

Article

Comprehensive Resilience Assessment Framework for Water Distribution Networks

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Abstract: A novel comprehensive resilience assessment framework for drinking water systems is proposed integrating different resilience perspectives (i.e., robustness, autonomy, flexibility, reliability, preparedness and recovery), oriented by objectives, criteria and metrics, applicable at the tactical level. The resilience assessment framework is applied to a Portuguese real water distribution network, enabling the evaluation of the system's resilience. The infrastructure dimension is the main contributor to the low resilience results, particularly in terms of infrastructural robustness, as the infrastructure has exceeded the average service life and has low rehabilitation rates. In terms of autonomy, the system highly depends on external water and energy sources. Regarding the service dimension, most of the drinking water available is used for non-potable uses (e.g., irrigation), without alternative sources. The detailed diagnosis identified network area R6 as the priority area. Assets rehabilitation, increasing storage capacity, finding alternative water and energy sources, and minimizing non-potable uses are relevant improvement measures that promote the reinforcement of the system's resilience. The resilience assessment framework is a very useful tool for the daily and tactical management of drinking water systems.

Keywords: drinking water systems; urban water management; performance assessment; reference values



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1. Introduction

Drinking water systems face social, economic, political and environmental changes that increase the uncertainty over the system's future. Events of different natures are classified as [1]: (i) challenges, a contextual or environmental change with the potential to impact the ability and capacity of the system (i.e., climate change); (ii) shocks, as uncertain, abrupt events (i.e., floods, earthquakes, terrorist attacks); and (iii) stresses, as chronic and ongoing dynamic pressure originated within the system (i.e., infrastructure degradation, demand increase). These events can negatively impact drinking water systems, by causing service interruptions, reducing water availability, decreasing water quality and causing pipe bursts or components malfunctions. An event for which losses have occurred that exceed the ability of the system to respond and recover using its own resources is described as a disaster (adapted from [2]).

Resilience has been gaining relevance in the last decade. Defined as the “ability of a system to anticipate, prepare, respond to and absorb shocks, positively adapt and transform in the face of stresses and challenges” [2], resilience is a broad subject. A resilient system must, therefore, have three main capacities: (i) absorptive capacity, the system's ability to continue operating during events; (ii) restorative capacity, the ability to respond and restore the system functionality after a failure or interruption; (iii) adaptive capacity, the ability

to adapt the system to increase the absorptive capacity of the system to events (adapted from [3,4]).

The analysis of a system's resilience is different from risk analysis. Risk analysis evaluates the probability of occurrence of an adverse event and the respective negative consequences on a system. Resilience analysis considers uncertainty and change by exploring long-term trends and shocks' impacts without regarding its probability, focusing on the system and aiming to strengthen it [3]. The existence of a comprehensive, well-tested and robust resilience assessment that can be incorporated in the management of water distribution systems is crucial for water utilities. This should include the strategic planning level, driven by corporate and long-term perspectives and be aimed at establishing strategic priorities and the tactical level, defining medium-term intervention priorities and solutions [5].

Recognizing the relevance of resilience assessment, some tools and frameworks for assessing resilience in urban areas have been proposed. A resilience assessment framework was developed regarding nature-based stormwater management solutions [6]. Another resilience assessment framework was developed in the RESCCUE project for urban services (water, wastewater, energy and mobility), aimed at establishing and communicating strategic priorities to improve cities' resilience to climate change [7]. However, this assessment framework is applicable to a strategic level, lacking the approach to identify priority areas, improvement alternatives and measures at the medium-term (tactical level). Nonetheless, an interesting aspect is its insight regarding resilience in water services, as it integrates multiple resilience dimensions (i.e., organizational, spatial, functional, physical). Particularly, the functional and the physical dimensions (herein service and infrastructure, respectively) are crucial for resilience assessment and support decisions at the tactical level. Through the evaluation of the service, it is possible to determine the system's capacity to continue ensuring the water supply in the face of different events. The service is ensured through the infrastructure; thus, the service must also be considered in the resilience assessment system [8]. Infrastructure condition changes over time and can become compromised if rehabilitation or maintenance are insufficient to cope with systems' needs or inadequately implemented. In addition, the infrastructure was designed and constructed for specific demand scenarios, which can evolve and become significantly different.

In drinking water systems, several metrics can be used to assess resilience and support medium-term intervention priorities and solutions. Surrogate resilience metrics have been widely used in the optimization design of drinking water systems [9]. These can be based on surplus energy, as the Todini resilience index [10] and its derivations [11–14], assessing the hydraulic flexibility to an increase in demand; entropy-based metrics [15–17], assessing the redundancy of the network; or graph-theory metrics [18,19], assessing the network's topology. The capacity of a system to recover from a disaster has also been the subject of different studies. The main problem addressed is pipe failure, particularly due to earthquakes [20] or flash flood events [21]. Ref. [22] considered a dual water distribution infrastructure as a resilient system. Another point of view of assessing the resilience of drinking water systems is quantifying the system's service capacity through increased stress levels [23] or the magnitude of events [24]. In these, a single performance metric based on the water supplied to the consumer is used to assess the service capacity of the system. Overall, resilience has been addressed from different and separate perspectives, each one being a part of resilience. So far, in the literature, resilience assessment at the tactical level has only considered a particular resilience dimension, not looking at the broad picture of resilience and lacking a comprehensive resilience assessment system.

For assessing and improving urban water services to users, existing standards ISO 24510 [25–27] have been applied for the regulation of urban water services [28], infrastructure assets management [5,29], energy efficiency [30] and strategic resilience [7], among others. The standards establish recommendations for defining service objectives, assessment criteria and performance indicators to support the application of the "Plan-Do-Check-Act" principle. Ref. [7] proposed a resilience assessment system at a strategic level, based on this

concept. This research extends the previous resilience assessment framework to the tactical level and incorporates additional resilience perspectives.

The current paper presents and demonstrates a novel resilience assessment system for drinking water systems, considering different resilience perspectives oriented by objectives, criteria and metrics that are relevant and applicable at the tactical level. The combination of literature metrics with new metrics proposed herein allows the resilience assessment at two different levels: Level I at a global and network area level, requiring less available data, and Level II at a detailed level, requiring more meticulous data, along with the network model, but allowing a more complete diagnosis of the system. This resilience assessment system is applied to a real Portuguese water distribution network to identify the main resilience problems and the priority areas for intervention.

Besides the introduction section, the paper follows the following structure: Section 2 provides the methodology of the general approach for resilience assessment, details the resilience assessment framework, and defines dimensions, objectives, criteria and metrics for both infrastructure and service dimensions, and the implementation of the resilience framework for resilience diagnosis. Section 3 presents the results of the resilience assessment framework application to a case study, providing the resilience diagnosis, a network area prioritization and a detailed diagnosis. Section 4 includes a discussion of the results and Section 5 presents the main conclusions and recommendations for future work.

2. Methodology

2.1. Resilience Assessment Approach

A novel comprehensive methodology to assess the resilience of drinking water systems is presented herein. The methodology consists of three main stages (Figure 1): (i) the establishment of the resilience assessment framework, by identifying the resilience objectives and by selecting criteria and metrics for the evaluation of those objectives; (ii) the resilience assessment and diagnosis, which includes collecting the necessary data to calculate, assess and standardize the different metrics to obtain the diagnosis of the whole system and network areas, allowing the identification of the main problems as well as of priority areas, components or processes; and (iii) establishment of resilience improvement measures, by identifying the potential improvement measures, assessing them in terms of performance and cost, selecting the most appropriate ones to the identified problems and prioritizing the measures to be implemented.

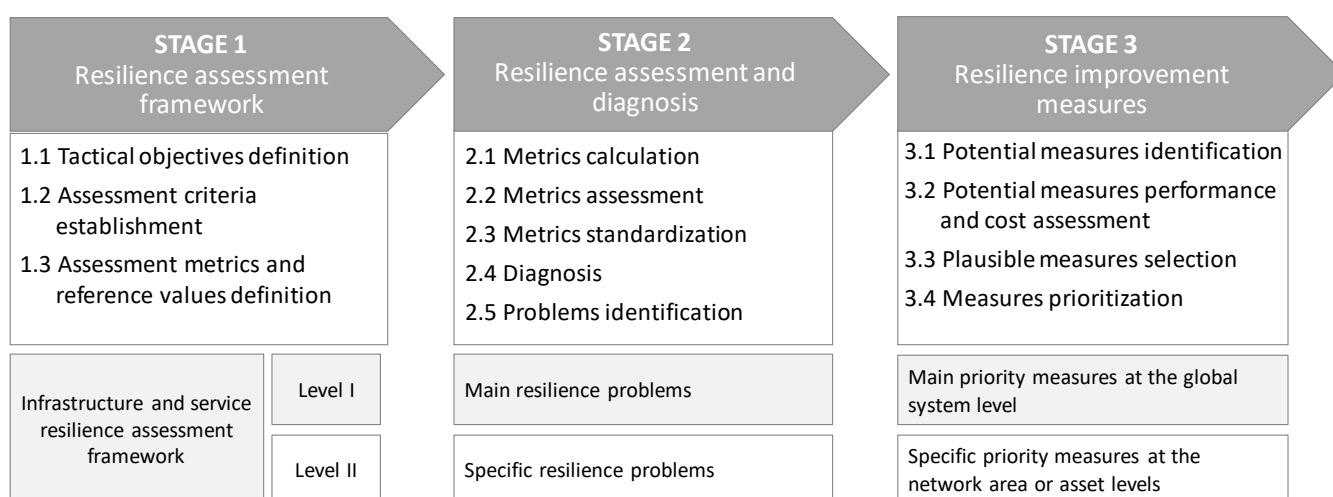


Figure 1. Proposed methodology for the establishment and application of a framework of a resilience assessment system.

The proposed resilience assessment framework is based on the ISO 22300:2021 [2] resilience definition “ability of a system to anticipate, prepare, respond to and absorb

shocks, positively adapt and transform in the face of stresses and challenges”, presenting a broad number of (14) criteria and (58) metrics. The framework can be used as a whole to assess every resilience perspective, or certain criteria and metrics can be selected according to the scope in which the resilience is being assessed.

Water utilities in Portugal have a very heterogeneous maturity level in terms of data availability and reliability, as reported in the annual report of the Portuguese Water and Wastewater Regulator [31]. For example, some water utilities have difficulty separating real water losses from apparent water losses. The selection of metrics for the resilience assessment system considered that these can be used by many water utilities, independently of their data maturity level. As such, two levels of metrics are defined, Levels I and II. Level I metrics (indicated with a grey background) require basic historical data (e.g., rehabilitation rates, authorized consumption, water losses) and the results from the water and simplified energy balance. These metrics are applicable to the global system, providing an overall system assessment in terms of resilience, but they can also be applied to the network areas, providing a first prioritization of these areas. Level II metrics need more detailed data about the system (e.g., real water losses and failure data per component), and the results from the water balance, the complete energy balance and the hydraulic system simulation. These are used complementarily to those from Level I, providing more insights about the system behavior and allowing us to identify the problem, the cause and the location in detail.

2.2. Resilience Assessment Framework

The first stage of the proposed methodology is the definition of the Resilience Assessment Framework to be used at the tactical planning level (Figure 1). The following approach, based on the international standards ISO 24510, includes two main dimensions (Infrastructure and Service) and three main steps, namely the definition of the objectives, the selection of the criteria and the identification of metrics.

The first step, the definition of the objectives, consists of identifying the goals to be achieved in the two resilience dimensions. These objectives defined at the tactical level must be aligned with the objectives and criteria established at the strategic level [5]. The RESCCUE framework [7] is used herein as the basis of the proposed framework since this is one of the most complete resilience assessment frameworks at a strategic level, ranging most of the resilience objectives, such as safe water infrastructure, autonomous and flexible water infrastructure, water infrastructure preparedness, planning and risk management, autonomous water service, water service preparedness. Figure 2 depicts the alignment between the strategic objectives and criteria of the RESCCUE framework and the proposed tactical resilience assessment system. Both consider the same dimensions (Infrastructure and service). Although the RESCCUE framework is focused mainly on climate change, the resilience framework presented herein is not limited to climate change-related events, but it can also regard other event natures (e.g., earthquakes, demographic changes). Accordingly, six tactical objectives (O1–O6) are established in the proposed framework.

The second step concerns the selection of the criteria to be assessed for evaluating each established tactical objective (Figure 2). Relative to the infrastructure dimension, to ensure good infrastructure assets robustness (objective O1), the water utility must consider criteria that reflect the infrastructure knowledge and criticality of existing assets, the infrastructure integrity and condition, as well as the efficient use of water and energy. Ensuring an autonomous and flexible infrastructure (objective O2) requires the evaluation of the infrastructure's dependency on other services, autonomy and redundancy. Promoting infrastructure recovery and building back in disasters (objective O3) involves assessing the number and duration of failures in the last disaster (e.g., earthquake, cyberattack). Relative to the service dimension, to ensure a reliable service (objective O4), water supply interruptions, adequacy of the delivered water quantity, quality and pressure requirements have to be evaluated. Adequate service flexibility (objective O5) is evaluated in terms of drinking water supply for non-potable uses and hydraulic flexibility. Finally, the number

and duration of service interruptions in the last disaster are considered to promote service preparedness for recovery and build-back in disasters (objective O6).

