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Special Issue Reprint

Enhancing Planning in the Management Urban Water Systems to Increase Resilience

Edited by
Dália Cruz Loureiro and Maria Adriana Cardoso

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Guest Editors

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About the Editors

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Dália Cruz Loureiro is a Senior Researcher at the Hydraulics and Environment Department of LNEC. Her work focuses on hydraulic modelling, statistical modelling of water demand, and the management of water and energy efficiency in drinking water systems. She also conducts research on performance assessment in urban water systems and collective irrigation systems. She has coordinated several research and development projects funded at European and national levels and has led multiple consultancy studies. Her work has involved close collaboration with water utilities, regulatory bodies, regional authorities, and national and international universities. She has supervised several doctoral and master students and is actively involved in professional and standardisation activities, serving as President of the Commission on Urban Water Services of the Portuguese Association of Water Resources (APRH), and as President of the national standardisation commission on urban water systems (TC90-SC04). She has authored more than 250 publications, including papers indexed in international databases, conference proceedings, and book chapters.

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Maria Adriana Cardoso is a Senior Researcher at the Hydraulics and Environment Department of LNEC. Her work focuses on urban water management, urban hydrology and hydraulics; urban drainage modelling and monitoring; performance assessment of urban water services; sewer system rehabilitation; asset management of urban water infrastructures; planning and assessment of water-cycle-related urban resilience; and planning and assessment of urban water smart management. She has coordinated several research and development projects funded at European and national levels and has led multiple advanced consultancy studies. Her work has involved close collaboration with water utilities, regulatory bodies, regional authorities, and national and international universities. She has supervised several doctoral and master students and is involved in professional and standardisation activities. She has authored more than 300 publications, including scientific papers indexed in international databases, conference proceedings, book chapters, and books.

Preface

Urban water infrastructures are essential to the functioning and sustainability of cities, yet they are increasingly exposed to climate variability, extreme events, and other disruptive pressures. Drinking water, wastewater, and stormwater infrastructures must therefore be planned and managed with a stronger focus on resilience, adaptability, and long-term performance of the service provided.

This Reprint addresses the subject of enhancing planning in the management of urban water systems to increase resilience. Its scope covers a range of approaches that support the different stages of the planning process, including system diagnosis, identification of improvement measures, decision making, implementation, monitoring, and revision. Particular attention is given to methods that incorporate uncertainty, scenario building, and performance assessment, as well as to emerging solutions such as decentralised systems, the integration of multiple water sources, and nature-based approaches.

The motivation for this Reprint arises from the recognition that traditional planning approaches are no longer sufficient to address current and future challenges. Exposure to extreme climate events, together with ageing infrastructure, increasing efficiency requirements, and evolving demand patterns, requires more integrated, flexible, and evidence-based approaches. By bringing together contributions that present robust and practical methods, this Reprint aims to support the transition towards more resilient urban water services.

This Reprint is intended for researchers, practitioners, and decision-makers involved in the planning, design, and management of urban water systems. It aims to provide both conceptual advances and practical tools that can be adapted to different contexts and levels of resource availability.

Dália Cruz Loureiro and Maria Adriana Cardoso
Guest Editors

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Editorial

Enhancing Planning in the Management of Urban Water Systems to Increase Resilience

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Urban water infrastructures are vital to cities, yet they are complex and vulnerable to both climate-related events—such as extreme precipitation, urban floods, droughts, heat waves, and cyclones—and other disruptive events like earthquakes, tidal effects, and tsunamis. Enhancing resilience in urban water systems—including drinking water, wastewater, and stormwater networks—is crucial to ensure the sustainability of these essential urban services and cities.

With ageing infrastructure, growing demand or changes in demand behaviour, as well as the need to improve resource and energy efficiency, traditional planning approaches are no longer sufficient. The paradigm is shifting towards integrated, flexible, and systemic planning frameworks incorporating uncertainty, long-term scenario building, and hybrid solutions, including decentralised networks, multiple water sources, and nature-based approaches. At the same time, practical methods for diagnosis, decision-making, implementation, monitoring, and revision are essential, especially for utilities with limited resources.

Despite these advances, significant challenges remain:

- Limited approaches for integrated planning: Strategies, tactics, and operational frameworks that incorporate resilience, risk management, uncertainty, and scenario-based methods are scarce.
- Lack of accessible diagnostic and monitoring tools: Utilities require practical, affordable, and cost-effective methods to assess, diagnose, and track system performance.
- Insufficient integration of efficiency, resource recovery, and nature-based solutions: Incorporating the water–energy–nutrient nexus, water reuse, and nature-based solutions into urban water systems remains limited.
- Unclear trade-offs between centralised and decentralised systems: Evidence-based guidance for hybrid or context-specific configurations is lacking.

Ten articles are published in this Special Issue:

1. Water–Energy Nexus-Based Optimization of the Water Supply Infrastructure in a Dryland Urban Setting;
2. The Role of Scenario-Building in Risk Assessment and Decision-Making on Urban Water Reuse;
3. Water Supply Security—Risk Management Instruments in Water Supply Companies;
4. Assessing Pipe Condition in Water Distribution Networks;
5. Integrating Uncertainty in Performance Assessment of Water Distribution Networks by Scenario Building;
6. Water–Energy–Nutrients Nexus of Urban Environments;
7. A Framework for Operational Management of Urban Water Systems to Improve Resilience;

8. Water Resources Carrying Capacity Based on the DPSIRM Framework: Empirical Evidence from Shiyan City, China;
9. Stormwater Harvesting Potential for Local Reuse in an Urban Growth Area: A Case Study of Melton Growth Area in the West of Melbourne;
10. How Scale Influences the Resilience of Urban Water Systems: A Literature Review of Trade-Offs and Recommendations.

These papers address the mentioned gaps in complementary ways:

1. Planning, Risk Management
   - Contributions 3 and 8 present structured approaches for risk assessment in water supply systems and to determine city-level water resources' carrying capacity, supporting long-term strategic planning. Contribution 3 proposes using semi-dynamic Balance Sheet Structure Models (BSM) for vulnerability analysis, as a valuable addition to existing instruments. Contribution 8 contributed with an evaluation index system based on the DPSIRM framework to determine the water resource carrying capacity of Shiyan City.
   - Contributions 1, 4, and 7 demonstrate how optimisation, condition assessment, and operational frameworks can enhance short and medium-term planning decisions in utilities. Contribution 1 integrates a genetic algorithm to generate pumping patterns and uses the EPANET hydraulic simulator to optimise pump schedules, ensuring water distribution at minimal operational costs. Contribution 4 developed and applied a methodology for predicting the physical condition of water distribution pipes without requiring visual inspection, to support prioritisation of rehabilitation interventions. Contribution 7 proposed a methodology for the operational management of hydraulic infrastructures that incorporates concepts of asset management, risk management, and technical management. It is organised into three operational areas (assessment, operation, and intervention) and aims to increase the efficiency of water utilities.
   - Contributions 2 and 5 introduce innovative frameworks for integrating uncertainty in water reuse planning and distribution network performance assessment. In Contribution 2, the proposed framework for health risk assessment and management of urban non-potable water reuse includes an additional step to establish the context, and the risk identification step is extended to include a description of activities from which hazard exposure scenarios can be derived. Contribution 5 presents a novel scenario-building methodology that integrates contextual and future-time uncertainties into the performance assessment of water distribution networks.
2. Efficiency and Nexus Approaches
   - Contributions 1, 6, and 7 show how the water–energy(–nutrient) nexus can be embedded in planning to improve efficiency, sustainability, and resource recovery. In Contribution 1, the proposed methodology, optimising the Water Distribution Network (WDN) and its management, also presents a model to save energy by optimising pump schedules. Contribution 6 presents a literature review highlighting the strong connections among water, energy, and nutrients at the building level, integrating results from different studies and demonstrating the global importance of this nexus. In Contribution 7, a methodology for the operational management of hydraulic infrastructures is proposed, addressing energy efficiency and consumption.
3. Alternative water sources, decentralisation and Nature-Based Solutions

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- Contributions 6, 9, and 10 explore alternative water sources, stormwater harvesting and scale-dependent trade-offs, providing insights for hybrid centralised–decentralised system design and adaptive management, considering nature-based solutions. Contribution 6 focuses on alternative water sources in buildings within the water–energy nexus. Contribution 9 presents a methodology for assessing stormwater quantity and quality under land-use change and varying climatic conditions, considering alternative water sources for water-service planning in new developments in urban areas. Contribution 10 presents a systematic review to understand the trade-offs associated with the adoption of different scales in urban water systems' design, addresses nature-based solutions, and examines how this impacts systems' resilience. Collectively, these contributions illustrate that enhancing planning—through strategic foresight, operational tools, and systemic integration—is central to building resilient urban water systems.

To further advance resilience, research should focus on:

- Developing robust, simple, and open-source planning tools for water utilities with diverse capacities, incorporating risk assessment and management principles.
- Incorporating nature-based and hybrid solutions into planning frameworks to balance centralised and decentralised infrastructure.
- Strengthening multi-resource integration (water, energy, nutrients, ecosystems) as a guiding principle.
- Utilising digital technologies (IoT, AI, big data) for adaptive planning and real-time decision support.
- Broadening understanding of governance and social dimensions, including stakeholder engagement and adaptive policy frameworks.

This Special Issue emphasises the transformative potential of planning as a driver of resilience. By combining strategic foresight, operational efficiency, and systemic integration, urban water systems can address the challenges of climate change and urban growth whilst ensuring sustainability and resilience for future generations.

Conflicts of Interest: The authors declare no conflict of interest.

List of Contributions:

1. Sharma, A.; Sanciolo, P.; Behroozi, A.; Navaratna, D.; Muthukumaran, S. Stormwater Harvesting Potential for Local Reuse in an Urban Growth Area: A Case Study of Melton Growth Area in the West of Melbourne. *Water* **2023**, *15*, 2093. https://doi.org/10.3390/w15112093.
2. Cheng, W.; Zhu, J.; Zeng, X.; You, Y.; Li, X.; Wu, J. Water Resources Carrying Capacity Based on the DPSIRM Framework: Empirical Evidence from Shiyan City, China. *Water* **2023**, *15*, 3060. https://doi.org/10.3390/w15173060.
3. Cardoso-Gonçalves, J.; Tentúgal-Valente, J. A Framework for Operational Management of Urban Water Systems to Improve Resilience. *Water* **2024**, *16*, 154. https://doi.org/10.3390/w16010154.
4. Silva-Afonso, A.; Pimentel-Rodrigues, C. Water–Energy–Nutrients Nexus of Urban Environments. *Water* **2024**, *16*, 904. https://doi.org/10.3390/w16060904.
5. Carneiro, J.; Loureiro, D.; Cabral, M.; Covas, D. Integrating Uncertainty in Performance Assessment of Water Distribution Networks by Scenario Building. *Water* **2024**, *16*, 977. https://doi.org/10.3390/w16070977.
6. Cabral, M.; Gray, D.; Brentan, B.; Covas, D. Assessing Pipe Condition in Water Distribution Networks. *Water* **2024**, *16*, 1318. https://doi.org/10.3390/w16101318.
7. Arnaud, N.; Poch, M.; Popartan, L.; Corominas, L.; Verdaguer, M. How Scale Influences the Resilience of Urban Water Systems: A Literature Review of Trade-Offs and Recommendations. *Water* **2024**, *16*, 1571. https://doi.org/10.3390/w16111571.
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9. Ribeiro, R.; Rosa, M. The Role of Scenario-Building in Risk Assessment and Decision-Making on Urban Water Reuse. *Water* **2024**, *16*, 2674. https://doi.org/10.3390/w16182674.
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Article

Water–Energy Nexus-Based Optimization of the Water Supply Infrastructure in a Dryland Urban Setting

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Abstract: Managing water supply systems is essential for developing countries to face climate variability in dryland settings. This is exacerbated by high energy costs for pumping, water losses due to aging infrastructures, and increasing demand driven by population growth. Therefore, optimizing the available resources using a water–energy nexus approach can increase the reliability of the water distribution network by saving energy for distributing the same water. This study proposes a methodology that optimizes the Water Distribution Network (WDN) and its management that can be replicated elsewhere, as it is developed in a data-scarce area. Indeed, this approach shows the gathering of WDN information and a model to save energy by optimizing pump schedules, which guarantee water distribution at minimal operational costs. The approach integrates a genetic algorithm to create pumping patterns and the EPANET hydraulic simulator to test their reliability. The methodology is applied for a water utility in the dryland urban setting of Lodwar, Turkana County, Kenya. The results indicate a potential reduction in energy costs by 50% to 57% without compromising the supply reliability. The findings highlight the potential of WEN-based solutions in enhancing the efficiency and sustainability of data-scarce water utilities in dryland ecosystems.

Keywords: water–energy nexus; optimization; pump scheduling; dryland urban setting; water supply infrastructures

1. Introduction

Drylands are defined as hyper-arid, arid, semi-arid, and dry sub-humid parts of the Earth. They can be found in all the continents and cover approximately 41 to 47 percent of the Earth's surface and host 39% of the global population [1–3]. According to UNEP/GRID [4], Asia and Africa have the largest amount of dryland areas, while Central America and Europe have the least dryland areas. A higher human population in drylands is found in Asia and Africa. The dryland ecosystem supports both rural and urban settings, with examples of large cities like Cairo, New Delhi, and Mexico being located in dryland areas [5,6]. It is projected that about 40% of the urban population will be living in cities located in dryland areas by 2050 [5]. According to Li et al. [6], communities in dryland ecosystems are faced with numerous stressors threatening their livelihood resilience and causing water scarcity, especially as a consequence of climate change, which is one of the main drivers of stressors.

In all dryland areas, water scarcity is a constant feature. This is exacerbated by erratic rainfall from season to season, leading to disasters of drought or floods and increased temperatures attributed to climate variabilities that negatively affect groundwater reserves,

which represent the main water supply source in the dryland ecosystem [7–9]. According to Gain et al. [10], water security can be viewed in four dimensions: water availability, accessibility, stability, and quality. Pradhan et al. [11] posit that the impact of climate change on water security goes beyond these four dimensions and is closely linked to many other dimensions of sustainable development goals and that increasing water scarcity in dryland areas will make the attainment of these goals more difficult [11–13].

Water Distribution Networks (WDNs) play a crucial role in ensuring water security and providing consumers with sufficient water of appropriate quantity and quality. A WDN comprises various elements (such as water sources, reservoirs, treatment plants, pumps, pipes, tanks, and valves), and pumps are the largest energy consumers among the components of a water supply system [14]. Due to high energy prices and the associated GHG emissions, there is an increasing demand to minimize energy requirements and to develop and implement sustainable water use strategies [15].

In this context, adopting a nexus-based approach to managing natural resources appears crucial [16]. Indeed, water management in dryland areas is strictly connected with food security targets and energy production constraints and is considered to be a grand nexus approach [17]. The Water–Energy Nexus (WEN) is a sub-nexus that focuses on the interdependencies between water and energy. On the one hand, energy is used in water production, such as in the water supply systems, while on the other hand, water is used in the generation of energy, such as in hydropower generation [17,18]. As an example, the groundwater depletion observed throughout the world [19] can lead to an escalation of pumping energy costs and affect water yield [20].

Nexus issues in the dryland areas bring water supply management and operations issues to the forefront and demand attention. Sustainable development goals are difficult to reach in developing countries, where 70% of dryland areas are located, and there are several challenges in the management and operation of water services in urban settings. According to Sadoff [12] and Stringer et al. [1], such challenges are the result of population increases in dryland urban ecosystems, climate change, unmatched rates of infrastructure expansion, depletion of groundwater sources, and pollution. It is against this background that Wang et al. [21] observe that the concept of WEN is gaining traction as a useful viewpoint in analyzing and managing the utilization of the two resources with future research directions focusing on modeling and optimization techniques for the WEN. Abegaz et al. [22] observe that there has been an increase in the literature on the assessment of interdependency between energy and water to sustain global water and energy security, whereas Carneiro et al. [23] appreciate the interplay between water and energy in a water utility where water and energy efficiency were used in one of the matrices in their proposed framework to assess the resilience of water distribution system.

Indeed, researchers and practitioners in the water sector are focusing on innovative ways of managing water supply and the associated energy consumption to achieve sustainable development in dryland regions [22,24]. In this context, the application of various optimization techniques has been increasingly explored and reached a degree of maturity in a wide spectrum of industries, including water resources systems [25,26]. WDN optimization entails creating a dependable, efficient, and cost-effective distribution network that meets the necessary water demands while maintaining adequate pressure heads [27]. The recent need for research on WDN operational optimization has been emphasized by factors such as aging network infrastructures leading to more water losses, increased demand due to urbanization, climate change-induced variables, and socio-economic factors within supply areas [28,29]. Several optimization techniques have been developed and applied to water supply systems with continuous refinement as technology advances. They are broadly classified as deterministic optimization techniques or single objective optimization, which include linear programming, nonlinear programming, dynamic programming, and metaheuristic/stochastic or multi-objective optimization techniques, in which genetic algorithm, simulated annealing, ant colony, and particle swarm are among the used techniques [30]. These techniques are used in both the design and operational

stages of water supply systems to optimize system component parameters such as pipe diameters, optimal network design, node locations, and optimal pump scheduling [25]. Particularly interesting in the context of WDN optimization appears to be genetic algorithms [31,32], a multi-objective optimization technique that has already been applied to different aspects of optimization in water supply systems to obtain optimal design and operational levels and has demonstrated its capacity to obtain better solutions than classical methods [33–36]. According to Luna et al. [37], although the use of genetic algorithms in water supply systems optimization suffers from a computational burden, it has proven to be most suited to deal with problems of pump scheduling, which can be parameterized to suit the genetic algorithm structure. Other studies have shown a cost reduction of around 30% when genetic algorithms are applied in pump scheduling optimization [38]. More efficient optimization methods have been introduced, such as the nonlinear chaotic honey badger algorithm (NCHBA). Jafari-Asl et al. [39] state that there is a general consensus among the researchers that there is still no single universal optimizer that can efficiently solve all complex problems related to water distribution systems, a fact earlier reinforced by [40] in their review of different optimization techniques.

The main aim of this study was to develop a WEN-based modeling and optimization technique to support the efficient management of water supply networks in dryland areas. The developed approach is tested in a data-scarce area to provide the optimal strategy for assuring water supply while minimizing energy costs. The study is organized as follows: the next section describes the case study area and the data that are used, the third section presents the applied methodology, and then the results, discussion, and conclusions are given.

2. Data and Study Area Description

The selected study area is the town of Lodwar in Turkana County, Kenya (Figure 1). The town is in the downstream part of the Turkwel River basin, which is characterized by a warm and hot climate with a temperature range between 20 °C and 41 °C and a mean of 30.5 °C. It has an erratic and unreliable rainfall pattern with a mean annual precipitation of 200 mm. Rainfall often results in flash floods, while surface runoff and potential evaporation rates are extremely high due to little vegetation cover in the river basin [41]. The Turkwel River originates from the Uganda side of Mt. Elgon and flows through Lodwar town, eventually draining into Lake Turkana [42]. The water supply source to the Lodwar municipality relies entirely on groundwater abstracted from 11 boreholes with an average depth of 50 m drilled within shallow aquifers along the Turkwel River [7,42,43] and three boreholes within intermediate to deep aquifers of a depth greater than 50 m in Napuu.

Lodwar municipality's population growth rate is estimated as 3.6% annually according to Kenya's population and housing census [44,45], which recorded its population at 58,290 and 82,970 in the years 2009 and 2019, respectively, with a population density of 243 inhabitants per km^2. The town is the regional transport and communication hub of Turkana County and a commercial center with major economic activities of small-scale trading, nomadic pastoralists, basket weaving, tourism, and small-scale farming along the Turkwel River [46].

Historically, Lodwar municipal water services have been provided by different agencies such as the Catholic Diocese of Lodwar and other non-governmental organizations that sponsored the drilling, equipping, and construction of water supply infrastructures for different zones within the town. The work finished around the year 2007 without a clear as-built network map [47]. Therefore, an update of the existing network map was necessary to implement the analysis (as explained in Section 3.1). The main water user category is domestic, with a small percentage of commercial and industrial activities. The area is divided into eight supply zones supplied by 14 boreholes with an estimated total daily demand of 2445 m^3, which varies with the seasons [48] (Figure 1d). The total network storage capacity is 1249 m^3 and the network node elevation within the area covered by the network ranges from 487 m a.s.l. to 547 m a.s.l. Water is pumped from the boreholes to

raised steel and masonry tanks located at higher elevations within the supply zones and distributed to consumers via gravity. The pump setup is a hybrid of solar photovoltaic and grid electricity, but the utility occasionally fails to pump water due to disconnected grid electricity, which results in unsettled bills. Out of the eight supply zones, a detailed analysis was carried out in just one of them, namely the Nakwamekwi supply zone (Figure 1a). The procedure can be replicated in other supply zones or in other cities.

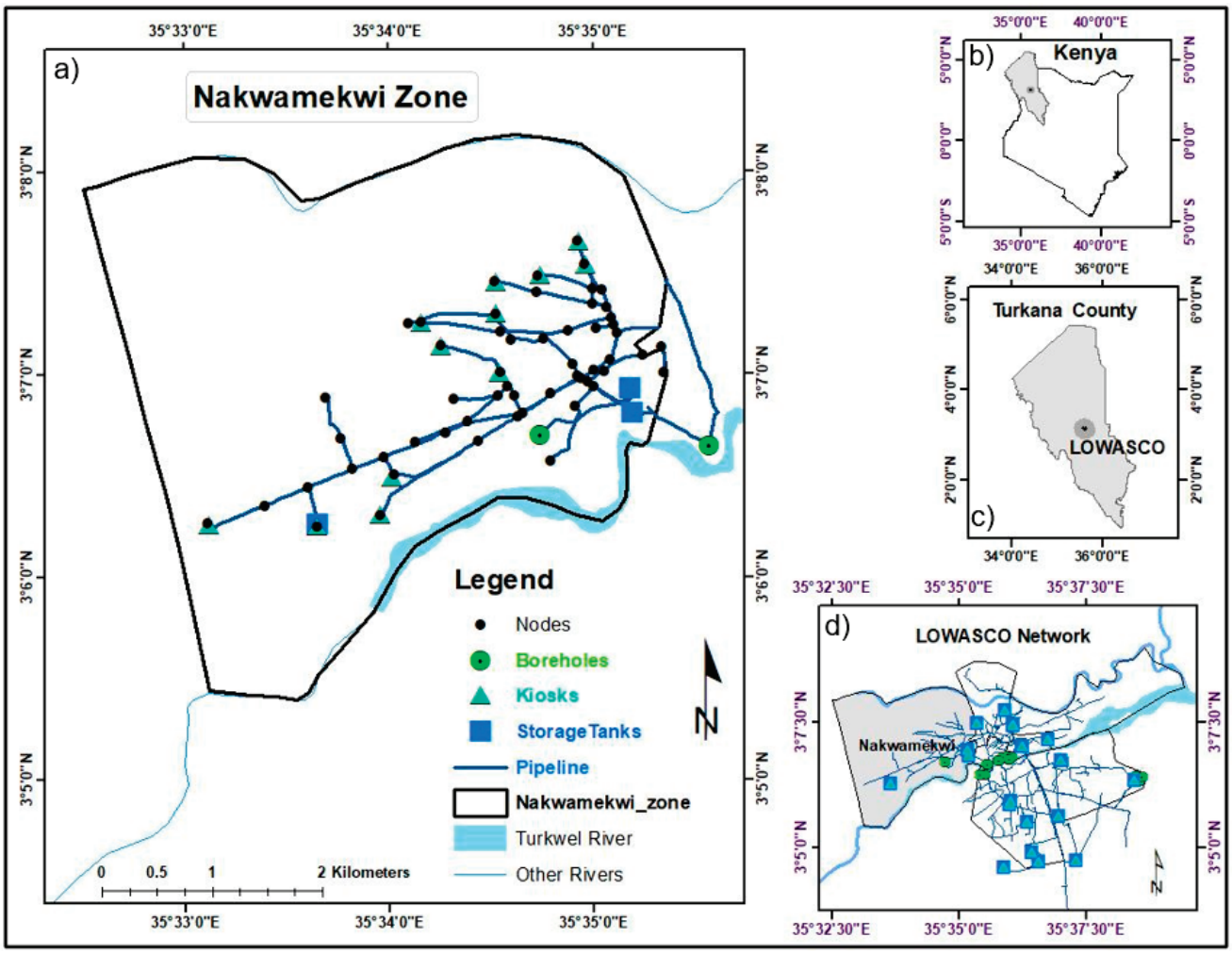

Figure 1. Study area location. The water distribution network of the town of Lodwar (**d**) is managed by the Lodwar Water and Sanitation Company (LOWASCO). The town of Lodwar is in Turkana County (**c**) in the northwestern part of Kenya (**b**). The methodology to retrieve the water distribution network data was applied to the entire town, while the optimization procedure was conducted in the Nakwamekwi supply zone (**a**).

