Figure 5b): the Maximum pressure performance is not sensitive to the change of efficiency in the pump groups (like-for-like pump group replacement) but highly sensitive to the correct design of pump groups, as opposed to the Resilience index.



a)

b)

Figure 5. Bi-directional bar chart to compare alternatives' Resilience index and: a) Energy in excess per unit of authorized consumption, b) Maximum pressure performance

Todini's Resilience index reflects the percentage of the energy in excess provided to the system that is available at nodes as surplus energy. From the energy balance scheme [6], energy in excess can be decomposed into three main components: (i) pumping inefficiencies, (ii) energy associated with water losses, (iii) energy associated with friction and singular head losses and surplus energy. Water systems with a Resilience index closer to 1 are more robust to demand increase, and since the numerator is the surplus energy, this metric infers that the energy in excess main component should be available as surplus energy. The system should have low pumping inefficiencies, water losses and energy dissipated due to friction and singular head losses.

The alternatives proposed to improve energy efficiency of subsystem S3 and do not contemplate improvement of Network redundancy. The flow paths remain the same for the alternatives attested along with the Entropy index. To explore this metric, a couple of exploratory alternative measures to change the original layout of the northern looped part of the network were assessed: (A0') northern looped area *status quo*, (A1') closure of valve in pipe 1 of the loop, (A2') closure of valve in pipe 2 of the loop, and (A3') alternative supply from the north connection to subsystem S4. The scheme and illustration of these exploratory alternatives are shown in Figure 6.

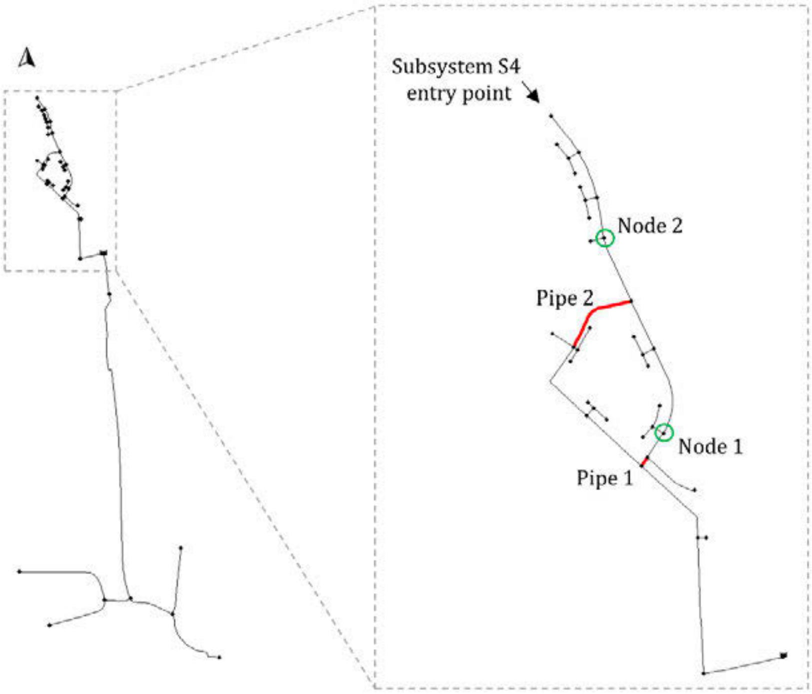
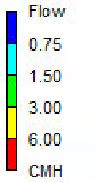
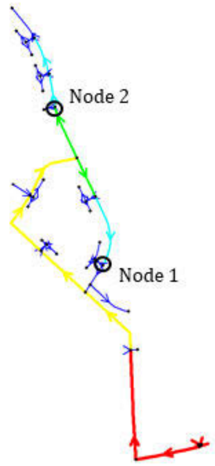
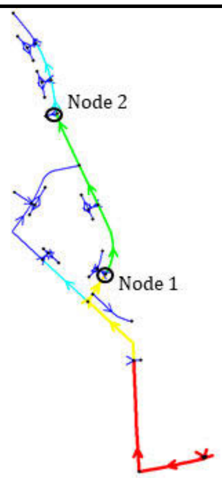
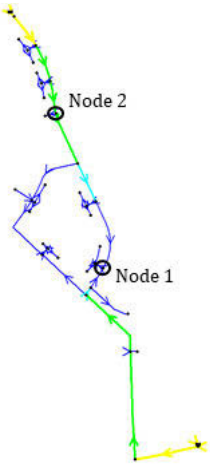