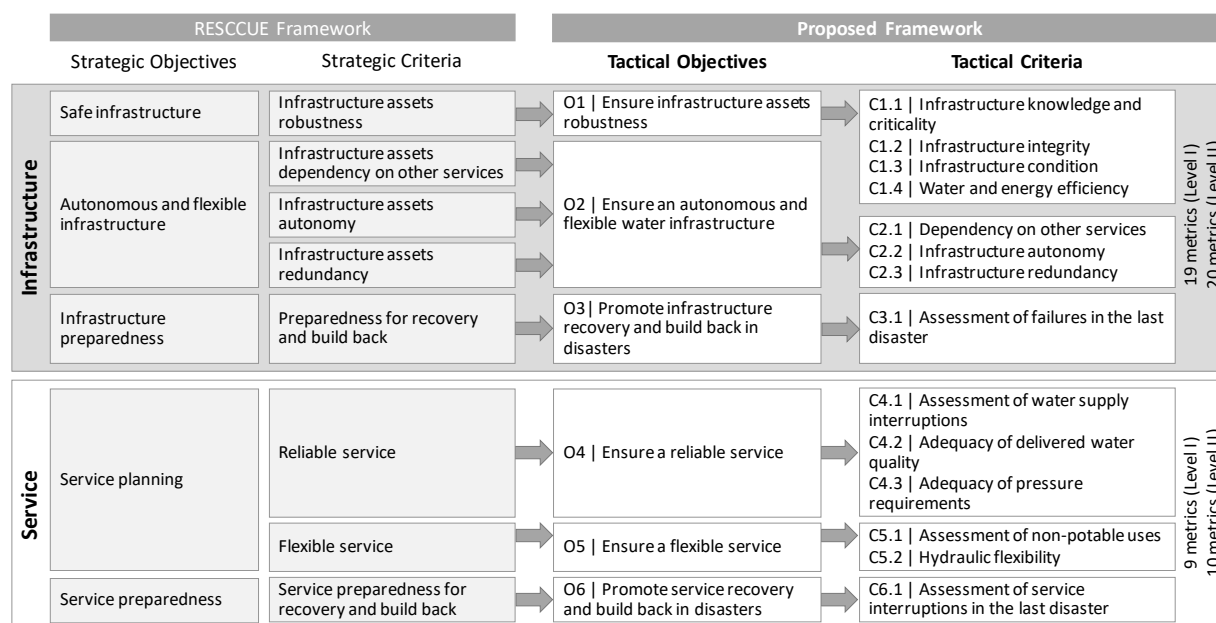


Figure 2. Alignment of the proposed resilience assessment framework at the tactical level with the RESCCUE framework [7] defined for the strategic level.

The third step is the identification of a set of performance metrics to assess the defined criteria. Following [5], performance metrics can be: (i) performance indicators, quantitative metrics of efficiency or effectiveness, calculated based on historical data, and express intensity (e.g., €/m³) or are non-dimensional (e.g., %); (ii) performance levels, qualitative metrics, expressed in discrete levels (good, fair, poor), usually used when it is not possible to calculate quantitative metrics; and (iii) performance indices, metrics that result from the combination of performance measures (e.g., performance indicators, performance levels) or from the application of analysis tools (e.g., numerical models). If the performance indices have the same value range, these can be easily compared and merged and, therefore, have the advantage of being able to combine multiple analysis perspectives into a single measure. By standardizing the different metrics into performance indices with the same range (in this case 0–3), it is possible to merge them to assess the different criteria, objectives, and dimensions and even to a global resilience measure.

Although some metrics from the RESCCUE framework may be applicable to the tactical level, most metrics refer to a strategic level and do not offer specific insights into the system and network areas. As such, other metrics are needed. A compilation of existing metrics (as originally defined or adapted) and new ones is proposed in the scope of the current framework. Tables 1 and 2 summarize the proposed metrics (for infrastructure and service dimensions, respectively), indicating in the last column the reference where the metric was taken from, namely the RESCCUE framework [7], Portuguese technical guides [31,32], IWA performance indicators [33], or other references [18,34–40].

Table 1. Assessment system for infrastructure dimension: objectives, criteria, metrics and respective reference values. Level I metrics are shadowed.

Criteria	Metrics	Reference Values			Source
		Good ●	Fair ●	Poor ●	
C1.1 Infrastructure knowledge and criticality	M1.1.1 Infrastructural knowledge index [-]	[142; 200]	[87; 142]	[0; 87]	[28] **
	M1.1.2 Knowledge and protection of critical assets index [-]	[2; 3]	[1; 2]	[0; 1]	[7] *, **
	M1.1.3 Assets criticality index [-]	[0; 0.1]	[0.1; 0.5]	[0.5; 1]	[36,37] **, **
	M1.1.3a Pipes criticality index [-]	[0; 0.1]	[0.1; 0.5]	[0.5; 1]	[36,37] **, **
	M1.1.3b Pumps criticality index [-]	[0; 0.1]	[0.1; 0.5]	[0.5; 1]	[36,37] **, **
	M1.1.3c Storage tanks criticality index [-]	[0; 0.1]	[0.1; 0.5]	[0.5; 1]	[36,37] **, **
C1.2 Infrastructure integrity	M1.2.1 Number of failures [No./ (100 km· year)]	[0; 30]	[30; 60]	[60; +∞]	[33] *, **
	M1.2.1a Pipes failures [No./ (100 km·year)]	[0; 30]	[30; 60]	[60; +∞]	[28]
	M1.2.1b Pump failures [days/ (pump·year)]	[0; 1]	[1; 3]	[3; +∞]	[7,33]
	M1.2.1c Service connection failures [No./ (1000 connections· year)]	[0; 1]	[1; 2.5]	[2.5; +∞]	[7,33]
	M1.2.2 Total duration of failures [Days/No. failure]	[0; 1]	[1; 3]	[3; +∞]	[7] *, **
	M1.2.2 Total duration of failures [Days/No. failure]	[0; 1]	[1; 3]	[3; +∞]	[7] *, **
C1.3 Infrastructure condition	M1.3.1 Pipes rehabilitation [%/year]	[1.5; 4]	[0.8; 1.5] or [4; 20]	[0; 0.8]	[28]
	M1.3.2 Infrastructure value index [-]	[0.6; 1]	[0.4; 0.6]	[0; 0.4]	[28,34]
	M1.3.2a Pipes value index [-]	[0.6; 1]	[0.4; 0.6]	[0; 0.4]	[28,34] **, **
	M1.3.2b Pumps value index [-]	[0.6; 1]	[0.4; 0.6]	[0; 0.4]	[28,34] **, **
	M1.3.2c Tanks value index [-]	[0.6; 1]	[0.4; 0.6]	[0; 0.4]	[28,34] **, **
C1.4 Water and energy efficiency	M1.4.1 System supplied energy index [-]	[1; 2]	[2; 3]	[3; +∞]	[30]
	M1.4.1a Energy efficiency in pumping stations [kWh/(m ³ · 100 m)]	[0.27; 0.43]	[0.43; 0.6]	[0.6; +∞]	[28]
	M1.4.1b Surplus energy index [-]	[0; 0.75]	[0.75; 1]	[1; +∞]	
	M1.4.1c Average unit head loss [m/km]	[0; 2]	[2; 5]	[5; +∞]	[38,41] **
	M1.4.2 Water losses [L/(connection·day)]	[0; 120]	[120; 170]	[170; +∞]	[28] *, **
	M1.4.2a Real water losses [L/(connection·day)]	[0; 100]	[100; 150]	[150; +∞]	[28]
	M1.4.2b Apparent water losses [%volume]	[0; 3]	[3; 6]	[6; 100]	[33,35]
C2.1 Dependency on other services	M2.1.1 Level of dependency to bulk water utility [% input volume]	[0; 10]	[10; 20]	[20; 100]	[7] *
	M2.1.2 Level of dependency on pumping [% input volume]	[0; 10]	[10; 20]	[20; 100]	[7] *
C2.2 Infrastructure autonomy	M2.2.1 Treated water storage capacity [Days]	[2; +∞]	[1; 2]	[0; 1]	[7,33]
	M2.2.2 Level of autonomy to electric grid from alternative infrastructures [% dependent volume]	[80; 100]	[70; 80]	[0; 70]	[7]
	M2.2.3 Energy self-production [% pumped energy]	[10; 100]	[5; 10]	[0; 5]	[28]
	M2.2.3a Wind energy self-production [% pumped energy]	[10; 100]	[5; 10]	[0; 5]	[28] *
	M2.2.3b Solar energy self-production [% pumped energy]	[10; 100]	[5; 10]	[0; 5]	[28] *
	M2.2.3c Hydropower energy self-production [% pumped energy]	[10; 100]	[5; 10]	[0; 5]	[28] *
C2.3 Infrastructure redundancy	M2.3.1 Potential alternative water sources [% volume]	[75; 100]	[50; 75]	[0; 50]	[33] *
	M2.3.2 Pumping redundancy [% time]	[75; 100]	[50; 75]	[0; 50]	
	M2.3.3 Pipes topological redundancy index [-]	[0.1; 1]	[0.01; 0.1]	[0; 0.01]	[18] **
C3.1 Assessment of failures in the last disaster	M3.1.1 Number of failures in the last disaster [No./100 km]	[0; 30]	[30; 60]	[60; +∞]	[7] *
	M3.1.1a Pipes failures in the last disaster [No./ (100 km)]	[0; 30]	[30; 60]	[60; +∞]	[7]
	M3.1.1b Pump failures in the last disaster [days/ (pump)]	[0; 1]	[1; 3]	[3; +∞]	[7]
	M3.1.1c Service connection failures in the last disaster [No./ (1000 connections)]	[0; 1]	[1; 2.5]	[2.5; +∞]	[7]
	M3.1.2 Duration of failure till restoration in the last disaster [Days]	[0; 1]	[1; 3]	[3; +∞]	[7]

Notes: * Adapted in this study. ** Reference values proposed in this study. ● good performance; ● fair performance; ● poor performance.

Table 2. Assessment system for service dimension: objectives, criteria, metrics and respective reference values. Level I metrics are shadowed.

Criteria	Metrics	Reference Values			Source
		Good ●	Fair ●	Poor ●	
C4.1 Assessment of water supply interruptions	M4.1.1 Number of service interruptions [No./ (1000 connections·year)]	[0;1]	]1;2.5]	]2.5; +∞[	[32]
	M4.1.1a Number of interruptions due to pipe and equipment failures [No./ (1000 connections·year)]	[0;1]	]1;2.5]	]2.5; +∞[	[32] *
	M4.1.1b Number of interruptions due to rehabilitation or new constructions [No./ (1000 connections·year)]	[0;1]	]1;2.5]	]2.5; +∞[	[32] *
	M4.1.1c Number of interruptions due to water quality inadequacy [No./ (1000 connections·year)]	[0;1]	]1;2.5]	]2.5; +∞[	[32] *
	M4.1.1d Number of interruptions due to external issues [No./ (1000 connections·year)]	[0;1]	]1;2.5]	]2.5; +∞[	[32] *
C4.2 Adequacy of delivered water quality	M4.1.2 Average duration of service interruptions [h]	[0;4]	]4;6]	]6; +∞[	
	M4.2.1 Quality of supplied water [% tests]	[100;90]	]90;70]	]70; 0[	[33] **
	M4.2.1a Minimum velocity performance index [-]	[2; 3]	]1; 2[	]0; 1[	[39,40]
	M4.2.1b Water age performance index [-]	[2; 3]	]1; 2[	]0; 1[	[39,40] *
	M4.2.1c Network travel time performance index [-]	[2; 3]	]1; 2[	]0; 1[	[39,40] *
C4.3 Adequacy of pressure requirements	M4.3.1 Service complaints due to lack of pressure [No. complaints/ (1000 connections·year)]	[0; 0.15]	]0.15; 1.5[	]1.5; +∞[	[33] *, **
	M4.3.1a Minimum pressure performance index [-]	[2; 3]	]1; 2[	]0; 1[	[39,40]
	M4.3.1b Maximum pressure performance index [-]	[2; 3]	]1; 2[	]0; 1[	[39,40]
	M4.3.1c Pressure fluctuation performance index [-]	[2; 3]	]1; 2[	]0; 1[	[39,40]
C5.1 Assessment of non-potable uses	M5.1.1 Drinking water supplied for non-potable uses [% drinking volume]	[0; 25]	]25; 50]	]50; 100]	[7]
	M5.1.2 Recycled water for non-potable uses [% total volume]	[25; 100]	]10; 25[	]0; 10[	[33] *, **
C5.2 Hydraulic flexibility	M5.2.1 Network resilience index [-]	[0.75; 1]	]0.5; 0.75[	]0; 0.5[	[11] **
C6.1 Assessment of service interruptions in the last disaster	M6.1.1 Water supply interruptions for consumers in the last disaster [% connections]	[0; 2.5]	]2.5; 7.5]	]7.5; 100]	[7] *
	M6.1.2 Total duration of water supply interruption in the last disaster [days]	[0; 1]	]1; 3]	]3; +∞[	[7]

Notes: * Adapted in this study. ** Reference values proposed in this study. ● good performance; ● fair performance; ● poor performance.

The proposed resilience assessment system is composed of 58 metrics, from which 24 are retrieved from the literature, 30 have been adapted and 3 are new metrics, surplus energy index (M1.4.1b), pumping redundancy (M2.3.2) and average duration of service interruptions (M4.1.2). As some metrics do not have reference values in the literature (18), these are also proposed herein. The description and formulation of each metric is presented in Appendix A.

2.3. Resilience Assessment and Diagnosis

The second stage of the methodology is the resilience assessment and diagnosis. The evaluation and interpretation of the metric values allow us to identify the infrastructure and service main weaknesses and critical issues to be addressed by water utilities. To facilitate this judgement, the recommendation is to transform the assessment metrics into performance indices based on the establishment of reference values. These indices allow a straightforward performance classification and merge multiple metrics in a single value since these have normalized values.

The referred transformation of metrics in indices can be obtained by using performance functions, defined based on the reference values of each metric [39,40]. Typically, a 0 to 3 score is used. The reference values regarding poor performance correspond to the interval between 0 and 1, a fair performance between 1 and 2 and a good performance between 2 and 3.

Consider the example of the metric pumping redundancy (M2.3.2). This indicator represents the percentage of time all pumps of the pumping station are not working simultaneously including the reserve pump. As it is a new metric, reference values do not exist and are suggested herein considering that the pumping redundancy has poor performance, for metric values lower than half of the total pumping station operation time (50%); fair performance, for values between 50% and 75%; and good performance, for values higher or equal than 75%. The corresponding performance function is presented in Figure 3.

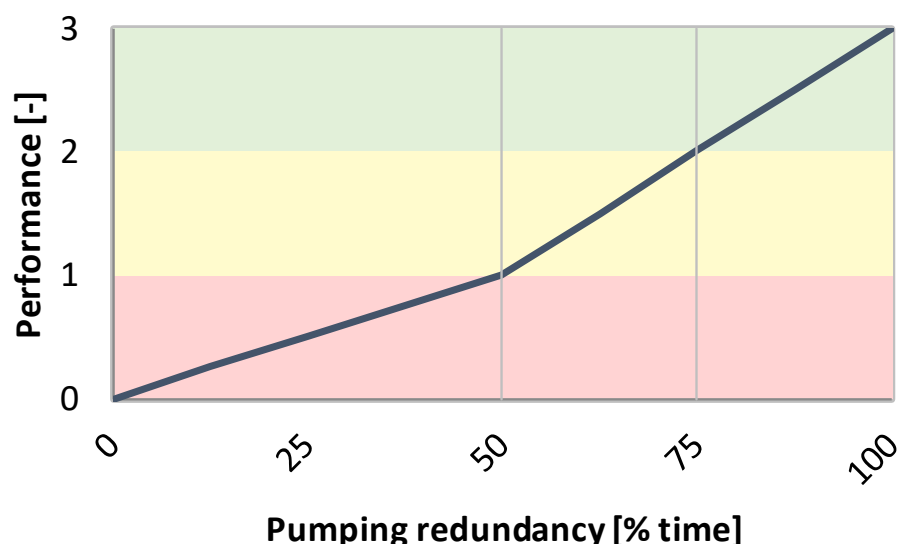


Figure 3. Performance function of the metric pumping redundancy (M2.3.2).