The Nakwamekwi supply zone has an approximate total network length of 24 km and a daily demand of 583 m^3. The area is served by two boreholes and two masonry storage tanks with a total capacity of 322 m^3 at elevations of 520 m a.s.l. and 509 m a.s.l., respectively. Pumps are operated in a hybrid system of solar photovoltaic and grid electricity, which are operated for 20 to 24 h per day. The water user categories are shown in Table 1.

Water consumption follows a diurnal pattern, with the peak hours between 06:00 and 09:00. and between 18:00 and 21:00. Node elevations within the analyzed supply zone range from 490 m a.s.l. to 514 m a.s.l. Table 1 shows the estimated average household size per connection, which is based on the Kenya Housing Population Census 2019 and a demand per capita (liters per day) recommended by the Kenya Ministry of Water and Irrigation Water Supply Services Design Manual 2005 for dryland urban settings.

Table 1. Nakwamekwi active water connections in 2021 (Source: WASREB, [49]).

Service Type	No. of Connections	Estimated Average Population Per Connection	Total Population	Per Capita in Liters/Day	Daily Demand in Liters
Residential	1309	5	6545	75	490,875
Water kiosk	12	50 households ×5	3000	20	60,000
Standpipe	20	10 households ×5	1000	20	20,000
School/Institution	5	300	1500	5	7500
Business/Commercial	10			500	5000
Total	1356		12,045	620	583,375

3. Methodology

The developed methodology is mainly composed of two phases. Firstly, a comprehensive characterization of the network was realized through surveys and GIS data elaboration (Section 3.1) to provide the required input for the model used for WDN simulation and optimization (Section 3.2). The latter section is subdivided into three main blocks: the water network optimization (Section 3.2.1) to determine the changes needed in the WDN to assure its proper hydraulic functioning; the energy optimization (Section 3.2.2) to determine the optimal pumping schedule to minimize energy consumption; and the water–energy nexus (Section 3.2.3) where the outputs of the previous two sections were combined to obtain the final WDN management strategy.

3.1. Water Network Distribution Mapping

Due to the inadequate data on the utility's water supply infrastructure, a series of surveys was organized to update the existing network map referring to 2014. Baseline data for hydraulic analysis were gathered for one month through field measurements, observations, and administration of questionnaires. The data collected are network node elevation, pipe lengths, materials and diameters where applicable, tanks' locations, elevations, and dimensions, flow velocities, and flow rates in exposed pipes and borehole drawdown. In some cases, where the nodes were unclear, an institutional memory of a former employee of the utility was solicited, as indicated in Figure 2, during physical mapping and subsequent measurements.

The information derived from the surveys was then combined with a scanned and digitized topographic map of the 2014 water supply network in a GIS environment (i.e., QGIS) to update the map to reflect the status as of 2021. QGIS tools were used to validate the spatial network data. Particularly, node elevation has been validated with a Digital Elevation Model and pipe length has been measured using the software.

3.2. WDN Simulation and Optimization

Once the WDN has been obtained, its optimization has been achieved following the methodology shown in the flowchart in Figure 3. The process is divided into three main components.

In the water network optimization (blue part of Figure 3 and Section 3.2.1), the process starts by creating a schematic diagram of water supply network elements in the EPANET 2.2 model [50] and characterizing each element using field data. The aim is to provide a coherent representation of the present situation, including the main WDN flaws. Indeed, the WDN had been changed during the recent year, adding new network elements without any hydraulic verification and determining inadequate supply at various points of the network.

The energy optimization component (yellow part of Figure 3 and Section 3.2.2) has the objective of finding pumping patterns with the lowest cost among a population of

randomly generated patterns derived from a genetic algorithm, considering some initial pumping schedules as a constraint and the variability of the pumping cost during the day.

The water–energy nexus component (green part of Figure 3 and Section 3.2.3) consists of testing the selected pumping pattern in the EPANET model to verify that each node in the WDN is served in each time step, without the pumps working 24 h a day.

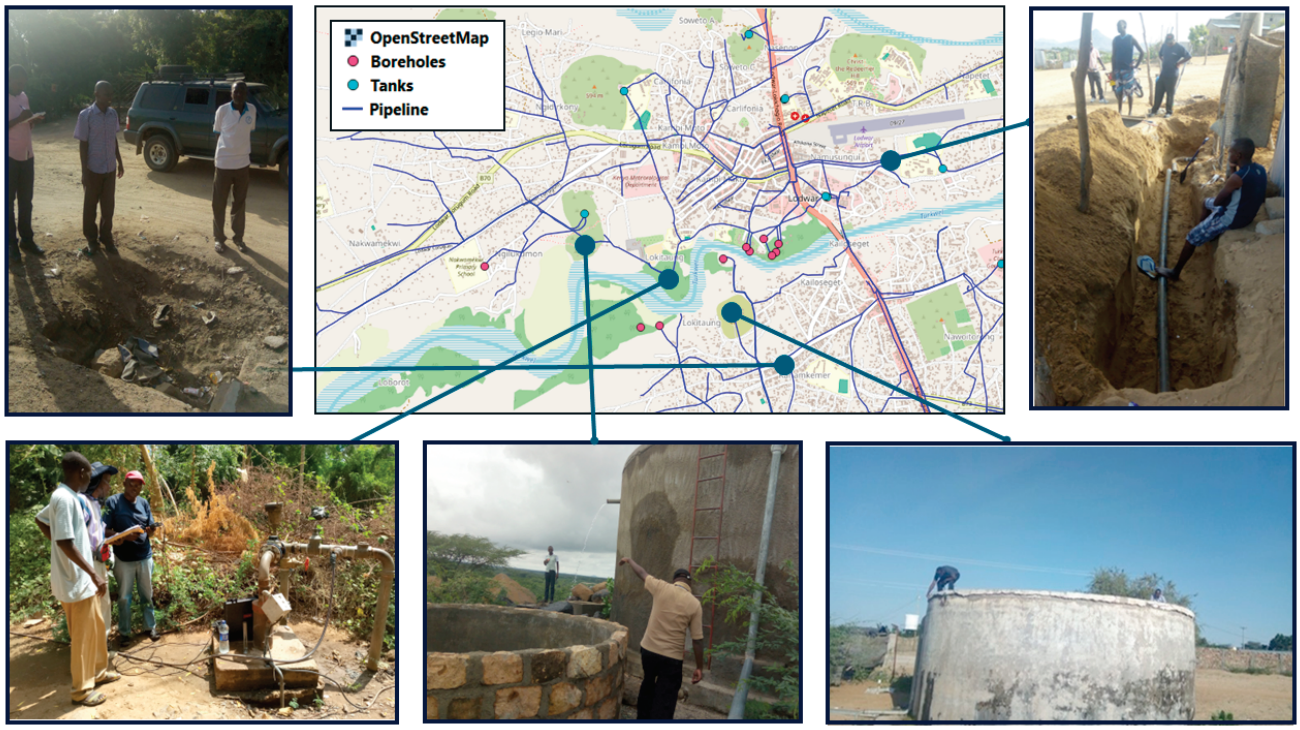

Figure 2. Water distribution network mapping conducted through local surveys. The photos show some elements (tanks, pipes, boreholes) that have been measured and localized since there was no clear knowledge about the water distribution network.

3.2.1. Water Network Optimization

The water network optimization can be conducted using the EPANET 2.2 model. In this study, only the Nakwamekwi water supply zone has been optimized, following the described approach (Figure 4).

The EPANET model was constructed using the field data, which were obtained from the WDN mapping (Section 3.1). In the surveys, all the essential network elements and their properties were collected (Table 2).

Table 2. EPANET elements and required inputs for model development.

Element Name	Properties Set
Junction (Node)	id, elevation, base demand, demand pattern
Reservoir	id, description, total head
Tank	id, elevation, initial, minimum and maximum level, and diameter
Pipe	id, start and end node, length, diameter, roughness
Pump	id, pump curve, pattern
Valve	id, start and end node, diameter, type, fixed status
Label	Text, font

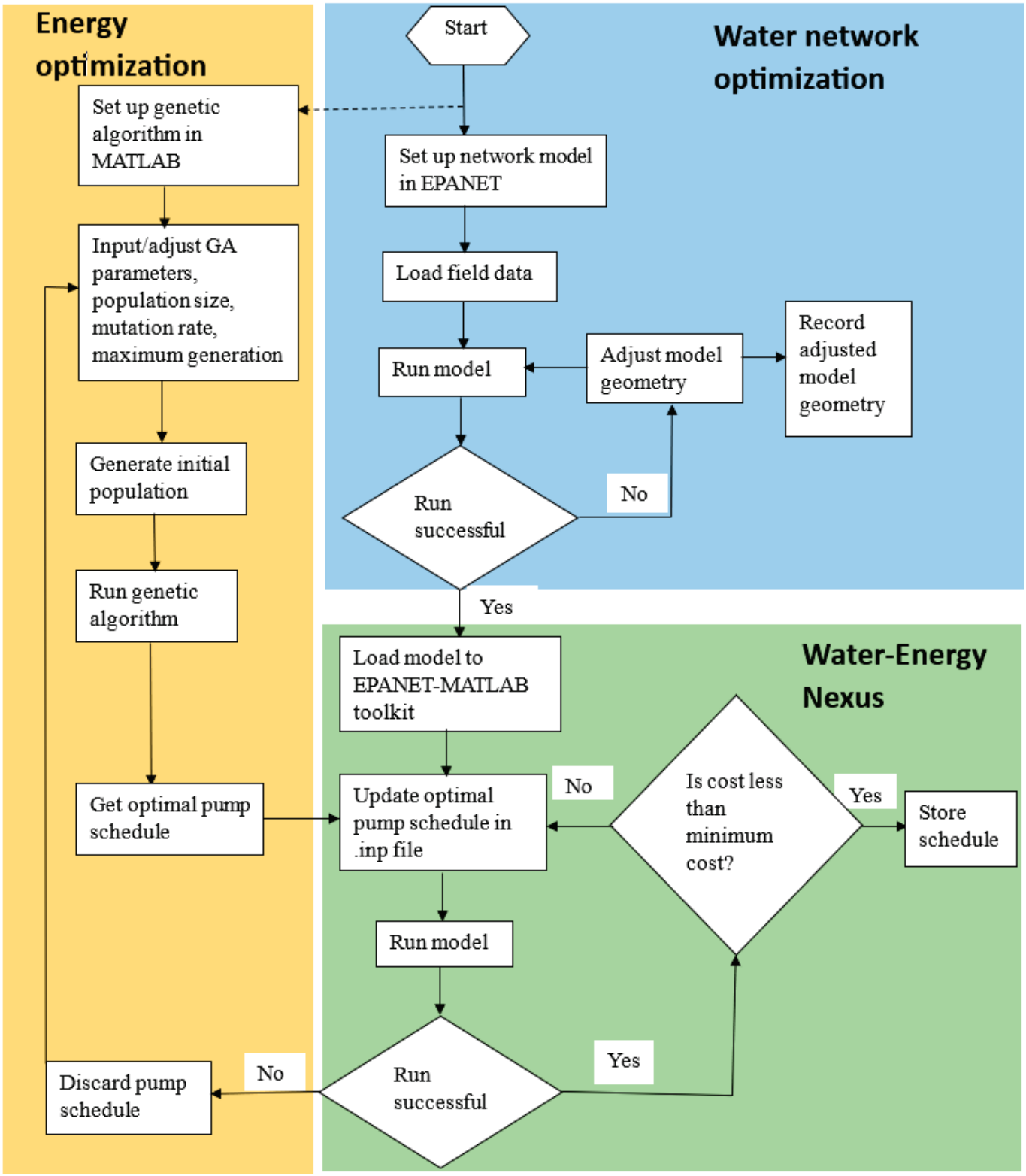

Figure 3. Flowchart of the methodology, which is divided into three parts: water network optimization to improve the reliability of the actual distribution network; energy optimization to obtain pumping schedules with low costs that are tested in the EPANET model; and water–energy nexus.

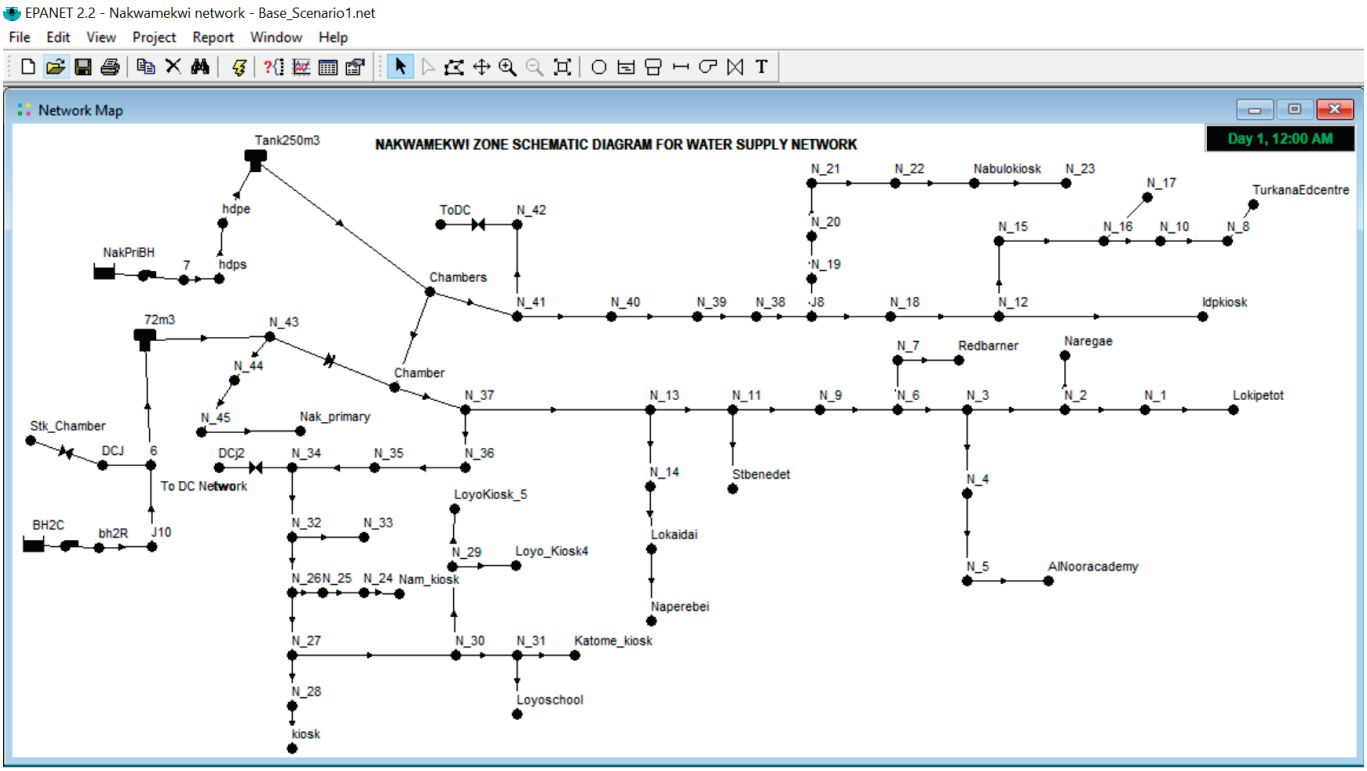

Figure 4. Schematic diagram of the water supply network for the Nakwamekwi zone in the EPANET model.

In particular, the pipe roughness of 110 for old steel pipes and 150 for new PVC pipes was used to factor in friction losses, while at the nodes suspected to experience leakage, proportionate values of emitter coefficients were set. Water losses due to pipe leakages were simulated by setting up emitter coefficient properties of the pipes to reflect the current state from the following equation:

$$Q = kP^n \tag{1}$$

where Q is the leakage flow rate, k is the emitter coefficient, P is the pressure in a given node, and n is the pressure exponent. Following the general guidelines for setting coefficient values in EPANET, k has been set following this rule: (i) from 0.001 to 0.01 for small cracks or pinholes in the pipe, (ii) from 0.01 to 0.1 for moderate-sized holes or large cracks, and (iii) from 0.1 to 1.0 for significant raptures or pipe breaks. For very large bursts within sections of the network, the value of k varied between 1.0 and 10.0 to simulate the actual situation on the ground. The actual water demand in each node was evaluated using the Voronoi polygon of distribution nodes and by calculating the population to be served in each area based on the population density in each polygon. The population data in the area were provided by LOWASCO [45,47]. Since the population and the demand do not have a season in which some months require more water than others, only a representative day was modeled in EPANET. Nonetheless, water demand fluctuates during the day, and this has been considered with the demand pattern.

Since the WDN in the town of Lodwar currently has problems in the distribution of water, the model run in EPANET was not successful due to some negative pressures. Therefore, the WDN has been optimized with an iterative process, in which some elements have been changed until a successful run is obtained, which is an indication of a reliable network. Therefore, the results of this iterative process (blue part of the flowchart in Figure 3) are new WDN geometry.

3.2.2. Energy Optimization

The optimization of a water distribution network can be achieved by reducing the energy costs associated with a given water volume or by increasing the water availability in the network with the same energy. For instance, the WDN can be optimized by increasing water availability through reducing leakages within the supply network by employing leakage management strategies [51]. In this study, the optimization was done by just looking at the energy cost of pumping in a hybrid system.

To optimize energy consumption, pumping schedules with the fewest number of pumping hours possible must be found. Daily pumping patterns can be thought of as a vector of 24 elements (one for each hour), with 1 and 0, respectively, for pumps being on or off. A genetic algorithm (GA) was set up in MATLAB R2024ato create random pumping patterns from an initial population, which was used as a constraint. Indeed, a completely random generation would create patterns that are not reliable with very few hours of pumping, causing network disconnection, i.e., negative pressure in some nodes. However, it is not necessary to explore the entire search space of 2^{24}, i.e., 16,777,216, daily pumping patterns, as the few optimal solutions must have at least a minimum number of pumping hours in the day. For this reason, the GA was used instead of a complete random generation to create pumping patterns from an initial population with a given mutation rate. Therefore, the parameters of the GA are initial population, mutation rate, and maximum iteration.

The pumping system is a hybrid of solar photovoltaic and grid electricity. According to the utility's estimates, the cost of running pumps on solar energy is a quarter of the cost of running pumps on grid energy, and in the existing setup, solar energy is available for 9 h a day for all seasons of the year. The energy cost function $f(x)$ to determine the cost incurred in running pumps per day is formulated as:

$$f(x) = \sum_{i=1}^{Np} \sum_{t=0}^{St} (E_{it} \times T_e) \quad (2)$$

where Np is the number of pumps operating within a supply zone, St represents the number of time steps or the simulation period taken as 24 h for an extended period simulation in this study, and E_{it} is the energy consumption of pump i during time interval t (kWh). This depends on the pump operation status of on/off and varies with the type and specifications of the pump installed in the borehole. T_e is the vector of energy tariff per time step through the simulation period as USD/kWh.

The cost function was evaluated for each generated pattern, and the one with the minimum cost for each run was loaded and tested with an EPANET file ".inp" in an EPANET–MATLAB Toolkit environment developed by Eliades et al. [52] to determine the feasibility of the solutions (see next section).

3.2.3. Water–Energy Nexus

Some of the pumping schedules obtained as described in the previous section may not be reliable, as they may cause negative pressure in the water distribution network. For this reason, the reliability of the generated pumping schedule was conducted using the EPANET–MATLAB toolkit [52], where the optimal pump schedule generated from the genetic algorithm is updated as input.

In case the model run is unsuccessful because of negative pressure in some elements of the network, the model parameters of the genetic algorithm are adjusted, and the procedure described in the previous section is conducted again. If the run in the EPANET–MATLAB toolkit is successful, the pumping schedule is stored. Nevertheless, a successful run is not strictly associated with a fully functioning distribution network, as some schedules can generate positive pressure but still very low pressure among some elements of the WDN. Indeed, according to LOWASCO [53], the common mode of water provision in areas further from the town center is through water kiosks and standpipes requiring a minimum nodal pressure of 2 m [54]. For this reason, the interdependency between water and energy

components was tested through optimal schedules of pumps, which resulted in a reliable water supply at a residual node pressure of more than 2 m in all the nodes during the simulation period for the supply zone.

4. Results and Discussion

4.1. Water Distribution Network Mapping Results

Water distribution network mapping with local surveys has produced an updated network map (Figure 5). This result would enable efficient management due to a clear understanding of the network and establishing hotspots associated with leakages and bursts contributing to the current high non-revenue water of 45% [49]. The realized WDN map captures the updated status of the LOWASCO water supply network as of the year 2021 (Figure 5). Three new boreholes, a steel storage tank of 300 m^3 in capacity, and an HDPE rising pipe of 6-inch diameter were added to the Nawoitorong supply zone. In the Nakwamekwi supply zone, one borehole was added to the network, while a borehole and its rising main pipes were removed from the network after having been washed away by floods in the year 2019 [48].

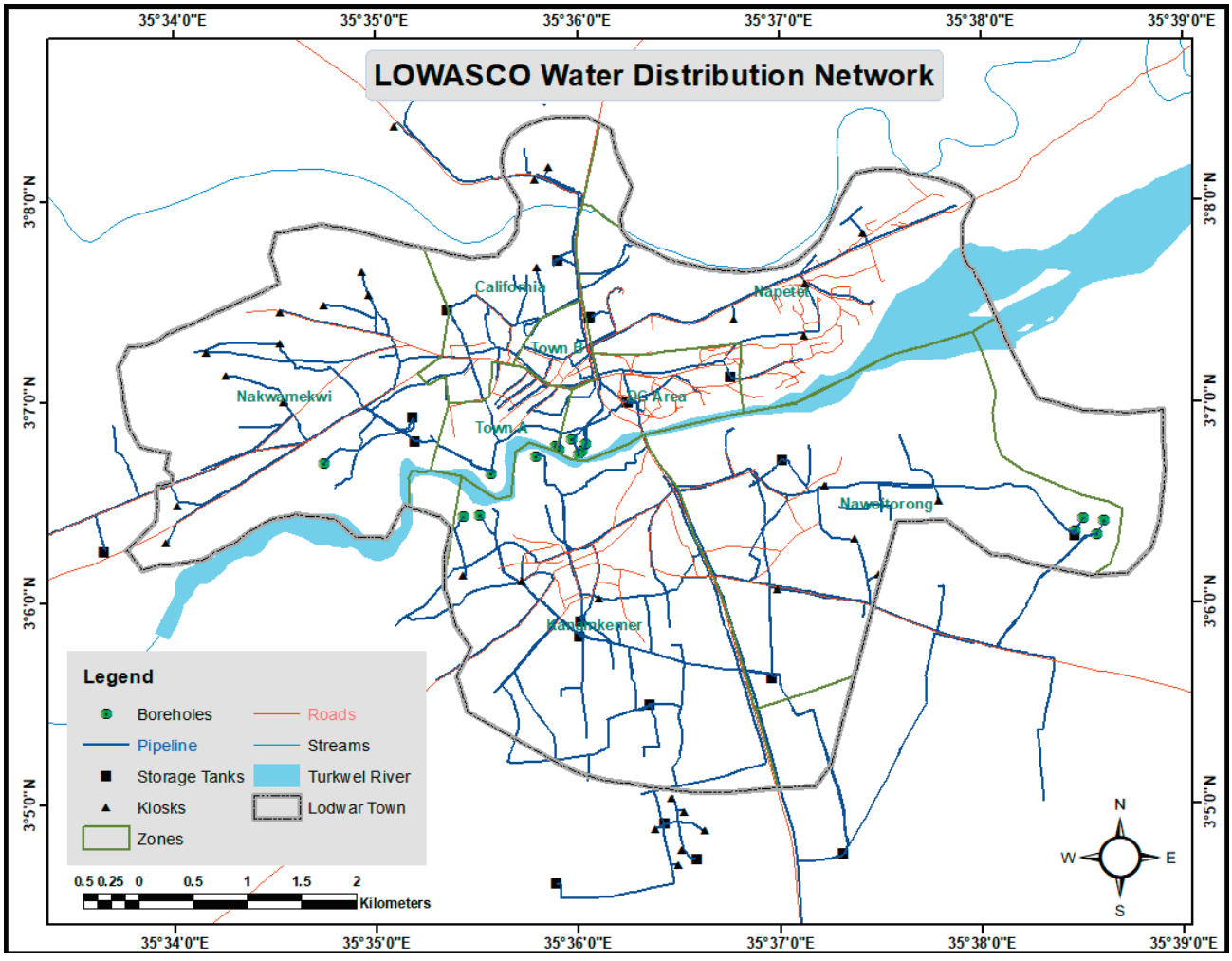

Figure 5. LOWASCO water supply network map of 2021.

