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Integrating Uncertainty in Performance Assessment of Water Distribution Networks by Scenario Building

Joana Carneiro [1], Dália Loureiro [2,*], Marta Cabral [1] and Dídia Covas [1]

[1] Civil Engineering Research and Innovation for Sustainability (CERIS), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal; joana.carneiro@tecnico.ulisboa.pt (J.C.); marta.f.cabral@tecnico.ulisboa.pt (M.C.); didia.covas@tecnico.ulisboa.pt (D.C.)

[2] Urban Water Unit, National Civil Engineering Laboratory, Hydraulics and Environmental Department, Av. Brasil 101, 1700-066 Lisbon, Portugal

* Correspondence: dloureiro@lnec.pt

Abstract: This paper presents and demonstrates a novel scenario-building methodology that integrates contextual and future time uncertainty into the performance assessment of water distribution networks (WDNs). A three-step approach is proposed: (i) System context analysis, identifying the main key factors that impact the WDN performance; (ii) Scenario definition, identifying the implicated WDN variables, describing its possible evolution, and conjugating them to further establish the reference scenario and the two most relevant and opposite ones; and (iii) Scenario modelling, simulating the WDN behaviour for those scenarios. The obtained spatial and temporal hydraulic results are further used to calculate performance metrics. The methodology is applied to a real WDN to assess resilience performance considering infrastructure asset robustness (real water loss performance indicator), service reliability (minimum pressure index), and service flexibility (network resilience index). A new formulation to assess the metric evolution over time is proposed, deducting the further-away performance results by using an uncertainty weight. The results demonstrate that the increase in metric amplitude for the opposite scenarios over time highlights future uncertainty, reflecting context uncertainty, and the comparison of metric spatial distribution (i.e., at the pipe/node levels) highlights critical areas with higher associated uncertainty.

Keywords: drinking water networks; aleatory uncertainty; scenario planning; scenario modelling; resilience metrics

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1. Introduction

Currently, water distribution networks (WDNs) face social, economic, political, and environmental changes that significantly increase uncertainty over the system's future performance. Events of different natures can occur: (i) challenges, which are contextual or environmental changes with the potential to impact the ability and capacity of the system (e.g., climate change, demand increase, and water scarcity); (ii) shocks, which correspond to uncertain and abrupt events (e.g., floods, earthquakes, and terrorist attacks); and (iii) stresses, which are chronic and continuous dynamic pressures on the system (e.g., infrastructure degradation) [1]. These events can cause negative impacts on WDNs, such as service interruptions, decreases in water availability, changes in water demand, decreases in water quality, pipe bursts, and component malfunctions.

Water utilities must efficiently manage and promptly plan interventions in their systems to cope with future challenges. Various approaches have been developed for managing urban water system infrastructures [2,3], energy efficiency [4], and water losses [5]. A WDN planning approach is usually composed of the following stages: (i) definition of objectives, assessment criteria, metrics, and targets; (ii) diagnosis and prognosis; (iii) plan production; (iv) plan implementation, and (v) monitoring and review [2]. The diagnosis and prognostic phases aim to assess the system performance. The diagnosis focuses on assessing the system performance in the present time, whilst the prognosis assesses over a planning horizon, using the established metrics for different scenarios [2]. For the prognosis phase, the future must be considered, along with the respective uncertainty.

Uncertainty is divided into two categories: epistemic uncertainty, related to the imperfection of our knowledge (i.e., limited and inaccurate data and measurement error) and aleatory or variability, uncertainty, related to the inherent variability in social, economic, and technological developments associated with WDN models by external input data, input functions, and parameters (i.e., spatial and temporal variability in water demand) [6,7]. While for epistemic uncertainty additional research may improve the quality of our knowledge, for aleatory uncertainty, additional research may not be sufficient to improve the output, and other methods are regarded, such as probability distributions [8], fuzzy approaches [9], and scenario techniques [10].

In the present paper, aleatory uncertainty of future events in the planning and management of WDNs is considered by creating different scenarios and assessing the system behaviour for each scenario [11], through a performance assessment.

Three scenario categories were identified [12]: (i) predictive scenarios, by developing future projections of one or more variables, usually based on historical data; (ii) explorative scenarios, by developing future situations that are plausible to happen, regarding different perspectives; and (iii) normative scenarios, by setting an idealised future and focusing on the path to reach that goal. Predictive and normative scenarios are not conceived and set up to analyse and address uncertainty, while exploratory scenarios represent a different approach in pairing critical uncertainties and creating a range of plausible futures [13].

In urban water systems, the analysis of predictive scenarios, using probabilistic and statistical analysis, is the traditional method to assess the future. Scenarios have mainly been used as the variation in urban demand, water availability, or water quality to obtain the optimised design, rehabilitation alternatives, or appropriate management interventions and policies [14–16]. Nonetheless, most scenarios lack the consideration of external factors and the analysis of different system contexts. For example, [14] considers the uncertainty in water demand by using a random variable of a given probability mass function to express the demand growth, though not taking into consideration the system's context. Explorative scenarios have been gaining relevance in urban management [13], as these allow to incorporate context information. These scenarios are appropriate for identifying multiple plausible futures, as they offer richer descriptions of future systems [17] and identify critical future uncertainties [7] by performing a context analysis and assessing how different aspects (i.e., political, economic, socio-cultural, technological, environmental, and internal management) can affect the system in the future [17].

Although different approaches can be used for scenario building, a standard scenario process starts with a context analysis to identify the forces and factors bound to happen, followed by the identification and ranking of key local factors and driving forces. In these phases, the PESTLE framework or a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis are some of the most-used tools to identify and rank contextual influences [13], with stakeholders or community inputs, through workshops or surveys [13,18]. Further on, the synthesis of combinations of key local factors and driving forces is implemented to develop scenarios and, finally, to elaborate on the scenarios' narratives [13]. As different scenarios are all plausible, they do not have an associated probability [17] and the future uncertainty is described as the range of the considered plausible evolutions [7]. The scenario narratives are, then, used as the base of a strategic plan.

To the authors' knowledge, no scenario-building methodology has yet been developed and detailed to assess the performance of WDNs by using hydraulic models. The main objective of the current paper is to develop and demonstrate a scenario-building methodology, based on explorative scenarios, to assist water utilities and engineers in the management of urban water infrastructures, incorporating uncertainty into the management and planning of drinking water systems. The main novel contribution of this paper is the integration of contextual and future time uncertainty in the performance assessment of WDNs by a detailed scenario-building methodology that can be applied to different assessment frameworks.

The paper is organised into five sections, including the current one. Section 2 describes the scenario-building methodology. Section 3 presents the case study to which the methodology is applied, and Section 4 discusses the scenario-building methodology's results in the case study. Lastly, Section 5 presents the main conclusions of this research and highlights foreseen future works.

2. Scenario-Building Methodology and Application

Scenario building is a tool capable of developing and exploring a wide range of plausible alternatives for the long-term future, being very useful in the planning and management of urban water systems. The methodology presented herein to build the scenarios is composed of three main steps (Figure 1): (i) system context analysis; (ii) scenario definition; and (iii) scenario modelling.