Additionally, these 0 to 3 score performance indices can be combined in a single value per criteria, objective, dimension and global resilience. This can be carried out considering a simple arithmetic or a weighted average of the corresponding performance indices. The use of the weighted average allows the resilience assessment system to give more importance to certain criteria, objectives or dimensions, according to the water utility concerns.

The merging process at the criteria, objective, dimensional or global level only considers performance indices of Level I, allowing the identification of the aspects that contribute to a lower resilience. Level I metrics can be applied to the global level, providing an overall assessment of the system performance from different perspectives, and to the sectoral level, providing an assessment and intervention prioritization of different network areas.

Level II metrics (referred to with letters 'a', 'b' or 'c' as a suffix of the metric ID) are complementary to the Level I assessment metrics, providing insights and allowing us to understand the problems' nature and to identify the component, asset or process with inadequate performance. For example, the Level I metric regarding water efficiency is "M1.4.2—Water losses", but water losses can be either real or apparent, being the corresponding Level II metrics, Real water losses (M1.4.2a) or Apparent water losses (M1.4.2b). To note that Level II metrics cannot be considered in the performance indices merger, as they provide redundant results with Level I metrics, biasing the final score of resilience criteria or objectives.

The results from stage 2 of the methodology are the overall assessment of the system and of network areas in the selected dimensions, objectives and criteria, as well as the identification of the main and specific problems of the system and the critical network areas.

2.4. Improvement Measures

Once the main weaknesses of the system and the critical network sectors are identified, the water utilities should analyze and implement adequate resilience improvement

measures. Some examples of identified problems as well as of the respective potential improvement measures are presented in Table 3.

Table 3. Example of drinking water system problems and weaknesses and potential improvement measures.

Dimension	Identified Problem/Weakness	Potential Improvement Measures
Infrastructure	Low infrastructure knowledge Low critical assets knowledge	– Promote human resources computational competencies (e.g., SIG, EPANET) – Improve inventory data collection
	Aged infrastructure	– Increase rehabilitation rate
	High water losses	– Manage pressure – Increase rehabilitation rate
	High dependency on other services	– Increase water abstraction capacity – Increase self-energy production
	Reduced autonomy	– Increase autonomous water sources – Add alternative water sources
Service	Excessive use of drinking water for non-potable uses	– Promote the use of alternative water sources (e.g., dual pipe systems, collect stormwater)
	High burst rate	– Manage pressure – Increase rehabilitation rate
	Low water quality	– Add/reinforce chlorination in strategic points of the network – Promote periodic network flushes
	High surplus energy	– Redesign the network (e.g., valve operation) to create new district-metered areas

Further on, the resilience assessment framework presented is also capable of evaluating the different alternatives to improve resilience and prioritize alternatives, helping the decision-maker in the selection of improvement measures.

3. Results

3.1. Case Study

The methodology is demonstrated in a real drinking water system located in the south of Portugal, in the Algarve Region, a high touristic area that is mostly comprised of houses with gardens, condominiums, and hotels. The total annual water consumption is around 4 hm³, provided by the bulk water utility. The system has 8% of water losses and approximately 60% of the supplied water is for non-potable uses, particularly for irrigation of green spaces. The water utility provided a version of the EPANET hydraulic model, set for 24-hour simulations, corresponding to the average daily supply in August 2021 (higher consumption).

The system comprises two water entry points supplying two storage tanks (R4 and R6), represented as reservoirs in the EPANET hydraulic model (Figure 4); three intermediate storage tanks (T1 to T3) throughout the network; and eight pumping stations (H1 to H8). The network has a total pipe length of 117 km, with an average age of 44 years (in 2021), and a rehabilitation rate of 0.2%/year. The system is divided into two network areas, referred to herein according to the respective main storage tanks, namely network areas R4 and R6 (Figure 4).

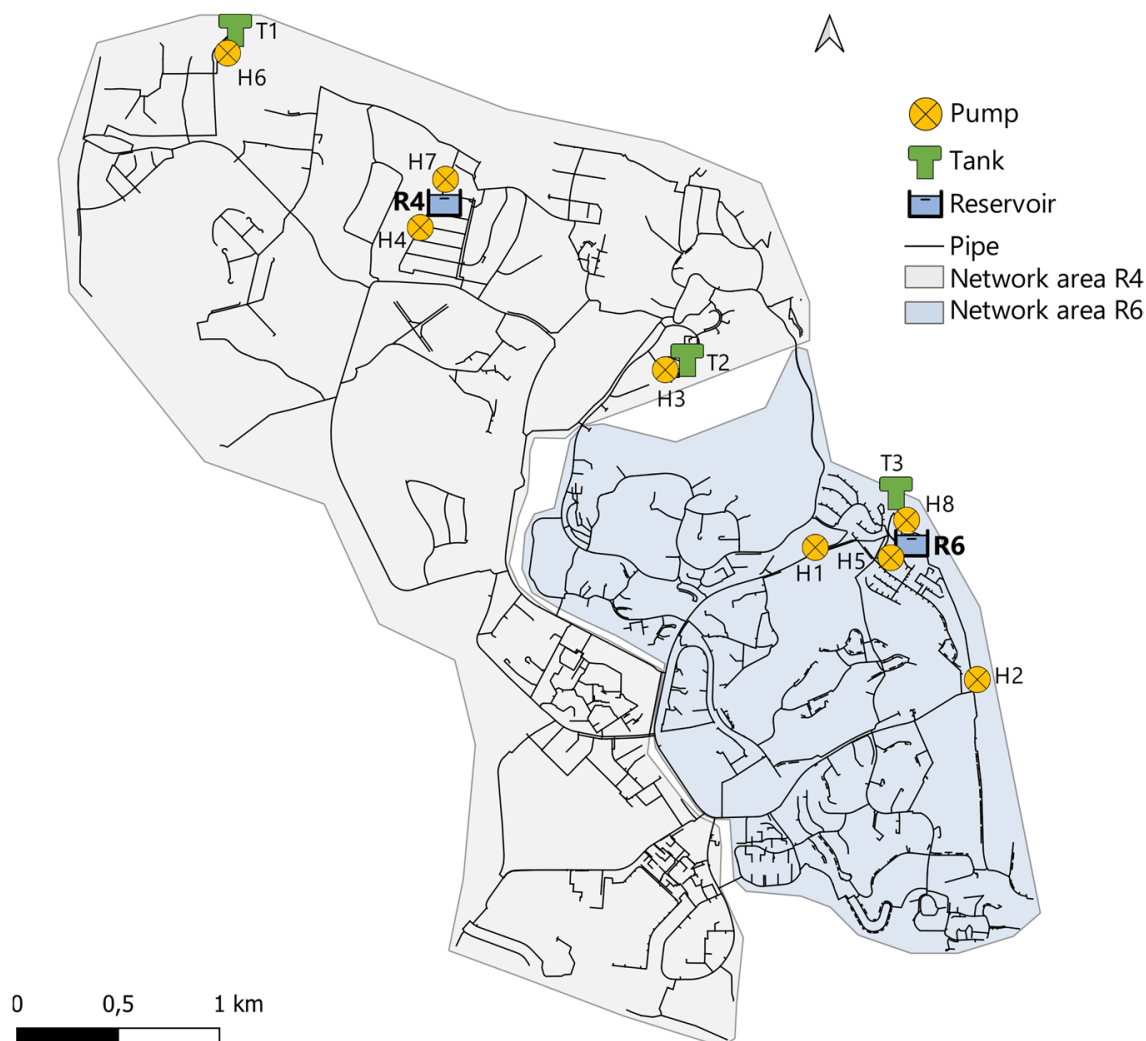


Figure 4. Network scheme and network area identification.

Network area R4 is the largest area, comprising 67 km of pipes, with diameters ranging from 50 to 700 mm. This area consumes approximately 1.9 hm³ of water annually. The storage tanks integrated in this area (R4, T1 and T2) have a storage capacity of 925 m³. The entry storage tank (represented as reservoir R4) has a water level of 64.5 m, the highest node elevation is 43 m and the lowest node elevation is 2.5 m. The network area has four pumping stations, two associated with the main storage tank (H4 and H7) and two boosting stations (H3 and H6) at intermediate network sections to reinforce the pressure head at higher elevation zones. From the volume supplied, only 16% is pumped with the other 84% supplied by gravity. In the south of the network area is the marine area, corresponding to a high-consumption zone with several hotels and restaurants.

Network area R6 comprises 50 km of pipes, with diameters ranging from 50 to 500 mm. It provides approximately 2.0 hm³ of water annually. The storage tanks (R6 and T3) have a storage capacity of 10,700 m³. The entry storage tank (represented as reservoir R6) has a water level of 53 m, the highest node elevation is 47 m and the lowest node elevation is 8 m. In this network area, 100% of the water supplied is pumped. The network area has four pumping stations, three associated with the main storage tank (H2, H5 and H8) and one further away (H1) to reinforce the water head to supply a higher elevation zone. The network area has one hotel that has a high consumption.

The water utility has regarded the possibility of alternative water sources for non-potable uses from underground water sources. In addition, for 2026, it is expected that reused water will be provided for irrigation of some green spaces.

3.2. Results of Metrics Assessment

The applicability of the proposed resilience assessment framework, in terms of metrics and reference values, is demonstrated and discussed herein. This section only presents the results of three metrics—pipes criticality index (M1.1.3a), surplus energy index (M1.4.1b) and water losses (M1.4.2b)—as examples of the results of the assessment system, since these metrics or their reference values are innovatively proposed and discussed in this paper.

The pipes criticality index (M1.1.3a) aims to identify the most important pipes on which the system depends. Herein, it is evaluated as the weighted average of the pipes' hydraulic importance index (HII_p) by the flowrate. The pipes' hydraulic importance index (HII_p) assesses the consumption that is not supplied due to the deactivation or failure of pipe p , are similar to Equations (A2) and (A3) presented in Appendix A. The index varies between 0 and 1, with higher values indicating greater criticality. The spatial distribution of HII_p for the system and the respective network areas (R4 and R6) is presented in Figure 5.

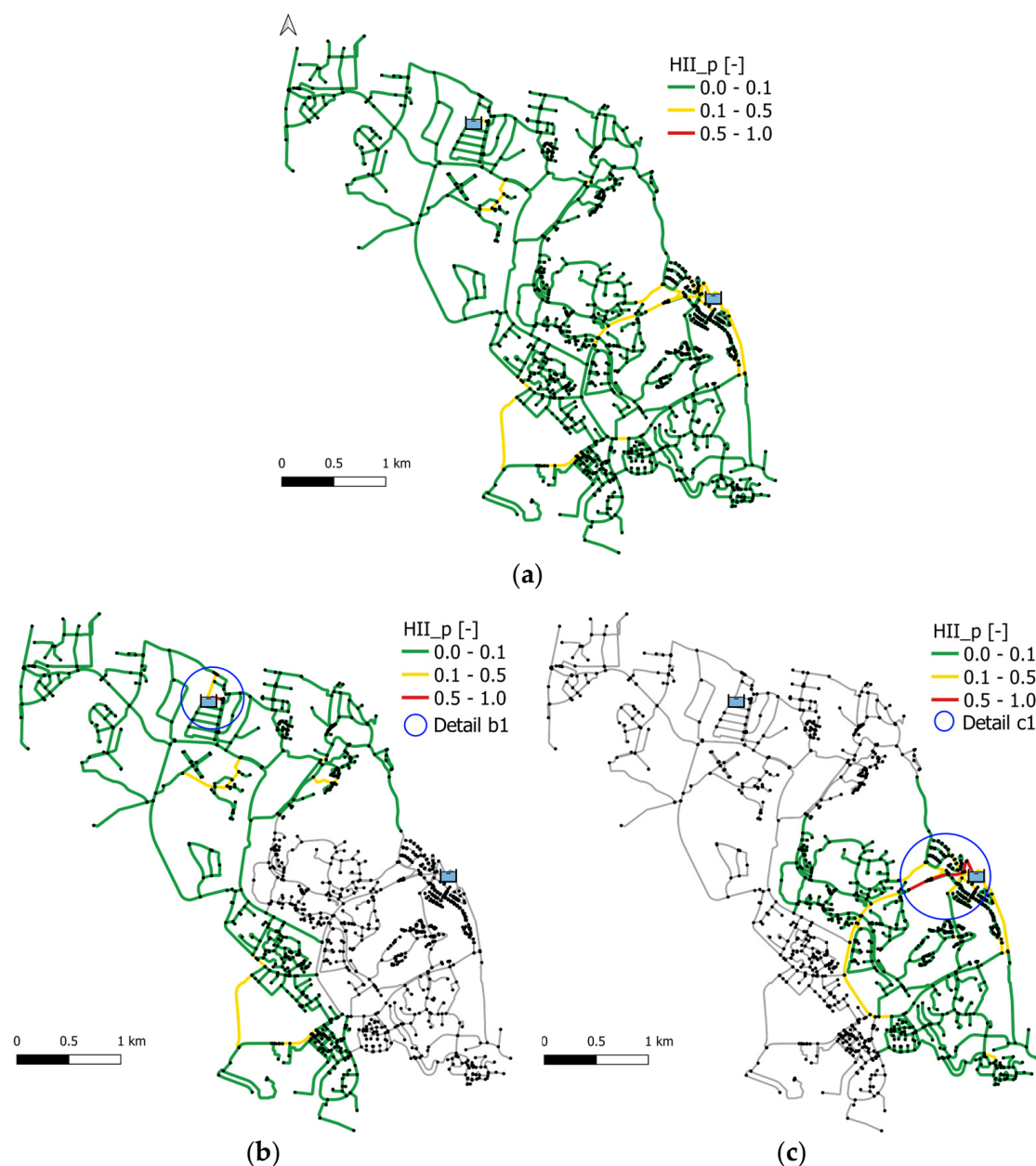


Figure 5. Pipes criticality index spatial distribution, HII_p : (a) system; (b) network area R4; (c) network area R6.