The network shown in Figure 5 is for the whole Lodwar municipality. The optimization results of the Nakwamekwi supply zone are shown in the following sections.

4.2. Water Distribution Network Optimization Results

Nakwamekwi's current network status is shown in Figure 6, which illustrates network node elevations in green and pipe diameters in blue in the EPANET interface. Figure 6 represents the real status of the network, which experiences high negative pressure because of the low elevation of the tank capacity of 72 m^3 at an elevation of 509 m a.s.l. and distribution pipe diameters of 50 mm within the network. The optimized network is proposed to have the masonry tank of 72 m^3 replaced with a steel tank raised to a height of 520 m a.s.l. and replacement of distribution pipes of 50 mm diameter to 60 mm diameter within the supply network, as marked in magenta in Figure 6.

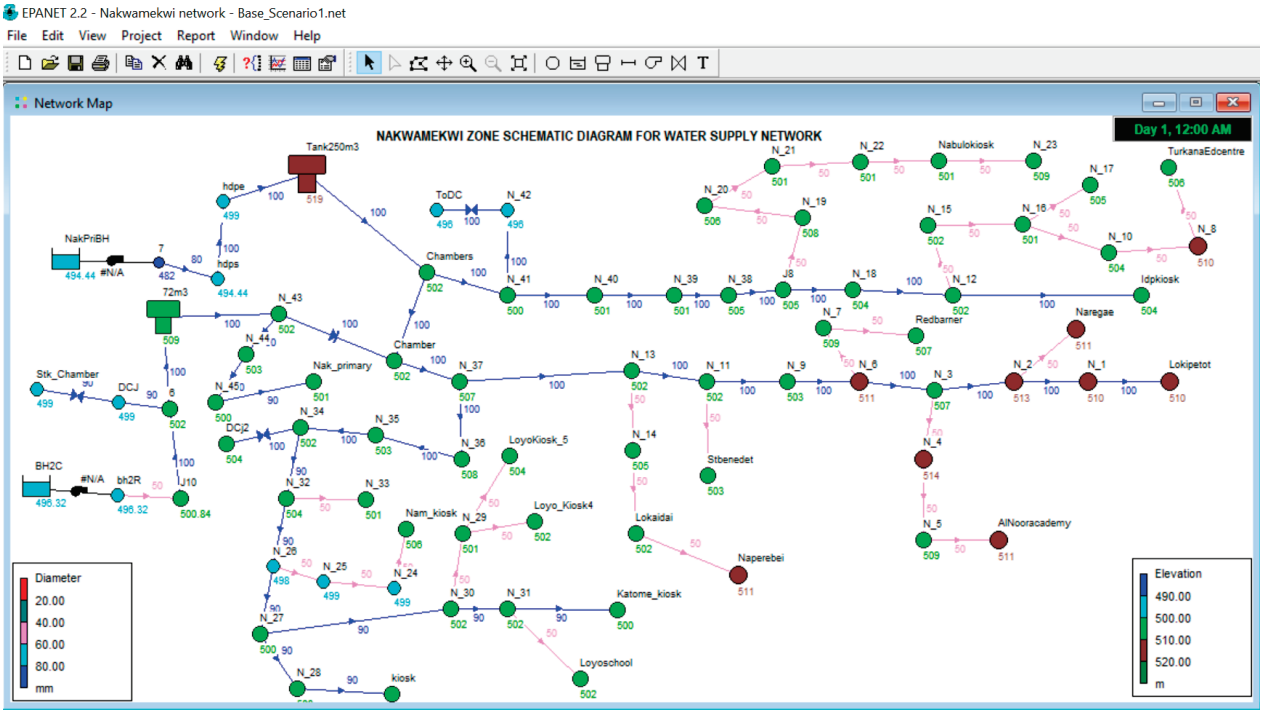

Figure 6. Nakwamekwi water supply network. The diameters of the pipes are shown in blue (100 mm) and magenta (50 mm), while the elevation of the nodes in meters above sea level follows the legend in the bottom-right corners. The modifications done on the water distribution network are the following: the 50 mm diameter pipes (magenta) have been increased to 60 mm, while the 72 m^3 (green) tank was raised by 11 m.

4.3. Water–Energy Nexus Results

Since solar energy is cheaper than grid electricity, an initial pumping schedule, from which the genetic algorithm generates random patterns, is shown in Figure 7, which maximizes peak solar hours by ensuring the pumps are on between 08:00 and 16:00. This finding is supported by the conclusion of Urkmez et al. [55], which showed that in an optimized hybrid pumping system, 66.95% of PV energy is required in order to reduce the cost incurred by grid pumping with the use of stochastic optimization.

Table 3 presents the results of randomly generated pump schedules by the genetic algorithm, illustrating the status of the pump in each hour (on "1" or off "0").

This table presents whether the proposed schedule results in a successful model run in EPANET and the accompanying cost in USD per day for each pattern. Therefore, it shows the reliability of the network based on reaching a minimum pressure in the EPANET simulations. Tao et al. [56] made a similar attempt by coupling genetic algorithms and EPANET simulations to target a balance between economy and reliability. The results indicate that an optimal and cost-effective schedule of USD 82.5 would lead to savings of between 50% and 57% from the current schedule of USD 165 and USD 189.75 when pumps run for between 20 h to 24 h per day. This view of cost saving in water supply

systems through GA and hydraulic simulation to pump schedules is also supported by Atkinson et al. [57], who applied GAs and commercial hydraulic simulation, reaching a reduction of the annual operational cost of almost 20% through better utilization of the off-peak electricity tariff periods for pumping.

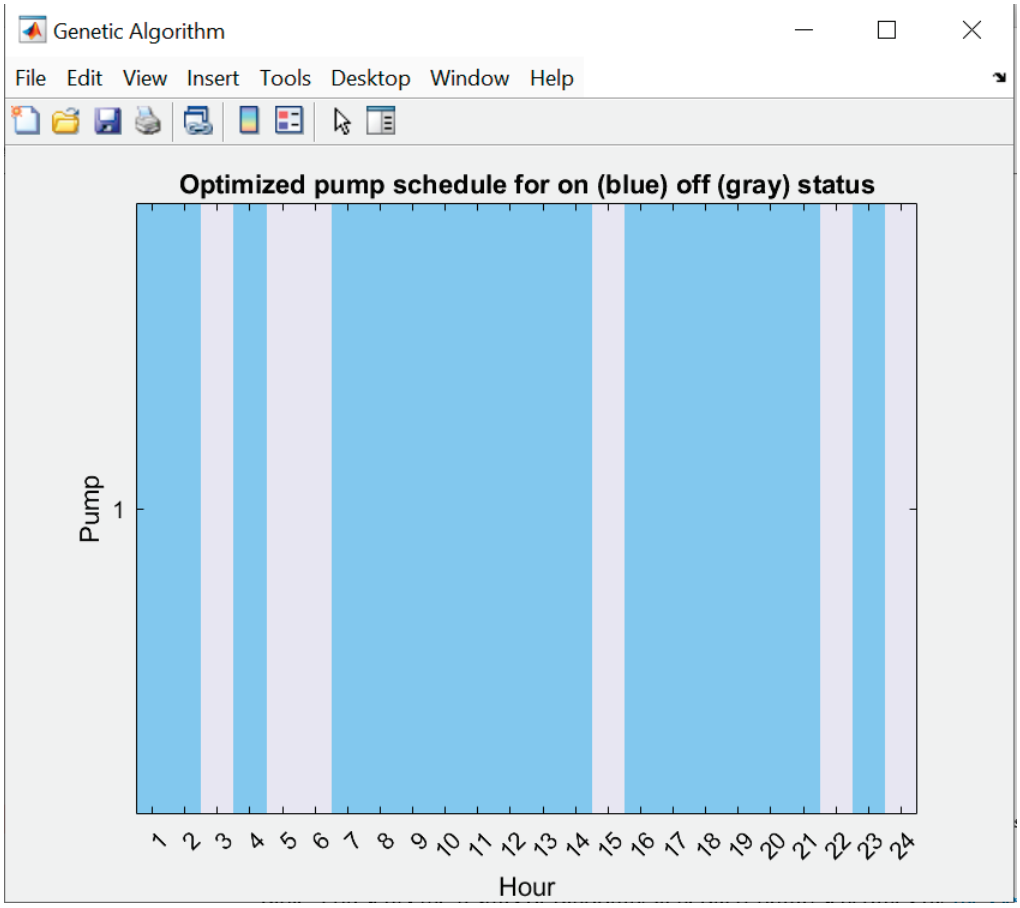

Figure 7. Example of pumping schedule that maximizes energy during solar hours.

Table 3. Sample scenarios of pump schedules randomly generated by a genetic algorithm and tested in EPANET.

No	GA Generated Pump Schedule in 24 h Period of Hybrid Pumping																								Successful Run?	Actual Cost in USD
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
1	0	0	0	0	1	1	1	0	1	1	1	0	0	1	1	1	0	1	1	0	0	0	0	0	Yes	71.5
2	1	0	0	0	1	1	0	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	0	0	Yes	82.5
3	1	0	0	0	1	1	0	0	1	1	1	0	0	1	1	1	1	1	0	1	1	0	0	0	Yes	93.5
4	1	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	Yes	99
5	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	Yes	101.75
6	1	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	0	Yes	112.75
7	0	0	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	Yes	134.75
8	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	Yes	165
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Yes	189.75
10	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	No	24.75
12	1	0	1	0	1	0	0	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	0		No	101.75
13	1	0	0	0	1	1	0	0	1	1	0	1	0	1	1	1	1	1	0	1	1	0	0	0	No	93.5

Different pumping schedules with the same cost can have different results (successful or not), as can be seen by comparing the highlighted schedules in the previous table (Schedules 3 and 5, successful, with Schedules 12 and 13, unsuccessful). Indeed, pumping schedules that follow the water demand pattern have a higher chance of being successful. According to Figure 8, the peak water demand hours are between 4:00 h to 8:00 h and 16:00 h and 20:00 h.

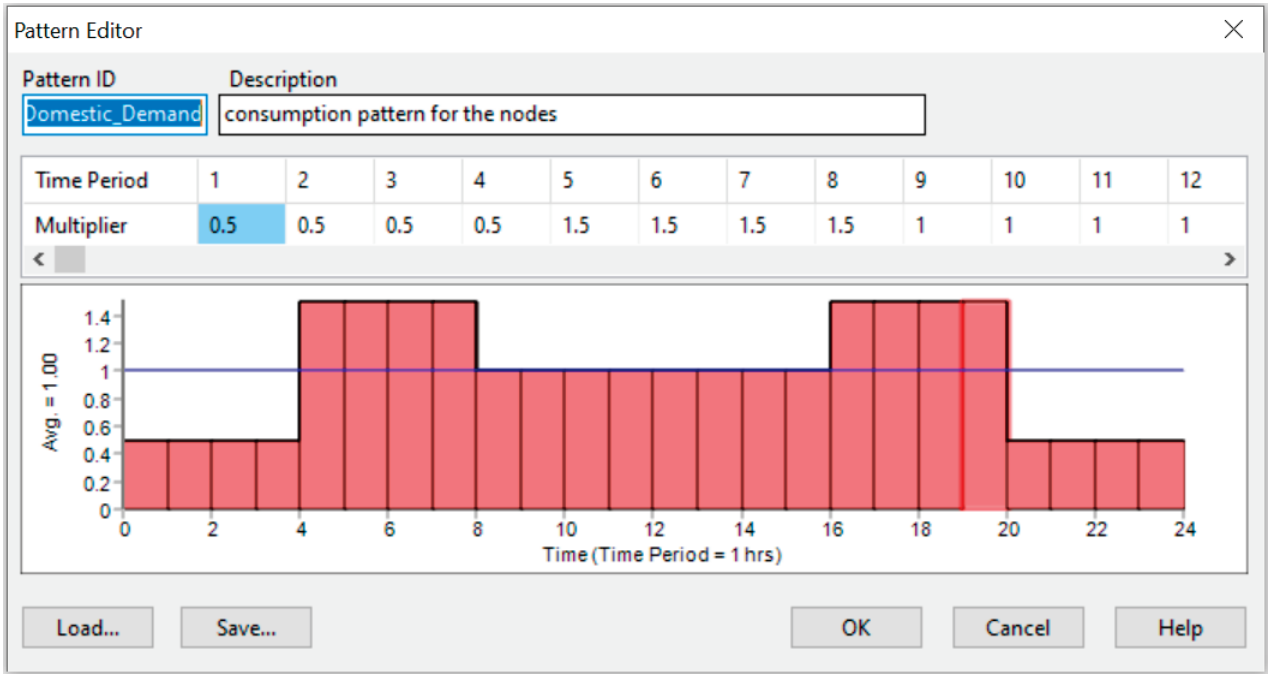

Figure 8. Water consumption pattern for the Nakwamekwi supply zone. The peak of water demand is from 4:00 h to 8:00 h and 16:00 h and 20:00 h.

There are a total of 62 water withdrawal nodes considered within the supply zone. A plot of successful cost schedules against minimum pressure and average pressure within the 62 nodes is presented in Figure 9. Figure 9 illustrates the minimum pressure obtained in a single node during the most critical hours associated with the peak of the water demand on the left, while it shows an average pressure considering all the nodes in the same time steps. The pump scheduling scenarios represented in Figure 9 are the first nine scenarios, also shown in Table 3. Since the scenarios are ordered in the table with respect to the daily cost, the first dot on the left is scenario 1 and the last on the right is scenario 9. The first scenario has one of the lowest costs of USD 71.5 /day and results in a minimum node pressure of 1.85 m during the peak demand hours. Nevertheless, the scenario is not reliable, as it is under the threshold of minimum pressure set by [53,54], i.e., the red dashed line in Figure 9 that crosses 2 m. In all the scenarios the average pressure is above 11 m. Scenario 9 in Table 3 (the last point on the right of Figure 9) relates to the current daily prices for the network, as it represents 24 h pumping in a day. This price is determined by the fact that solar and grid energy cost are respectively, USD 0.25 /KWh and USD 1 /KWh. Since the total installed power is 11 KWh and solar energy is available for 9 h in a day, the total price is USD 189.75 /day. Nevertheless, the minimum pressure in this scenario is 0.7 m above the minimum threshold that is needed, resulting in a higher expense than necessary. Indeed, using the pumping schedule of scenario 2, with a cost of USD 82.5 /day, the WDN is reliable, reducing cost by 57%. The cost could be reduced even more by considering the optimization of the water distribution network by reducing leakages [52]. Moreover, this study optimized the network by considering the actual availability and demand of water in the city of Lodwar. Therefore, future development will consider improving the methodology by considering leakage management, climate change, and population growth

for a more in-depth analysis that can also guarantee the future reliability of the water distribution network.

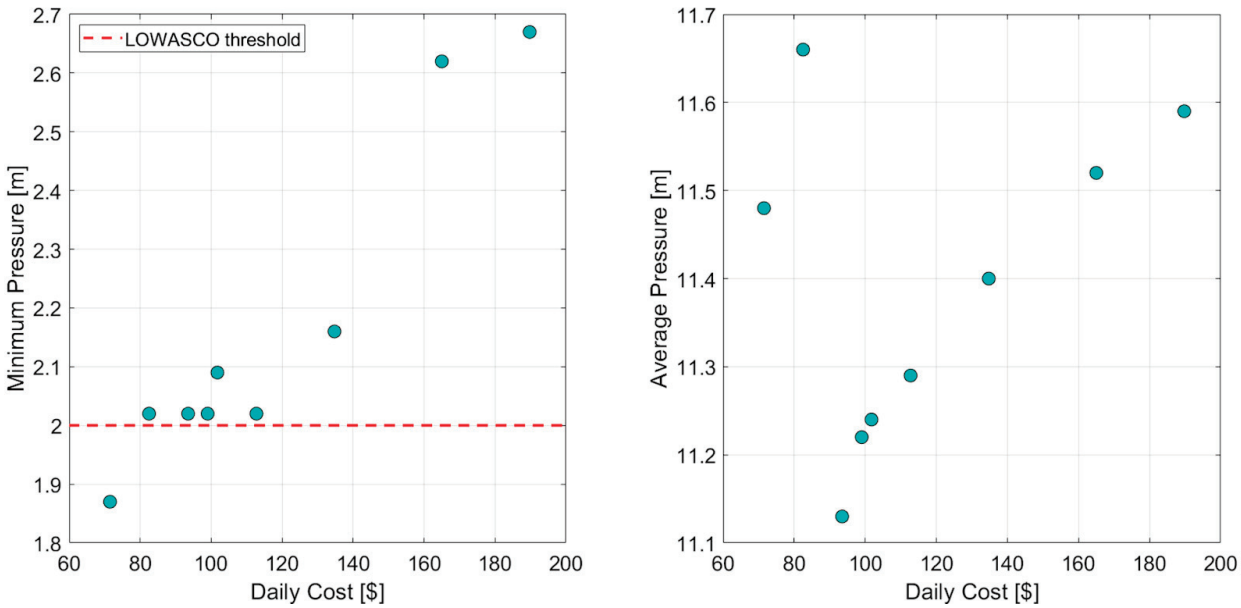

Figure 9. Network nodal pressure against daily pumping cost scenarios. The minimum pressure obtained in a single node during the peak of the water demand is shown on the left with the LOWASCO threshold of 2 m, i.e., the minimum pressure requirement in the network. The average pressure considering all the nodes in the same time steps is shown on the right.

5. Conclusions

This work presented a methodology to optimize a water distribution network that allows the distribution of water at the minimum cost of energy. Specifically, the procedure is based on a genetic algorithm that creates pumping schedules coupled with a hydraulic simulator EPANET to test the reliable ones. This study illustrates the possibility of enhancing water supply infrastructure in dryland urban settings by integrating the principles of the water–energy nexus, as the results have shown how the water distribution network can supply water by saving 50% of the energy with respect to the current situation. Moreover, this study demonstrates the potential of using a water–energy nexus approach to optimize the water supply infrastructure in a data-scarce dryland urban setting. Indeed, this work used almost no information except for that which has been retrieved from local surveys and uses an open and freely available hydraulic model. Therefore, this study could represent a model for other studies that want to replicate the approach in areas with a lack of information. The best configuration of the model, i.e., the selected pumping schedules, also allows a reduction in the average pressure on the network, which implies a decrease in water losses due to leakages as well. The water–energy nexus is a promising approach that can be easily followed with data scarcity constraints. This research highlights the possibility of developing optimization frameworks to enhance the sustainability of water infrastructure in dryland urban settings from a holistic nexus-based framework.

Optimizing energy and water in dryland areas is fundamental to increasing the resilience of communities and adapting them to the new challenges of the future when the population will increase in a changing climate.

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The Role of Scenario-Building in Risk Assessment and Decision-Making on Urban Water Reuse

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Abstract: Urban resilience and water resilience are both increasingly relying on urban non-potable water reuse under the context of the Climate Emergency, but sound risk assessment is lacking. Compared to the state of art, the proposed framework for health risk assessment and management of urban non-potable water reuse includes (i) an additional step for establishing the context and (ii) the risk identification step being extended to introduce a description of the activities from which the hazard exposure scenarios may be built. This novel scenario-building process allows for a clear and comprehensive risk description, assessment, and treatment. The model of risk management is structured around three primary components: the decision-makers, i.e., the municipal services and the population at risk (users and workers); data elements relevant for the risk management process (reclaimed water quality, hazards, hazardous events, sites where exposure can happen, exposure routes, and activities developed by the population at risk and their vulnerabilities); and the links between the decision-makers and these elements and between the elements themselves. Its application in a representative case study shows that the framework comprehensively guides decision-making and communication to relevant stakeholders. From this practical exercise, the main recommendations were derived for risk mitigation by the municipal risk manager and the park users.

Keywords: decision-making; communication; non-potable water reuse; risk assessment; risk management; risk perception; urban resilience

1. Introduction

Urbanization and climate change are two closely related phenomena that exacerbate water scarcity (i.e., a lack of freshwater to meet the water demand) in the cities, affecting the health and wellbeing of urban residents, urban environmental quality, and socioeconomic development [1]. In the context of urban planning, urban resilience has become an important strategy to tackle climate change [2]. According to Zeng et al. [3], urban vulnerabilities can be addressed by increasing cities' (i) adaptive capacity (based on water, health, food, and education), (ii) absorptive capacity (via urban green space, protective infrastructure, access to transportation, and community support), and (iii) transformative capacity (using multi-stakeholder collaboration, communication technology, and government emergency services).

Wang et al. [4] assessed "clean-water scarcity" in terms of the availability of surface water with an acceptable quality, focusing on nitrogen pollution in rivers. These authors estimated a triple increase in the number of global river basins with water scarcity in 2050 when comparing quantity and quality-induced scarcity with quantity-induced scarcity. To decrease the pressure on freshwater supplies, it is important to support the transition to smart and more integrative water management. Water reuse is an important adaptation measure for tackling climate change because it is a rainfall-independent water source and reduces the discharge of contaminants into freshwater, including nutrients associated with eutrophication phenomena, i.e., phosphorus and the earlier-mentioned nitrogen.

Safe water reuse requires the existence of a comprehensive risk assessment and management process and benefits from articulation with existing sustainability policies or strategies. Figure 1 illustrates how the water reuse risk assessment framework contributes to urban resilience, which is crucial for improving urban sustainability.

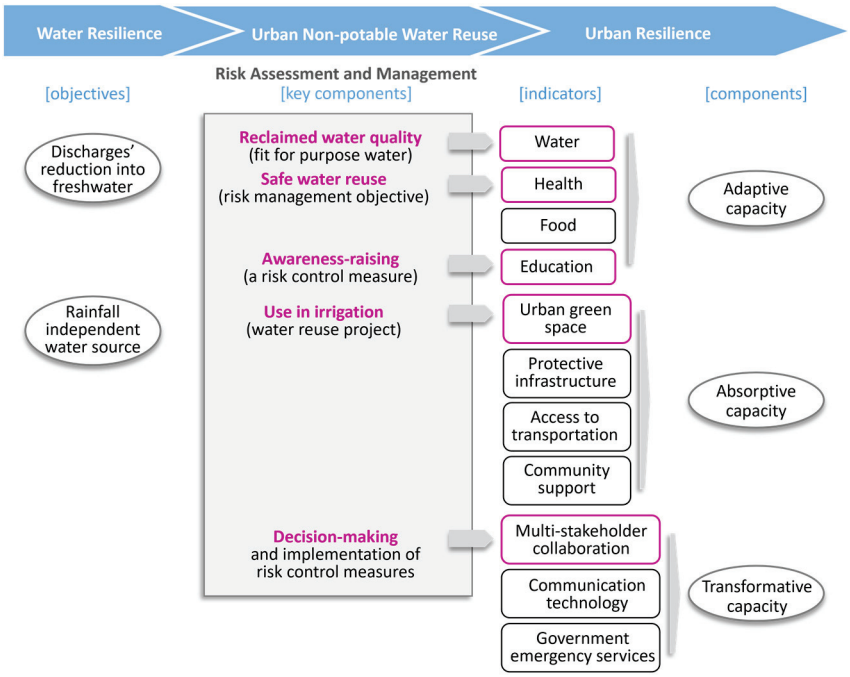

Figure 1. How risk assessment and management of urban non-potable water reuse contributes to urban resilience (urban resilience indicators and components obtained from [3]).