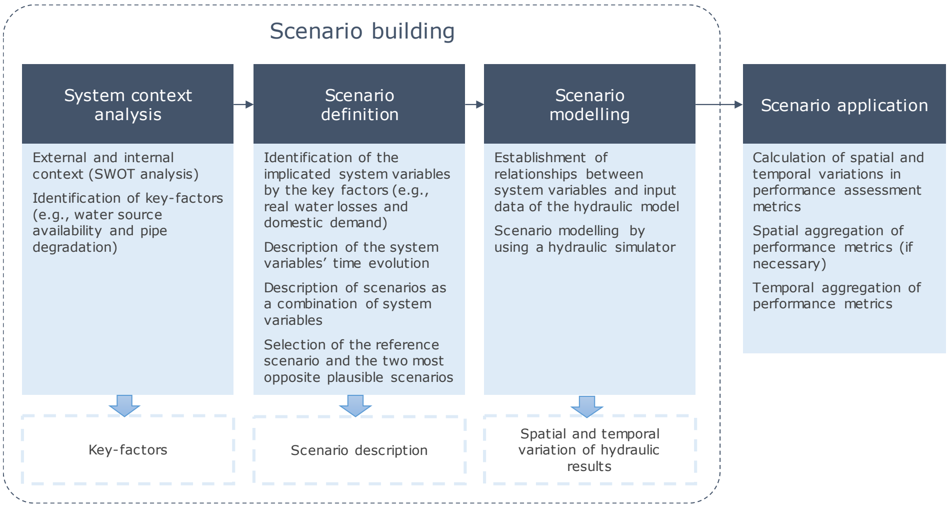


Figure 1. Proposed scenario-building methodology for urban water systems.

The methodology outputs are the spatial and temporal variations in the hydraulic results for each scenario, which can be used to calculate the spatial and temporal variations in the performance metrics. A new formulation is proposed to merge the evolution of the metrics over time into a single value, considering the time uncertainty. Uncertainty is, therefore, integrated into the performance assessment by the scenario's impact through the variability of the performance results and future time uncertainty. The latter was considered by using an uncertainty rate in which future values are less relevant than present ones. A detailed description of each step of the methodology is presented in the following sections:

System context analysis

The scenario-building methodology starts with a contextual analysis of the system, considering the implications of contextual uncertainties in the WDNs to develop and explore a wide range of plausible alternatives. The context analysis identifies key factors bound to happen that mostly affect the WDN performance. In this regard, the external context (e.g., climate change, population growth, economy, regulatory framework, social conditions, and technology) and the internal context (e.g., infrastructure resources, human resources, technological resources, and financial resources) should be analysed [19]. These analyses should be carried out by understanding the region and the local context of that specific WDN.

A questionnaire is answered by the water utility to classify the (positive or negative) impact of different factors on the system behaviour and, then, to rank it in a range of 0 to 3, in which 0 means that the factor is irrelevant and 3 means that the factor is very relevant to the system. The water utility can also add any factor that is considered relevant. Factors with a negative impact on the system, i.e., that are more threatening, lead to higher concerns and are more uncertain and correspond to system weaknesses (internal context) and threats (external context), whilst factors with a positive impact on the system, correspond to strengths (internal context) and opportunities (external context). An exhaustive example of factors considered in a SWOT analysis in the context of water supply is presented in Table 1. The final SWOT analysis identifies the higher-ranked priority external/internal and positive/negative factors, referred as key factors, which are to be addressed in the analysis.

Table 1. Example of external (opportunities and threats) and internal (strengths and weaknesses) factors in water supply in SWOT analysis.

	Factors with Positive Impact	Factors with Negative Impact
Internal context	*Strengths*: - Good infrastructure knowledge - High water storage capacity - Water abstraction capacity - Water treatment capacity - New infrastructures (recently built) - Budget availability - High rehabilitation rates - Low leakage levels - Good synergy with external entities - Motivated human resources and decision makers	*Weaknesses*: - Poor infrastructure knowledge - Low water storage capacity - No water abstraction capacity - No water treatment capacity - Aged infrastructures (assets near the end of service life) - Budget restrictions - Low rehabilitation rates - High leakage levels
External Context	*Opportunities*: - Availability of non-potable (reused) water by the bulk water utility - Public awareness of water conservation - Urban expansion (e.g., higher income) - External funding (e.g., Recovery and Resilience Plan, Portugal 2030, European funds) - Municipality plans for climate change and efficient water use - External consultants, contractors, and suppliers with experience and knowledge	*Threats*: - Regulatory restrictions on water uses - Reduction of water availability by the bulk water utility - Demand increase (e.g., population increase, tourism increase, and higher irrigation needs) - High illegal uses - Cyberattack - Inflation - Natural disasters (e.g., earthquakes, floods, tsunamis, droughts, and water scarcity)

Scenario definition

The scenario definition aims at the establishment of the different scenarios to be modelled, based on the key factors identified in the previous step [13]. Different key factors can affect WDN variables (e.g., a WDN reaching the end of its service life tends to have higher real water losses; the existence of alternative water sources for irrigation affects the demand), and other key factors can impact the same WDN variable in the opposite way (i.e., population growth increases authorised consumption, while stricter regulations decrease authorised consumption). As such, identifying the WDN variables (i.e., real water losses, domestic demand, and irrigation demand) implicated in the key factors is fundamental to the scenario's definition.

Once the system variables are identified, a properly justified future evolution is described (i.e., trends and strategic goals). The system variables are conjugated to formulate multiple scenarios that cover the combination of the system variables' evolution. The two most opposite plausible scenarios are selected, corresponding to the most positive and negative ones, adequately showing the uncertainty of the future [20]. In order to compare the obtained scenarios with the status quo situation, a reference scenario is also defined by forecasting the current situation and providing a predetermined scenario based on typical development patterns. For example, a decreased demand with a lower real water loss scenario is possible if the irrigation demand decreases with the implementation of reused water as an alternative non-potable supply source and if the rehabilitation rate increases to 2%/year (PENSAARP 2030 goal), increasing the infrastructure asset service life and therefore lowering the real water losses of the system. On the contrary, an increase in demand with higher real water losses could also happen if there is no alternative non-potable supply source and there is no investment in rehabilitation, increasing pipe age and, consequently, real water losses. The description of the different scenarios is the output of the scenario definition step.

Scenario modelling

In the present work, scenarios were applied to the hydraulic model of the WDN. As such, the evolutions of the WDN variables (i.e., real water losses, domestic demand, and irrigation demand) must be computed so that the input data of the model (i.e., patterns, base demands, demand categories, and pipe roughness) reflect the scenario description, allowing for the assessment of the behavior of the system over time. The relationship between the WDN variables and the input data of the model is, therefore, crucial to be established. As will be presented in Section 4, herein four WDN variables are identified (i.e., public irrigation demand, private irrigation demand, domestic demand, and real water losses) and implemented in the model as demand categories. In this case, the base demand of each category represents the dimensionless spatial distribution of the total category demand, while the category demand patterns provide the 24 h temporal distribution of the average daily consumption (m^3/h).