Figure 5 shows that most pipes (green pipes) have hydraulic importance lower than 0.1 and are not critical to the adequate operation of the network, that is, in case of pipe failure less than 10% of the consumption is affected. Pipes with hydraulic importance between 0.1 and 0.5 (yellow pipes) correspond to those that, in case of failure, between 10% and 50% of the demand is not satisfied due to insufficient hydraulic capacity, being thus relevant pipes for system operation. Pipes with hydraulic importance higher than 0.5 (red pipes) correspond to the network's main paths. A failure means that over 50% of consumers are not supplied, being critical pipes for the adequate operation of the network.

Looking at the network area results (Figure 5b,c), network area R4 has only one of the pipes connected to the main water source with a criticality higher than 0.5 (see detail b1 in Figure 5b). As the network bifurcates at immediately downstream the tank, the critical pipe is small. Conversely, the number of pipes with increased criticality in network area R6 is higher than in area R4 (see detail c1 in Figure 5c). As the pipes criticality index corresponds to the weighted average of HII_p , the respective values vary between 0 and 1, corresponding higher values to poorer performance. Accordingly, the proposed reference values for the pipes criticality index are the following: index values below 0.1 correspond to good performance, between 0.1 and 0.5 to fair performance and higher than 0.5 to poor performance.

The surplus energy index (M1.4.1b) is another new metric proposed herein that assesses how much surplus energy exists in the system concerning the minimum required energy (see Appendix A for a more detailed description). If, on one hand, the system should have the maximum equipment efficiency (ideally 100%) and the minimum dissipated energy (ideally zero), on the other hand, it should also have a certain amount of surplus energy to cope with supply in case of a sudden demand increase, though not too much in excess, as more energy than the necessary to satisfy demand is being used and problems associated with high pressures (e.g., frequent bursts, high leakage levels) are more likely to occur. Accordingly, the following reference values for surplus energy index (M1.4.1b) are established: a surplus energy index value higher or equal to 1 corresponds to poor performance, since the supplied energy corresponds to more than twice the minimum required energy, indicating that the system has much energy in excess, being possibly oversized or with significant elevation differences; values between 0.75 and 1 are associated to fair performance, to alert the approximation of high surplus energy; and values below 0.75 correspond to good performance. The metrics results for the case study (M1.4.1b in Appendix B) show that globally the system is near the 0.75 threshold.

Water losses are a major concern for water utilities in Portugal, particularly in this decade with major drought periods in which water is scarce and should be well managed. In 2023, Portuguese water utilities lost 162.2 hm³ of water in leaks, bursts and tank overflows, which are real water losses [31]. As for apparent water losses, most water utilities knowledge is insufficient and many utilities do not correctly report them to the water regulator, ERSAR. As water losses correspond to the sum of real and apparent water losses, there are no reference values for water losses regarding the Portuguese reality. A comparison between the reported real and apparent water losses has demonstrated that water losses mainly correspond to real water losses, without any relationship with the volume of apparent water losses. A similar tendency is shown when comparing real water losses and total water losses, with the latter being higher on 25 L/[connection.day] than the former. However, apparent water losses are particularly underestimated by water utilities with lower knowledge and applying this threshold would lead to penalizing water utilities with higher knowledge. As such, water loss reference values are considered similar to those corresponding to the real water losses added of 50 L/[connection.day]. Accordingly, the following reference values for water losses (M1.4.2) are established: water losses lower than 150 correspond to good performance, between 150 and 200 to fair performance and water losses higher than 200 to poor performance. Regarding the analyzed drinking water system, the water utility has telemetry and is able to estimate apparent water losses. As such, it is possible to disaggregate water losses' volumes and infer that the main factor

responsible for the fair performance (see M1.4.1 in Appendix B) is the real water losses of 120 L/(connection.day), being apparent water losses only 2% of the input volume.

3.3. Resilience Assessment Framework Application

3.3.1. Application of Resilience Assessment Framework for System Diagnosis

The application of the proposed methodology to the case study mentioned in Section 3.1 is presented herein. The results of all metrics are presented in Appendix B, though only the most relevant issues are discussed in this section.

The system has a global resilience of 1.19, corresponding to a low fair performance, and improvements can be implemented to increase the system's resilience. The results of resilience objectives and criteria for the infrastructure and the service dimensions are presented in Tables 4 and 5, respectively. In addition, the worst performance metric values for each criterion are also presented.

Table 4. Infrastructure resilience assessment (Level I) for drinking water system diagnosis.

Dimension	Objective	Criteria	Metric with Worst Performance	
Infrastructure 0.99 ●	O1 Ensure infrastructure assets robustness 1.32 ●	C1.1 Infrastructure knowledge and criticality	1.28 ●	M1.1.2 Knowledge and protection of critical assets index [-] 0.0 ●
		C1.2 Infrastructure integrity	1.53 ●	M1.2.2 Total duration of failures [Days/No. failure] 10.3 ●
		C1.3 Infrastructure condition	0.67 ●	M1.3.1 Pipe rehabilitation [%/year] 0.2 ●
		C1.4 Water and energy efficiency	1.81 ●	M1.4.1 System supplied energy index [-] 2.24 ●
	O2 Ensure an autonomous water infrastructure 0.59 ●	C2.1 Dependency on other services	0.25 ●	M2.1.1 Level of dependency on bulk water utility [%volume] 100% ●
		C2.2 Infrastructure autonomy	0.35 ●	M2.2.3 Energy self-production [% pumped energy] 0% ●
		C2.3 Infrastructure redundancy	1.28 ●	M2.3.1 Potential alternative water sources [%volume] 3% ●
	O3 Promote infrastructure recovery and build back in disasters NA	C3.1 Assessment of failures in the last disaster	NA	NA

Notes: ● fair performance; ● poor performance.

Table 5. Service resilience assessment (Level I) for drinking water system diagnosis.

Dimension	Objective	Criteria	Metric with Worst Performance	
Service 1.63 ●	O4 Ensure a reliable service 2.20 ●	C4.1 Assessment of water supply interruptions	1.41 ●	M4.1.1 Number of service interruptions [No./(1000 connections·year)] 2.5 ●
		C4.2 Adequacy of delivered water quality	3.0 ●	M4.2.1 Quality of supplied water [%tests] 100 ●
		C4.3 Adequacy of pressure requirements	3.0 ●	M4.3.1 Service complaints due to lack of pressure [No. complaints/(1000 connections·year)] 0.0 ●
	O5 Ensure a flexible service 0.86 ●	C5.1 Assessment of non-potable uses	0.34 ●	M5.1.2 Recycled water for non-potable uses [% total volume] 0% ●
		C5.2 Hydraulic flexibility	1.91 ●	M5.2.1 Network resilience index 0.73 ●
	O6 Promote service recovery and build back in disasters NA	C6.1 Assessment of service interruptions in the last disaster	NA	NA

Notes: ● good performance; ● fair performance; ● poor performance.

Looking into the resilience dimensions, the network infrastructure is shown to be in inadequate condition, with a poor performance of 0.99 (Table 4). In contrast, the service dimension has a fair performance of 1.63 (Table 5), although with potential for improvement.

Concerning the infrastructure dimension, a further analysis in terms of objectives (Table 4) shows that a fair performance (1.32) is obtained concerning ensuring infrastructure assets robustness (O1). In this objective, the infrastructure condition criteria (C1.3) has the lowest value, with a poor performance of 0.67. This is mainly due to the low rehabilitation rate (M1.3.1 with the lowest performance) and aged infrastructures. Both criteria infrastructure knowledge and criticality (C1.1) and infrastructure integrity (C1.2), albeit having fair performance (1.28 and 1.53, respectively), have poor performance in terms of knowledge and protection of critical assets index (M1.1.2) and total duration of failures (M1.2.2), respectively. Therefore, besides recommending better knowledge about critical assets, it is important to understand the nature of failures at the advanced diagnosis (Level II).

Regarding the objective dedicated to ensuring an autonomous water infrastructure (O2), it has poor performance, with dependency on other services (C2.1) and infrastructure autonomy (C2.2) criteria having poor performance (0.25 and 0.35, respectively). From the metrics with worse performance (M2.1.1 and M2.2.3, respectively), a great dependency exists on the bulk water utility and the utility lacks energy self-production. Although the infrastructure redundancy (C2.3) criterion has fair performance (1.28), the potential alternative sources (M2.3.1) metric has poor performance. The M2.3.1 indicator results presented in Appendix B show that only 3% of the current water demand can potentially be provided to the consumers from alternative sources, in this particular case, from an underground water source.

Regarding the service dimension, Table 5 demonstrates that the objective relative to ensuring a reliable service (O4) has good performance (2.20). In this objective, the assessment of water supply interruptions (C4.1) criteria is the worst with a fair performance of 1.41. The number of service interruptions per connection (M4.1.1) is considerable, being the worst performance metric. The service flexibility objective (O5), has a poor performance of 0.86, being mainly related to non-potable uses (C5.1), as the system has a high demand of non-potable uses (M5.1.1 of around 60%, see Appendix B) but does not have recycled water supplied (M5.1.2). As for hydraulic flexibility (C5.2) criteria, the system has fair performance (1.91), but is close to good performance, since the network resilience index has a result of 0.73, showing that the system can sustain an increase in water demand.

This assessment shows that the main problems of the drinking water system in terms of infrastructural condition are: (i) a low rehabilitation rate combined with the high age of infrastructures that have passed their average service life; (ii) a high dependency on the bulk water utility service; and (iii) a low level of autonomy, particularly in terms of energy, as it has no self-production. In terms of service, the main weakness is (iv) the excessive use of drinking water for non-potable uses. Given the lack of available data, the objectives O3 (infrastructure dimension) and O6 (service dimension) were not considered in the final resilience results.

3.3.2. Network Area Prioritization

The resilience assessment framework is also applied to the network areas of the system (Table 6). Regarding the infrastructure dimension, network area R6 has worse resilience performance than network area R4. The main difference comes from the ensuring infrastructure assets robustness objective (O1), in which network area R6 has a fair (close to poor) performance (1.07), while network area R4 has a fair performance of 1.54. The worst performance of network area R6 is mainly due to lower infrastructure integrity (C1.2), from a long duration of failures (see Section 3.3.3), and infrastructure condition (C1.3), with low considerable aged assets.

The objective of ensuring an autonomous water infrastructure (O2) has poor performance in both network areas because both areas are totally dependent on bulk water supply

(see M2.1.1 in Appendix B). Network area R6 is also totally dependent on pumping (see M2.1.2 in Appendix B), which leads to a dependency (C2.1) of 0.00. Network area R4 has fair performance in terms of pumping dependency (see M2.1.2 in Appendix B), leading to a dependency (C2.1) of 0.72. In terms of the autonomy criteria (C2.2), network area R6 has more storage capacity than network area R4 (see M2.2.1 in Appendix B), while both areas do not have any alternative infrastructures for pumping nor have energy self-production. Redundancy (C2.3) has fair performance in both network areas. From the results in Appendix B, both network areas hardly have any alternative water sources (e.g., underground sources) and have fair performance in terms of topological redundancy. Still, network area R4 has lower pumping redundancy than network area R6.

Table 6. Network areas resilience assessment.

	Dimension		Objective		Criteria		
	R4	R6	R4	R6		R4	R6
Infrastructure	1.10 ●	0.91 ●	O1 Ensure infrastructure assets robustness	1.54 ● 1.07 ●	C1.1 Infrastructure knowledge	0.98 ●	0.99 ●
					C1.2 Infrastructure integrity	2.90 ●	1.24 ●
					C1.3 Infrastructure condition	0.69 ●	0.33 ●
					C1.4 Water and energy efficiency	1.85 ●	1.76 ●
			O2 Ensure an autonomous water infrastructure	0.53 ● 0.69 ●	C2.1 Dependency on other services	0.72 ●	0.00 ●
					C2.2 Infrastructure autonomy	0.06 ●	0.62 ●
					C2.3 Infrastructure redundancy	1.05 ●	1.50 ●
Service	1.60 ●	1.68 ●	O3 Promote infrastructure recovery and build back in disasters	NA NA	C3.1 Assessment of failures in the last disaster	NA	NA
			O4 Ensure a reliable service	2.20 ● 2.20 ●	C4.1 Assessment of water supply interruptions	1.41 ●	1.41 ●
					C4.2 Adequacy of delivered water quality	3.0 ●	3.0 ●
					C4.3 Adequacy of pressure requirements	3.0 ●	3.0 ●
			O5 Ensure a flexible service	0.79 ● 0.99 ●	C5.1 Assessment of non-potable uses	0.34 ●	0.34 ●
					C5.2 Hydraulic flexibility	1.70 ●	2.31 ●
			O6 Promote service recovery and build back in disasters	NA NA	C6.1 Assessment of service interruptions in the last disaster	NA	NA

Notes: ● good performance; ● fair performance; ● poor performance.

Regarding the service dimension, both network areas have a close fair performance, with good performance in terms of reliable service (O4). The assessment of water supply interruptions (C4.1) has fair performance in both network areas, meaning that service interruption does happen in the system, but is not a major issue, since for both areas, water quality tests are compliant with the regulations and complaints in terms of pressure requirements are low (see M4.2.1 and M4.3.1 in Appendix B), demonstrated by the good performance in terms of adequacy of delivered water quality (C4.2) and pressure requirements (C4.3).

Similarly to the system assessment in terms of service flexibility (O5), non-potable uses (C5.1) are the main reason for the poor performance, with the same proportion of drinking water for non-potable uses in both network areas. The existing underground water sources were not used yet. No recycled water was supplied for non-potable uses (M5.1.2 in Appendix B). Hydraulic flexibility (C5.2), herein assessed based on the Network Resilience Index [11], has fair performance in network area R4 and good performance in network area R6, since the latter has higher hydraulic capacity to keep providing water in a demand increase scenario.

From this assessment, network area R6 is identified as having more problems, being the priority network area, particularly regarding infrastructure integrity and condition,

dependency on other services, infrastructure autonomy and regarding the use of drinking water for non-potable uses. Nonetheless, network area R4 should not be disregarded, as most problems are system-related and are also found in this network area.

3.3.3. Detailed Diagnosis of Priority Network Area

The detailed diagnosis is conducted to better understand what and where the sources of identified problems are. Both Levels I and II metrics are considered to identify the cause of the problems. Table 7 presents the metrics of the criteria with the worst performance: infrastructure integrity (C1.2), infrastructure condition (C1.3), dependency on other services (C2.1) and infrastructure autonomy (C2.2), of the priority network area R6 identified previously.

Table 7. Detailed resilience diagnosis of the worst performance criteria from network area R6.