While water reuse in agricultural irrigation has been recognized as a viable alternative for water supply [5–7], the integration of reclaimed water into the urban water supply has not reached its potential [8]. Water scarcity has been a catalyst for water reuse around the world, but, where there is no perceived severe water scarcity, there are few municipal reuse projects of meaningful scale [9]. This situation is becoming less and less sustainable in the context of the Climate Emergency. It is therefore necessary to prioritize water reuse at the municipal scale to promote a systemic change in water systems [10].

In contrast to a generally positive appreciation of water reuse as a possible solution for water supply, a usually negative public perception based on concerns related to risk, lack of trust, and cultural factors has hindered the implementation of various water reuse projects [9,11]. To solve this issue, scientists can contribute by simplifying the discussion around risk to enable informed decision-making on water reuse [12]. According to Durkin et al. [13], transparency, integrity, and stakeholder engagement should be the guiding principles for addressing concerns related to water reuse and recycling practices.

Understanding and managing risk, and communicating it in practice, is a complex process that should be carried out using clear and generally accepted procedures. The ISO, the International Organization for Standardization, has enabled consensus among global experts covering almost all aspects of technology, management and manufacturing. In the domain of risk management, two relevant international standards were published in 2018: the ISO 31000:2018 [14], which provides guidelines for risk management and was developed by the technical committee ISO/TC 262—Risk Management, and the ISO 20426:2018 [15], which provides guidelines for health risk assessment and management for non-potable water reuse and was developed by the technical committee ISO/TC 282—Water Reuse. The principles of the latter are embodied in the regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on the minimum requirements for water reuse [16].

ISO 31000:2018 (reviewed and confirmed in 2023) encompasses a generic approach for the management of risks. This standard provides a set of principles for guiding effective risk management; it also provides recommendations for establishing a risk management framework and a risk management process. According to ISO 31000:2018, risk is "the effect of uncertainty on an organization's ability to meet its objectives". By making the role of objectives explicit, risk management is presented as the activity of anticipating deviations from the plan and implementing corrective actions for achieving objectives despite uncertain futures events.

ISO 20426:2018 (reviewed and confirmed in 2023) provides guidelines for the assessment and management of the health risks related to non-potable water reuse. The risks are caused by potentially occurring pathogenic organisms when using reclaimed water and/or during the production, storage, and transportation of reclaimed water. Reclaimed water can be produced from different sources (raw sanitary sewage, treated municipal wastewater, industrial wastewater, and stormwater potentially influenced by sewage). Risks thus result from the combination of "the magnitude of consequences and the likelihood that those consequences can happen", where "consequence" refers to potential adverse health impacts of hazard exposure scenarios, "likelihood" indicates the probability of occurrence of a hazardous event, in a certain period, with potential harmful effects, and risk scenarios are set in terms of the occurrence of hazardous events (ISO 20426:2018).

In the context of urban non-potable water reuse, other risk assessment approaches can be considered for enhancing the scenario-building process. The Framework for Cumulative Risk Assessment [17], for instance, integrates a clear framework for organizing and analyzing information about the combined effects of exposure to multiple environmental stressors. In the first of three sequential phases, the development of a conceptual model (with the identification of stressors, health or environmental effects, and relationships among various exposures and effects) and an analysis plan (including data needs, selected approaches, and expected result types) facilitates the understanding of the risks by the decision-makers and stakeholders [18].

In essence, the uncertainty or variability in risk estimates is assessed by two means: a qualitative approach and a quantitative approach [19]. The first is based on data judged by the risk assessors, and the second is based on deterministic or probabilistic data [20].

Qualitative risk assessment involves estimating the potential risk using increasing relative scales to represent the magnitude of consequences, the likelihood of occurrence, and the combination of impact and likelihood [15]. Quantitative microbial risk assessment is a mathematical approach for estimating risk posed by pathogens to human health; it is commonly performed to model possible risks in case of potable water reuse schemes [21]. It is important to note that qualitative risk assessment, like the one presented in ISO 20426:2018 [15], is often considered a semi-quantitative risk assessment (e.g., [22]). Even if the categorical labelling is based on a numerical definition (e.g., 10^{-3} and 10^{-4} probability of occurring in a year [20]), the selection of a category still depends on the judgment of the risk assessor. This view is aligned with Revitt et al. [23] and Vidottti et al. [24], who developed qualitative approaches for assessing the risk of non-potable water reuse in agricultural irrigation based on numerically described ordinal scales.

According to ISO 20426:2018, qualitative risk assessment is the most appropriate and economically feasible methodology for most non-potable reuse projects, whereas quantitative risk assessment should be limited to water reuse schemes with a "very high" health risk. This in line with Callahan and Sexton [25], who consider the qualitative approach for cumulative risk assessment as a practical solution to overcome the problems of complexity and data deficiencies and to improve the understanding about the nature and magnitude of risks.

Though it is a function of magnitude and likelihood [14,15], risk is often perceived only in terms of the magnitude of the consequences, even if these are highly unlikely [26]. It is essential for risk managers to understand the reasons for this type of risk amplification by the decision-makers and other stakeholders [27]. The qualitative risk assessment process,

by describing how certain action developments may affect compliance with safe water reuse, can be instrumental to improving risk perception. This is particularly relevant in cases of municipal water reuse projects, and our aim is to accomplish this through a comprehensive scenario-building process.

The aim of this paper is to highlight the potential of the risk assessment process for facilitating the implementation of a sound risk management and increasing the transparency of the decision-making process in the context of urban non-potable water reuse. A framework for the health risk assessment of urban non-potable water reuse is proposed and applied in a case study. The scenario-building results and their contribution to decision-making are discussed.

2. Materials and Methods

2.1. Risk Assessment Framework

As previously mentioned, ISO 31000:2018 and ISO 20426:2018 provide similar structured approaches for understanding and managing risk, as presented in Table 1.

Table 1. Main aspects of the risk assessment and management approaches in ISO 31000:2018 and ISO 20426:2018.

Risk Management Process (Based on ISO 31000:2018)	**Health Risk Assessment and Management for Non-Potable Water Reuse (Based on ISO 20426:2018)**
Scope, context, and criteria (clause (c.) 6.3) Definition of objective(s) Identification of relevant stakeholders Definition of risk tolerability criteria	[Although not included in ISO 20426:2018 shown in Figure 1, c. 4.2 presents the scope and c. 4.3 presents the context and the objective, i.e., safe water reuse]
Risk identification (c. 6.4.2) Identification of uncertain future events that may have an impact on the achievement of the objectives	Identification of hazard and hazardous events (c. 5.1) Identification of hazards (pathogenic organisms) Identification of hazardous events (detected at the points of use of reclaimed water)
Risk analysis (c. 6.4.3) Rating the potential impact of each risk and its likelihood of occurrence Determination of the risk severity via the combination of these factors	Assessment of risk levels (c. 5.2) Qualitative risk assessment: combined evaluation of the magnitude of consequences (potential adverse health impacts) and the likelihood that those consequences can happen
Risk evaluation (c. 6.4.4) Determination of the tolerability of each risk for risk treatment definition	
Risk treatment (c. 6.5) Decision on risk mitigation for reducing the level of residual risk to an acceptable level	Risk management with risk-control measures (c. 6.1, 6.6, 6.3.1, and 6.4) Decision on risk-control measures: source control (preventing the entrance of hazards in source water); treatment control (removing hazards from source water); and end-use control (reducing exposure) Definition of a multiple-barrier approach for a reliable risk management
Monitoring and review (c. 6.6) Measuring risk management performance against indicators	Monitoring (c. 6.3.2, 6.3.3 and 7) Ensuring the continuous provision of safe water reuse
Communication and consultation (c. 6.2) Engaging stakeholders Obtaining information for reducing uncertainty	Training and documentation (c. 6.1) For improving the fulfilment of the risk-control measures determined in the risk management plan
Recording and reporting (c. 6.7) Documenting risk management	Review (c. 6.1) For recording the evidence of compliance and for planning continuous improvement

The ability to communicate the potential risks to human health to the population at risk is crucial in the case of urban water reuse because the exposure to hazards may be perceived as involuntary. To facilitate the identification of the situations where this exposure can happen, the framework includes in the scenario-building a description of regular activities developed on the green area irrigated with reclaimed water and during

the operation of the water reuse system (reclaimed water treatment and distribution). This approach is aligned with Månsson et al. [23], who observed in an empirical study that the inclusion of a supporting narrative with contextual information facilitated the risk assessment as well as the decision-making about risk-control measures.

Figure 2 illustrates the proposed framework for health risk assessment and management of urban non-potable water reuse. Compared to ISO 20426:2018, it includes an additional step for establishing the context, and the risk identification step is extended to introduce a description of the activities based on which the risk scenarios may comprehensively be built.

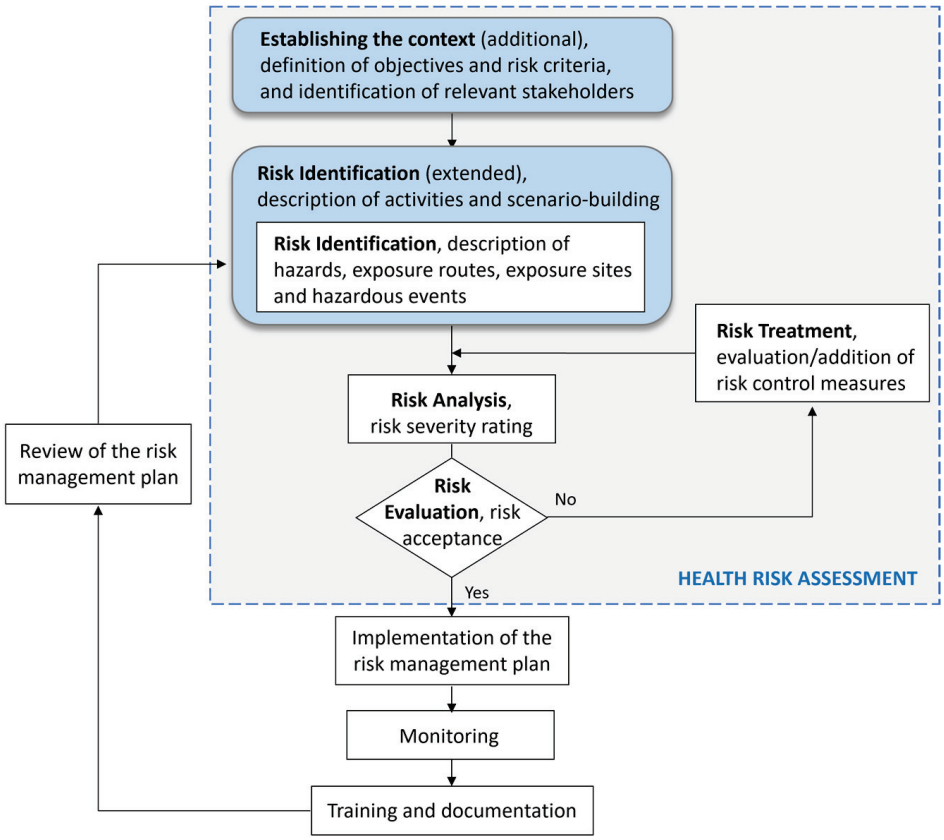

Figure 2. Proposed health risk assessment of urban non-potable water reuse (adaptation of Figure 1 of ISO 20426:2018, adding a step for establishing the context and extending the risk identification scope—blue boxes).

Besides ISO 20426:2018, there are other ISO standards relevant to risk management of urban non-potable water reuse. Table 2 indicates the most useful standards as of July 2024. Updated information is provided on the technical committee ISO/TC 282 website.

Table 2. Other ISO standards relevant for risk management of urban non-potable water reuse.

Risk Management	ISO Standards	Main Aspects
Establishing the context	ISO 20469:2018 [28]	Water quality grade classification for reuse application
Risk identification	ISO 20761:2018 [29]	Considerations of water reuse safety and public acceptance
Risk analysis and evaluation	ISO 20761:2018	Water reuse safety evaluation
Risk treatment	ISO 16075-2:2020 [30] ISO 16075-5:2021 [31] ISO 20469:2018 ISO 24416:2022 [32]	Water quality levels, irrigation barriers, multi-barrier approach Reclaimed water disinfection and equivalent treatments Notice boards signposting the water quality grades Reclaimed water stability evaluation
Monitoring	ISO 16075-4:2021 [33]	Monitoring the quality of reclaimed water

The link between the proposed framework for health risk assessment of urban non-potable water reuse (Figure 2) and risk-informed decision-making [18] is established in Figure 3. Table 3 summarizes the main strengths and weaknesses of the risk assessment approaches analyzed and proposed, highlighting the latter's novel aspects.

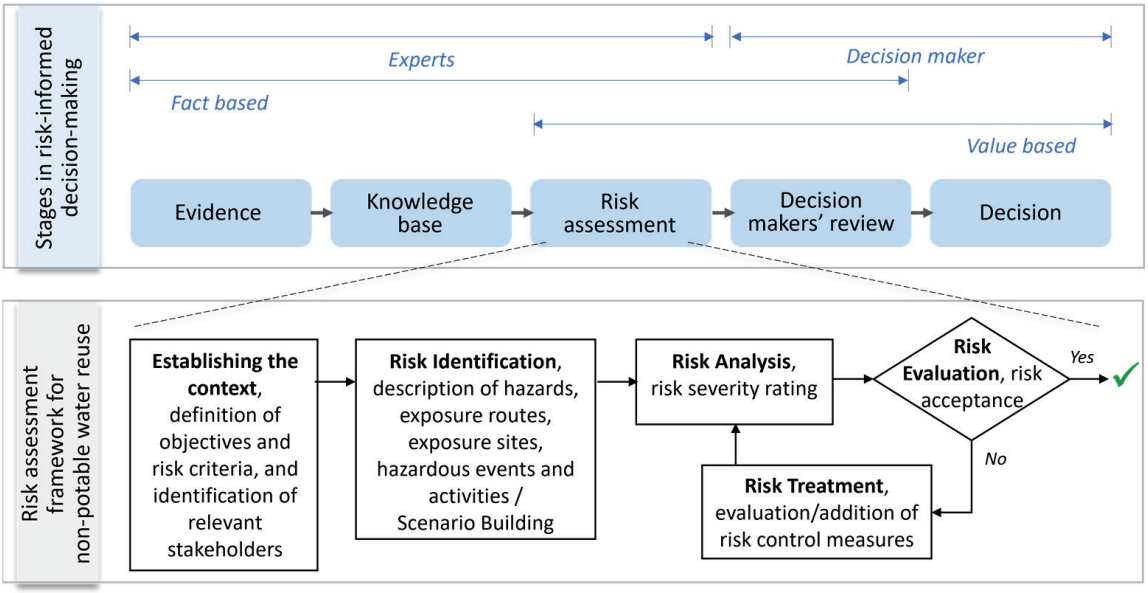

Figure 3. Stages in risk-informed decision-making and of the risk assessment framework for non-potable water reuse (adaptation of Figure 4 of [18]).

Table 3. Strengths and weaknesses of different approaches applicable to non-potable water reuse risk assessment.

Approach	Strengths	Weaknesses
Risk management process (ISO 31000:2018)	1. It is linked to an organizational-level risk management framework 2. It promotes a clear definition of objectives ♦ 3. It promotes the participation of stakeholders ♦	1. It is designed for general application
Health risk assessment and management for non-potable water reuse (ISO 20426:2018)	1. It is specific for non-potable water reuse ♦ 2. It includes a qualitative risk assessment methodology that is adequate for comparing risk levels and making decisions on risk treatment - 3. It is designed for enabling risk-informed decision-making as part of the process of continuous improvement in the management of risks ♦ 4. It promotes the participation of stakeholders ♦	1. It may lead to an amplified risk perception regarding water reuse due to the fact the exposure scenarios are centered on the hazardous events 2. It lacks a clear identification of the situations that may result in exposure to risks
Cumulative risk assessment framework (USEPA 2003)	1. It includes a framework for organizing and analyzing information 2. It includes a conceptual model for risk description ♦ 3. It promotes the participation of stakeholders ♦	1. It presents the risk assessment essentially as a sequential process, thus not formalizing the continuous improvement to be used in risk management

Table 3. *Cont.*

Approach	Strengths	Weaknesses
Proposed framework for health risk assessment and management of urban non-potable water reuse	1. It includes the aspects marked with "♦" 2. It includes a water reuse system model structured around three primary components: decision-makers, data elements and links between the decision-makers and these elements, and links between the elements themselves ✱ 3. It includes a novel rationale for the scenario-building process focused on everyday activities for risk-informed decision-making ✱ 4. It is designed for facilitating the communication of risks to stakeholders ✱ 5. It is implemented in a digital tool, in beta version [34]	1. The methodology is still at an initial stage of utilization by risk managers in urban water reuse projects

Notes: ♦ aspect integrated in the proposed framework; ✱ innovation of the proposed framework.

2.2. Configuration of the Water Reuse System

The configuration starts by establishing the context, i.e., defining the objectives set for water reuse, the relevant stakeholders, and how decision-making is integrated in the risk management process, including the criteria for risk acceptability.

Next, the risk identification provides the characterization of the settings where exposure to hazards may happen and is the basis of the risk management. The development of a site-specific conceptual model is very useful for the formulation of risk scenarios (e.g., [17]). The conceptual model should include the hypothesized source of hazards, transport routes of hazards, contaminated media, exposure routes, and endpoint receptors.

Figure 4 illustrates a conceptual model in the form of a flow chart, structured around three primary components:

- The municipal services and the population at risk (users and workers);
- The data elements relevant for the risk management process—reclaimed water quality, hazards, hazardous events (events in which people are exposed to a hazard within the system [15]), sites where exposure can happen, exposure routes, activities developed by the population at risk, and vulnerability of the population at risk;
- Links between the municipal services and the population at risk and these elements, and links between the elements themselves; the links can be actions, results, or features.

Table 4 illustrates how the different elements of the water reuse system can be described. The effect of the hazardous events and risk-control measures (i.e., barriers and prevention measures) on the risk level (by increasing or decreasing it) is clearly identified. This configuration scheme is the basis for building the risk scenarios and can easily be applied to other (i) types of non-potable water uses (e.g., street cleaning) or (ii) types of risk, namely, environmental risk. In the first case, the conceptual model is the same, and the exposure sites and the activities are site-specific. In the environmental risk assessment, the conceptual model involves different types of subjects at risk (surface water, ground water, or soil), hazards (e.g., nitrogen), exposure routes (e.g., infiltration), hazardous events (e.g., irrigation with reclaimed water exceeding the site's demand for water and/or nutrients), and vulnerabilities (e.g., groundwater vulnerability). The main difference is that no activities are to be associated with the subjects at risk in terms of risk-control measures.

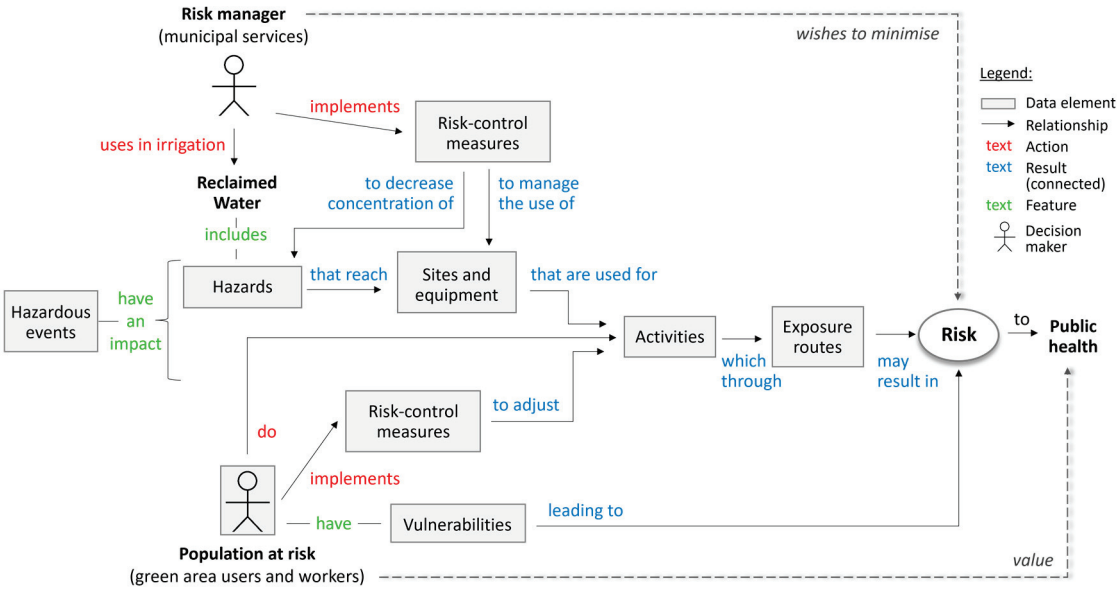

Figure 4. Conceptual model of a water reuse system for municipal green area irrigation.

Table 4. Configuration of the conceptual model of a water reuse system for municipal green area irrigation.

Element	Group	Category (Examples)	Designation (Examples)
Components	Hazards	Pathogenic bacteria (indicator)	*Legionella* spp. *Escherichia coli* (enteric bacteria)
		Intestinal nematodes	Helminth eggs
	Exposure routes	Direct route	Inhalation Ingestion Dermal contact
		Indirect route	Ingestion Dermal contact
	Exposure sites	Vegetated area	Irrigated areas—lawns, flower beds Non-irrigated areas—meadows
		Non-vegetated area	Paths Water features—lakes
		Equipment	Drinking fountains Children playgrounds, fitness areas, etc. Terraces
	Activities	Stay	Lie/sit down on lawns, etc. Play sports—yoga, football, etc., on lawns Eat on terraces, lawns, etc. Drink from water fountains Use children's playground, fitness equipment, etc.
		Pass by	Walk on paths, lawns, etc. Cycle on paths, etc.
		Work	Operation of the irrigation system Maintenance of vegetation Serving food on terraces
	Population at risk	Users	Immature immune system (young children) Competent immune system (older children, teenagers, and adults in general) Weakened immune system (elderly people and people with a poor immune system)
		Workers	Competent immune system (adults in general)

Table 4. *Cont.*

Element	Group	Category (Examples)	Designation (Examples)
Hazardous events	Occurrence of hazards	Increase in hazards in the source water	Due to undue industrial discharge in the municipal drainage system
		Increase in hazards in the reclaimed water [1]	Due to a failure in the reclaimed water treatment system Due to contamination of or regrowth in the reclaimed water distribution network
		Increase in hazards at the points of use	Due to the contamination of irrigation devices (sprinklers and drippers) by dog excrement
	Likelihood of exposure	Inadvertent misuse [1]	Due to potential misuse: drinking from an unidentified water tap Due to inadequate education and information about permitted uses for the reclaimed water
		Accidental exposure [1]	Due to design or operational deficiencies: pipe bursts or leaks, inadequate irrigation timing Due to end-use system failures resulting from sabotage, natural disasters, or extreme weather conditions
		Cross-connection [1]	Due to an improper connection to a drinking water network, leading to its contamination by the reclaimed water Due to an improper connection to a sewage network, leading to the contamination of the reclaimed water network by wastewater
Barriers	Occurrence of hazards	Decrease in hazards in the reclaimed water [2]	By additional, low-level disinfection [1 barrier ≈ 2 log reduction value (LRV)] By additional, high-level disinfection [2 barriers ≈ 4 LRV]
	Likelihood of exposure	Reduce the potential for accidental exposure [2]	By access control [1 barrier ≈ 2 LRV] By irrigation technology to mitigate aerosol formation: use of drip irrigation [1 barrier ≈ 2 LRV] By requirements for sprinkler irrigation: maximum wind speed, distance to sensitive areas [1 barrier ≈ 1 LRV]
Preventive measures	Awareness	Reduce the potential for inadvertent misuse [3]	By signage: "Reclaimed water is being used in irrigation" and "Water not suitable for drinking"
	Information	Reduce the potential for accidental exposure	By information about self-protection against contact with reclaimed water: on a website
		Reduce the potential for cross-connection	By clear identification of the reclaimed water network pipes and accessories, signaling the existence of non-potable water
	Training	Reduce the potential for accidental exposure	By implementation of good practices: use of protective equipment when working with vegetation and the irrigation system
		Reduce the potential for cross-connection	By adoption of procedures for detection of cross-connections between water distribution networks

Notes: [1] ISO 20426:2018 (clause 5.1.2); [2] ISO 16075-2:2020 (clause 4.3); [3] ISO 20469:2018 (clause 5).