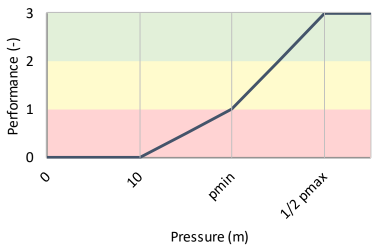
Public irrigation demand, private irrigation demand, and domestic demand evolutions (i.e., trends) are applied to the respective category demand patterns, in accordance with the scenarios described. The modelling of real water losses is more complex. Herein, it is considered that real water losses are related with the pipe age. As real water losses are calculated in each future year, the following relationship is calculated for every year of the horizon time. Knowing the installation year of each pipe, the pipe age is obtained by subtracting the installation year from the year under analysis. The pipe age is then related to real water losses, as proposed by [21,22], in which older pipes have higher real water losses. Pipe age will vary according to the rehabilitation rate that the water utility will implement. To model the rehabilitation process, the pipes are ranked by age and the older pipes are substituted until they reach the length of pipes to be replaced according to the rehabilitation rate. The pipes are replaced like-for-like, and the respective installation year is updated to the year of analysis. Different rehabilitation rates will provide different pipe ages and consequently different real water losses. The volume of real water losses is then evenly distributed through the 24 h demand pattern of the real water loss category.

In the scenario modelling step, the input data of the model were computed following the WDN variable evolution for each scenario and applied to the numerical model of the system. Using a hydraulic simulator (e.g., EPANET), the spatial and temporal hydraulic results of the system behaviour for each scenario are achieved by the simulation runs.

Scenario application

The proposed methodology provides a scenario evolution of hydraulic results (i.e., actual demand, pressure head, flow rate, and head loss) through time that can be used to calculate a wide range of performance assessment metrics. Three metrics associated with the hydraulic resilience of WDN were used to illustrate the use of the scenario-building approach, namely, (i) the network resilience index (NRI) [23,24] to ensure a flexible service, particularly to increase water demand; (ii) the minimum pressure index [25–27]; and (iii) the real water loss performance indicator (PI) [28]. These metrics are presented in Table 2.

Table 2. Description of the performance assessment metrics selected in the scenario application step.

Metric [Units]	Formulation
Network resilience index [-]	$$NRI = \frac{\sum_{i=1}^{N} U_i Q_i \left(H_i - H_i^{req}\right)}{\sum_{r=1}^{Nr} Q_r H_r + \sum_{b=1}^{Nb} \frac{P_b}{\gamma} - \sum_{i=1}^{N} Q_i H_i^{req}} \quad (1)$$ $$\text{being } U_i = \frac{\sum_{l=1}^{np_i} D_l}{np_i \times \max\{D_1, \ldots, D_l\}} \quad (2)$$
Minimum pressure index [-]	The minimum pressure index in network nodes is based on relating the nodal pressure results with a performance function for each node. Herein, the performance function is as follows, where pmin = 20 m and pmax = 60 m.  The minimum pressure index of the WDN is obtained by aggregating the minimum pressure index in network nodes through a generalising function, herein, the weighted average by the node demand.
Real water loss performance indicator [l(connection·day)]	Average daily volume lost/Number of connections

Note: Where γ is the specific weight of water (9800 N/m^3),N is the total number of demand nodes, Nr is the total number of reservoirs, Nb is the total number of pumps, Q_i is the demand in node i (m^3/s), Q_r is the flow input from reservoir r (m^3/s), Q_i^{in} is the flow entering node i (m^3/s), $Q_{i,l}^{in}$ is the flow entering in node i through pipe l (m^3/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), H_r is the head in reservoir r (m), U_i is the uniformity coefficient of node i, np_i is the number of pipes entering into node i, and D_l is the diameter (mm) of pipe l that is connected to node i. pmin = 20 m and pmax = 60 m.

The network resilience index is used to evaluate the service flexibility for eventual increases in water demand. Its values range between 0 and 1, where values near 0 have small service flexibility to an increase in demands and values close to 1 correspond to systems with good service flexibility [24]. The minimum pressure index, used to assess the service reliability, has reference values similar to those used in [26] (see Table 2). The real water loss PI, used to assess WDN infrastructural sustainability, has the reference values defined in [28], namely, a system has good performance when this PI is below 100 l/(connection·day), fair performance if this PI is between 100 and 150 l/(connection·day), and poor performance if this PI is above 150 l/(connection·day).

As perceived by the minimum pressure index, some metrics are calculated at the component level to obtain a performance value for each node and are further aggregated to provide a system index.

A temporal aggregation is also necessary to obtain a single-value metric for each scenario. The more distant the metric's value is in the future, the more uncertain it is and the less important it becomes to the scenario. Herein, an uncertainty weight, $w(t_i)$, Equation (3), similar to the discount rate for estimating net present costs [29], is used in the aggregation function weighted average, deducting the further-away performance results.

$$w(t_i) = \left(\frac{1}{1+r}\right)^t \quad (3)$$

where r is the uncertainty rate and t is the respective year.

Three scenarios are analysed—the reference scenario and two opposite and plausible scenarios. Intermediate scenarios can also occur; thus, the range of the assessment results between those opposite scenarios represents the uncertainty of the future.

3. Case Study Description

The case study is a Portuguese continuous water supply network (Figure 2) located in the south of Portugal, in the Algarve region, a high tourist area that is mostly comprised of houses with gardens, condominiums, and hotels. The WDN comprises 96 km of pipes, with the main pipes' diameters ranging from 50 to 700 mm (Figure 2a) and 4 171 service connections. The WDN has an average elevation of 20 m, ranging between 3 and 48 m. The network has two entry points, Sources 1 and 2, as depicted in Figure 2a. Source 1 is a water tower, with 800 m^3 and a water level of 63 m. Source 2 comprises a ground water storage tank with 10,200 m^3 and a water level of 53 m; this tank is associated with a pumping station that raises water to a water tower with 500 m^3 and a water level of 62.8 m. The network model describes both sources as constant-level storage tanks (reservoirs). The WDN has also a booster pumping station (represented as a pump in Figure 2) that raises ca. 7% of the total water volume to a head of 81 m (i.e., the pump head is 18 m). The water utility provided an initial version of the EPANET hydraulic model, set for 24-h simulations, corresponding to the average daily supply in August 2021.

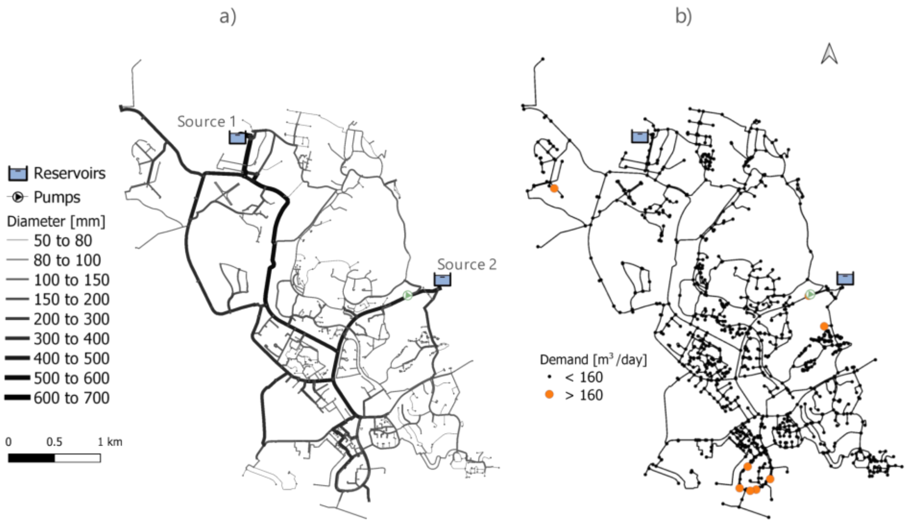


Figure 2. Schematic representation of the water distribution network: (**a**) pipe diameters and (**b**) location of large consumers.