Figure 6. Illustration of explorative alternatives in the network northern looped area for entropy analysis

The present work calculates Entropy according to [12] and depends on link flows and network topology. Entropy accounts for redundancy among the network nodes and the dependence of paths from the source to any demand node by introducing parameter a_{ij} a correction factor to reduce the number of alternate paths, if some are dependent, to the network entropy measure. Entropy results are shown in Table 6, along with flow distribution, the number of paths (independent or dependent) and a_{ij} for two example nodes (Node 1 and Node 2 identified in Figure 6).

Table 6. Results of Entropy, number of paths and parameter a_{ij} to nodes 1 and 2 for the alternatives.

	A0’		**A1’**		**A2’**		**A3’**	
Flow 								
Number of paths	Node 1	1	Node 1	1	Node 1	1	Node 1	2
	Node 2	2	Node 2	1	Node 2	1	Node 2	1
a_{ij}	Node 1	1	Node 1	1.0	Node 1	1.0	Node 1	[1;1]
	Node 2	1.37	Node 2	1.0	Node 2	1.0	Node 2	1
Entropy	2.75		2.68		2.66		2.94	

To understand the parameter a_{ij}, looking at Node 2 of alternative A0', there are two possible paths, one from each side of the loop. However, for both paths the flow must pass through the same links before and after the loop, demonstrating the dependence on these paths. Though there is only one path, it has redundancy and, therefore, the correction factor a_{ij} has a value higher than 1. When looking at the alternative with two water sources (A3'), Node 1 receives water from two different paths, and as the source of each path is different, it is considered two independent paths. The closure of pipes in the network loop (A1' and A2') transforms the looped network to a branched network with independent paths from the source to all consumption nodes, leaving the network with no redundancy and, consequently, with lower entropy values. In this case, the influence in entropy measure is mainly due to the flows where alternative A1' has slightly more equally flow paths than alternative A2'.

5 CONCLUSIONS

The methodology presented herein promotes a broader and more complete assessment of drinking water systems, including the resilience dimension. It allows assessing different dimensions providing different information capable of complementing each other. The best alternative to improve the priority subsystem identified in the diagnosis phase is to improve energy efficiency without compromising the quality of service provided and improve the system's infrastructural sustainability. The introduction of resilience metrics provides new information in the alternative assessment, particularly in assessing the capacity of the system to overcome increasing demands and pipe failures. The resilience index endorses that the energy in excess should be available as surplus energy at the consumption nodes. Systems with smaller values of resilience index indicate that from the total energy in excess provided to the system, a small amount is available as surplus energy in the consumption nodes and was dissipated in the system, either as pumping inefficiencies, water losses or friction losses. The entropy metric depends on the variability of network flow inside the system and considers the network's redundancy with the accountability of alternative paths to each node. As the case study alternative assessment did not promote a variation in this component, this metric did not bring new information to the performance assessment in terms of energy efficiency. However, this metric is helpful in alternatives that contemplate flow path alterations and should be assessed in studies where network redundancy is under assessment since none of the other metrics considers alternative paths in case of pipe failure.

The present methodology is the first approach to developing a complete water system resilience-based approach performance assessment. This performance assessment system should evaluate other and more complex case studies to improve the methodology and validate the conclusions drawn.

Funding: This work was supported by the Fundação para a Ciência e a Tecnologia through Ph.D. Research Studentship of Joana Carneiro (grant number PD/BD/150694/2020) and the WISDom project (grant number DSAIPA/DS/0089/2018).

Acknowledgements: The authors would like to thank the Fundação para a Ciência e Tecnologia (FCT) through funding UIDB/04625/2020 from the research unit CERIS.

6 REFERENCES

[1] S. T. Coelho, Performance in Water Distribution - a systems approach. Series Water Engineering and management systems, Research Studies Press, John Wiley and Sons, Lisboa, 1997.

[2] A. O. Lambert, T. G. Brown, M. Takizawa, and D. Weimer, “A review of performance indicators for real losses from water supply systems,” J. Water Supply Res. Technol., vol. 48, no. 6, pp. 227–237, Sep. 1999, doi: 10.2166/aqua.1999.0025.