C1.2 Infrastructure integrity		1.24 ●
M1.2.1	Number of failures [No./ (100 km·year)]	23.9 ●
M1.2.1a	Pipes failures [No./ (100 km·year)]	21.9 ●
M1.2.1b	Pump failures [days/ (pump·year)]	9.3 ●
M1.2.2	Total duration of failures [Days/No. failure]	13.7 ●
C1.3 Infrastructure condition		0.33 ●
M1.3.1	Pipes rehabilitation [%/year]	0.20 ●
M1.3.2	Infrastructure value index [-]	0.20 ●
M1.3.2a	Pipes infrastructure value index [-]	0.05 ●
M1.3.2b	Pumps infrastructure value index [-]	0.00 ●
M1.3.2c	Storage tanks infrastructure value index [-]	0.36 ●
C2.1 Dependency on other services		0.0 ●
M2.1.1	Level of dependency on bulk water utility [%volume]	100% ●
M2.1.2	Level of dependency on pumping [% input volume]	100% ●
C2.2 Autonomy		0.62 ●
M2.2.1	Treated water storage capacity [Days]	1.9 ●
M2.2.2	Level of autonomy to electric grid from alternative infrastructures [% dependent volume]	0% ●
M2.2.3	Energy self-production [% pumped energy]	0% ●
M2.2.3a	Wind energy self-production [% pumped energy]	0% ●
M2.2.3b	Solar energy self-production [% pumped energy]	0% ●
M2.2.3c	Hydropower energy self-production [% pumped energy]	0% ●
C5.1 Non-potable uses		
M5.1.1	Drinking water supplied for non-potable uses [% drinking volume]	58% ●
M5.1.2	Recycled water supplied for non-potable uses [% total volume]	0% ●

Notes: Level I metrics are shadowed. ● good performance; ● fair performance; ● poor performance.

Looking at the fair performance in infrastructure integrity (C1.2) in network area R6, a detailed analysis demonstrates that the problem is not due to the number of failures (good performance), but due to the duration of a pump failure, as shown by the poor performance in M1.2.1b and M1.2.2. Concerning infrastructure condition (C1.3), the rehabilitation rate (0.2%) has been quite low (M1.3.1) and the infrastructure value index (M1.3.2) is also considerably low (0.20), since most system assets (pipes, pumps and tanks) have low performance, with values close to 0.

Regarding dependency on other services (C2.1), network area R6 is totally dependent on external water and energy sources. In terms of autonomy (C2.2), this area has a fair storage capacity but does not have any alternative infrastructure for the water to bypass when there is a power outage, nor does it have any energy self-production.

Looking at the non-potable uses of the drinking water system (C5.1), this network supplies approximately 60% of drinking water to non-potable uses, although there is the

possibility of an alternative recycled water source not being used yet as the distribution pipes are under construction.

3.4. Improvement Measures Recommendations

The application of the resilience assessment system to this network has shown that the system's main problems are old infrastructures with low rehabilitation, high dependency on external sources of water and energy, low autonomy and a high amount of drinking water supplied for non-potable uses. Network area R6 is in worse condition in terms of resilience, with very low infrastructure sustainability, a failure in a pump that took a long period to be replaced and a high dependency on pumping. Network area R4 has a low capacity for storing treated water.

Old infrastructures with low rehabilitation make the system assets more susceptible to failure when facing a disaster (i.e., earthquake) that may put the infrastructure integrity at risk. The water utility must, therefore, start to invest in rehabilitation, not only of pipes but also in pumping equipment, particularly in network area R6, and, in storage tanks, as these assets have exceeded their expected service lives. Additionally, repairing failed assets must be implemented faster, as a pump should not take approximately six months to be replaced.

Another main issue is the dependency on other services. By being totally dependent on the bulk water utility, without an alternative source, the drinking water system is at risk of not having water to supply its consumers if a problem occurs regarding water quality or water quantity. Although network area R6 has a storage capacity of 1.9 days, network area R4 can only store drinking water for 0.2 days (M2.2.1 in Appendix B). Increasing the storage capacity, connecting the network areas to other network areas or systems and finding potential alternative water sources, even if they are not constantly used as a water source, are measures to ensure an autonomous and flexible water infrastructure (O2).

Regarding energy, network area R6 is totally dependent on the national electric grid, since all supplied water is pumped, and there is no energy self-production. As such, in the event of a power outage, there is no water supply in network area R6. Nonetheless, part of the network area could be gravity supplied, as it has a lower elevation (lowest elevation is 5 m) than the R6 storage tank (water head of 53 m). Implementing or redesigning district metering areas so that water from the tanks directly supplies the lowest elevation areas, will reduce the amount of water that needs to be pumped. Additionally, in case of an energy failure, the system's consumption could be more easily ensured by power generators or self-production energy.

Finally, the system provides a considerable amount of drinking water to non-potable uses, without having alternative sources of non-potable water. This consumption should be minimized from the drinking water system, allowing more water to be available for potable uses, relevant in a water scarcity event. For that, the investment in recycled water should be considered.

4. Discussion

A novel resilience assessment framework, including two main dimensions of drinking water networks, infrastructure and service, has been presented. The assessment of each dimension comprises multiple objectives and criteria capable of addressing different resilience features relevant to drinking water systems (i.e., robustness, dependency, autonomy, flexibility, reliability, preparedness and recovery). The proposed framework allowed us to identify the main issues in the infrastructure dimension, highlighting problems in terms of infrastructure conditions, dependency and autonomy (as seen in Table 4) and, in addition, problems in terms of service, particularly in the supply of drinking water to non-potable uses (Table 5).

This approach is a novelty in the assessment of resilience in drinking water systems since most previous studies assess resilience based on a single resilience perspective [13,19,21]. For example, when service reliability is considered to assess resilience [23,24], the infrastructure dimension is not considered. As per [42], metrics based on surplus energy [10–14] consider

mainly the hydraulic flexibility to comply with an eventual demand increase but do not consider pipes redundancy, or any infrastructure objectives. Contrarily, graph-theory metrics focus on pipe redundancy by assessing network topology [18,19], disregarding the service dimension. For example, the network resilience index (M5.2.1), used herein to assess service flexibility, only infers that the system can sustain an increase in water demand (see Section 3.3). When considering only this metric, other problems may not be identified that, in the current case, are related to infrastructure, dependency and autonomy.

The proposed framework promotes a prompter assessment using Level I metrics, globally assessing the resilience of the system, the objectives and criteria, allowing a first diagnosis, highlighting the main resilience issues and identifying priority network areas. In addition, the framework also allows for a detailed diagnosis, using Level II metrics, investigating the components that must be the target of improvement measures. At the tactical level, most of the resilience assessments in the literature require, at least, the hydraulic model of the system [13,18,23]. Due to the lack of knowledge and human capacity in smaller Portuguese water utilities, these approaches cannot be applied, as they do not have the hydraulic model of the system. As no resilience assessment framework at the tactical level has been developed so far, in the framework proposed here, most of the Level I metrics require basic data and the assessment in two levels also allows for water utilities with lower data maturity to be able to assess resilience.

As a comprehensive resilience assessment, the framework is originally developed to assess multiple resilience aspects, providing results for criteria, objectives, dimensions and a global resilience value. For that, a considerable number of metrics are proposed, which involve a significant amount of data that can be time-consuming to collect and calculate. Nonetheless, if the water utility is focused on a certain resilience dimension, the resilience analysis can be simplified to include only metrics related to that aspect. For example, if a water utility wants to address dependency and autonomy, then it could only calculate metrics respective to those criteria (C2.1 and C2.2).

The selection of metrics was carefully conducted so that the metrics were complementary to each other, providing new information about the system. For example, pipes rehabilitation (M1.3.1) and infrastructure value index (M1.3.2) may seem overlapping metrics, but pipes rehabilitation can be low and the system is relatively new; therefore, the infrastructure value index is high. The opposite may also be possible, a low infrastructure value index and a high rehabilitation rate could mean that the water utility is already working on renovating the system. This shows that the metrics are complementary and not redundant. As for Level I and Level II metrics, redundancy can occur. Level II metrics are a disaggregation of Level I metrics, aiming to provide a deeper understanding of where the problem may be. These are to be calculated after identifying critical criteria and metrics. Only Level I metrics are to be used in the merging of metrics to reach the criteria, objectives, dimensions and global resilience results, preventing the skewing of the resilience assessment results.

Another positive aspect of the presented framework is its flexibility to accommodate new and to adapt existing metrics, objectives or criteria as new insights are gained. If a metric demonstrates to assess a certain criterion better than those proposed herein, then that metric can be added to the resilience assessment. Regarding reference values, those presented here are majorly based on Portuguese regulations or water utilities' data. However, those can be adapted to other countries' realities. In addition, water utilities can adjust the reference values according to their service objectives.

The proposed resilience assessment framework must be applied to other case studies to further test and consolidate its objectives, criteria and metrics, also assessing the framework's potential and improving it to better evaluate the resilience of drinking water systems.

5. Conclusions

This study proposes a novel and comprehensive resilience assessment applicable to drinking water systems and network areas, as an approach to support diagnosis and decision-making in the medium term for drinking water systems (tactical level). Resilience objectives drive the resilience assessment framework, allowing a comprehensive assessment of the infrastructure and the service dimensions, in alignment with the strategic framework RESCCUE proposed in previous studies. The infrastructure dimension addresses perspectives related to knowledge and criticality, integrity, condition, efficiency, dependency on other services, autonomy, redundancy and recovery from disasters. The service dimension focuses on assessing water supply interruptions, adequacy of delivered water quality and pressure requirements, assessment of non-potable uses, hydraulic flexibility and service recovery in disasters.

The resilience assessment framework, with Level I metrics, allows the assessment of global resilience and an assessment decomposed by dimensions, objectives, criteria, and metrics. This resilience assessment highlights aspects and network areas that are a priority for intervention. In addition, it also allows for a detailed diagnosis and decision support (with Level II metrics), which is also useful for utilities with different maturity levels in terms of available information. The detailed diagnosis allows the identification of the components or assets responsible for lower resilience levels and the prioritizing of resilience improvement measures.

The application of the resilience assessment framework to the case study has shown that the system has fair performance in terms of global resilience. The network infrastructure was shown to be in inadequate condition, with the main problems being a low rehabilitation rate combined with the high age of infrastructures, a high dependency on the bulk water utility service, and a low level of autonomy, particularly with respect to energy. In terms of service, the main weakness is the excessive use (60%) of drinking water for non-potable uses. Both network areas (R4 and R6) have resilience problems, but network area R6 is identified as the priority area. Improvement measures include the investment in asset rehabilitation, the increase in storage capacity, the connection of network areas between each other, using alternative water sources, and the investment in energy self-production and in recycled water.

In the present paper, the resilience assessment framework was used only to assess the drinking water system as it is currently, without considering any disaster or future event. Future work should apply the resilience assessment system to a scenario-building methodology, where a wide range of plausible scenarios for the long-term future is developed and modeled, and the system behavior for that scenario is reached [43].

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Appendix A

Table A1. Description of metrics used in the resilience assessment framework.

M1.1.1	Infrastructural knowledge index	[-]	Level I
Assesses the water utility knowledge over its infrastructure, evaluating the following classes:			
Class A—Existence of infrastructure maps (58 points)			
Class B—Registry about pipes and connections (57 points)			
Class C—Registry about the other infrastructures (36 points)			
Class D—Registry about metering devices (6 points)			
Class E—Registry about infrastructure conservation state (12 points)			
Class F—Registry about public network interventions (12 points)			
Class G—Interconnection between GIS and risk factors registry (19 points)			
Source: [28], identified as dAA09.			
Calculation			
Sum of each analysis class, which are composed by a set of questions, with a predefined number of points for each question. See LNEC and ERSAR (2017) for more information.			
In case of not applicable classes or subclasses to the system, a conversion factor proportional to the score of the applicable classes or subclasses is considered.			
The index varies between 0 and 200.			
Data source: Water utility survey.			
Reference values: Proposed in this study, considering that minimum knowledge for fair performance corresponds to having the information needed in paper (87 points), and a minimum knowledge for good performance corresponds to having the information needed in computer-readable form (142 points).			
M1.1.2	Knowledge and protection of critical assets index	[-]	Level I
Assesses the water utility knowledge and protection of critical assets, evaluating the following questions:			
Q1. Are the critical infrastructure assets identified? (single choice)			
Yes—1 Partially—0.5 No—0			
Q2. Identification of infrastructure critical assets is based on: (multiple choice)			
Population served—1 Sensitive customers—1 Location—1 None—0			
Q3. Are the infrastructure critical assets monitored and included in preventive plans? (multiple choice)			
Monitored—1.5 Included in risk plans—1.5 Not monitored nor included—0			
Adapted from [7].			
Calculation			
If critical infrastructure assets are not identified (Q1 = 0), then Q2 and Q3 are not assessed, and final score is 0.			
If critical infrastructure assets are totally or partially identified (Q1 = 1 or 0.5), knowledge and protection of critical assets index (KPCAI) is calculated as:			
$KPCAI = \frac{(QS2+QS3)}{2} * QS1 \quad (A1)$			
where QS2 (-) is the score of question Q2, QS3 (-) is the score of question Q3 and QS1 (-) is the score of question Q1. The index varies between 0 and 3.			
Data source: Water utility survey.			
Reference values: Proposed in this study. Considering the index varies between 0 and 3, the minimum KPCAI for fair performance corresponds to a score of 1, and a minimum KPCAI for good performance to a score of 2.			
M1.1.3	Assets criticality index	[-]	Level I
Assesses the assets (pipes, pumps and storage tanks) criticality by evaluating the drop in consumption due to the deactivation or failure of each asset.			
Adapted from [36,37].			
Calculation			
Assets criticality index (ACI) corresponds to the weighted average of the assets hydraulic importance index (HII_a) by the flowrate, defined as follows:			
$ACI = \frac{\sum_{a=1}^A (HII_a \cdot Q_a)}{\sum_{a=1}^A Q_a} \quad (A2)$			
where A is the total number of assets (No.), Q_a is the flowrate relative to asset a (m^3/h), HII_a assesses the consumption that is not supplied due the deactivation or failure of asset a (-), calculated as:			
$HII_a = \frac{1}{N} \sum_{i=1}^N \left(1 - \frac{Q_i}{Q_{0,i}} \right) \quad (A3)$			
where N is the total number of nodes (No.), $Q_{0,i}$ is the required consumption at node i (m^3/h) and Q_i is the effective demand at node i when asset a is deactivated (m^3/h).			
In order to simulate nodal consumption after the failure, pressure driven analysis is preferred to simulate nodal consumption after the deactivation or failure of the assets. If a demand driven analysis is made, it is suggested that nodes with pressure lower than the minimum required are considered with null demand.			
HII_a and ACI varies between 0 and 1. Higher values indicate greater criticality.			