The network has high seasonal demand variation, with the summer consumption being approximately six times higher than in the winter. The model comprises 11 consumer categories: domestic consumers (including non-domestic demands that are negligible), private irrigation, public irrigation (water utility responsibility), and eight different large consumers (e.g., hotels). Identifying these consumer categories is possible due to the use of two water meters per household, one for domestic consumption and one for irrigation (which includes outside uses). The water utility has water meter telemetry, which measures consumption every hour. Figure 2b presents the location of the eight large consumers of the network.

Water losses (i.e., real and apparent losses) correspond to 13% of the input water volume annually, with 21% of water losses in the summer and 8% in the winter. The water utility claims that, during the summer, a considerable amount of water losses is due to illegal uses. As such, real water losses are considered to be constant throughout the year and equal to the total amount of water losses during the winter period. The additional water loss volume in the summer is related to apparent losses.

The network supplies approximately 21,000 m^3 of water per day. The total demand per consumption category distribution is presented in Figure 3a, in which private and public irrigation are joined, and the eight largest consumers are also aggregated. Irrigation for gardening is the principal water use during the summer, corresponding to ca. 60% of the total consumption. From the disaggregated irrigation graph (Figure 3b), the main contribution is private irrigation. Irrigation consumption is particularly high during the nightly hours, as it corresponds to the lower temperature period and is recommended for irrigation. Nonetheless, it is also visible a demand consumption during the day.

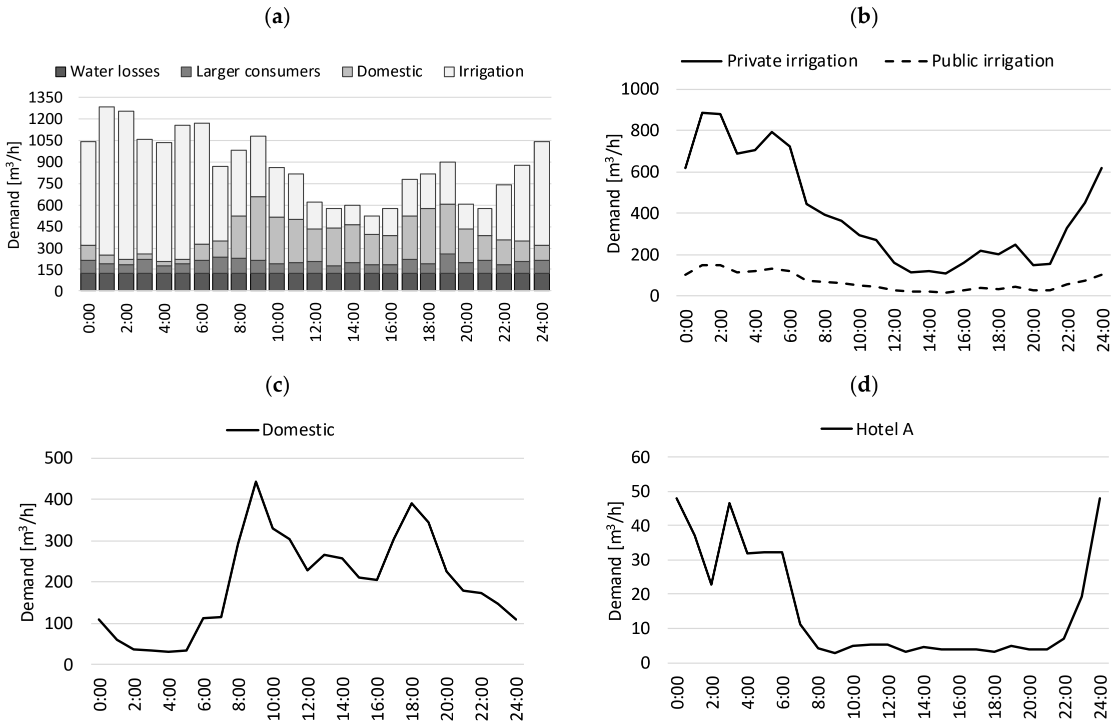


Figure 3. Summer period hourly pattern for (**a**) demand categories; (**b**) irrigation demand; (**c**) domestic demand; and (**d**) largest hotel consumer.

The domestic demand is considerably higher during the day, particularly at 9 h and 18 h (Figure 3c). The demand pattern of the largest consumer, a hotel, is presented in Figure 3d, with its main consumption being at night, which could be due to the renovation of water in swimming pools and irrigation.

Regarding historical data, the water utility provided the authorised consumption of the previous 10 years (2011–2020). However, the water utility only disaggregated the authorised consumption from 2019 onwards. Thus, the authorised consumption trend of the previous 10 years (2011–2020) was calculated through linear regression, giving an increase of 0.2%/year, which is considered the same for every demand category. The rehabilitation rate trend was obtained by the average of the previous 10 years, 0.27%/year, obtained in the annual report of the sector developed by the Water and Waste Services Regulation Authority in Portugal (ERSAR).

4. Scenario-Building Results

4.1. System Context Analysis

The context analysis was carried out by understanding the region and the local situation of the water utility. A questionnaire was provided to the water utility to classify several context factors according to their importance, using a scale from 0 (less impact) to 3 (more impact) and their positive or negative effect on the WDN. This allowed for the identication of the internal and external key factors that most affect the WDN.

The external context is highly influenced by the water availability and the region's tourism. The region in which the case study is located is under a prolonged period of low rainfall in a severe drought situation [30], leading to water scarcity problems. Water restrictions are starting to be implemented in Algarve due to the current severity of the drought (in 2023). Thus, an identified key factor with a negative impact on the system is water scarcity, which can also increase the saltwater intrusion into groundwater, compromising the supply of water consumption through private wells by users and the possibility of the bulk water utility to reduce the amount of supplied water. On the other hand, tourism is expected to increase in the region, which may increase the difference between summer and winter demands even more. Finally, an identified key factor with a positive impact on the system is the possibility of an alternative water source (reused water) for irrigation supplied by the bulk water utility, which is expected to occur by 2026.

Regarding the internal context, the identified key factors include an alternative non-potable water network (positive impact) and the end of infrastructure asset service life (negative impact). The drinking water utility is responsible for investing in an alternative network to distribute non-potable water for public garden irrigation. The final key factor is the end of infrastructure asset service life, especially because most water pipes were constructed around 1980 and presented an age of 37 years (in 2021), near the 40 years of pipe service life. The rehabilitation rate over the years has been low, not guaranteeing the infrastructural sustainability of the system, with around 0.27%/year in the last 10 years.

The results of the SWOT analysis are summarised in Table 3. The main opportunity is the expected availability of reused water by the Águas do Algarve (bulk water utility) delivery point. The water utility's main strength is the possibility of constructing a new network to distribute reused water to the main irrigation consumers. The main threats are water scarcity and the increase in seasonal tourism, whereas the main weakness of the utility is the end of infrastructure asset service life.