In Table 4, the hazardous events are described according to the convention suggested by the World Health Organization [35] for the development of the drinking water safety plans, specifically, "X happens because (of) Y", where X is the effect on the water supply and Y is the cause.

2.3. Scenario-Building Process

The identification of the hazard exposure scenarios (the key result of the risk identification step) is critical for the success of the risk assessment; it should not be too narrow nor too broad. It is therefore important to establish a systematic approach to the scenario-building process, considering the following assumptions (built upon [36]):

- Each scenario should have an impact on the objective(s).
- Each scenario should be a plausible story, with information to support the potential action development.
- Each scenario should be psychologically effective, with a narrative which predisposes its acceptance.
- All scenarios should be structured in a consistent and logical manner.
- All scenarios are possible in principle but do not present the same likelihood.

Within the scope of the standard ISO 20426:2018, likelihood is mainly determined by the probability of human exposure to hazardous events. It is defined that human exposure to pathogens can occur through the combined likelihood of two circumstances: (a) potential for exposure to the media containing hazards (i.e., reclaimed water); and (b) the likelihood of the presence of hazards in the reclaimed water at a concentration higher than that defined for the reuse project (i.e., the reclaimed water presents lower quality than expected). In Table 4, the description of the hazardous events and the risk-control measures acknowledges these two conditions.

Figure 5 illustrates the rationale developed for building the risk scenarios applicable to urban non-potable water reuse, which is structured around the following three elements:

- The cause, i.e., the hazard that may potentially affect human health.
- The events, i.e., the circumstances of the exposure. Everyday activities are the main reason why people can be exposed to reclaimed water. Thus, it is important to align the risk scenarios with the expected activities. In each, one or more hazardous events may apply, and it is necessary to consider the combined effect of these events in the assessment of the risk.
- The consequence of the exposure to that hazard, translated by the vulnerability of the population at risk.

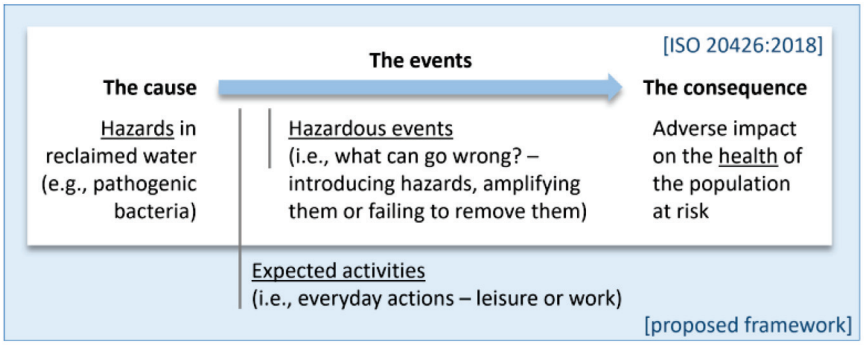

Figure 5. Rationale for building water reuse risk scenarios (elements obtained from ISO 20426:2018).

Applying this rationale, a health risk scenario can be described as follows:

"The *hazard* A as present in reclaimed water of Class X may affect, via the *exposure route* B and on the *exposure site* C, the *population at risk* D when they carry out the *activity* E. In case the *hazardous event(s)* F occur, the baseline risk level corresponds to Y. If this risk level is acceptable, considering the risk criteria for this water reuse project, there is no need to reinforce the risk treatment. If the resulting risk level is not acceptable, the risk-control measures in place (*barriers* G and *preventive measures* H) need to be improved or the additional risk-control measures (*barriers* I and *preventive measures* J) need to be adopted to lower the level of risk to an acceptable value (final risk level)."

Scenario-building is a multi-factorial process that requires careful planning and execution. Figure 6 presents the process diagram for building risk scenarios for water reuse for municipal green area irrigation, where the proposed sequence for selecting the different data elements ensures that all relevant risks are analyzed.

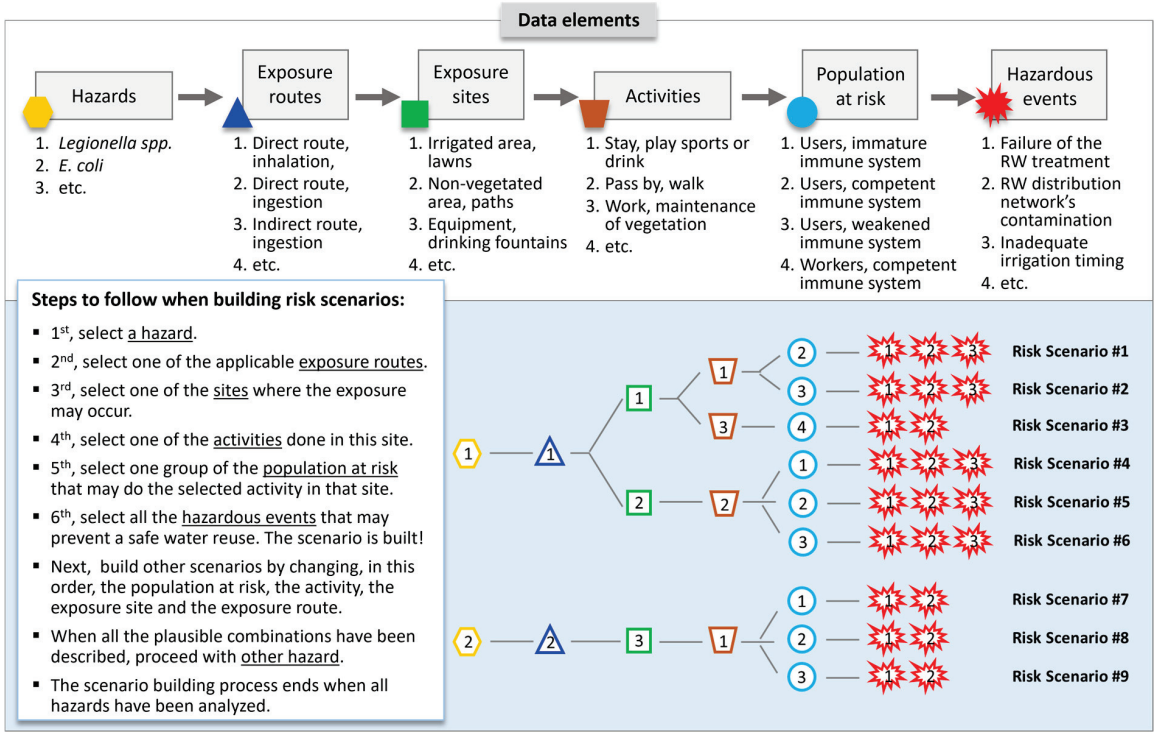

Figure 6. Risk scenario-building diagram.

3. Case Study Description

As with many cities, Lisbon, the capital city of Portugal, faces water challenges related to (i) an increased concentration of the population and a growing economy, (ii) climate change effects, (iii) a need to increase urban green areas to guarantee the quality of life of citizens and the sustainability of urban life, and (iv) a need to reduce the current use of drinking water for non-potable municipal uses. The green and blue infrastructure is a solution applied in Lisbon for tackling climate change impacts related to droughts, heat waves, heat islands, and floods (absorptive capacity/urban resilience). As reclaimed water is a sustainable source, largely independent of rainfall and climate uncertainty, it can contribute to reducing pressure on strategic freshwater resources to satisfy non-potable uses, such as irrigation of green areas, while allowing for resource recovery, such as phosphorus (adaptive capacity/urban resilience).

The case study herein presented is an urban park located in Lisbon. This public park is open 24 h/day (unrestricted access), it covers more than 29 hectares, and it is bordered on the south by the Tagus River estuary. The park is limited by residential areas to the west and to the north and by an urban wastewater treatment plant (WWTP) to the east. This park is very popular and used by people who live in the area and by visitors. Most of the activities carried out on site are walking, relaxing, picnicking, playing sports (yoga and others), and using the playgrounds, among others. As for sports, yoga was selected because it is a risk-prone activity since it is usually an early-morning activity involving close contact with the lawns irrigated overnight.

The case study's park presents a mix of landscaped areas, serving multiple purposes—both recreational and ecological. It is made up of wide areas of lawns with trees and shrubs, intersected by a network of footpaths. It includes some areas specifically designed for sports (one fitness area, one skate park, one tennis center, and one padel center) and outdoor recreation (two children's playgrounds). This park has a picnic area and a terrace. Other amenities include drinking fountains and benches, located on the border of the footpaths. The irrigation system is made up of sprinklers (lawn areas) and drippers (shrub areas).

Since March 2022, this urban park has been irrigated with reclaimed water produced by the nearby WWTP. Because access to the park is unrestricted and spray and sprinkler

irrigation is used, this water reuse project was licensed for the use of reclaimed water with a Class-A quality (on a scale from A to D, A being the best quality water). The classification established in the Portuguese Decree-Law 119/2019 [37] is aligned with the classes proposed in the ISO standard 16075-2:2020 and defined in the Regulation (EU) 2020/741. The main barrier in place is the provision of additional (low-level) disinfection in the reclaimed water distribution network. Notice boards informing about the use of reclaimed water for irrigation (designed according to the Portuguese legislation Government Order 266/2019 [38]) are in place.

4. Scenario-Building Results and Contribution to Decision-Making

Risks may change over time, and hence, risk management must be dynamic and iterative. It is useful to review the risk management plan to improve the understanding and treatment of already-identified risks. Thus, scenario-building was applied to the selected case study to exemplify its role on the following aims:

- Support decision-making by the risk manager about risk-control measures already in place—evaluate if reinforcement is needed (scenarios (Sc) 1 and 5).
- Support decision-making by the users of the park—encourage yoga practitioners to adopt self-protection measures to reduce the likelihood of exposure (Sc2 and Sc6).
- Improve risk communication—present risks to the park's neighbors for improving the quality of risk perception (Sc3 and Sc4).

Transformative capacity (urban resilience) includes, among other aspects, multi-stakeholder collaboration and safety promotion [3]. Risk scenario-building, if developed with this purpose in mind, can facilitate the implementation of changes to reduce the risk level associated with urban water reuse.

Next, the results of the application of the health risk assessment framework to the case study are presented as follows: establishing the context (Table 5); risk identification (Tables 6 and 7); baseline risk analysis and risk evaluation (Table 8); and final risk evaluation after risk treatment (Table 9).

Table 5. Establishing the context.

Context Elements	Description
Scope (water reuse project)	Use of reclaimed water: irrigation of an unrestricted-access urban park Irrigation system (end-use points): sprinklers and drippers Reclaimed water quality: *E. coli* $\leq$ 10 cfu/100 mL, $BOD_5 \leq 10$ mg/L O_2), TSS $\leq$ 10 mg/L, turbidity $\leq$ 5 NTU (Decree-Law 119/2019 Class-A); *Legionella* spp.: $\leq$100 cfu/L (Act 52/2018 [39])
Objective	To use reclaimed water as fit-for-purpose water for irrigation without affecting the health of the park users and workers, aiming to provide a safe water reuse
Relevant stakeholders	Municipality services: reclaimed water end-user (responsible for the risk management), green area management, reclaimed water distribution system management Water utility: reclaimed water production Authorities (environment and public health): water reuse licensing Citizens: green area users, green area neighbors
Criteria for risk acceptability	Each risk scenario is evaluated qualitatively based on the levels of consequences and likelihood The severity of each risk is determined by a combination of the rating of its potential consequence on a five-level scale (1 to 5, as presented in Table A1) and the likelihood of occurrence on a five-level scale (A to E, as presented in Table A2) The tolerability of each risk is expressed on a three-level scale (low, moderate, and high) applied to different combinations of consequence and likelihood. A low level encompasses negligible risks that can be treated if the associated cost is insignificant. A moderate level refers to significant risks that require specific risk-control measures to lower the risk level. A high level represents outstanding risks that require a re-evaluation of the water reuse project's suitability and, in case it is confirmed, specific risk-control measures to lower the risk level. Figure 7 presents the risk matrix Water reuse for irrigating the urban park can only happen when all the risk scenarios present a low level of risk

Likelihood \ Consequence	1 - Insignificant	2 - Minor	3 - Moderate	4 - Major	5 - Catastrophic
A - Rare	Low	Low	Low	Low	Moderate
B - Unlikely	Low	Low	Moderate	Moderate	Moderate
C - Possible	Low	Moderate	Moderate	Moderate	High
D - Likely	Low	Moderate	Moderate	High	High
E - Almost certain	Moderate	Moderate	High	High	High

Figure 7. Proposed risk matrix for urban non-potable water reuse.

Table 6. Configuration of the studied water reuse system.

Element	Group	Category	Designation
Components	Hazards	Pathogenic bacteria (indicator)	*Legionella* spp. *Escherichia coli* (enteric bacteria)
	Exposure routes	Direct route	Inhalation Ingestion
		Indirect route	Ingestion
	Exposure sites	Vegetated area	Irrigated area—lawns
		Non-vegetated area	Paths
		Equipment	Fitness area
	Activities	Stay	Carry out yoga on the lawns Work out on the fitness area
		Pass by	Walk on the paths around the park
	Population at risk	Users	Immature immune system (young children) Competent immune system (older children, teenagers, and adults in general) Weakened immune system (elderly people and people with poor immune system)
Hazardous events	Occurrence of hazards	Increase in hazards in the reclaimed water	Due to a failure in the reclaimed water (RW) treatment system Due to the contamination of the reclaimed water distribution network
Barriers	Occurrence of hazards	Decrease in hazards in the reclaimed water	By additional, low-level disinfection (1 barrier, 2 LRV). Additional information presented in [40]
	Likelihood of exposure	Reduce the potential for accidental exposure	By requirements for sprinkler irrigation: distance to sensitive areas (1 barrier, 1 LRV)
Preventive measures	Awareness	Reduce the potential for inadvertent misuse	By signage: "Reclaimed water is being used in irrigation" and "Water not suitable for drinking"
	Information	Reduce the potential for accidental exposure	By information on a website about self-protection against contact with reclaimed water

Table 7. Building the risk scenarios.

ID	Hazard	Exposure Route	Exposure Site	Activity	Population at Risk	Hazardous Events
Sc1	*Legionella*	Inhalation, direct route	Fitness area	Work out	Weakened immune system	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing
Sc2	*Legionella*	Inhalation, direct route	Lawns	Carry out yoga	Competent immune system	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing

Table 7. *Cont.*

ID	Hazard	Exposure Route	Exposure Site	Activity	Population at Risk	Hazardous Events
Sc3	*Legionella*	Inhalation, direct route	Paths	Walk	Immature immune system	Failure of the RW treatment Contamination of the RW distribution network
Sc4	*Legionella*	Inhalation, direct route	Paths	Walk	Competent immune system	Failure of the RW treatment Contamination of the RW distribution network
Sc5	*E. coli*	Ingestion, indirect route	Fitness area	Work out	Weakened immune system	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing
Sc6	*E. coli*	Ingestion, indirect route	Lawns	Carry out yoga	Competent immune system	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing

Table 8. Baseline risk analysis and risk evaluation; *l* = likelihood; *c* = consequence.

ID	Hazardous Events	Risk Analysis		Baseline Risk Evaluation (Figure 7)	Comments
		l	*c*		
Sc1	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing	B	3	Moderate [not accepted, risk treatment needs to be reinforced]	If the use of the fitness area coincides with irrigation, inhalation of *Legionella* may occur when aerosols are produced in conjunction with water sprays (*l* = B) In case of a weakened immune system, a contact with *Legionella* at a low infectious dose could potentially result in minor illness (*c* = 3)
Sc2	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing	B	2	Low [accepted, risk treatment will also be reinforced]	If the use of the lawns coincides with irrigation, inhalation of *Legionella* may occur when aerosols are produced in conjunction with water sprays (*l* = B) In case of a competent immune system, contact with *Legionella* at a low infectious dose could potentially result in minor health effects (*c* = 2)
Sc3	Failure of the RW treatment Contamination of the RW distribution network	B	3	Moderate [not accepted, risk treatment needs to be reinforced]	If the use of the paths coincides with irrigation, inhalation of *Legionella* may occur when aerosols are produced in conjunction with water sprays (*l* = B) In case of an immature immune system, contact with *Legionella* at a low infectious dose could potentially result in minor illness (*c* = 3)

Table 8. *Cont.*

ID	Hazardous Events	Risk Analysis		Baseline Risk Evaluation (Figure 7)	Comments
		l	*c*		
Sc4	Failure of the RW treatment Contamination of the RW distribution network	B	2	Low [accepted, risk treatment will also be reinforced]	If the use of the paths coincides with irrigation, inhalation of *Legionella* may occur when aerosols are produced in conjunction with water sprays (l = B) In case of a competent immune system, contact with *Legionella* at a low infectious dose could potentially result in minor health effects (c = 2)
Sc5	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing	B	3	Moderate [not accepted, risk treatment needs to be reinforced]	If RW reaches the fitness equipment and the latter is used wet, ingestion of *E. coli* may occur when a hand is brought to the mouth (l = B) In case of a weakened immune system, contact with *E. coli* at a low infectious dose could potentially result in minor illness (c = 3)
Sc6	Failure of the RW treatment Contamination of the RW distribution network Inadequate irrigation timing	B	2	Low [accepted, risk treatment will also be reinforced]	If the lawns are still wet with RW when used for practicing yoga, ingestion of *E. coli* may occur when a hand is brought to the mouth (l = B) In case of a competent immune system, contact with *E. coli* at a low infectious dose could potentially result in minor health effects (c = 2)

This methodology was primarily designed to be user-friendly for risk assessment teams. However, the resulting information is not easily readable by a non-expert. In Commedia dell'Arte, a scenario involves a play sketch to be used as a basis for the actors' improvisation on stage. Applying this way of thinking to the information presented in Tables 5–9, the scenario Sc1 can be narrated as follows: "The bacteria *Legionella* as usually occurring in Class-A reclaimed water may affect, via inhalation and on the fitness area, the senior population when working out. In case there is a degradation of the reclaimed water quality (due to a failure in the treatment system or the contamination of the irrigation network) and if the use of this open-air area coincides with the irrigation time, the inhalation of *Legionella* may occur. Because senior people are expected to have a weakened immune system, contact with *Legionella* potentially results in minor illness. The combination of these factors leads to a baseline risk level equal to moderate, which is unacceptable. Thus, it is necessary to apply risk control measures to ensure safe water reuse. The already in place barrier "additional, low-level disinfection" provides the necessary microbiological stability for the reclaimed water. The prevention measure "signage" will be reinforced by using additional informative panels, more attention-catching and including suggestions of self-protection measures when using the fitness area." Similar narratives can be applied to the remaining risk scenarios.

Table 9. Final risk evaluation after risk treatment; *l* = likelihood; *c* = consequence.

ID	Risk-Control Measures	Risk Analysis		Final Risk Evaluation (Figure 7)	Comments
		l	*c*		
Sc1	Additional, low-level disinfection [1 barrier, in place]. Park signage informing about water reuse [can be improved]	A	3	Low [accepted]	The barrier ensures the RW's microbiological stability, maintaining Class-A quality throughout the RW distribution network If people are properly informed about potential risks, contact with RW is highly improbable (*l* = A) In case of a weakened immune system, contact with *Legionella* at a low infectious dose could potentially result in minor illness (*c* = 3)
Sc2	Additional, low-level disinfection [1 barrier, in place]. Park signage informing about water reuse [can be improved] Online information about good practices [new measure]	A	2	Low [accepted]	The barrier ensures the RW's microbiological stability, maintaining Class-A quality throughout the RW distribution network If people are properly informed about potential risks and encouraged to take self-protection measures, contact with RW is highly improbable In case of a competent immune system, contact with *Legionella* at a low infectious dose could potentially result in minor health effects (*c* = 2)
Sc3	Additional, low-level disinfection [1 barrier, in place]. Park signage informing about water reuse [can be improved]	A	3	Low [accepted]	The barrier ensures the RW's microbiological stability, maintaining Class-A quality throughout the RW distribution network If people are properly informed about potential risks, contact with RW is highly improbable (*l* = A) In case of a weakened immune system, contact with *Legionella* at a low infectious dose could potentially result in minor illness (*c* = 3)
Sc4	Additional, low-level disinfection [1 barrier, in place]. Park signage informing about water reuse [can be improved] Face-to-face communication [new measure]	A	2	Low [accepted]	The barrier ensures the RW's microbiological stability, maintaining Class-A quality throughout the RW distribution network If people are properly informed about potential risks, contact with RW is highly improbable (*l* = A) In case of a competent immune system, contact with *Legionella* at a low infectious dose could potentially result in minor health effects (*c* = 2)

Table 9. *Cont.*

ID	Risk-Control Measures	Risk Analysis		Final Risk Evaluation (Figure 7)	Comments
		l	*c*		
Sc5	Additional, low-level disinfection [1 barrier, in place] Park signage informing about water reuse [can be improved] Face-to-face communication [new measure]	A	3	Low [accepted]	The barrier ensures the RW's microbiological stability, maintaining Class-A quality throughout the RW distribution network If people are properly informed about potential risks, contact with RW is highly improbable (l = A) In case of a weakened immune system, contact with *Legionella* at a low infectious dose could potentially result in minor illness (c = 3)
Sc6	Additional, low-level disinfection [1 barrier, in place] Park signage informing about water reuse [can be improved] Online information about good practices [new measure]	A	2	Low [accepted]	The barrier ensures the RW's microbiological stability, maintaining Class-A quality throughout the RW distribution network If people are properly informed about potential risks and encouraged to take self-protection measures, contact with RW is highly improbable (l = A) In case of a competent immune system, contact with *E. coli* at a low infectious dose could potentially result in minor health effects (c = 2)

The results of the case study (Tables 5–9) strongly support the use of a coherent system in the building of risk scenarios for effective risk management of urban non-potable water reuse. The herein-presented scenarios, which exemplify different combinations of hazards (*Legionella* spp. or *E. coli*), exposure routes (inhalation or ingestion), activities (workout, carrying out yoga, or walking), and population at risk (children, adults, or seniors), enable risk-informed decision-making by the park's risk manager as well by the park's users. Green area managers and users are key elements for the sustainable risk management of water reuse in irrigation, and the same applies in other non-potable water uses, e.g., street cleaning, car washing, fire protection, air conditioning, and toilet flushing.

The main recommendations derived from this scenario-building exercise are as follows:

- Support decision-making by the risk manager of the water reuse project, Sc1 and Sc5: (a) Maintain the additional, low-level disinfection for an effective multi-barrier risk management; (b) introduce additional park signage with information about water reuse, especially near the areas where the risk level is considered higher. The information to be presented in these additional panels should include clear messages on how to adopt self-protection measures, e.g., "Don't use the fitness equipment when the nearby lawn is being irrigated" or "Please, wipe the fitness equipment before use if it is wet". To improve the acceptance of water reuse, and taking advantage of these panels, information should also be given about related environmental benefits; for example, "Reusing water for irrigation in this park avoids abstracting from nature (value) m^3 of water per year. Keep safe, help save natural water!".
- Support decision-making by the people who use the park, Sc2 and Sc6: (a) Maintain the additional, low-level disinfection for effective multi-barrier risk management; (b) introduce additional park signage with information about water reuse. To promote the awareness and acceptance of the yoga practitioners, attention-catching messages, e.g., "Wait for the grass to dry so that your yoga may shine" can be used in the new

panels. Again, it is important to use the latter to inform about water reuse benefits; for instance, "By reusing water to irrigate the park's lawns, the use of (value) kg of chemical fertilizers is avoided every year". It is recommended, as an additional risk-preventive measure, to use the municipal website to inform the yoga practitioners about good practices when practicing yoga in urban green areas. This communication may include information about yoga, in addition to recommendations of risk-control measures.

- Improve communication, Sc3 and Sc4: (a) Maintain the additional, low-level disinfection for effective multi-barrier risk management; (b) introduce additional park signage with information about water reuse. Similarly to the previous scenarios, the information about risk management and the benefits of water reuse should be appellative. In this case, it is recommended, as a new risk-preventive measure, to have face-to-face communication, such as an open-house meeting, for presenting the water reuse risks to the park's neighbors in a clear and simple way that is understandable by non-scientists. This type of initiative provides an opportunity for risk managers to understand risk perceptions of park neighbors, which can be very useful for future water reuse projects.