Table A1. Cont.

Data source: System hydraulic model.			
Reference values: Proposed in this study, in Section 3.2. Considering <i>ACI</i> varies between 0 and 1, <i>ACI</i> below 0.1 correspond to good performance, between 0.1 and 0.5 correspond to fair performance, and above 0.5 correspond to poor performance.			
M1.1.3a	Pipes criticality index	[-]	Level II
Assesses the pipes criticality by evaluating the drop in consumption due to the deactivation or failure of each pipe. Adapted from [36,37].			
Calculation Similar to M1.1.3, considering only pipes as assets.			
Data source: System hydraulic model.			
Reference values: Proposed herein to be equal to M1.1.3.			
M1.1.3b	Pumps criticality index	[-]	Level II
Assesses the pumps criticality by evaluating the drop in consumption due to the deactivation or failure of each pump. Adapted from [36,37].			
Calculation Similar to M1.1.3, considering only pumps as assets.			
Data source: System hydraulic model.			
Reference values: Proposed herein to be equal to M1.1.3.			
M1.1.3c	Storage tanks criticality index	[-]	Level II
Assesses the storage tanks criticality by evaluating the drop in consumption due to the deactivation or failure of each tank. Adapted from [36,37].			
Calculation Similar to M1.1.3, considering only storage tanks as assets.			
Data source: System hydraulic model.			
Reference values: Proposed herein to be equal to M1.1.3.			
M1.2.1	Number of failures	[No./(100 km·year)]	Level I
Addresses failures frequency in the system. It is defined as the total number of failures (all assets) per 100 km of network length. Adapted from [33], identified as Op31.			
Calculation Performance indicator number of failures, PI_{NF} , is calculated as:			
$PI_{NF} = \frac{NF_a}{L} \times 100$			(A4)
where NF_a is the total number of failures in all assets (No.) and L is the total length of the network (km).			
Data source: Water utility work orders.			
Reference values: Proposed in this study to be the same as indicator AA10b of [28], herein corresponding to M1.2.1a, as the main contributor are the network pipes.			
M1.2.1a	Pipes failures	[No./(100 km·year)]	Level II
Addresses pipe failures frequency in the system. It is defined as the total number of pipe failures per 100 km of network length. Source: [28], identified as AA10b.			
Calculation Performance indicator pipes failures, PI_{PF} , is calculated as:			
$PI_{PF} = \frac{PF_p}{L} \times 100$			(A5)
where PF_p is the total number of failures in pipes (No.) and L is the total length of the network (km).			
Data source: Water utility work orders.			
Reference values: Retrieved from [28] for indicator AA10b.			
M1.2.1b	Pump failures	[days/pump]	Level II
Addresses pump failures frequency in the system. It is defined as the sum, for all pumps, of the number of days when the pump is out of order by the total number of pumps. Source: [33], identified as Op30.			
Calculation Performance indicator pump failures, PI_{BF} , is calculated as:			
$PI_{BF} = \frac{BF_b}{nb}$			(A6)
where BF_b is the total pump failures duration (days) and nb is the total number of pumps (No.).			
Data source: Water utility work orders.			
Reference values: Retrieved from [7] for indicator PWts08, which corresponds to Op30 from [33]. Reference values were not proposed in [33].			

Table A1. Cont.

M1.2.1c	Service connection failures	[No./(1000 connections·year)]	Level II
Addresses service connection failures frequency in the system. It is defined as the number of service connection failures per 1000 connections. Source: [33], identified as Op32.			
Calculation			
Performance indicator service connection failures PI_{CF} is calculated as:			
$PI_{CF} = \frac{CF_c}{nc} \times 1000$			(A7)
where CF_c is the total number of failures in service connection (No.) and nc is the total number of service connections (No.).			
Data source: Water utility work orders.			
Reference values: Retrieved from [7] for indicator PWts10, which corresponds to Op32 from [33]. Reference values were not proposed in [33].			
M1.2.2	Total duration of failures	[Days/No. failure]	Level I
Addresses failures duration in the system. It is defined as the total inoperative period for all failures (including recovery time) per number of failures. Adapted from [7], identified as PWts16.			
Calculation			
Performance indicator number of failures, PI_{TF} , is calculated as:			
$PI_{TF} = \frac{TF}{nf}$			(A8)
where TF is the sum of inoperative period for all failures (days) and nf is the total number of failures (No.).			
Data source: Water utility work orders.			
Reference values: Proposed in this study to be the same as indicator PWts16 of [7].			
M1.3.1	Pipes rehabilitation	[%/year]	Level I
Addresses the continuous rehabilitation practice. It is defined as the annual average percentage of pipes with age over 10 years rehabilitated in the last 5 years. Source: [28], identified as AA09.			
Calculation			
Pipes rehabilitation, R_p , is calculated as:			
$R_p = \frac{L_{reab}}{L_{age>10}} \times \frac{100}{5}$			(A9)
where L_{reab} is the length of pipes rehabilitated in the last 5 years (km) and $L_{age>10}$ is the length of pipes with age over 10 years (km).			
Data source: Water utility infrastructure data.			
Reference values: Retrieved from [28], for indicator AA09.			
M1.3.2	Infrastructure value index	[-]	Level I
Defined as the ratio between the current value of the infrastructure and its replacement cost. Source: [28], identified as PAA04.			
Calculation			
The infrastructure value index, IVI , is calculated as:			
$IVI = \frac{\sum_{a=1}^N (rc_a \cdot \frac{rsl_a}{esl_a})}{\sum_{a=1}^N rc_a}$			(A10)
in which rc_a is the replacement cost of asset a (€), rsl_a is the residual service life of asset a (years), esl_a is the expected service life of asset a (years) and N is the total number of assets (No.).			
Data source: Water utility infrastructural data.			
Reference values: Adapted from [34], since reference values were not proposed in [28].			
M1.3.2a	Pipes value index	[-]	Level II
Defined as the ratio between the current pipes value and its replacement cost. Adapted from [28], identified as PAA04.			
Calculation			
Similar to M1.3.2.			
Data source: Water utility infrastructural data.			
Reference values: Proposed herein to be equal to M1.3.2.			
M1.3.2b	Pumps value index	[-]	Level II
Defined as the ratio between the current pumps value and its replacement cost. Adapted from [28], identified as PAA04.			
Calculation			
Similar to M1.3.2.			
Data source: Water utility infrastructural data.			
Reference values: Proposed herein to be equal to M1.3.2.			
M1.3.2c	Tanks value index	[-]	Level II
Defined as the ratio between the current storage tanks value and its replacement cost. Adapted from [28], identified as PAA04.			

Table A1. Cont.

Calculation			
Similar to M1.3.2.			
Data source: Water utility infrastructural data.			
Reference values: Proposed herein to be equal to M1.3.2.			
M1.4.1	System supplied energy index	[-]	Level I
Addresses energy efficiency. It is defined as the energy supplied to the system per the minimum energy necessary. Source: [30], identified as dE3.			
Calculation			
System supplied energy index, $E3$, is calculated as:			
$E3 = \frac{E_{inp}}{E_{min}}$			(A11)
where E_{inp} is the energy supplied to the system (kWh) and E_{min} is the minimum energy necessary (kWh).			
Data source: Simplified energy balance.			
Reference values: Retrieved from [30], for indicator dE3.			
M1.4.1a	Energy efficiency in pumping stations	[kWh/(m³·100m)]	Level II
Addresses energy efficiency, particularly regarding pumping inefficiencies. It is defined as the normalised average energy consumption of pumping stations. Source: [28], identified as AA16.			
Calculation			
Energy efficiency in pumping stations, EE_b , is calculated as:			
$EE_b = \frac{EC_b}{UF}$			(A12)
where EC_p is the total energy consumption for pumping and UF is the uniformization factor, calculates as:			
$UF = \frac{\sum_{b=1}^{NB} (Q_b \cdot H_b)}{100}$			(A13)
where NB is the total number of pumping stations (No.), Q_b the water volume of pumping station b (m ³ /h) and H_b the manometric pressure head of pumping station b (m).			
Data source: Pumping data.			
Reference values: Retrieved from [28], for indicator AA16.			
M1.4.1b	Surplus energy index	[-]	Level II
Addresses energy efficiency, particularly regarding surplus energy. It is defined as the surplus energy of the system per the minimum energy necessary. Proposed in this study.			
Calculation			
Surplus energy index, Es , is calculated as:			
$Es = \frac{E_{sur}}{E_{min}} = \frac{\gamma \alpha \sum_{n=1}^{N_d} \sum_{t=1}^{N_t} q_{ac,n}^t (H_{tot,n}^t - z_0) \Delta t - E_{min}}{E_{min}}$			(A14)
where E_{sur} is the surplus energy of the system (kWh), E_{min} is the minimum energy (kWh), γ is the specific weight of water (9800 N/m ³), α is the conversion factor from Ws to kWh, N_n is the total number of demand nodes (No.), N_t is the total number of timesteps (No.), $q_{ac,n}^t$ is the demand associated with authorised consumption in node n (m ³ /s) for time t , $H_{tot,n}^t$ is the hydraulic head in node n (m) at time t , z_0 is the reference elevation (m) and Δt is the timestep (s).			
Data source: Complete energy balance and system hydraulic model.			
Reference values: Proposed in this study, see Section 3.2, as such: if is equal to 0, the supplied energy equals the minimum required energy and there is no additional energy available to be used in case of a demand increase. If surplus energy index equals 1, the supplied energy is the double of the minimum required energy, indicating that the system may be oversized. A threshold of 0.75 of the minimum energy is proposed to alert the approximation of high surplus energy.			
M1.4.1c	Average unit head loss	[m/km]	Level II
Addresses energy efficiency, particularly regarding unit head loss. It is defined as the average head loss weighted with flow and length for the entire pipe network. Source: [38].			
Calculation			
Average unit head loss, HL , is calculated as:			
$HL = \frac{\sum_{p=1}^{NP} (hl_p \cdot Q_p \cdot L_p)}{\sum_{p=1}^{NP} (Q_p \cdot L_p)}$			(A15)
where NP is the total number of pipes (No.), hl_p is the head loss in pipe p (m/km), Q_p is the flowrate relative to pipe p (m ³ /s) and L_p is the length of pipe p (m).			
Data source: System hydraulic model.			
Reference values: Suggested herein based on threshold values from [41], since reference values were not proposed in [38].			

Table A1. Cont.

M1.4.2	Water losses	[L/(connection·day)]	Level I
Addresses water efficiency. It is defined as the total water losses (real and apparent water losses) per service connections. Adapted from [28], identified as AA15.			
Calculation			
Water losses, WL , is calculated as:			
$WL = \frac{wl}{nc} = \frac{rwl + awl}{nc}$			(A16)
where wl is the volume of water losses (l), rwl is the volume of real water losses (l), awl is the volume of apparent water losses (l) and nc is the total number of service connection (No.).			
Data source: Water balance.			
Reference values: Proposed in this study, see Section 3.2. Water losses are a sum of real and apparent water losses. A comparison between the reported real water losses and apparent water losses, demonstrated that water losses are mainly due to real water losses, without a relationship with the number of apparent water losses. As such, water losses reference values are considered similar to the real water losses (see M1.4.2a) added 50 L/[connection.day].			
M1.4.2a	Real water losses	[L/(connection·day)]	Level II
Addresses water efficiency, particularly regarding real water losses. It is defined as the real water losses per service connections. Source: [28], identified as AA15.			
Calculation			
Real water losses, RWL , is calculated as:			
$RWL = \frac{rwl}{nc}$			(A17)
where rwl is the volume of real water losses (l) and nc is the total number of service connection (No.).			
Data source: Water balance.			
Reference values: Retrieved from [28], for indicator AA15.			
M1.4.2b	Apparent water losses	[% volume]	Level II
Addresses water efficiency, particularly regarding apparent water losses. It is defined as the percentage of the water provided to the system that corresponds to apparent losses. Source: [33], identified as Op25.			
Calculation			
Apparent water losses, AWL , is calculated as:			
$AWL = \frac{awl}{wp} \times 100$			(A18)
where awl is the volume of apparent water losses (l) and wp is the water provided to the system (l). Note: in water distribution systems, wp refers to the system input volume minus exported water.			
Data source: Water balance.			
Reference values: Retrieved from [35], since reference values were not proposed in [33].			
M2.1.1	Level of dependency to bulk water utility	[% input volume]	Level I
Assesses the system's level of dependency on the bulk water utility. It is defined as the percentage of the system input volume that is provided by the bulk water utility. Adapted from [7], identified as PWts23.			
Calculation			
Level of dependency on the bulk water utility, $Dbulk$, is calculated as:			
$Dbulk = \frac{V_{bulk}}{V_{inp}} \times 100$			(A19)
where V_{bulk} is the volume is provided by the bulk water utility (m^3) and V_{inp} is the system input volume (m^3).			
Data source: Water utility volumes data.			
Reference values: Retrieved from [7], for indicator PWts23.			
M2.1.2	Level of dependency on pumping	[% input volume]	Level I
Assesses the system's level of dependency on pumping. It is defined as the percentage of the system input volume that is pumped. Adapted from [7], identified as PWts23.			
Calculation			
Level of dependency on pumping, $Dpump$, is calculated as:			
$Dpump = \frac{V_{pump}}{V_{inp}} \times 100$			(A20)
where V_{inp} is the system input volume (m^3) and V_{pump} is the volume that is (once) pumped (m^3), that is, water that is pumped twice or more times must only be accounted once.			
Data source: Water utility volumes data.			
Reference values: Retrieved from, for indicator PWts23.			

Table A1. Cont.