Table 3. Results of the SWOT analysis identifying external (opportunities and threats) and internal (strengths and weaknesses) key factors.

	Key Factors with Positive Impact	Key Factors with Negative Impact
Internal context	*Strengths*: Possible alternative non-potable water network (reused water)	*Weaknesses*: End of infrastructure asset service life
External Context	*Opportunities*: Alternative non-potable water source (reused water) by 2026	*Threats*: Water scarcity Increase in seasonal tourism

4.2. Scenario Definition

The identified key factors in the context analysis will strongly affect the drinking water system performance in the future, involving changes in different WDN variables (e.g., irrigation demand, domestic demand, and real water losses), which are tangled in uncertainty and can evolve in various ways. The WDN variables affected by the key factors are presented in Table 4.

Table 4. Relation between key factors and WDN variables.

Key Factors/System Variables	Public Irrigation Demand	Private Irrigation Demand	Domestic Demand	Real Water Losses
Alternative reused water source	x	x		
Alternative reused water network	x	x		
Water scarcity		x	x	
Increase in seasonal tourism		x	x	
End of infrastructure asset service life				x

The availability of reused water for non-potable uses, such as irrigation, street washing, or firefighting, will change public and private irrigation demands in the WDN, because part of the current irrigation will be supplied by a non-potable network. However, reused water has restrictions regarding water quality and the amount of water provided is still less than the necessary irrigation volume. As such, it is considered that the reused water can only satisfy 50% of the volume used in the reference year for private irrigation through the time horizon, whereas for public irrigation, it can provide the total amount of water needed by 2026. Nonetheless, if the reused water network is not constructed, or the supplied reused water is not sufficient, irrigation will continue to be supplied by the existing WDN. Water scarcity leads to groundwater salinization, and the consumers relying on it for irrigation may change its source to the drinking water network, increasing private irrigation demand. In terms of public irrigation, the water utility is committed to decreasing the water used and, in the worst case, maintaining the demand. For this reason, it is not considered an increasing trend in public irrigation demand.

The increase in seasonal tourism will promote an increase in domestic demand. Therefore, it is considered that both demands (private irrigation and domestic) could increase by 5%/year. A decreasing trend of domestic demand was not considered because the reduction in tourism or population in the Algarve region is not expected.

Overall, the following different irrigation trends were considered: maintain the historical trend; gradually reducing irrigation needs, 50% in private irrigation through the time horizon, and 100% in public irrigation in 5 years; and gradually increasing irrigation needs by 5%/year. In terms of domestic demand, it is considered that it could maintain the historical trend or gradually increase by 5%/year.

The low rehabilitation rate (0.27%/year in the last 10 years) does not allow for the renewal of the WDN infrastructure, which will continue to age, and its overall physical condition will continue to degrade. Note that the average age of the pipes in 2021 was 37 years. Despite the WDN not showing signs of degradation, leakage levels and burst rates will start to increase if the water utility does not change the status quo situation and increase the pipe rehabilitation rate. Experience has demonstrated that, amongst many factors, real water losses are strongly related to pipe age [21,22] and, thus, can increase if the rehabilitation rate is maintained or decreased. On the other hand, real water losses can decrease if the water utility renews the network by increasing the rehabilitation rate to 2%/year, as recommended by the National Strategic Plan for the Water Supply, Wastewater, and Stormwater Management Sector (PENSAARP 2030). Thus, three rehabilitation rate trends were considered: 0%/year, the current rate of 0.27%/year, and the increase to 2%/year; which will impact the real water losses of the WDN.

The possible evolution trends for each system variable are summarised in Figure 4. Although any conjugation of different variable trends is possible, all are within the two opposite scenarios, demonstrating the total range in the system results. Figure 4 presents the conjugation of WDN variable trends to define the two most opposite plausible scenarios and the reference scenario.

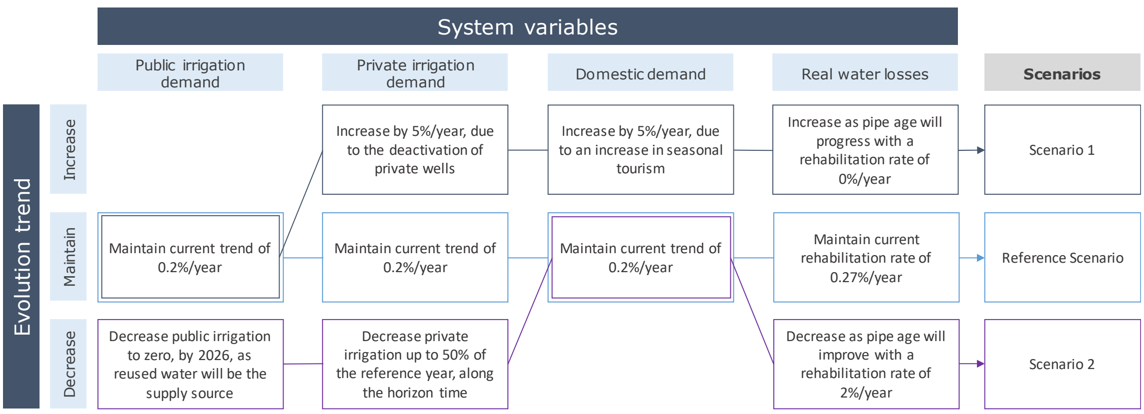


Figure 4. WDN variable trend conjugation to define the two most opposite plausible scenarios and the reference scenario.

The reference scenario and the two opposite scenarios are the following:

- The reference scenario (S0) assumes that (i) both irrigation (public and private) and domestic demands will continue at 0.2%/year (following the last 10-year trend) and that (ii) the current rehabilitation rate of 0.27%/year is maintained (i.e., the real water losses will continue to increase).
- Scenario 1 (S1) corresponds to the most pessimistic scenario characterized by (i) the private irrigation and domestic demands increasing by 5%/year due to the deactivation of private wells and increasing tourism; (ii) the public irrigation demand continuing to follow the current trend of 0.2%/year, and (iii) the rehabilitation being null (0%), leading to a significant increase in real water losses.
- Scenario 2 (S2) is the most optimistic scenario, in which (i) private irrigation demand decreases up to 50% in 20 years (i.e., at a rate of 2.5%/year); (ii) public irrigation decreases to zero by 2026; and (iii) the rehabilitation rate is 2%/year (i.e., the PENSAARP 2030 goal), resulting in a decreasing average pipe age and a decrease in real water losses.

4.3. Scenario Modeling

The scenario modelling was developed in a Python environment, using the EPANET 2.2 simulator [31] by the WNTR package [32], so that the scenarios were applied to the hydraulic model of the WDN, in a demand-driven analysis. The WDN variable evolutions were computed so that the input data of the model reflected the scenario description, allowing for the assessment of the system behaviour over time.

Domestic, public irrigation, and private irrigation demands were modelled as demand categories, as these already exist in the model provided by the water utility. The base demand of each category represents the dimensionless spatial distribution in the network of the total demand, while the category demand patterns provide the 24 h temporal distribution of the average daily consumption (m^3/h). As such, the trend evolution of public irrigation demand, private irrigation demand, and domestic demand were modelled by changing the demand pattern of each category.