The example provided is not exhaustive since many activities were not covered, e.g., eating, using the children's playground, and cycling. However, the effort of completing the process is greatly facilitated by the modular way in which the scenarios are built and by the fact that it is easy to identify the specific circumstances that can enable human exposure to pathogens. Additionally, the identification of the objective(s) for the water reuse project at the beginning of the risk assessment process helps prioritize the circumstances to be evaluated in terms of risk and, thus, limits the number of risk scenarios.

The framework's coherence with the reference ISO standards in the field of risk management and its flexibility for assessing the risks of non-potable water reuse is expected to catalyze its application to non-potable water reuse projects in different cities or regions.

5. Conclusions

In the case of urban non-potable water reuse, the contribution of the population at risk is often neglected because it is considered that "they" do not understand the risks and, for that reason, "they" are naturally excluded from the risk management process. This rationale presents two main setbacks: (i) it results in higher requirements for the reclaimed water quality since, in case of direct contact, the population at risk is not informed about the applicable self-protection measures; and (ii) it can induce an amplified risk perception by the population because, due to a lack of knowledge about the water reuse system, the exposure to hazards can be perceived as involuntary. Thus, it is important to invest in the development of risk assessment solutions that facilitate the risk communication to the population at risk via the scenario-building process.

This study presents a framework for the health risk assessment and management of urban non-potable water reuse, mainly based on the relevant ISO standards (especially ISO 31000:2018, ISO 20426:2018, ISO 16075-2:2020, and ISO 20469:2018) and on aspects of the USEPA Cumulative Risk Assessment Framework. It includes a novel scenario-building process that helps define how far to take the building of risk scenarios, a recurrent challenge for water reuse practitioners and regulators, and it facilitates the validation of the risk management framework. The framework makes available expert knowledge for risk managers and stakeholders responsible for non-potable water uses, guiding them through the often-complex process of licensing urban non-potable water reuse projects. Hopefully, this standardized solution may facilitate urban management policies for achieving a full integration of reclaimed water into the urban water supply systems, i.e., increasing urban water resilience.

The framework is implemented in the digital tool "Risk Assessment for Urban Water Reuse Module" (TRL 8, in beta version) developed within the B-WaterSmart project. The user-friendly tool for risk assessment and management is integrated in a set of four applications designed to provide water-smart allocation for urban non-potable uses, assessing combinations of water supply/demand alternatives, including reclaimed water, to enable prioritizing strategic and tactical options in urban planning [40].

Future studies could analyze the influence of the cultural and socio-economic context in water reuse risk evaluation, namely, if the description of the consequence and likelihood categories needs to acknowledge local factors. Another aspect of interest for future research is the role of how the risk associated with urban water reuse is assessed and managed as a starting point for the implementation of wider processes of multi-stakeholder collaboration on the path to increasing sustainability in cities.

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Appendix A

Table A1. Suggested measures of consequence or impact (Table 2 of ISO 20426:2018).

Level	Descriptor	Description of health impact level
1	Insignificant	Hazard or hazardous event resulting in no or negligible health effects compared to background levels.
2	Minor	Hazard or hazardous event potentially resulting in minor health effects.
3	Moderate	Hazard or hazardous event potentially resulting in self-limiting health effects or minor illness.
4	Major	Hazard or hazardous event potentially resulting in illness or injury and/or may lead to legal complaints and concern and/or major regulatory non-compliance.
5	Catastrophic	Hazard or hazardous event potentially resulting in serious illness or injury or even loss of life and/or will lead to a major investigation by the regulator with prosecution likely.

Table A2. Suggested measures of likelihood that exposure events can happen (Table 3 of ISO 20426:2018).

Level	Descriptor	Description of likelihood level
A	Rare	Has not happened in the past and it is highly improbable it will happen in the reasonable period.
B	Unlikely	Has not happened in the past but may occur in exceptional circumstances in the reasonable period.
C	Possible	May have happened in the past and/or may occur under regular circumstances in the reasonable period.
D	Likely	Has been observed in the past and/or is likely to occur in the reasonable period.
E	Almost certain	Has often been observed in the past and/or will almost certainly occur in most circumstances in the reasonable period.

Note: The reasonable period depends on the level of risk and local jurisdiction.

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Water Supply Security—Risk Management Instruments in Water Supply Companies

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Abstract: Piped drinking water supplies are exposed to a range of threats. Changing hazard situations arise from climate change, digitisation, and changing conditions in the power supply, among other things. Risk and crisis management adapted to the hazard situation can increase the resilience of the piped drinking water supply. Analogous to the risk management system, this article describes a methodology that ranges from hazard analysis with the prioritisation of 57 individual hazards to vulnerability assessment with the help of balance sheet structure models (BSM) and the planning and implementation of measures to increase the resilience of the piped drinking water supply in a targeted manner. The work steps mentioned build on each other and were tested using the case study of a water supply company in Saxony (Germany). As a result, priority hazards are identified, the remaining supply periods and replacement and emergency water requirements are determined as part of the vulnerability assessment, and finally, planning principles for increasing resilience are documented. The methodology focuses primarily on practicable application by water supply companies.

Keywords: water supply; resilience; vulnerability; crisis management; hazards; blackout; balance sheet structure models

1. Introduction

Drinking water infrastructure can be severely impaired by a number of hazards. Water supply companies are also exposed to a number of potential hazards in their operations and in the fulfilment of their tasks [1–3]. Climate change is one of the greatest threats to the water supply. The intensity and frequency of extreme hydrological events such as floods, flash floods, and droughts are expected to increase worldwide [4–9]. However, other natural hazards can also affect the water supply. For example, the SARS-CoV-2 pandemic led to staff shortages and supply difficulties for operating and auxiliary materials for water treatment [10–12]. Technical faults also pose a major potential risk. For example, a blackout can lead to long-lasting supply interruptions in the piped water supply [13–15]. Other threats to the water supply come from sabotage and acts of war. An increase in cyberattacks on critical infrastructure is currently to be expected [16–18].

But which hazards are relevant for maintaining the piped water supply and should be prioritised in scenarios?

In order to increase resilience to crises and disasters, the water supply needs a risk and crisis management system. At the European level, the Water Safety Plan of the World Health Organisation (WHO) [19] has been implemented in regulations with the standards DIN EN 15975-1 [20] and DIN EN 15975-2 [21]. The work steps for risk and crisis management are shown in Figure 1.

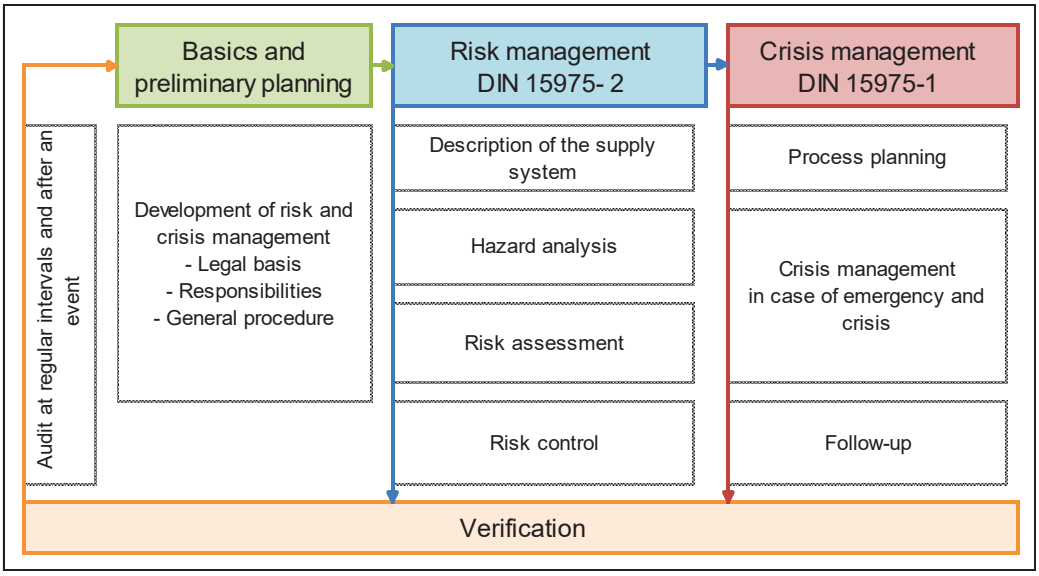

Figure 1. Work steps for risk and crisis management, based on [20,21].

However, in the implementation of risk management, there are deficits in the preparation and practical application of risk analyses [5,22,23]. To determine the resilience of water distribution systems, Todini [24] already described the basis for assessing the systems using a heuristic optimisation approach 24 years ago. The mathematical framework described in [24] has recently been further developed by Caldarola et al. [25–29], among others. The mathematical principles are used in many hydraulic models, such as EPANET (Version 2.0) or the WaterNetGen software (EPANET extension–pipe dimensioning) [30–37]. In [25], the challenges of hydraulic simulation are described, including the need for large amounts of data for the components of the network (systems, gate valves, valves, pipe materials), knowledge of the network topology, and water demand (consumption behaviour, peak demand). In addition to hydraulic models, system dynamic modelling [38–41], society-oriented, economy-based, and combined methods are known in the literature [42]. Many methods require expert knowledge in their application and, due to their complexity, offer only limited application possibilities in crisis management.

The question arises as to whether a simplified modelling approach with semi-dynamic models can offer greater user-friendliness with the least possible loss of information.

To manage the risks, measures to increase the resilience of the piped water supply should be derived from the risk analysis and implemented [21]. There is a lack of planning principles for the dimensioning of systems in emergency and crisis situations compared to normal operation. In addition, an international comparison shows different volume approaches for backup and emergency water supply (Table 1).

Table 1. Quantities of backup and emergency water supply.

Literature Source	Unit	WHO [43]	Sphere [44]	Switzerland [45]	Austria [46]	Germany [47]
Emergency water supply Minimum population requirement	L/(P·d)	20	15	15	15	15
Replacement water supply incl. domestic hygiene	L/(P·d)	70		100 *	Accord. to water demand plan *	50 *

Further information on drinking water requirements for healthcare and livestock farming can be found in [43–47], * Line-bound.

This paper presents a consecutive approach for (i) identifying relevant threats, (ii) analysing the vulnerability of a water supply system and (iii) developing mitigation measures. The

proposed approach offers a good balance between the required accuracy and practical applicability. Its application is demonstrated for a water supply system of medium complexity.

2. Materials and Methods

2.1. Hazard Analysis

A tool for semi-quantitative prioritisation was developed to determine the relevance (R) of each hazard. The aim of the procedure is not an exact quantification of the risk but a relative prioritisation of the hazards. The first step was to systematically record the hazards (Table 2, columns A–M) on the basis of known and potential hazards. For this purpose, various technical guidelines [1,3,48–50] and the water supplier's incident documentation from the last 20 years were used. To determine the probability of occurrence (E) and the respective affectedness (B_i) of the individual hazards, literature research was carried out, data provided by authorities or insurers was used, information from the technical regulations was included, operating experience was analysed, experts were interviewed, and/or local media reports were consulted. The areas of facilities, structures, personnel, and regional impact were analysed as part of the impact assessment. This procedure results in an estimated categorisation of the probability (E) (Table 2, column S):

1—low (all > 1000 a),
2—medium (every 101–1000 a) and
3—high (all 0–100 a).

Table 2. Sample table for hazard analysis, adopted from [48].

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
hazard analysis																				
Hazards			**Source**				**Reason**			**Responsible**			**Affectedness**					**Relevance**		
Category	No.	Hazard source	Drinking water supply safety guidelines [3]	Protection of critical infrastructures [1,49]	DVGW W 1001-B1 [50]	Incident documentationof the water supplier	Internal	External	Exposure in the supply area	Water supplier	Country/ Municipality	Covenant	Plants, buildings	Drinking water network	Staff	Region	Degree of danger	Probability ofoccurrence	Relevance	Evaluation of scenario selection, comments
N	1	Hazard 1	X	X	X			X	X	X			1	1	1	1	**1**	3	**3**	
T	2	Hazard 2		X				X	X	X	X	X	3	3	3	3	**3**	2	**6**	Derive scenario
A	n	Hazard n				X	X		X	X			1	1	2	3	**1.8**	2	**3.6**	

N = natural hazards, T = technical faults/human error, A= attacks, sabotage, acts of war.
Classification of the impact: 1—not relevant, 2—localized impact, 3—widespread impact
Classification of the probability of occurrence: 1—low, 2—medium, 3—high probability of occurrence

and the respective affectedness B_i (Table 2, columns N–Q) in:

1—not relevant,
2—selectively and
3—area-wide.

The hazard level (G) was calculated as the mean value of the B_i (Table 2, column R). The relevance (R) of the hazard under consideration was calculated as the product of G and E (Equation (1); Table 2, column T). Finally, the relevant hazards were summarised into as few scenarios as possible in order to limit the number of subsequent simulations.

$$R = E \cdot G = E \cdot \frac{1}{n} \sum_{i=1}^{n} B_i \quad (1)$$

R—Relevance
E—Probability of occurrence (Range of values 1 to 3)
G—Level of risk
Bi—Affectedness i = 1 . . . n (Range of values: 1 to 3)
i—Index of the respective affectedness
n—Number of affected parties analysed

The results of the hazard analysis using the example of a water supply company are presented in Section 3.2. a detailed description of the methodology is published in [48].

2.2. Vulnerability Analysis with Balance Sheet Structure Models (BSM)

2.2.1. Calculation Approach

The subsequent vulnerability analysis (resilience assessment) was carried out using a semi-dynamic model. This is fundamentally based on a quantitative water balance (Equation (2)).

$$\frac{dS(t)}{dt} = \Sigma Q(t) = \Sigma Q_{in}(t) - \Sigma Q_{out}(t) \quad (2)$$

The balance is made up of the inflows (ΣQ_{in}), such as the inflow from water extraction plants or feed-in points, and the outflows (ΣQ_{out}), such as drinking water consumers, losses and feed-out points. The difference between inflows and outflows results in the balance value (ΣQ). The integral of the difference between the inflows and outflows therefore represents the change in the system status over a certain period of time. To determine the remaining supply time (t), all available storage capacities (S), such as underground or elevated tanks, are taken into account (Equation (3)).

$$t = \frac{S}{-(Q_{in} - Q_{out})} \quad (3)$$

To map the various operating scenarios, a mathematical case differentiation of Equation (3) was carried out (Equations (4)–(7)):

Normal operation (case 1: $S > 0$; $Q_{in} \approx Q_{out}$):

$$\lim_{(Q_{in} - Q_{out}) \to 0} t = \frac{S}{\lim(-(Q_{in} - Q_{out}))} = \infty \quad (4)$$

Balance sheet deficit (case 2: $S > 0$; $Q_{in} < Q_{out}$):

$$t = \frac{S}{-(Q_{in} - Q_{out})} > 0 \quad (5)$$

Cascade effects (case 2 extended, 1 . . . n = index of the memory considered in the cascade system, n = number of memories in the cascade system):

$$t_n = \frac{S_1}{-(Q_{in,1} - Q_{out,1})} + \frac{S_2}{-(Q_{in,2} - Q_{out,2})} + \ldots + \frac{S_n}{-(Q_{in,n} - Q_{out,n})} \quad (6)$$

without memory (case 3: $S = 0$; $Q_{in} < Q_{out}$):

$$t = \frac{S}{-(Q_{out} - Q_{in})} = 0 \quad (7)$$

The theoretical cases of a negative denominator (case 4: $Q_{in} > Q_{out}$) and a negative storage volume (case 5: $S < 0$) are not taken into account in the BSM. This means that no negative time ($-t$) can result. Assuming a full storage tank, a surplus feed-in leads to a storage tank overflow and is therefore mathematically balanced by increased losses on the consumption side. A negative storage volume at the time the simulation starts is practically impossible. Further information on the calculation approach is published in [51].

2.2.2. Modelling Implementation

The model structure is explained in this chapter using a sample scenario with a three-day outage of a waterworks as an example. The publication of the models actually created is limited to the simulation results (Section 3.3). This procedure was chosen in order to protect the sensitive data of the water supply companies.

The mathematical approach was implemented in a spreadsheet programme. The BSM consists of several system components. The existing system components, including the necessary parameterisation and links, are shown and explained in Table 3.

The model structure is based on the topology and takes flow directions and technological relationships, such as pressure zones, into account. The data are analysed via the visual representation in the model and via overall balances. Figure 2 shows the abstracted model scenario for the failure of a waterworks at the simulation period of three days. The areas shown in Figure 2 correspond to the following specifications:

- An area module (coloured box) comprises 0–50 inhabitants,
- Red areas—inhabitants without drinking water supply,
- Yellow areas—residents with a temporary drinking water supply and
- Green areas—residents with an unlimited supply of drinking water.

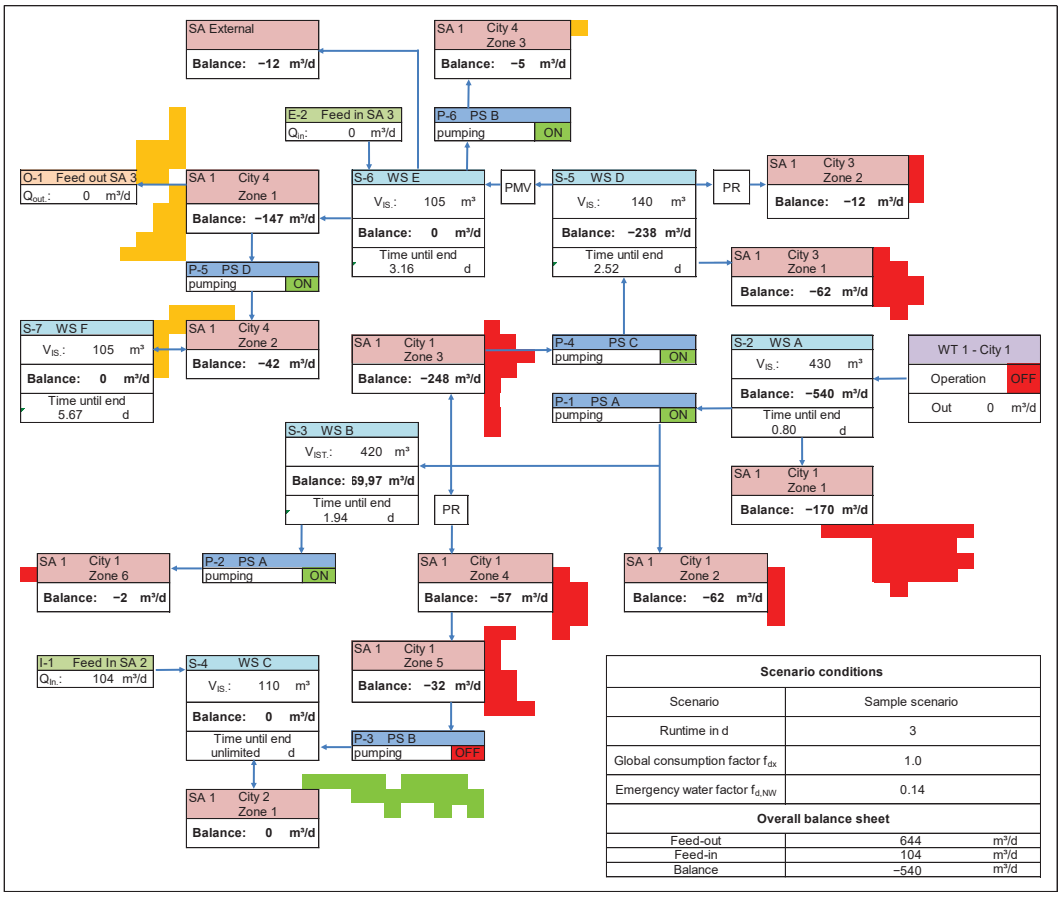

Figure 2. BSM—sample scenario failure waterworks (abstracted representation).

Table 3. Parameterisation and linking of the system components.

	System Component	Parameters	Unit	Remarks
Global	Global input field	Scenario		Description of the scenario
		Runtime	d	Depending on the scenario
		Consumption factor f_{dx}		has a constant effect over the entire scenario period and reflects increases or decreases in drinking water consumption
		Emergency water factor $f_{d,NW}$		acts constantly over the entire scenario time and calculates the required emergency water quantity
		Remarks		
		Connection points		All consumption points
Drinking water supply (inflows)	Feed-in	Designation/No.		Abbreviation "I"
		Capacity Q_{cap}	m^3/d	Decisive capacity of the feed-in (technical or regulatory)
		Feed-in Q_{Input}	m^3/d	Actual feed-in in the scenario, with reference Q_{dm} of the feed-in
		Connection points		Feed-in point grid, water storage, water pumping
	Water catchments	Designation/No.		Abbreviation "WC"
		Usability	%	Utilisation of capacity, consideration of e.g., reduction due to dry periods
		Capacity Q_{cap}	m^3/d	Decisive capacity of the feed-in (technical or regulatory)
		Connection points		Water treatment
	Water treatment	Designation/No.		Abbreviation "WT"
		Operational switching		Selector switch between "ON" and "OFF"
		Capacity Q_{cap}	m^3/d	Decisive capacity of the feed-in (technical or regulatory)
		Connection points		Feed-in point grid, water storage, water pumping
Drinking water network	Water reservoir	Designation/No.		Abbreviation "S"
		Useful volume V_{Use}	m^3	Available usable volume
		Useful volume V_{IS}	m^3	Minimum volume of normal operation
		Connection points		Grid feed-ins and feed-outs, consumption points, water delivery
	Water pumping	Designation/No.		Abbreviation "P"
		Capacity Q_{cap}	m^3/d	Decisive capacity of the feed-in (technical or regulatory)
		Connection points		Grid feed-ins and feed-outs, consumption points, water storage tanks
Drinking water consumption (drains)	Consumption point	Designation/ No.		Abbreviation "SA"
		Inhabitants	P	Indication of inhabitants supplied
		Storage system		Specification of linked memory
		Consumption factor f_{dx}		Selector switch "GLOBAL" or "HAND", differentiated input required for "HAND", e.g. for commercial customers
		Manual value f_{dx}		If "Hand" is preselected, it has a constant effect over the entire scenario time and maps excess or reduced quantities of drinking water consumption
		Drinking water consumption	m^3/d	Specification of drinking water consumption Q_{dm}, as direct input or database link
		Meter number		Specification of existing meter numbers
		Connection points		Grid feed-ins and feed-outs, downstream consumption points, water storage tanks, drinking water consumption if applicable
	Feed-out	Designation/No.		Abbreviation "O"
		Capacity Q_{cap}	m^3/d	Relevant capacity of the feed-out (technical or regulatory)
		Feed-out $Q_{Feed-out}$	m^3/d	Actual feed-in in the scenario, with reference Q_{dm} of the feed-in
		Connection points		Grid feed-out point, water storage tank, water pumping

Supply diagrams (Figure 3) and evaluation tables (Table 4) supplement the analysis of the BSM. Figure 3 shows, as function of failure time, the number of affected residents with normal supply (green), the time until supply failure (yellow) and the duration of the supply interruption (red).

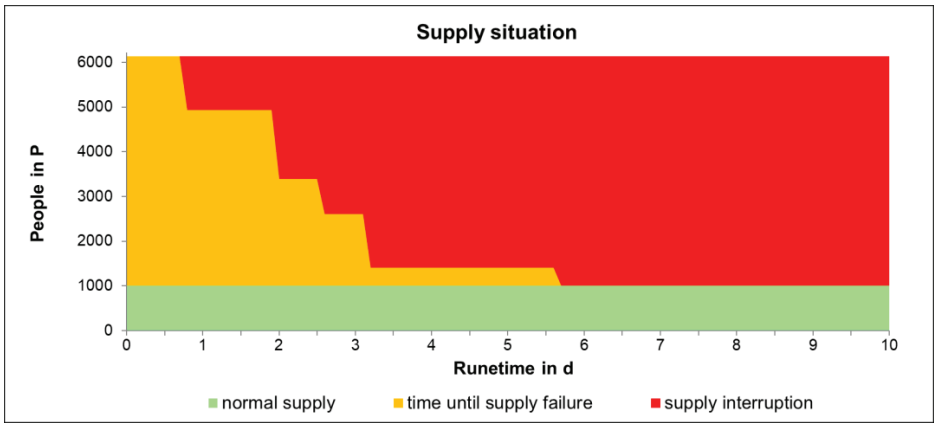

Figure 3. Supply diagram for the example scenario with y-axis showing the affected inhabitants by supply zones and x-axis showing the selected simulation time.