M2.2.1	Treated water storage capacity	[days]	Level I
Assesses the treated water supply autonomy through storage tanks. It is defined as the total capacity of treated water storage over the system input volume. Source: [33], identified as Ph3.			
Calculation The treated water storage capacity, ST , is calculated as:			
$ST = \frac{\sum_{r=1}^{NR} V_r}{V_{inp}} \times 365$			(A21)
where V_r is the volume of reservoir r (m^3), V_{inp} is the system input volume (m^3 /year) and NR is the number of reservoirs (No.).			
Data source: Infrastructure and volumes data.			
Reference values: Retrieved from [7], for indicator PWts23, which corresponds to Ph3 from [33]. Reference values were not proposed in [33].			
M2.2.2	Level of autonomy to electric grid from alternative infrastructures	[% dependent volume]	Level I
Assesses the system capacity to keep providing water in case of an electric grid failure, through alternative infrastructures. treated water supply autonomy through storage tanks. It is defined as the percentage of pumping dependent volume, that benefit from alternative infrastructures (e.g., bypass to pumping station). Adapted from [7], identified as PWts25.			
Calculation Level of autonomy to electric grid from alternative infrastructures, Aut , is calculated as:			
$Aut = \frac{V_{alt}}{V_{pump}} \times 100$			(A22)
where V_{alt} is the pumping dependent volume that benefit from alternative infrastructures (m^3) and V_{pump} is the pumped volume (m^3).			
Data source: Water utility volumes data.			
Reference values: Retrieved from [7], for indicator PWts25.			
M2.2.3	Energy self-production	[% pumped energy]	Level I
Assesses the water utility energy self-production. It is defined as the percentage of the consumed energy that came from self-production. Source: [28], identified as AA18.			
Calculation The energy self-production index, ESP , is calculated as:			
$ESP = \frac{E_{self}}{E_{cons}} \times 100$			(A23)
where E_{self} is the energy from self-production (kWh) and E_{cons} is the total consumed energy (kWh).			
Data source: Energy data.			
Reference values: Retrieved from [28], for indicator AA18.			
M2.2.3a	Wind energy self-production	[% pumped energy]	Level II
Assesses the water utility wind energy self-production. It is defined as the percentage of the consumed energy that came from wind self-production. Adapted from [28], identified as AA18.			
Calculation Similar to M2.2.3.			
Data source: Energy data.			
Reference values: Proposed herein to be equal to M2.2.3.			
M2.2.3b	Solar energy self-production	[% pumped energy]	Level II
Assesses the water utility solar energy self-production. It is defined as the percentage of the consumed energy that came from solar self-production. Adapted from [28], identified as AA18.			
Calculation Similar to M2.2.3.			
Data source: Energy data.			
Reference values: Proposed herein to be equal to M2.2.3.			
M2.2.3c	Hydropower energy self-production	[% pumped energy]	Level II
Assesses the water utility hydropower energy self-production. It is defined as the percentage of the consumed energy that came from Hydropower self-production. Adapted from [28], identified as AA18.			
Calculation Similar to M2.2.3.			
Data source: Energy data.			
Reference values: Proposed herein to be equal to M2.2.3.			

Table A1. Cont.

M2.3.1	Potential alternative water sources	[% volume]	Level I
Assesses the potential alternative water sources from the water utility, active and inactive. It is defined as the percentage of yield capacity of alternative sources per system input volume. Adapted from [33], identified as WR3.			
Calculation The potential alternative water sources index, <i>PAWS</i> , is calculated as:			
$PAWS = \frac{Valt}{Vinp} \times 100$			(A24)
where <i>Valt</i> is the yield capacity of alternative sources (m ³) and <i>Vinp</i> is the system input volume (m ³).			
Data source: Water utility data.			
Reference values: Suggested herein, considering that a yield capacity of alternative sources lower than 50% of the total input volume has poor performance, between 50% and 75% it has fair performance, and above 75% has good performance.			
M2.3.2	Pumping redundancy	[% time]	Level I
Assesses the redundancy of pumping stations. It is defined as the percentage of time pumping groups are not working simultaneously (including the reserve pump) by the total pumping station functioning time. Proposed in this study.			
Calculation The redundancy of pumping stations, <i>PR</i> , is calculated as:			
$PR = \left(1 - \frac{Tsim}{Tfunct}\right) \times 100$			(A25)
where <i>Tsim</i> is the time pumping groups are working simultaneously (h) and <i>Tfunct</i> is the total pumping station functioning time (h).			
Data source: Water utility.			
Reference values: Suggested herein, considering that the time pumping groups have, at least, one pump not working lower than 50% of the total pumping station functioning time has poor performance, between 50% and 75% it has fair performance, and above 75% has good performance.			
M2.3.3	Pipes topological redundancy	[-]	Level I
Assessed by the meshedness coefficient, defined as fraction between the total and the maximum number of independent loops in planar graphs. Source: [18].			
Calculation The meshedness coefficient, <i>MC</i> , is calculated as:			
$MC = \frac{m-n+1}{2n-5}$			(A26)
where <i>m</i> is the number of edges, <i>n</i> is the number of nodes of the mathematical graph.			
Data source: System hydraulic model.			
Reference values: Suggested herein, where <i>MC</i> bellow 0.01 corresponds to poor performance, <i>MC</i> between 0.01 and 0.1 corresponds to fair performance and values higher than 0.1 corresponds to good performance.			
M3.1.1	Number of failures in the last disaster	[No./100 km]	Level I
Addresses failures in the last disaster. It is defined as the total number of failures (all assets) in the last disaster per 100 km of network length. Adapted from [7], identified as PWts42.			
Calculation Equal to Equation (A4), with <i>NFa</i> being the total number of failures in the last disaster (No.).			
Data source: Water utility data.			
Reference values: Proposed in this study to be the same as indicator PWts42 of [7], herein corresponding to M3.1.1a, as the main contributor are the network pipes.			
M3.1.1a	Pipes failures in the last disaster	[No./((100 km·year))]	Level II
Addresses pipe failures frequency in the last disaster. It is defined as the total number of pipe failures in the last disaster per 100 km of network length. Source: [7], identified as PWts42.			
Calculation Equal to Equation (A5), with <i>PF_p</i> being the total number of pipe failures in the last disaster (No.).			
Data source: Water utility data.			
Reference values: Retrieved from [7], for indicator PWts42.			
M3.1.1b	Pump failures in the last disaster	[days/(pump)]	Level II
Addresses pump failures frequency in the system. It is defined as the number of days that pumps are out of order, due to the last disaster, by the total number of pumps. Source: [7], identified as PWts41.			
Calculation Equal to Equation (A6), with <i>BF_b</i> being the total pump failures duration in the last disaster (days).			
Data source: Water utility data.			
Reference values: Retrieved from [7], for indicator PWts41.			

Table A1. Cont.

M3.1.1c	Service connection failures in the last disaster	[No./(1000 connections)]	Level II
Addresses service connection failures frequency in the last disaster. It is defined as the number of service connection failures in the last disaster per 1000 connections. Source: [7], identified as PWts43.			
Calculation Equal to Equation (A7), with CF_c being the number of service connection failures in the last disaster (No.).			
Data source: Water utility data.			
Reference values: Retrieved from [7], for indicator PWts43.			
M3.1.2	Duration of failure till restoration in the last disaster	[Days]	Level I
Addresses failures duration in the last disaster. It is defined as the maximum out-of-service period for all failures (including recovery time) in the last disaster. Source: [7], identified as PWts49.			
Calculation Duration of failure (days) till restoration in the last disaster is calculated as the maximum out-of-service period for all failures (including recovery time) in the last disaster.			
Data source: Water utility data.			
Reference values: Retrieved from [7], for indicator PWts49.			
M4.1.1	Number of service interruptions	[No./(1000 connections·year)]	Level I
Addresses frequency of service interruptions. It is defined as the number of service interruptions pondered by 1000 connection. Source: [32], identified as AA03b.			
Calculation Performance indicator number of service interruptions PI_{SI} is calculated as: $PI_{SI} = \frac{SI_c}{nc} \times 1000 \quad (A27)$ where SI_c is the total number of failures in service connection (No.) and nc is the total number of service connections (No.).			
Data source: Water utility data.			
Reference values: Retrieved from [32], identified as AA03b.			
M4.1.1a	Number of interruptions due to pipe and equipment failures	[No./(1000 connections·year)]	Level II
Addresses frequency of service interruptions due to pipe and equipment (pumps, valves, hydrants) failures. It is defined as the number of service interruptions due to pipe and equipment failures pondered by 1000 connection. Adapted from [32], identified as AA03b.			
Calculation Similar to M4.1.1, considering only service interruptions due to pipe and equipment failures.			
Data source: Water utility data.			
Reference values: Proposed herein to be equal to M4.1.1.			
M4.1.1b	Number of interruptions due to rehabilitation or new constructions	[No./(1000 connections·year)]	Level II
Addresses frequency of service interruptions due to rehabilitation or new constructions. It is defined as the number of service interruptions due to rehabilitation or new constructions pondered by 1000 connection. Adapted from [32], identified as AA03b.			
Calculation Similar to M4.1.1, considering only service interruptions due to rehabilitation or new constructions.			
Data source: Water utility data.			
Reference values: Proposed herein to be equal to M4.1.1.			
M4.1.1c	Number of interruptions due to water quality inadequacy	[No./(1000 connections·year)]	Level II
Addresses frequency of service interruptions due to water quality inadequacy. It is defined as the number of service interruptions due to water quality inadequacy pondered by 1000 connection. Adapted from [32], identified as AA03b.			
Calculation Similar to M4.1.1, considering only service interruptions due water quality inadequacy.			
Data source: Water utility data.			
Reference values: Proposed herein to be equal to M4.1.1.			

Table A1. Cont.

M4.1.1d	Number of interruptions due to external issues	[No./(1000 connections·year)]	Level II	
Addresses frequency of service interruptions due to external issues. It is defined as the number of service interruptions due to external issues pondered by 1000 connection. Adapted from [32], identified as AA03b.				
Calculation Similar to M4.1.1, considering only service interruptions due external issues.				
Data source: Water utility data.				
Reference values: Proposed herein to be equal to M4.1.1.				
M4.1.2	Average duration of service interruptions	[h]	Level I	
Addresses duration of service interruptions. It is defined as the average duration of all service interruptions. Suggested herein.				
Calculation Performance indicator number of service interruptions PI_{SI} is calculated as:				
$PI_{SI} = \frac{\sum_{i=1}^{ni} d_i}{ni} \times 1000$			(A28)	
where d_i is the duration (h) of interruption i and ni is the total number of service interruptions (No.).				
Data source: Water utility data.				
Reference values: Suggested herein, based on the technical guides from the Portuguese regulatory entity for the water sector. It is considered that an average duration below 4 h correspond to good performance, between 4 and 6 h it corresponds to air performance, and service interruptions above 6 h is has poor performance.				
M4.2.1	Quality of supplied water	[% tests]	Level I	
Addresses water quality delivered to the consumers. It is defined as the percentage of total number of treated water tests complying with the applicable standards or legislation per total number of tests of treated water carried out. Source: [33], identified as QS18				
Calculation Performance indicator quality of supplied water, PI_Q , is calculated as:				
$PI_Q = \frac{test_{comp}}{test_{tot}} \times 100$			(A29)	
where $test_{comp}$ is the of total number of treated water tests complying with the applicable standards or legislation (No.) and $test_{tot}$ is the total number of tests of treated water carried out (No.).				
Data source: Water quality data.				
Reference values: Suggested herein, considering that over 90% of complying tests corresponds to good performance, between 70% and 90% corresponds to fair performance and below 70% the system has poor performance.				
M4.2.1a	Minimum velocity performance index	[-]	Level II	
Addresses the performance of minimum velocity in the network pipes. Source: [39,40].				
Calculation Relates pipes velocity (m/s) with a performance function for each pipe. Herein, the performance function is as follows:				
Excellent [3]	Good [2–3]	Fair [1–2]	Poor [0–1]	Null [0]
$\geq 0.5 v_{max}$	$\geq \frac{v_{min} + 0.5 \cdot v_{max}}{2}$ and $< 0.5 v_{max}$	$\geq v_{min}$ and $< \frac{v_{min} + 0.5 \cdot v_{max}}{2}$	≥ 0 and $< v_{min}$	0
where v_{max} (m/s) = $0.1274 \cdot D^{0.4}$, with D the pipe’s diameter (mm), and v_{min} = 0.3m/s. The network minimum velocity performance ($Pvmin$) is obtained through the weighted average by the pipes flowrate.				
$Pvmin = \frac{\sum_{p=1}^{NP} (Pvmin_p \cdot Q_p)}{\sum_{p=1}^{NP} (Q_p)}$				(A30)
where NP is the total number of pipes (No.), $Pvmin_p$ is the minimum velocity performance of pipe p (-) and Q_p is the flowrate relative to pipe p (m³/s).				
Data source: System hydraulic model.				
Reference values: Considering the performance index varies between 0 and 3, the reference values correspond to the same intervals.				

Table A1. Cont.

M4.2.1b	Water age performance index			[-]	Level II
Addresses the performance of water age at the network nodes. Source: [39,40].					
Calculation Relates water age (h) with a performance function for each node. Herein, the performance function is as follows:					
Excellent [3]	Good [2–3]	Fair [1–2]	Poor [0–1]	Null [0]	
0	>0 and ≤ T ₁	>T ₁ and ≤ T _{max}	>T _{max} and ≤ 1.5 T _{max}	>1.5 T _{max}	
where T ₁ = 24 h, and T _{max} = 48 h. The network water age performance (Pwa) is obtained through the weighted average by the node demand.					
$Pwa = \frac{\sum_{n=1}^{N_n} (Pwa_n \cdot q_n)}{\sum_{n=1}^{N_n} (q_n)}$				(A31)	
where N _n is the total number of demand nodes (No.), Pwa _n is the minimum velocity performance of node n (-) and q _n is the demand in node n (m ³ /s).					
Data source: System hydraulic model.					
Reference values: Considering the performance index varies between 0 and 3, the reference values correspond to the same intervals.					
M4.2.1c	Network travel time index			[-]	Level II
Addresses the performance of network travel time at the network nodes. Adapted from [39,40].					
Calculation Relates network travel time (h) with a performance function for each node. Herein, the performance function is as follows:					
Excellent [3]	Good [2–3]	Fair [1–2]	Poor [0–1]	Null [0]	
≤ T ₁	>T ₁ and ≤ $\frac{T_1+T_{max}}{2}$	> $\frac{T_1+T_{max}}{2}$ and ≤ T _{max}	>T _{max} and ≤ 1.5 T _{max}	≥ 1.5 T _{max}	
where T ₁ = 10 h, and T _{max} = 20 h. The network travel time performance is obtained through the weighted average by the node demand, similar to Equation (A31).					
Data source: System hydraulic model.					
Reference values: Considering the performance index varies between 0 and 3, the reference values correspond to the same intervals.					
M4.3.1	Service complaints due to lack of pressure			[No. complaints/(1000 connections)]	Level I
Addresses lack of pressure in the system through service complaints. It is defined as the number of service complaints due to lack of pressure per 1000 connections. Adapted from [33], identified as AA05.					
Calculation Performance indicator quality of service complaints due to lack of pressure, PI _{comp} , is calculated as:					
$PI_{comp} = \frac{SC_{pressure}}{nc} \times 1000$				(A32)	
where SC _{pressure} is the number of service complaints due to lack of pressure and nc is the total number of service connections.					
Data source: Water utility					
Reference values: Suggested herein based on the results of Portuguese water utilities, considering that bellow 0.15 corresponds to good performance, between 0.15 and 1.5 corresponds to fair performance and over 1.5 corresponds to poor performance.					
M4.3.1a	Minimum pressure performance index			[-]	Level II
Addresses the performance of minimum pressure at the network nodes. Source: [39,40].					
Calculation Relates pressure (m) with a performance function for each node. Herein, the performance function is as follows:					
Excellent [3]	Good [2–3]	Fair [1–2]	Poor [0–1]	Null [0]	
≥ ½ p _{max}	≥ $\frac{p_{min}+\frac{1}{2}p_{max}}{2}$ ≥ p _{min} and and < ½ p _{max}	< $\frac{p_{min}+\frac{1}{2}p_{max}}{2}$	≥ 10 and < p _{min}	10 m	
where p _{max} = 60 m, corresponding to maximum regulatory pressure, and p _{min} = 20 m, corresponding to the minimum required pressure established by the water utility. The network minimum pressure performance is obtained through the weighted average by the node demand, similar to Equation (A31).					
Data source: System hydraulic model.					
Reference values: Considering the performance index varies between 0 and 3, the reference values correspond to the same intervals.					