Real water losses were also modelled as a demand category. The rehabilitation rate will influence the number of pipes that will be like-for-like replaced, changing the pipe age and, consequently, the real water losses of the system, as detailed in Section 2. The volume of real water losses was evenly distributed through the 24 h demand pattern of the real water loss category.

Once the time evolution of the different WDN variables (public irrigation demand, private irrigation demand, domestic demand, and real water losses) and their relation with input data of EPANET were modelled, it was possible to obtain the real water losses and the authorised consumption (i.e., the sum of domestic, public irrigation, and private irrigation demands) variation through time for each scenario, as presented in Figure 5. According to this approach, input data uncertainty is described by the difference between the two opposite scenarios (see shadowed zone in Figure 5).

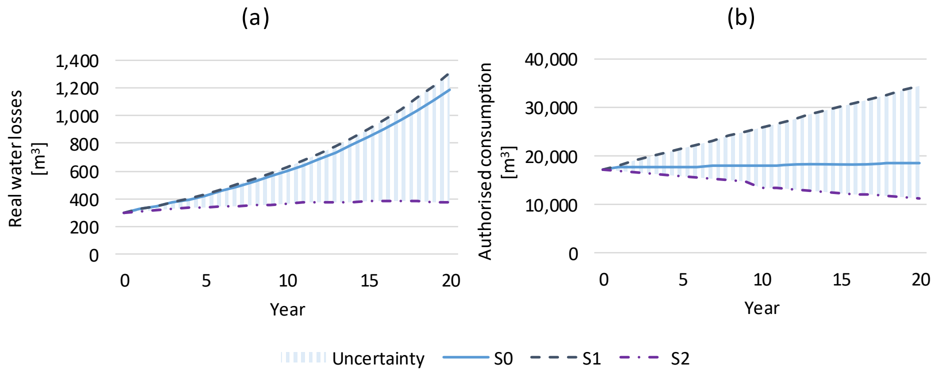


Figure 5. Time variation for the three scenarios of: (**a**) real water losses; (**b**) authorised consumption.

The hydraulic results (i.e., pressure head, water head, and flow rate) for each scenario were obtained by running the hydraulic simulation of the system's model for each scenario. The uncertainty introduced into the model by the different scenarios can also be perceived at the WDN component level (e.g., nodes and pipes). The simulation results in terms of the minimum pressure heads and the maximum velocities (at peak-hour consumption, 2 h) are presented in Figures 6a–c and 7a–c, respectively, for the three scenarios in year 20. The relative variation between S1 and S2 with respect to S0 is shown in Figures 6d and 7d.

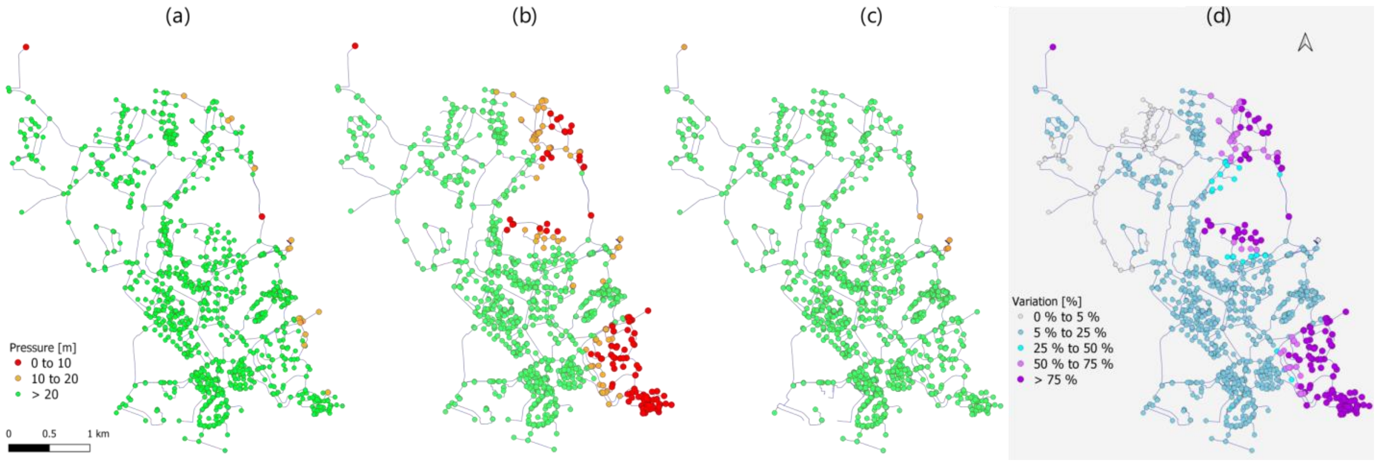


Figure 6. Spatial distribution of minimum pressures in nodes for year 20, at the peak-hour consumption (2 h): (**a**) Reference scenario; (**b**) Scenario 1 (demand increase and low rehabilitation rate); (**c**) Scenario 2 (demand decrease and adequate rehabilitation rate); and (**d**) Relative variation from Scenario 1 and Scenario 2 with respect to the reference scenario.

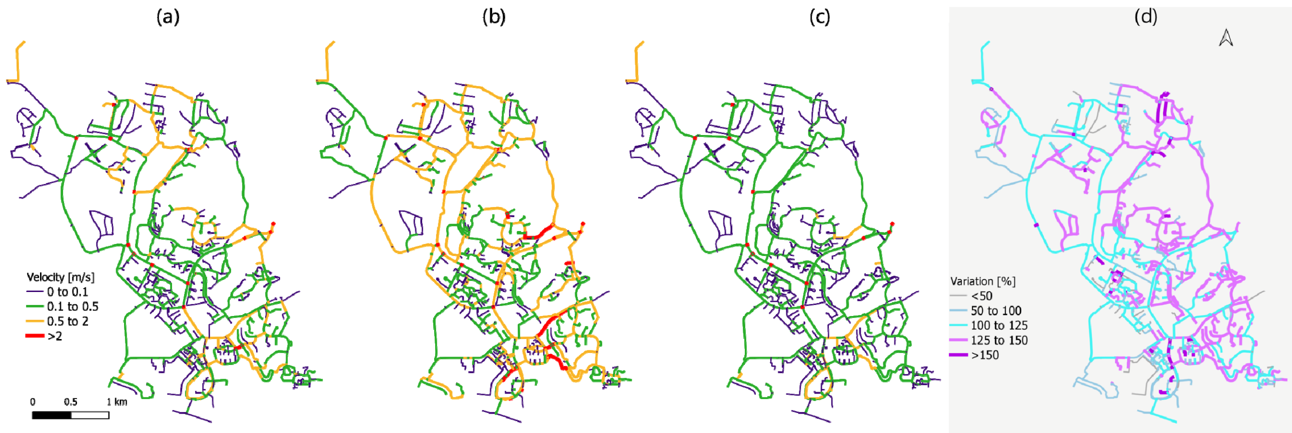


Figure 7. Spatial distribution of maximum velocities in pipes for year 20 at the peak-hour consumption (2 h): (**a**) Reference scenario; (**b**) Scenario 1 (demand increase and low rehabilitation rate); (**c**) Scenario 2 (demand decrease and adequate rehabilitation rate); and (**d**) Relative variation from Scenario 1 and Scenario 2 with respect to the reference scenario.