Table 4. Evaluation table in the sample scenario.

No.	Zone	People in P	Supply Time in d	Normal Supply in P	Limited Supply in P	Supply Interrup. in P	Q_{dm} in m^3/d	$Q_{d,NW}$ in m^3/d	Sensitive Consumers
S-2	City 1 Zone 1	1200	0.80	0	0	1200	169.8	23.8	Nursing home A
S-3	City1 Zone 2-5	1510	1.93	0	0	1510	129.6	18.1	
P-2	City 1 Zone 6	30	1.93	0	0	30	2.5	0.3	
S-4	City 2 Zone 1	1000	unlimited	0	1000	0	103.9	14.5	
S-5	City 3 Zone 1	780	2.52	0	0	780	73.8	10.3	
S-6	City 4 Zone 1	1030	3.16	0	1030	0	105.5	14.8	Hospital B
S-6	SA external	120	3.16	0	120	0	11.7	1.6	
P-6	City 4 Zone 3	50	3.16	0	50	0	4.9	0.7	
S-7	City 4 Zone 2	410	5.67	0	410	0	41.9	5.9	
	Total	**6130**		**0**	**2610**	**3520**	**643.6**	**90.1**	

Table 4 contains information on the affected inhabitants, the affected sensitive consumers, the remaining supply time and an estimate of the emergency water demand not connected to the mains.

More detailed information on the systematics of the models is contained in the sample model (Supplementary Material).

2.2.3. Input Parameterisation

In order to assess the actual impact of the relevant hazards (Section 2.1) on the water supply, the BSMs of the supply system have to be parametrized accordingly. For the standard operation, the average drinking water consumption quantities (Q_{dm}) were recorded and linked to the consumption units. The correct calculation was checked for the reference year by comparing the overall balance of the system with monitored data. For this validation scenario, the consumption factor (f_{dx}) was set to 1.0 and a runtime of 365 days was selected.

Scenarios were identified on the basis of the hazard analysis (Section 2.1), and system settings were derived from them. The scenarios are defined by the duration of the regarded event, the affected system components, and the usability of the water catchments n. Furthermore, the extent to which a change in drinking water demand is to be expected must be estimated. Changes in drinking water demand are taken into account in the BSM using the consumption factor (f_{dx}). The consumption factor (f_{dx}) remains constant over the entire simulation period. If the recovery period after the event is simulated too, this can be carried out as a "hot-start" after the event by switching back all settings to standard.

In the model scenario, the failure of a waterworks (selector switch 'OFF') was assumed to last 3 days. A sub-area in the model can continue to be supplied permanently via an emergency network. Such a scenario could be derived, for example, from the failure of a technical component and its subsequent repair.

The approaches chosen in this study are shown in Table 5 and are described below:

- Scenarios in which no change in drinking water demand is to be expected, such as the failure of a waterworks, were calculated with a $f_{dx} = 1.0$. The use of maximum values ($Q_{d,max}$) was deliberately avoided in order to prevent the scenarios from overlapping.
- In the event of a prolonged dry period, a $f_{d,7} > 1.0$ was calculated, whereby not the maximum consumption ($Q_{d,max}$) but a 7-day maximum was assumed for the increased drinking water quantities in order not to generate an extreme value over a long period of time.
- Reduced consumption rates ($f_{dx} < 1.0$) were assumed in the case of area-affecting events such as blackouts. The national specifications for risk management [47] in Germany were selected as the approach for calculating a piped replacement water quantity ($Q_{d,EW}$). The total drinking water consumption, including the consumption of industry and commerce, was calculated as a lump sum using the consumption factor for the replacement water supply ($f_{d,EW}$).
- The calculation of the non-piped emergency water demand ($Q_{d,NW}$) was also based on [47].

Table 5. Determining water requirements for emergencies and crises**.**

Scenario	Consumption Factor (f_{dx})	Water Requirement (Q_{dx})	Remarks
Failure of system-relevant-component	$f_{dm} = 1.0$	Q_{dm}	No change in consumption behaviour
Pipe burst	$f_{dm} = 1.0$	Q_{dm}	No change in consumption behaviour
Hazardous substance input	$f_{dm} = 1.0$	Q_{dm}	No change in consumption behaviour
Dry periods	$f_{d,7} = Q_{d,7}/Q_{dm}$	$Q_{d,7} = f_{d,7} \cdot Q_{dm}$	Increased consumption
Blackout	$f_{d,EW} = \frac{q_{EW} \cdot E}{Q_{dm,HB}}$	$Q_{d,EW} = f_{d,EW} \cdot Q_{dm}$	Reduced consumption, $Q_{d,EW} = 50$ l/(P·d), flat rate industrial and commercial consumption, $Q_{dm,HB}$ = consumption of household and small business
Emergency water supply	$f_{d,NW} = \frac{q_{NW} \cdot E}{Q_{dm,HB}}$	$Q_{d,NW} = f_{d,NW} \cdot Q_{dm}$	$Q_{d,NW} = 15$ l/(P·d)Determination of emergency water requirements in the event of a mains supply failure

The simulation results of the case study are shown in Section 3.3. The consumption approaches are described in more detail in [51,52].

2.3. Measures to Increase Resilience

The BSMs offer the possibility of supporting the planning process to increase the resilience of water supply systems. They can also be used for decision-making in crisis management.

The first step is to identify and plan existing and potential interconnection structures. The planning should take into account possible variants for connection lines, transfer points and an expansion of technical capacities.

The planning objectives selected in the study can be summarised as follows;

- Maintaining the piped drinking water supply during a blackout with as few systems as possible;
- Utilisation of normal operation facilities also for emergencies and crises;

- Creation of redundancies of system-relevant components, e.g., the failure of an entire waterworks, and;
- Consideration of scenario-dependent drinking water consumption.

Once the planning variants have been defined, the consumption rates must be determined. The following consumption rates were selected for planning the systems:

For normal operation:

- National technical standards (in Germany: DVGW regulations).

For emergencies and crises:

- Scenario-dependent consumption estimates according to Table 5,
- Waiver of minimum supply pressure and
- Utilisation of the full technical capacity without taking redundancies into account.

The planning variants are to be mapped in the BSM as extended balance areas, whereby several supply areas are considered in one balance area (Figure 4, Equation (8)).

$$\frac{dS(t)}{dt} = \Sigma Q(t) = \Sigma Q_{zu,1}(t) - \Sigma Q_{ab,1}(t) + \Sigma Q_{zu,2}(t) - \Sigma Q_{ab,2}(t) + \ldots + \Sigma Q_{zu,n}(t) - \Sigma Q_{ab,n}(t) \quad (8)$$

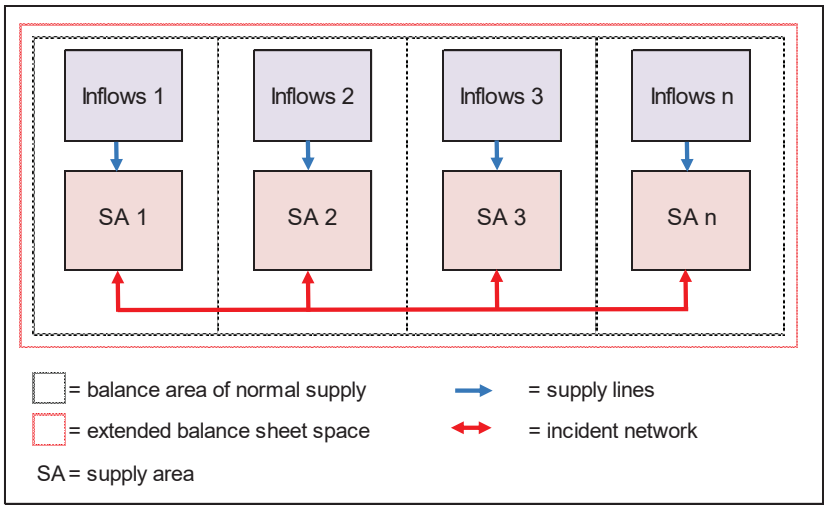

Figure 4. Illustration of an extended balance space, adopted from [52].

The decisive load case for the dimensioning of the systems results from the comparison of the required capacities in normal operation and the consideration of emergency and crisis situations. Detailed descriptions of the planning and consumption approaches can be found in [52].

During a blackout, the necessary diesel supply for emergency power operations can be determined based on the systems to be operated and the production capacities. Careful consideration should be given to whether the external supply can be guaranteed under these conditions or whether self-sufficient supply systems are advisable. A checklist for the construction of company refuelling stations and a tool for determining fuel requirements were developed for the planning and construction of the fuel supply [53].

The planning results of the case study are presented in Section 3.4.

3. Results

3.1. Description of the Case Study

The study area is located in the German state of Saxony. The water supply company in question supplies around 75,000 people with drinking water. There are 21 supply areas with 17 waterworks, 40 pumping stations, 62 drinking water reservoirs, 63 entry and exit points, and 1035 km of drinking water supply pipes. In total, there are 182 system components to be analysed.

3.2. Hazard Analysis

The case study analysed and assessed 57 individual hazards, including 18 natural hazards, 29 technical faults, and 10 hazards caused by attacks, sabotage, or acts of war. A list of the hazards analysed and the results of the investigation can be found in supplementary materials. The detailed hazard analysis is published in [48]. Information on the assessment is provided below, and the assessment is explained using individual examples.

The 18 natural hazards include floods, flash floods, droughts, earthquakes, and pandemics. The extent of damage and the probability of the occurrence of the natural hazards could be determined using existing modelling or statistical evaluations of data series [3,54–61].

For example, incident documentation from the water supplier and local climate projections [59,61] are available for the assessment of dry periods and the development of groundwater recharge. Experience from the dry periods in 2018 and 2019 shows a high level of impact due to: high water demand, declining water supply from the catchments, utilisation of the capacity of the technical systems, and an increased number of pipe bursts with additional personnel requirements. The water supplier suspects that pressure fluctuations due to high consumption and stresses in the dried-out ground are the cause of the high number of burst pipes. According to climate projections [59,61], an increase in dry periods is to be expected across the board. Differences in the forecast data exist in the projection of groundwater recharge. The fluctuations lie between a decrease in groundwater recharge from the current actual level by up to 80% (basis of the climate projection: WETTREG2010_A1B_66) [60] and a slight increase in groundwater recharge (basis of the climate projection: mean annual groundwater recharge (rel. changes)—ensemble median RCP 8.5) [61] by the year 2100. In all simulations, the precipitation dynamics increase. Studies on the development of quality parameters are lacking. Based on the available findings, the impact and the probability of occurrence were assessed as high.

Overall, the results of the natural hazards are site-specific, meaning that their relevance can vary depending on the catchment area. In the study, area, the highest relevance was found for expected climatic changes, such as prolonged dry periods and extreme weather events.

The 29 hazards due to technical malfunctions and human error are made up of, for example, operational organisational hazards, pipe bursts, discharges into the water catchments, or dependencies on other sectors. When assessing the hazards caused by technical faults and human error, different data were found.

The risks of the general company organisation, such as the risk of inadequate substance maintenance, were easy to assess. Here, the water supplier was able to demonstrate a rehabilitation strategy and operation in accordance with DVGW regulations (national regulations). An insufficient reinvestment rate could disrupt the operation of the water supply facilities in the long term, which leads to an assessment of the higher impact on the facilities and the network as well as an assessment of a medium probability of occurrence. Overall, the analysed facilities and the drinking water network are in very good technical condition (network age 37 a, losses < 0.04 $m^3/(h \cdot km)$, and the treatment quality of the distributed drinking water is very high. Possible side effects of risk management measures on drinking water quality can thus be ruled out.

The cross-sectoral impacts on water management, as described by [62], were more difficult to assess. For example, the extent of damage caused by a blackout could be easily determined based on the technical conditions in the study area, but a reliable determination of the probability of occurrence was lacking, which was also found in comparable studies [63,64]. The assessment of special technical incidents sometimes requires expert knowledge, e.g., in the case of nuclear accidents. The probabilities of occurrence and expected extent of damage were determined for the risk of nuclear accidents based on [65,66]. However, validation is hardly possible due to the lack of real events.

In the overall assessment of technical faults, the highest relevance was given to a blackout, the supply of non-drinking water, major pipe bursts, and substance inputs into drinking water catchments, e.g., due to hazardous substances or agricultural inputs.

Of the 10 dangers from attacks, sabotage and acts of war, cyberattacks, sabotage, theft, and attacks of various causes were analysed.

Cyberattacks were identified as a relevant source of risk [16–18], although the risk to the technical systems in the study area is considered to be low due to the spatial separation of the systems. In the present case study, the operation of the water supply systems is only at low risk from cyberattacks. The installed technology sends data and cannot receive data. The data are sent using a programming language developed by the water supply company. For this reason, the cyberattack was not analysed further in the case study. As the degree of digitisation increases, cyberattacks are expected to become more relevant.

A high level of damage is conceivable for the other hazards from attacks, sabotage, or acts of war; information on the probability of occurrence could not be researched.

A total of 12 priority hazards (score > 4) were identified. The priority hazards were summarised into 5 scenarios (Table 6) and form the basis for scenario identification as the next step in the risk analysis.

Table 6. Priority hazards in the supply area under consideration, adopted from [48].

No.	Source of Danger	Relevance	Evaluation of Scenario Selection, Comments
N-5	Flooding water intake	5.25	1st scenario: Hazardous substance entry
N-7	Dryness	9	2nd scenario: Long dry period with potential deficit in demand coverage
N-10	Storm, tornado, thunderstorm	5.25	3rd scenario: Failure of a system-relevant component
T-1	Company organisation	4.5	Safeguarding via quality, environmental and energy management systems.
T-20	Pipe burst on long-distance water pipe	5.25	4th scenario: Burst pipe on a main supply line
T-21	Feed-in of non-potable water	6.75	1st scenario: Hazardous substance entry
T-22	Power failure short, selective	5.25	3rd scenario: Failure of a system-relevant component
T-23	Long, widespread power outage	6	5th scenario: Widespread power failure
T-24	Information technology failure	4.5	3rd scenario: Failure of a system-relevant component
T-28	Accidents involving hazardous substances	6	1st scenario: Hazardous substance entry
T-29	Water pollution	4.5	1st scenario: Hazardous substance entry
T-30	Agricultural entries	6	1st scenario: Hazardous substance entry
A-3	Inadequate property protection, burglary, theft, vandalism	4.5	3rd scenario: Failure of a system-relevant component

3.3. Vulnerability Analysis with Balance Sheet Structure Models

The 21 supply areas of the water supplier in question were modelled in 19 BSMs. The balance areas of the models vary between 20,470 inhabitants with 52 system components and 10 inhabitants with 3 system components. The year 2018 was selected as the reference year with a prolonged dry period. The choice of the reference year 2018 is considered a realistic load assumption for a low water supply in the coming years. A reference scenario with normal consumption was created to calibrate the models.

The following scenarios were selected from the relevant hazards (Section 3.2) as input variables for the simulation:

1. Hazardous substance input into a water intake, duration 30 d, average water consumption;
2. prolonged dry period in the entire supply area, duration 110 d, increased water consumption;
3. failure of a system-relevant component, runtime 7 d, average water consumption;

4. pipe burst on a main supply line, duration 2 d average water consumption;
5. power failure across the board, duration 7 d, replacement water consumption.

A total of 90 simulations were carried out to show the existing vulnerability. The simulation results are shown in Figure 5, clustered according to interconnection possibility and size.

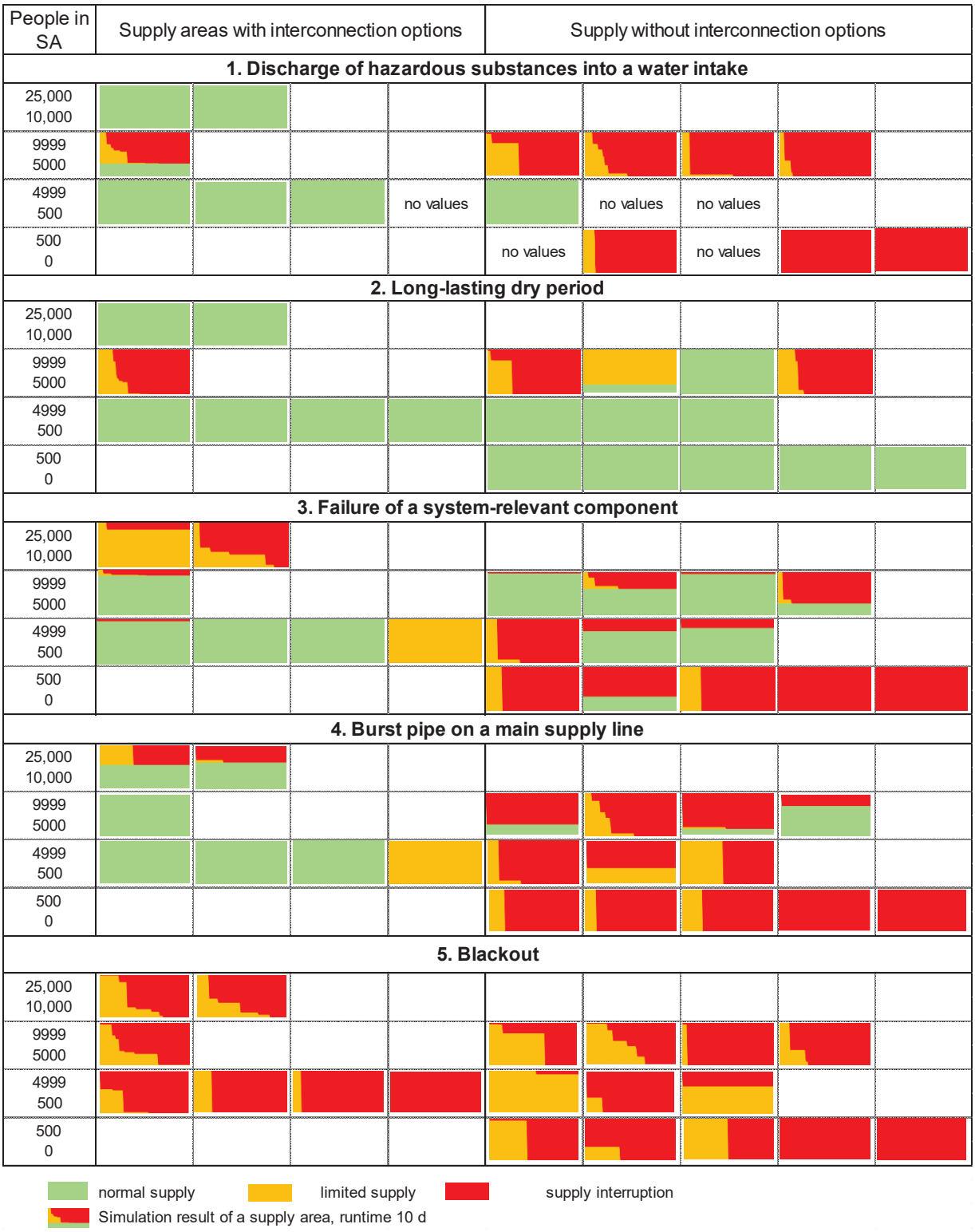

Figure 5. Simulation results of the BSM, adopted from [51].

The analysis of the case studies documents the existing vulnerability and, as expected, shows the most critical impact in the scenario of a widespread power outage. However, the failure of system-relevant components can also lead to massive supply disruptions. In these scenarios, systems with interconnected lines are less vulnerable. The cause of the failure of system-relevant components is initially independent of the system impact but influences the time until normal operation is restored. By intersecting the expected downtime with the remaining supply time, the scenarios can be further analysed accordingly.

3.4. Measures to Increase Resilience

In the study, measures to increase resilience were analysed in accordance with the specifications in Section 2.3. A detailed description of the plan is not possible in order to protect the sensitive data of the supplier. Abstract planning principles for the dimensioning of an intermediate pumping station are published in [52].

In the study, area, the preferred option is the construction of interconnected pipelines and the expansion of the technical capacity of two intermediate pumping stations. The planned measures can almost completely compensate for the failure of individual waterworks (the system-relevant component) and also significantly increase resilience to a blackout (comparison of Figures 6 and 7). By operating just one waterworks and two intermediate pumping stations that are connected to the district water supply, 75% of the population in the study area can continue to be supplied in the event of a blackout (Figure 7). The fuel supply of the remaining plants was planned and constructed according to the specifications of [53].

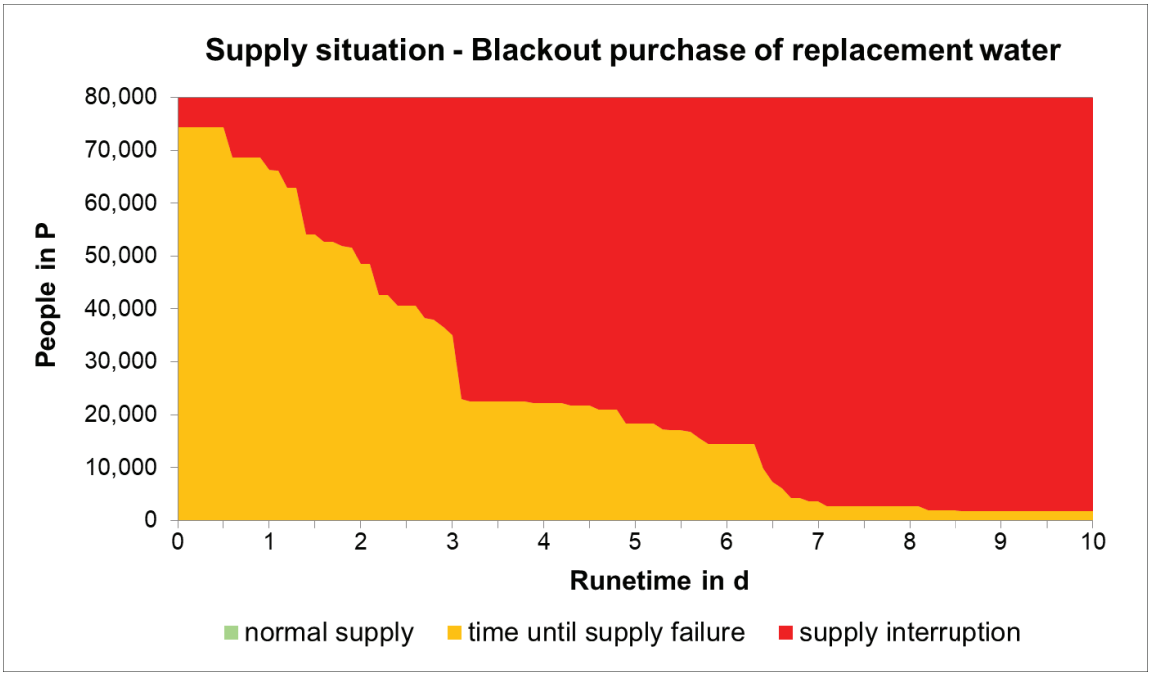

Figure 6. Vulnerability—area-wide power outage actual status, consideration of an extended balance area over the entire 21 supply areas, consumption approach of the replacement water quantity with 50 L/(P·d), adopted from [52].

The production capacities required for emergencies and crises were determined by analysing the extended balance area and the scenarios to be considered. The full system capacities and no redundancies were taken into account in the event of an emergency or crisis. In the case study, the scenario of a prolonged dry period and the associated failure of a near-surface groundwater catchment were relevant to the design.