Table A1. Cont.

M4.3.1b	Maximum pressure performance index			[-]	Level II
Addresses the performance of maximum pressure at the network nodes. Source: [39,40].					
Calculation Relates pressure (m) with a performance function for each node. Herein, the performance function is as follows:					
Excellent [3]	Good [2–3]	Fair [1–2]	Poor [0–1]	Null [0]	
$\leq \frac{2}{3} p_{\max}$	$> \frac{2}{3} p_{\max}$ and $\leq \frac{\frac{2}{3} p_{\max} + p_{\max}}{2}$	$> \frac{\frac{2}{3} p_{\max} + p_{\max}}{2}$ and $\leq p_{\max}$	$> p_{\max}$ and $\leq 1.5 p_{\max}$	$\geq 1.5 p_{\max}$	
where $p_{\max} = 60$ m, corresponding to maximum regulatory pressure. The network maximum pressure performance is obtained through the weighted average by the node demand, similar to Equation (A31).					
Data source: System hydraulic model.					
Reference values: Considering the performance index varies between 0 and 3, the reference values correspond to the same intervals.					
M4.3.1c	Pressure fluctuation performance index			[-]	Level II
Addresses the performance of pressure fluctuation at the network nodes. Source: [39,40].					
Calculation Relates pressure fluctuation (m) with a performance function for each node. Herein, the performance function is as follows:					
Excellent [3]	Good [2–3]	Fair [1–2]	Poor [0–1]	Null [0]	
0 m	>0 and $\leq \frac{\Delta H_{\max}}{2}$	$> \frac{\Delta H_{\max}}{2}$ and $\leq \Delta H_{\max}$	$> \Delta H_{\max}$ and $\leq 1.5 \Delta H_{\max}$	$> 1.5 \Delta H_{\max}$	
where $\Delta H_{\max} = 30$ m. The network pressure fluctuation performance is obtained through the weighted average by the node demand, similar to Equation (A31).					
Data source: System hydraulic model.					
Reference values: Considering the performance index varies between 0 and 3, the reference values correspond to the same intervals.					
M5.1.1	Drinking water supplied for non-potable uses			[% drinking water]	Level I
Addresses non-potable uses. It is defined as the percentage of drinking water used for non-potable uses per total input volume. Source: [7], identified as FWts35.					
Calculation The drinking water supplied for non-potable uses index, PI_{Inpu} , is calculated as:					
$PI_{Inpu} = \frac{V_{npu}}{V_{inp}} \times 100$					(A33)
where V_{npu} is the drinking water supplied for non-potable uses (m ³) and V_{inp} is the system input volume (m ³).					
Data source: Water utility volumes data.					
Reference values: Retrieved from [7], identified as FWts35.					
M5.1.2	Recycled water supplied for non-potable uses			[% total volume]	Level I
Addresses recycled water. It is defined as the percentage of recycled water supplied for non-potable uses per total input volume. Adapted from [33], identified as WR4.					
Calculation The recycled water supplied for non-potable uses index, PI_{Irec} , is calculated as:					
$PI_{Irec} = \frac{V_{rec}}{V_{inp} + V_{rec}} \times 100$					(A34)
where V_{rec} is the recycled water supplied (m ³) and V_{inp} is the potable system input volume (m ³).					
Data source: Water utility volumes data.					
Reference values: Suggested herein, considering that below 10% of recycled water corresponds to poor performance, between 10% and 25% corresponds to fair performance and above 25% the system has good performance.					
M5.2.1	Network resilience index			[-]	Level I
Addresses the hydraulic capacity to overcome eventual increasing demands. It is defined as the ratio of surplus energy per energy in excess, providing the energy available at the consumption nodes above the minimum required to supply the consumers, incorporating a uniformity coefficient rewarding the uniformity of the pipes’ diameter. Source: [11].					

Table A1. Cont.

Calculation

The network resilience index, *NRI*, is calculated as:

$$U_i = \frac{\sum_{l=1}^{np_i} D_l}{np_i \times \max\{D_1, \dots, D_l\}} \quad (A35)$$

$$NRI = \frac{\sum_{i=1}^N U_i Q_i (H_i - H_i^{\text{req}})}{\sum_{r=1}^{Nr} Q_r H_r + \sum_{b=1}^{Nb} \frac{P_b}{\gamma} - \sum_{i=1}^N Q_i H_i^{\text{req}}} \quad (A36)$$

where γ is the specific weight of water (9800 N/m³), *N* is the total number of demand nodes (No.), *Nr* is the total number of reservoirs, *Nb* is the total number of pumps (No.), *Q_i* is the demand in node *i* (m³/s), *Q_r* is the flow input from reservoir *r* (m³/s), *P_b* is the power of pump *b* (kW), *H_i* is the head in node *i* (m), *H_i^{req}* is the required head in node *i* (m), *U_i* is the uniformity coefficient of node *i* for the network resilience index (-), *np_i* is the number of pipes entering into node *i* (No.), *D_l* is the diameter (mm) of pipe *l* that is connected to node *i*.

Data source: System hydraulic model.

Reference values: Suggested herein, considering that *NRI* below 0.5 correspond to poor performance, between 0.5 and 0.75 corresponds to fair performance and above 0.75 correspond to good performance.

M6.1.1	Water supply interruptions for consumers in the last disaster	[% connections]	Level I
Addresses water supply interruptions in the last disaster. It is defined as the percentage of connections affected by water supply interruptions in the last disaster.			
Adapted from [7], identified as FWts58.			

Calculation

Performance indicator number of service interruptions, *PI_{SI_dis}*, is calculated as:

$$PI_{SI_dis} = \frac{nc_{int}}{nc} \times 100 \quad (A37)$$

where *nc_{int}* is the number of connections (No.) affected by water supply interruptions in the last disaster and *nc* is the total number of service connections (No.).

Data source: Water utility data.

Reference values: Retrieved from [7], identified as FWts58.

M6.1.2	Total duration of water supply interruption in the last disaster	[days]	Level I
Addresses water supply interruptions in the last disaster. It is defined as the days of water supply interruptions in the last disaster.			
Adapted from [7], identified as FWts66.			

Calculation

Number of days that supply was interrupted in the last disaster.

Data source: Water utility data.

Reference values: Retrieved from [7], identified as FWts66.

Appendix B

Table A2. Resilience assessment framework results for system and network areas R4 and R6.

C1.1 Infrastructure Knowledge		System	R4	R6
M1.1.1	Infrastructural knowledge index [-]	196 ●	196 ●	196 ●
M1.1.2	Knowledge and protection of critical assets index [-]	0.0 ●	0.0 ●	0.0 ●
M1.1.3	Assets criticality index [-]	0.53 ●	0.99 ●	0.97 ●
M1.1.3a	Pipes criticality index [-]	0.14 ●	0.13 ●	0.31 ●
M1.1.3b	Pumps criticality index [-]	0.35 ●	0.09 ●	0.71 ●
M1.1.3c	Storage tanks criticality index [-]	0.53 ●	0.99 ●	0.97 ●
C1.2 Infrastructure integrity		System	R4	R6
M1.2.1	Number of failures [No./(100 km·year)]	13.6 ●	6.0 ●	23.9 ●
M1.2.1a	Pipes failures [No./(100 km·year)]	12.8 ●	6.0 ●	21.9 ●
M1.2.1b	Pump failures [days/(pump·year)]	6.1 ●	0.0 ●	9.3 ●
M1.2.1c	Service connection failures [No./(1000 connections·year)]	NA	NA	NA
M1.2.2	Total duration of failures [Days/No. failure]	8.8 ●	0.0 ●	11.7 ●
C1.3 Infrastructure sustainability		System	R4	R6
M1.3.1	Pipes rehabilitation [%/year]	0.2 ●	0.2 ●	0.2 ●
M1.3.2	Infrastructure value index [-]	0.4 ●	0.4 ●	0.2 ●
M1.3.2a	Pipes infrastructure value index [-]	0.18 ●	0.26 ●	0.05 ●
M1.3.2b	Pumps infrastructure value index [-]	0.16 ●	0.49 ●	0.00 ●
M1.3.2c	Storage tanks infrastructure value index [-]	0.43 ●	0.43 ●	0.36 ●

Table A2. Cont.

C1.4 Water and energy efficiency		System	R4	R6
M1.4.1	System supplied energy index [-]	2.24 ●	2.32 ●	2.15 ●
M1.4.1a	Energy efficiency in pumping stations [kWh/(m ³ · 100 m)]	0.57 ●	0.51 ●	0.58 ●
M1.4.1b	Surplus energy index [-]	0.73 ●	1.00 ●	0.43 ●
M1.4.1c	Average unit head loss [m/km]	2.98 ●	2.97 ●	2.99 ●
M1.4.2	Water losses [L/(connection·day)]	157 ●	147 ●	166 ●
M1.4.2a	Real water losses [L/(connection·day)]	120 ●	98 ●	140 ●
M1.4.2b	Apparent water losses [%volume]	2% ●	2% ●	1% ●
C2.1 Dependency on other services		System	R4	R6
M2.1.1	Level of dependency on bulk water utility [%volume]	100% ●	100% ●	100% ●
M2.1.2	Level of dependency on pumping [% input volume]	60% ●	16% ●	100% ●
C2.2 Autonomy		System	R4	R6
M2.2.1	Treated water storage capacity [Days]	1.1 ●	0.2 ●	1.9 ●
M2.2.2	Level of autonomy to electric grid from alternative infrastructures [% dependent volume]	0% ●	0% ●	0% ●
M2.2.3	Energy self-production [% pumped energy]	0% ●	0% ●	0% ●
M2.2.3a	Wind energy self-production [% pumped energy]	0% ●	0% ●	0% ●
M2.2.3b	Solar energy self-production [% pumped energy]	0% ●	0% ●	0% ●
M2.2.3c	Hydropower energy self-production [% pumped energy]	0% ●	0% ●	0% ●
C2.3 Redundancy		System	R4	R6
M2.3.1	Potential alternative sources [%volume]	3% ●	5% ●	0% ●
M2.3.2	Pumping redundancy [%time]	88% ●	75% ●	100% ●
M2.3.3	Pipes topological redundancy [-]	0.02 ●	0.03 ●	0.02 ●
C3.1 Assessment of failures in the last disaster		System	R4	R6
M3.1.1	Number of failures in the last disaster [No./100 km]	NA	NA	NA
M3.1.1a	Pipes failures in the last disaster [No./(100 km)]	NA	NA	NA
M3.1.1b	Pump failures in the last disaster [days/(pump)]	NA	NA	NA
M3.1.1c	Service connection failures in the last disaster [No./(1000 connections)]	NA	NA	NA
M3.1.2c	Duration of failure till restoration in the last disaster [Days]	NA	NA	NA
C4.1 Water supply interruptions		System	R4	R6
M4.1.1	Number of service interruptions [No./(1000 connections·year)]	2.5 ●	2.5 ●	2.5 ●
M4.1.1a	Number of interruptions due to pipe and equipment failures [No./(1000 connections·year)]	NA	NA	NA
M4.1.1b	Number of interruptions due to rehabilitation or new constructions [No./(1000 connections·year)]	NA	NA	NA
M4.1.1c	Number of interruptions due to water quality inadequacy [No./(1000 connections·year)]	NA	NA	NA
M4.1.1d	Number of interruptions due to external issues [No./(1000 connections· year)]	NA	NA	NA
M4.1.2	Average duration of service interruptions [h]	5.7 ●	5.7 ●	5.7 ●
C4.2 Adequacy of delivered water quality		System	R4	R6
M4.2.1	Quality of supplied water [%tests]	100 ●	100 ●	100 ●
M4.2.1a	Minimum velocity performance in network links [-]	0.75 ●	0.62 ●	0.94 ●
M4.2.1b	Water age performance [-]	2.85 ●	2.79 ●	2.91 ●
M4.2.1c	Network travel time performance [-]	2.75 ●	2.50 ●	3.00 ●
C4.3 Adequacy of pressure requirements		System	R4	R6
M4.3.1	Service complaints due to lack of pressure [No. complaints/(1000 connections·year)]	0.0 ●	0.0 ●	0.0 ●
M4.3.1a	Minimum pressure performance index [-]	2.11 ●	2.34 ●	1.83 ●
M4.3.1b	Maximum pressure performance index [-]	2.55 ●	2.23 ●	2.86 ●
M4.3.1c	Pressure fluctuation performance index [-]	2.74 ●	2.74 ●	2.76 ●

Table A2. Cont.

C5.1 Assessment of non-potable uses		System	R4	R6
M5.1.1	Drinking water supplied for non-potable uses [% drinking volume]	58% ●	58% ●	58% ●
M5.1.2	Recycled water for non-potable uses [% total volume]	0% ●	0% ●	0% ●
C5.2 Hydraulic flexibility		System	R4	R6
M5.2.1	Network resilience index [-]	1.91 ●	1.70 ●	2.31 ●
C6.1 Assessment of service interruptions in the last disaster		System	R4	R6
M6.1.1	Water supply interruptions for consumers in the last disaster [% connections]	NA	NA	NA
M6.1.2	Total duration of water supply interruption in the last disaster [days]	NA	NA	NA

Notes: Level I metrics are shadowed. ● good performance; ● fair performance; ● poor performance.

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