Regarding the minimum pressure head, a variation from scenario S0 towards S2 will lead to minor changes in the WDN performance (Figure 6a,c), because the demand and the leakage volume decrease due to the 2%/year rehabilitation rates that reduce friction losses and maintain minimum pressures. In contrast, a future evolution from scenario S0 towards S1 (Figure 6a,b) will significantly affect part of the network, particularly nodes with higher elevations and lower minimum pressures; these zones do not comply with the necessary minimum pressure to provide the supply service (red nodes with pressures below 10 m). This is because the increase in demand and leakage losses will also increase friction losses and, thus, reduce available pressures. Through the calculation of the minimum relative pressure variation, from S1 and S2 with respect to S0, the most sensitive zones can be identified (Figure 6d), which are more exposed to demand and rehabilitation rate changes (purple nodes). These zones have higher differences in pressure of the opposite scenarios and, consequently, have more uncertainty associated with the minimum pressure variation.

Regarding the maximum velocity, a variation from scenario S0 towards S1 or S2 will also promote different outputs. Although there is a global velocity increase in S1 (Figure 7b), most of the network continues with velocities much below 2 m/s, which does not significantly impact this variable. It is also observed in Figure 7d that the velocity variability in the main pipes is lower than 100% (see thicker trace pipes in Figure 2a). This situation indicates that the network is overdesigned and the velocities in the system are relatively small. Thus, the variation results are high in absolute number (over 100%), without a visible area or main path with a considerable impact.

Scenario modelling allows for the determination of the system variables' time variation (i.e., velocity and pressure) for each scenario. From the furthest year of each scenario, it is possible to quantify the possible variation in hydraulic variables and identify zones with higher uncertainty that are prone to have problems in the future.

4.4. Scenario Application to System Performance Assessment

The three metrics used herein to assess the system performance are the following: network resilience index, minimum pressure index, and real water loss performance indicator (Table 2). These metrics were calculated for each time step along the 24 h period, for each year of analysis. While the network resilience index and the real water loss performance indicator are system metrics, the minimum pressure index was calculated at the component level (i.e., node or pipe). As such, a spatial distribution of the minimum pressure index can be obtained (Figure 8), similar to the spatial distribution of hydraulic variables, particularly minimum pressures (Figure 6).

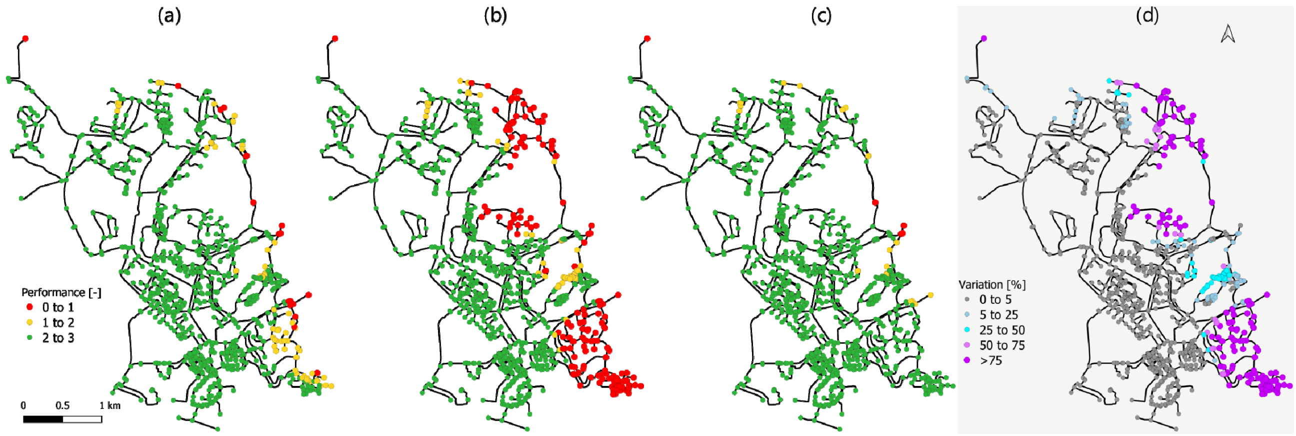


Figure 8. Spatial distribution of the minimum pressure index for year 20, at the peak-hour consumption (2 h): (**a**) Reference scenario; (**b**) Scenario 1 (demand increase and older pipes); (**c**) Scenario 2 (demand decrease and renewed pipes); and (**d**) Relative variation from Scenario 1 and Scenario 2 relative to the reference scenario.

An evolution towards S2 (Figure 8c) will not promote a substantial difference relative to S0, whilst a future evolution towards S1 (Figure 8b) will effectively impact part of the network. The same zones are identified in the variation between Scenario 1 and Scenario 2 relative to the reference scenario (Figure 8d). This new approach of incorporating aleatory uncertainty of future events in WDN prognosis analysis provides higher insights into the future system behaviour, by considering the two opposite context scenarios instead of simply looking at uncertainty as a probabilistic distribution [8,9], where the system's context is not considered.

A spatial aggregation of the results was made to reach a result for the system at each time step. Herein, the aggregation function for the minimum pressure index is the weighted average by the respective nodal demand [26]. The other metrics were already applicable to the system level. The temporal evolution of the assessment metrics is presented in Figure 9.

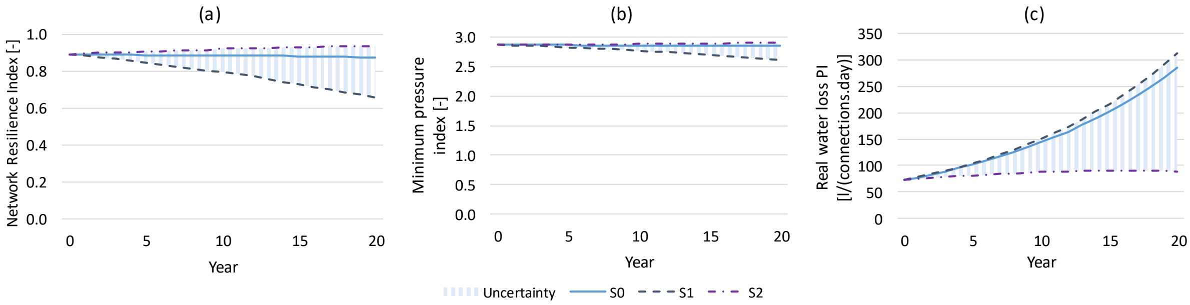


Figure 9. Evolution of the performance assessment metrics for the different scenarios: (**a**) network resilience index; (**b**) minimum pressure index; and (**c**) real water loss performance indicator.

Metrics become more apart between the opposed scenarios as time progresses, and Scenario 1 and Scenario 2 have significantly different impacts on the selected metrics. The real water loss performance indicator is the most-variable metric, while the minimum pressure index is the least-variable performance metric. The temporal variation, over the horizon analysis, of the assessment metrics for each scenario is presented in Figure 10.