[3] H. Alegre, S. T. Coelho, D. I. C. Covas, M. Do Céu Almeida, and A. Cardoso, “A utility-tailored methodology for integrated asset management of urban water infrastructure,” Water Sci. Technol. Water Supply, vol. 13, no. 6, pp. 1444–1451, 2013, doi: 10.2166/ws.2013.108.

[4] M. Cabral, “Towards a better urban water infrastructure asset management by condition assessment and cost modelling,” Ph.D dissertation, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, 2021.

[5] D. Loureiro, C. Silva, M. A. Cardoso, A. Mamade, H. Alegre, and M. J. Rosa, “The development of a framework for assessing the energy efficiency in urban water systems and its demonstration in the portuguese water sector,” Water (Switzerland), vol. 12, no. 1, 2020, doi: 10.3390/w12010134.

[6] A. Mamade, D. Loureiro, H. Alegre, and D. Covas, “A comprehensive and well tested energy balance for water supply systems,” Urban Water J., vol. 14, no. 8, pp. 853–861, Sep. 2017, doi: 10.1080/1573062X.2017.1279189.

[7] Q. Shuang, H. J. Liu, and E. Porse, “Review of the quantitative resilience methods in water distribution networks,” Water (Switzerland), vol. 11, no. 6, pp. 1–27, 2019, doi: 10.3390/w11061189.

[8] D. Jung and J. H. Kim, “Water Distribution System Design to Minimize Costs and Maximize Topological and Hydraulic Reliability,” J. Water Resour. Plan. Manag., vol. 144, no. 9, p. 06018005, 2018, doi: 10.1061/(asce)wr.1943-5452.0000975.

[9] E. Todini, “Looped water distribution networks design using a resilience index based heuristic approach,” Urban Water, vol. 2, no. 2, pp. 115–122, Jun. 2000, doi: 10.1016/S1462-0758(00)00049-2.

[10] A. Yazdani, R. A. Otoo, and P. Jeffrey, “Resilience enhancing expansion strategies for water distribution systems: A network theory approach,” Environ. Model. Softw., vol. 26, no. 12, pp. 1574–1582, 2011, doi: 10.1016/j.envsoft.2011.07.016.

[11] H. Liu, D. Savić, Z. Kapelan, M. Zhao, Y. Yuan, and H. Zhao, “A diameter-sensitive flow entropy method for reliability consideration in water distribution system design,” Water Resour. Res., vol. 50, no. 7, pp. 5597–5610, Jul. 2014, doi: 10.1002/2013WR014882.

[12] K. Awumah, I. Goulter, and S. K. Bhatt, “Entropy-Based Redundancy Measures in Water-Distribution Networks,” J. Hydraul. Eng., vol. 117, no. 5, pp. 595–614, 1991, doi: 10.1061/(asce)0733-9429(1991)117:5(595).

[13] ERSAR, LNEC, and NOVA, “Guide for the Assessment of the Quality of Service in Water and Waste Services,” 4rd ed.; Technical guide 27; Entidade Reguladora dos Serviços de Águas e Resíduos, Laboratório Nacional de Engenharia Civil, Nova School of Science and Technology. Lisbon, Portugal, 2021.

[14] A. C. Jacob, “Avaliação de perdas em sistemas de distribuição de água: o caso de estudo da ZMC 320 da EPAL,” M.S. Thesis, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, 2006.

[15] D. G. Eliades, M. Kyriakou, S. Vrachimis, and M. . Polycarpou, “EPANET-MATLAB Toolkit: An Open-Source Software for Interfacing EPANET with MATLAB,” 2016, doi: 10.5281/zenodo.831493.

[16] K. A. Klise, M. Bynum, D. Moriarty, and R. Murray, “A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study,” Environ. Model. Softw., vol. 95, pp. 420–431, Sep. 2017, doi: 10.1016/j.envsoft.2017.06.022.

[17] L. Rossman, H. Woo, M. Tryby, F. Shang, R. Janke, and T. Haxton, EPANET 2.2.0. Cincinnati, USA: U. S. Environmental Protection Agency, 2020.

[18] A. Mamade, “Enhancement of water and energy efficiency in water supply systems,” Ph.D dissertation, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, 2019.