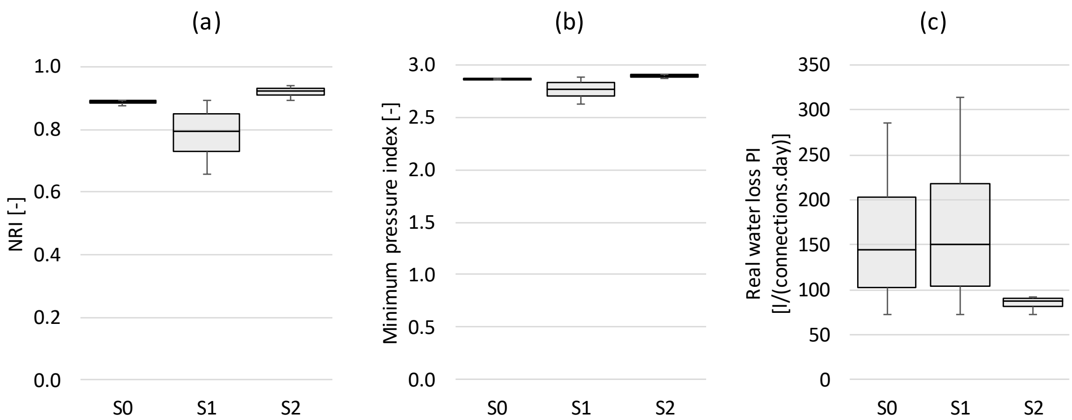


Figure 10. Resilience assessment metric box and whiskers plot of the temporal variation for each scenario: (**a**) network resilience index; (**b**) minimum pressure index; and (**c**) real water loss performance indicator.

In S1, the network resilience index (Figures 9a and 10a) decreases from 0.9 (year 0) to 0.65 (year 20), corresponding to a decrease in the flexibility capacity of the service. In S0, the NRI slightly drops its value, whilst in S2, it slightly increases during the period of analysis. However, in S0 and S2, the NRI remains close to 0.9, showing that the system continues to have high service flexibility regarding an increase in demand.

Regarding the minimum pressure index (Figures 9b and 10b), the variability is minimal between scenarios, although there is a higher difference in S1 relative to S0. Nonetheless, in the spatial distribution of the performance for S1 (Figure 8a), there are network zones where, in 20 years, the pressure will be lower than the required minimum, 20 m (performance below 1, red nodes). These critical zones must be considered in future system planning, and higher pipe diameters or alternative main flow paths should be analysed to reinforce the water supply in those zones.

The real water loss PI shows an entirely different behaviour. The temporal evolution of Scenario 1 is similar to the reference scenario, increasing from 75 to around

300 l/(connection day), which corresponds to a poor performance. On the other hand, Scenario 2 is considerably better in terms of real water loss PI, maintaining a good performance, with values under 100 L/(connection day) (Figures 9c and 10c).

The previous analysis shows that the scenarios affect the time variation of the metrics in different ways. For a good evaluation of the system, the assessment system should be developed considering different perspectives of analysis, eventually including more resilience criteria that are not yet being assessed (e.g., autonomy, reliability, and robustness).

A temporal aggregation is necessary to obtain a single-assessment metric result for each scenario. The main assumption is that the further away time is from the reference year, the higher the uncertainty associated with that metric scenario. Thus, the uncertainty weight, Equation (3), was applied to each future value of the metrics, deducting the further-away metrics results by using a discount rate of 10%. The quantification of the metric values for each scenario is presented in Table 5. This table also shows the quantification of the uncertainty that corresponds to the relative variation between the values of scenarios S1 and S2 with respect to the value of scenario S0.

Table 5. Global scenario results of the assessment metrics.

	Aggregated Metric Value along Time (Relative Variation with Respect to S0 Value)		
	S0	**S1**	**S2**
Network resilience index [-]	0.89	0.83 (7.1% ↓)	0.91 (2.6% ↑)
Minimum pressure index [-]	2.87 ●	2.80 ● (2.2%↓)	2.88 ● (0.6%↑)
Real water loss PI [l/(connection·day)]	124 ●	129 ● (4.3%↑)	82 ● (33.9%↓)

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

Globally, the real water loss PI is the most uncertain metric regarding the identified scenarios. The ageing of the network considerably impacts real water losses, varying by more than 30%. Although with some variation, the network resilience index remains with similar results for the different scenarios, varying less than 10%. The minimum pressure index is the least uncertain metric; however, some critical zones could be hidden because this is a spatially aggregated metric, weighted by consumption (e.g., if nodes with higher consumption are in good minimum pressure conditions). A spatial distribution, as presented in Figure 8, is extremely important to identify these situations.

5. Conclusions

The proposed scenario-building methodology integrated contextual and future time uncertainty in the WDN performance assessment.

Contextual uncertainty was reached by performing a SWOT analysis of the system that identified external and internal key factors that impact the WDN performance. The affected WDN variables by the key factors were identified, and their future evolution described and conjugated to formulate multiple scenarios. Along with the reference scenario, the two most opposite plausible scenarios were selected, adequately showing the uncertainty of the future. Herein, the reference scenario consisted of maintaining the current demand and rehabilitation rate trends. The most pessimistic scenario, Scenario 1, corresponded to an increase in private irrigation and domestic demands, public irrigation maintaining the current demand, and no rehabilitation. The most optimistic scenario, Scenario 2, corresponded to a decrease in public and private irrigation and domestic demands and a rehabilitation rate of 2%/year. The scenarios were applied to the WDN hydraulic model by computing the input data of the model to reflect the scenario's description. Through its simulation, the spatial and temporal hydraulic results were obtained and further used to calculate the resilience performance metrics. The proposed methodology reflected the contextual uncertainty in the spatial and temporal distributions of hydraulic variables and of the selected performance metrics, by comparing the results of the most opposite scenarios. The methodology offers richer descriptions of the future with a higher range, as opposed to looking at uncertainty as a probabilistic distribution of a single variable or parameter, where the system's context is not considered [8,9] and the range is smaller.

In addition, in the metrics applied at the component level (e.g., nodes and links), it is possible to identify components or critical areas with higher variability throughout the analysis, making planning more effective. Moreover, temporal uncertainty was considered by assigning an uncertainty weight for each, which diminishes the relevance of the performance results as they extend into the distant future, and a global scenario result for each performance assessment was obtained.

Three performance metrics were used to assess infrastructure asset robustness, service reliability, and flexibility: real water loss performance indicator, minimum pressure index, and network resilience index. The real water loss PI was the most uncertain metric regarding the identified scenarios, as the ageing of the network considerably impacts real water losses. The network resilience index remains with similar results for the different scenarios, varying by less than 10%, indicating that the network has service flexibility regarding an increase in demand. The minimum pressure index is the least uncertain metric; however, some critical zones could be hidden because this is a spatially aggregated metric and a spatial distribution is extremely important to identify these situations.

This methodology can be applied to planning and management approaches in the diagnosis and planning phases. The methodology proposed should be tested with other case studies with different contexts and complexities. Although the methodology was applied to different resilience criteria, it can also be applied to other planning approaches (e.g., infrastructure asset management, energy efficiency, and water loss). In addition, only three resilience criteria were assessed (infrastructure asset robustness, service reliability, and flexibility). Nevertheless, resilience is a much broader subject and other criteria can be considered, such as infrastructure autonomy, robustness, and redundancy. A broader resilience assessment framework should be further developed. The proposed methodology should also be implemented in alternative improvement measures to help decision makers identify the best alternatives for the system. A possible optimisation of system rehabilitation could include context uncertainty as an additional objective, in multi-objective optimisation problems.

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