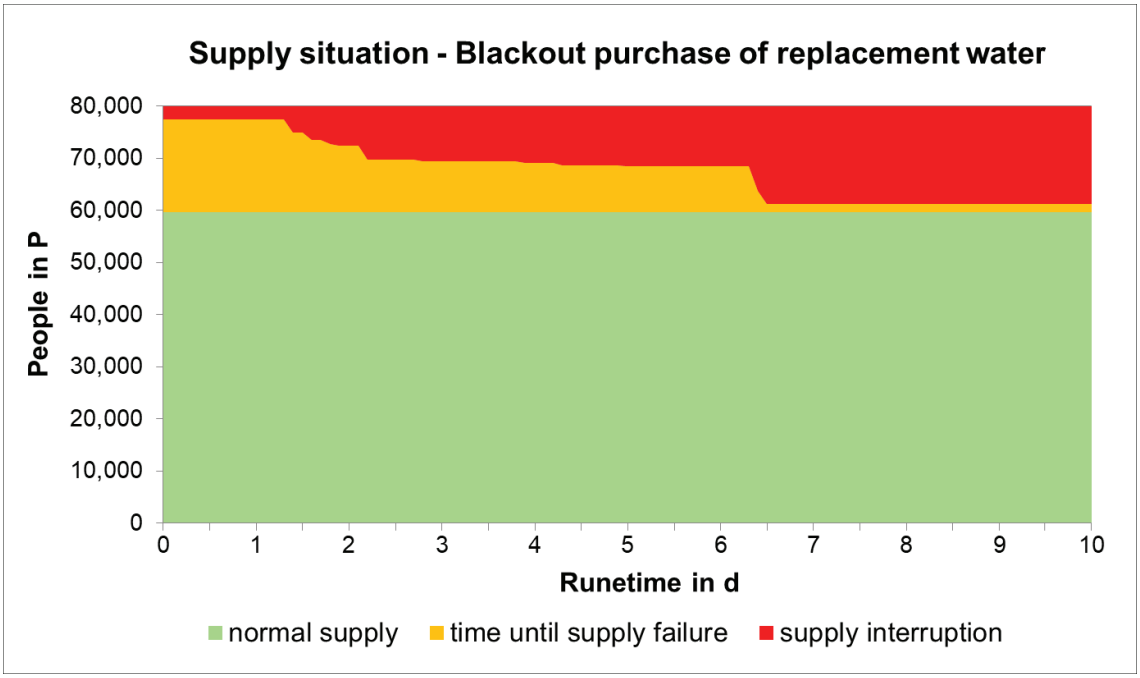

Figure 7. Vulnerability—area-wide power outage and expansion of the interconnected system, consideration of an extended balance area over the entire 21 supply areas, consumption approach of the replacement water quantity with 50 L/(P·d), adopted from [52].

4. Discussion

The hazard analysis methodology presented corresponds to the requirements of European risk management [20,21] and identifies potential hazards to the public water supply with technical justification. The categorisation, with subsequent quantification, achieves a clearly comprehensible order and reduces the subjective component. However, the assessment of each individual hazard requires extensive research. The results of the research show that there is not always sufficient data available for an exact assessment, for example, of the probability of a blackout occurring. The subjective component increases, especially when there is little data available, which can lead to inaccuracies in the process. In addition, the assessment of some hazards, such as the effects of a nuclear accident, requires expert knowledge. As a rule, the expert knowledge required to assess the aforementioned hazards is only available to a limited extent at the water supply company.

For this reason, it is proposed that a minimum scope (Table 7) of the hazards to be considered be specified by a higher authority. The hazards contained in Table 4 were developed from the findings of the literature [63,64] and are based on the database of the present study.

Table 7. Minimum scope of the hazard analysis, adopted from [48].

Natural Hazards	Technical and Human Error	Attacks, Sabotage, Acts of War
Flood	Failure of individual systems *	Cyberattack
Flash flood	Pipe burst on composite pipes	
Dryness	Blackout *	
Earthquake	Accidents with hazardous substances	
Large and wildfires		
Epidemic, pandemic		

* Priority use for scenario building.

As part of risk management in accordance with [20,21], the next step is to carry out a risk assessment. The extent of damage is determined by creating scenarios derived from the hazard analysis and a vulnerability analysis using the BSM. The BSM represents a useful addition to existing instruments for determining vulnerability [24–42]. The differences in the existing literature are summarised below:

- Compared to hydraulic simulations with pipe network models [24–37], the system structure is depicted in a much simpler way. The exact pipe routing, elevation data, pipe dimensioning, material data, and consumption curves are only indirectly taken into account in the BSM by modelling a functioning system in terms of a balance. The hydromechanical limit values are taken into account via the capacity data of the system components and are not verified in the simulation of the BSM.
- A comparison of the system dynamics models [38–42] shows that the BSMs map the causal operating conditions directly on the basis of the real system structure and the topology of the water supply and not via abstracted chains of effects. The simulation of the BSM is carried out using selected system settings under constant conditions. In contrast to the system dynamics models, it is not possible to model dynamic system conditions in the BSM, which could lead to uncertainties in the calculation results of the BSM.

The BSM therefore replaces complex hydraulic or system dynamic models with a graph-based semi-dynamic balance. However, due to the simplified system structure of the BSM, these are not suitable for an exact determination of water demand or hydraulic simulation. The simulation result provides a visual representation of the vulnerability in relation to the topology and a time-dependent forecast of the extent of damage, indicating the affected inhabitants. In addition, the simulation is used to estimate drinking, replacement, and emergency water requirements.

The consumption calculations were carried out under constant conditions. Excess or reduced quantities were selected depending on the scenario under consideration and taken into account as a lump sum in the models via the consumption factor (f_{dx}). The international data on replacement and emergency water requirements [43–47] contain different consumption estimates. The validation of the consumption approaches is only possible to a limited extent due to a lack of data on known emergencies and crises. In addition, a scenario-dependent consumption analysis has (to our knowledge) not yet been described. However, the authors believe that a scenario-dependent consumption analysis is important in order to adapt the measures to increase resilience to the actual drinking water demand. For example, when considering dry periods, peak values such as $Q_{d,max}$ should not be used, and moderate increases in consumption such as $Q_{d,7}$ should be applied. In the case of widespread events such as a blackout, for example, a reduced consumption approach appears to be correct, as reduced consumption behaviour can also be expected here due to the lack of power supply, e.g., lack of hot water supply, non-operation of washing machines or dishwashers and reduced consumption in the industrial and commercial sectors. The following consumption approaches based on scenarios are proposed as part of the initial parameterisation of the BSM;

- $f_{dx} > 1.0$ Application during dry periods as $f_{d,7}$;
- $f_{dx} = 1.0$ Application for scenarios that do not exceed normal consumption; Utilisation of f_{dm}, e.g., the failure of a waterworks;
- $f_{dx} < 1.0$ Application for determining replacement of $f_{d,EW}$ and the emergency water volumes $f_{d,NW}$ in the case of large-scale events such as blackouts.

Due to the existing uncertainties regarding the input parameterisation of the BSM, the simplified model structure with limited accuracy in the assessment of the replacement and emergency water demand appears to be sufficient. As expected, the evaluation of the case studies shows the most critical impact in the scenario of a widespread power outage, with a very high vulnerability up to a total failure of the piped drinking water supply. However, the failure of system-relevant components can also lead to massive supply interruptions. In

systems with interconnected pipelines, a significantly higher resilience of the piped water supply could be demonstrated.

Measures to increase resilience must be identified for risk control as the final step in risk management, according to [20,21]. BSM can support the identification and planning of measures. In particular, with the help of an extended balance area, measures can be identified that enable a piped drinking water supply with as few systems as possible. This enables transparent optimisation of the use of resources in risk management. The following principles are proposed for the future consideration of emergencies and crises when designing systems;

- Risk analyses of the water supply systems, taking into account the relevant hazards;
- Maintaining operations with a minimum number of systems;
- Waiver of minimum supply pressure;
- Utilisation of the full technical capacity without consideration of redundancies for emergencies and crises;
- Scenario-dependent consumption estimates according to Table 2.

The implementation of the planning principles was evaluated using a case study. It was demonstrated that the resilience of the drinking water supply systems can be significantly increased by taking into account the necessary pumping capacities for emergencies and crises. Specifically, interconnected pipes and transfer points were created, the pumping capacity of two intermediate pumping stations was increased, and three emergency power generators were procured. With the measures described above, 75% of the population can be supplied in the future with the operation of just three systems in the event of a blackout.

Compared to advanced risk management instruments, the proposed approach is fairly straightforward and oriented to operators needs and capacities. Each step can be performed without specific expert knowledge. This applies also to BSMs, which can be developed and parametrized by operators and coded with standard office software. The lack of detail appears sufficient in view of the uncertainties when selecting operational parameters for an assumed crisis/disruption.

5. Conclusions

What findings does the study provide for the application of the developed risk management instruments in water management?

The hazard analysis step is very extensive and requires expert knowledge in several fields. It should therefore be considered that a meta-hazard analysis is first carried out by a higher water authority to prioritise relevant hazards. The limited number of prioritised hazards should then be made available to the water supplier to reduce the workload not only in the hazard analysis itself but also in the subsequent risk management steps.

There are many good tools for assessing the resilience of pipework systems [24–42]. The known methods are complex and require sufficient and qualified data for an exact simulation. Particularly in view of the deficits in the preparation and practical application of risk analyses [5,22,23], BSMs can lower the application threshold due to their simplicity and thus make a valuable contribution to the implementation of risk management.

Measures must be identified and planned to increase the resilience of the network-based drinking water supply. There is a lack of reliable standardised specifications for planning outside of normal operation. An increase in resilience could be achieved in the case study through interconnected pipelines and by expanding the capacity of existing systems. Operation with a minimum number of plants should also be made possible in order to ensure operation even in the event of large-scale events.

Where is there a need for further research into the implementation of risk management in water supply companies?

There is a specific need for research in the study area with regard to a more precise forecast of the quantitative and qualitative development of the usable groundwater supply.

The heterogeneous quantity approaches in international comparison [43–47], especially for the requirements for a replacement water supply, lead to uncertainties in the

risk analysis and also in the planning of measures to increase resilience. Cross-national standards, norms, or legal foundations should be developed on the basis of further investigations. This requires a systematic evaluation of water consumption in historically recorded emergency and crisis situations, as well as considerations for controlling water withdrawal in such situations.

In which other areas could BSM be used?

The use of BSMs in crisis management is also conceivable in the future. BSMs are easy to use, do not require any special software, and deliver simulation results quickly. The simulation results can also be used to determine ad hoc effects in the system, such as the separation of sub-areas and the resulting emergency water requirements.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16131814/s1, Download sample model incl. all links and model functions. Hazard list incl. all assessed hazards.

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Article

Assessing Pipe Condition in Water Distribution Networks

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Abstract: The condition assessment of water distribution pipes is of utmost importance for the prioritization of rehabilitation interventions. However, the application of available methodologies for condition assessment by water utilities with limited human, technological and financial resources is becoming increasingly complex. The current paper aims at the development and application of a methodology for the prediction of the physical condition of water distribution pipes without the need for visual inspection. The methodology includes the development and application of three different algorithms (heuristic, linear regression and support vector regression). The methodology is applied to a water distribution network located in the Algarve region, Portugal. The results obtained from each algorithm are compared with a well-known performance indicator, the ratio of useful life, and present significant differences in its overall pipe condition classification. Results have demonstrated the following: the ratio of useful life tends to distribute pipe classification more equally in the three classes (i.e., good, average and unsatisfactory); the heuristic algorithm classifies most pipes as average condition; and the linear regression algorithm classifies with unsatisfactory conditions. The support vector regression algorithm stands out as the main classifier for identifying pipes in good condition when compared to other algorithms.

Keywords: condition assessment; water distribution pipes; heuristic; linear regression; support vector regression

1. Introduction

Water distribution networks inevitably undergo a degradation process, leading to the occurrence of multiple anomalies, such as leaks, bursts, blockages, entrapped air, unsealed valves and water contamination [1]. Numerous utilities are challenged by the urgent need to replace their most degraded assets to meet existing and future requirements. This aspect is more significant in developed countries, where infrastructures were built decades ago and, often, little investment has been made in their renovation [2]. The assessment of the physical condition of water pipes is an important process of infrastructure asset management (IAM), which corresponds to a set of processes that can be applied by water utilities to balance the three dimensions of analysis in the long-term—cost, risk and performance [3]. An efficient IAM aims to provide an asset management plan, allowing for the minimization of the life-cycle costs by lowering renewal costs, identifying the necessary measures for optimized resource allocation and prioritizing the necessary interventions [4].

A comprehensive methodology for IAM to be applied at the three decision levels—strategic, tactical and operational—for asset management is needed [5]. Condition assessment is integrated into IAM in the process of asset performance evaluation. Different methods can be considered for the condition assessment of water distribution pipes, such as direct or indirect methods [6]. Direct condition assessment methods require the inspection of the pipe, which can be intrusive (i.e., requiring access to the interior of the pipe

with or without interruption of the supply service) and non-intrusive methods (i.e., not requiring access to the interior of the pipe, but often requiring excavation) [7]. Indirect condition methods include the collection and analysis of the assets' physical characteristics (e.g., pipe material, diameter, installation date), failure history (e.g., number of busts per year, burst location) and the previous inspection information to estimate the current physical condition [8,9]. These methods can be classified in two categories—environmental (i.e., involving the surveying of soil and water chemistry) and operational (i.e., involving leak/burst history, pipe material embedment, coating or linings calculation)—and aim to analyze trends and changes in the system to provide information on the condition of assets [10,11]. The main advantage of indirect condition assessment methods compared to direct methods is that inspection is not necessary in most cases. As a result, the interruption of the service is avoided, as is the associated cost [11].

The development of indirect condition assessment methods is often based on the known relationships between deterioration and the factors that affect the physical condition of buried pipes. These factors can be divided as follows [12]: (i) physical factors, which are factors related to intrinsic pipe properties, such as pipe material, age, nominal diameter, wall thickness, pipe lining and coating, type of joints and manufacturing process; (ii) environmental factors that are related to the environment in which the pipe is located, such as soil pH, groundwater level, pipe location in relation to traffic, seismic activity, stray electric currents, trench backfill material, pipe bedding, installation practices and underground disturbances; and (iii) operational factors that are associated with the operating conditions of the pipe, such as water quality, water pressure, backflow potential, flow velocity and operational and maintenance (O and M) practices. A burst in a water distribution pipe, if not caused by third parties, can be attributed to pipe deterioration and interpreted as a sign of decreased physical condition. This occurrence can be due to a single influencing factor or a combination. While the factors that contribute to the deterioration of water distribution pipes are known, the relative influence of each factor is widely discussed [13]. As a result, even though research has proven the existence of failure mechanisms, the uncertainty associated with the exact relationship between factors is still the focus of several studies.

Several algorithms have been developed to assess and predict the physical condition of water distribution pipes. These vary from basic techniques that rely on limited data to highly precise prediction models leveraging the latest advancements in machine learning. The use of key performance indicators to assess the asset condition is one of the most used approaches in Portugal, especially the use of the Infrastructure Value Index (IVI). This index was firstly proposed by [14] and is defined as the ratio between the current value of the infrastructure and its replacement cost:

$$IVI\,(t) = \frac{\sum_{i=1}^{n_i} \left(rc_{i,t} \cdot \frac{rul_{i,t}}{eul_i} \right)}{\sum_{i=1}^{n_i} rc_{i,t}} \tag{1}$$

in which $IVI\ (t)$ is the infrastructure value index at time t, $rc_{i,t}$ is the replacement cost of asset i at time t, $rul_{i,t}$ is the residual useful life of asset i at time t, eul_i is the expected useful life of asset i and n_i is the total number of assets. This index aims at assisting long-term planning of urban water assets; however, it can also represent the current age and the intervention needs of a given infrastructure. When calculating IVI at the asset level, the key performance indicator represents the ratio of useful life (RUL) of each pipe, corresponding to the ratio between the asset age and its useful life.

Other algorithms include deterministic, heuristic or machine learning techniques. Deterministic techniques are commonly used when a non-random relationship between variables is considered. A well-known study that has developed deterministic algorithms is [15]. This study estimated the remaining useful life for gray cast iron water pipes, using a total of 29 parameters. These algorithms are easy to apply and understand; however, they are inappropriate in scenarios where the risk of an event is a relevant criterion for

decision-making, e.g., seismic risk and vulnerability studies [16]. Heuristic techniques are more common when the influencing factors are not well understood, allowing for the development of algorithms through subjective opinions from experienced field engineers and experts [17]. Ref. [18] proposed a pipe condition rank method using fuzzy PROMETHEE II. This model was applied to eight pipe samples and the results ranked each pipe by the highest to lowest breakage risk. These algorithms are developed with limited or no pipe data; however, results are highly influenced by the opinion of the expert groups. Finally, new algorithms that rely on machine learning techniques have been proposed, including generalized linear models, deep learning, decision trees, random forests, XGBoost, AdaBoost and support vector machines [19]. Ref. [20] studied different machine learning algorithms, such as random forests, decision trees, neural networks and support vector machines to accurately locate water leaks in water distribution systems.

These algorithms are very challenging to implement in water distribution systems, given the limited infrastructure data. In Portugal, 51 out of 136 water utilities do not have any form of formal inventory of assets, including information related to pipe location and historical data, and only 20 water utilities are reported to have any information regarding the condition of the assets [21]. Overall, there is an urgent need to address the gap between the condition assessment algorithms and the existing required resources in water utilities, namely, financial, human and technological. Thus, the main objective of this research is to develop a methodology to assess the physical condition of water distribution pipes based on three different algorithms and without the need for visual inspection or service interruption. The proposed methodology takes into consideration the knowledge gaps that Portuguese water utilities face, regarding the low infrastructure knowledge and the limitations of the current method used for indirect condition assessment (i.e., IVI). Three different algorithms are developed, compared and applied to assess the pipe physical condition of a Portuguese water distribution network, including heuristic, linear regression and support vector regression algorithms.

The paper is organized in five sections, including the current one. Section 2 presents the proposed methodology to assess the physical condition of water distribution pipes, describing the three algorithms. Section 3 presents the case study to which the methodology is applied and Section 4 shows, compares and discusses the condition assessment results. Lastly, Section 5 presents the main conclusions of this research and highlights foreseen future works.

2. Proposed Methodology

2.1. General Framework

The proposed methodology for assessing the physical condition of water distribution pipes is a three-step procedure:

(1) Data collection and validation;
(2) Algorithm development;
(3) Condition assessment.

This methodology allows water utilities to efficiently assess the physical condition of their water distribution networks without the need for inspection or extensive field survey, which represents a less resource-consuming process. The application of this methodology also aims to contribute to the improvement of resource allocation and investment planning, resulting in the enhancement of the physical sustainability and integrity of water distribution networks.

The first step of the proposed methodology aims at collecting the factors that influence the physical condition of water pipes, which can be divided into three main categories: physical, operational and environmental. The collection of the failure history is also required to assess the physical condition of water pipes without inspection, including the type and date of bursts and their location. All collected data needs to be validated and checked for any inconsistencies (e.g., incorrect installation year of water pipes or

inappropriate material choice for the nominal diameter). The most relevant factors that influence pipe deterioration are identified in the literature and summarized in Table 1.

Table 1. Potential influencing factors of pipe deterioration.

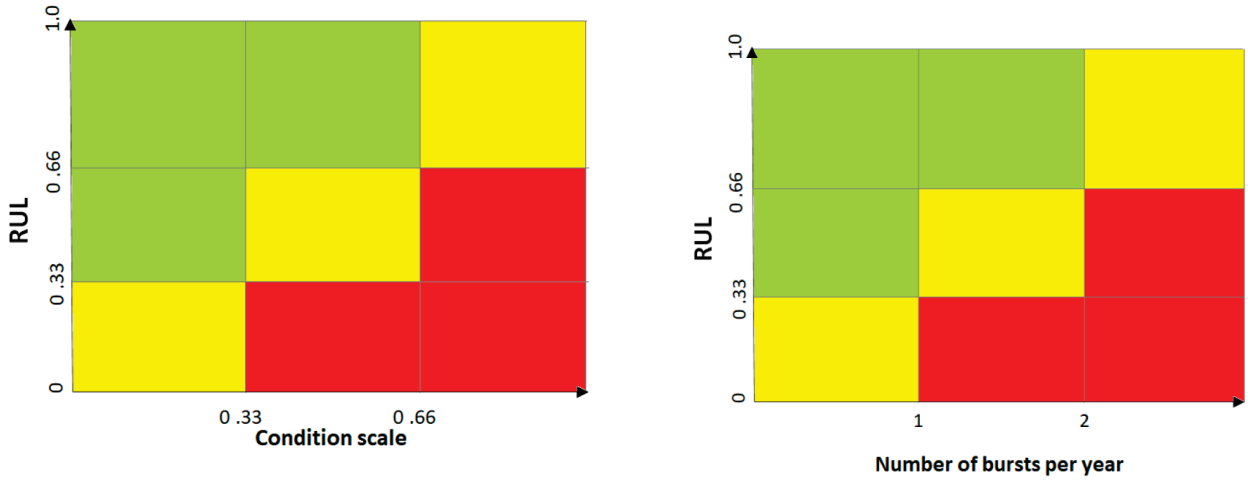
Category	Factors
Physical	Pipe material, year of installation, nominal diameter, length, installation depth, wall thickness, Hagen Williams coefficient, cathodic protection, manufacturing process, location, laying conditions and number of households supplied.
Operational	Static pressure, pressure variance, water pH, chlorine levels, phosphate inhibitors, water temperature, water pressure and pressure surge allowance.
Environmental	Type of soil, groundwater level, soil pH, soil resistivity, soil density, backfill material, traffic intensity, wheel load ratio, soil aeration index, road surface type, external loads and ratio of horizontal to vertical pressure in the soil.
Failure history	Failure history, date of burst, corrosion depth, bursting tensile strength and ring modulus of rupture.

The second step of the proposed methodology is the development of different algorithms to assess the physical condition of water pipes, e.g., heuristic, linear regression and support vector regression. Heuristic algorithms rely on a theoretical framework for model construction, aiming at applying intuition to problem-solving and reducing the resources needed to achieve an adequate result. On the other hand, linear regression and support vector regression algorithms receive and analyze input data to predict output values within an acceptable range. The study of these two different algorithms allows us to identify their advantages and limitations and to compare the condition assessment results to ensure informed decision-making. A detailed description of each algorithm is presented in the following sections.

The third step of the proposed methodology aims at developing a comprehensive condition rating scale to interpret the algorithms' results and to assess the physical condition of water distribution pipes. A condition matrix with three condition rating levels, namely good (represented by the green colour), average (represented by the yellow colour) and unsatisfactory (represented by the red colour), is developed.

Different condition matrices are developed for combining the algorithm results with the performance indicator of the ratio between the asset age and the useful life, designated as the Ratio of Useful Life (RUL). The idea behind the construction of these condition matrices is to combine a well-known performance indicator with data related to observations (e.g., pipe burst) made during the operation of the network. The RUL scale varies between zero and one, one being the value associated with newly installed pipes and zero being the value associated with pipes that have already reached their reference useful life and still remain in service. Three ranking levels equally divided are considered for the RUL scale.

The scale adopted for the algorithm results varies for each technique. In the heuristic algorithm, the proposed scale is similar to RUL with three ranking levels equally divided according to the interval of variation of the pipe condition model. The proposed condition matrix for the heuristic algorithm is presented in Figure 1a. For the remaining two algorithms (i.e., linear regression and support vector regression), the scale is based on the number of bursts during the observation period. This scale could vary with acceptable condition thresholds considered for each water utility, which in most cases depends on the available annual budget for interventions. Figure 1b illustrates a condition matrix for the two remaining algorithms, considering that zero bursts per year during the observation period (OP) are associated with pipes in good condition, with one burst for pipes in average condition and two bursts or more for pipes in unsatisfactory condition.



(**a**) (**b**)

Figure 1. Condition assessment matrices with three ranking levels (good condition represented by the green colour, average condition represented by the yellow colour and unsatisfactory condition represented by the red colour): (**a**) heuristic algorithms; (**b**) linear regression and support vector regression algorithms.

2.2. Heuristic Algorithm

The heuristic algorithm aims at developing condition models using weights for each factor that influences pipe deterioration calculated through a survey of experts in this field. The heuristic algorithm is composed of three main steps:

- Development of a survey on the influence of internal and external factors on pipe deterioration.
- Processing and analysis of the survey data and calculation of weighting factors.
- Development of condition models.

The first step aims at developing a survey to assess the importance of different factors on the physical condition (translated by the deterioration) of water distribution pipes, considering the following categories: (i) pipe characteristics and operating conditions; and (ii) external factors. The survey should be short, clear and unambiguous and the structure chosen should facilitate data collection. Experts should only answer questions regarding factors they are familiar with, avoiding the collection of guessing data. Additionally, the number of years of experience that experts have in the field is also collected to assess the perception that each experience group has of the influencing factors. In the developed survey, the influencing factors are evaluated on a scale from zero to five, in which zero means that the factor is irrelevant to pipe deterioration and five means that the factor is very relevant.

The second step aims at processing and analyzing the collected data from the surveys and calculating the weights that each factor has on physical condition. To calculate these weights, weighting methods are applied to assess different aspects of the collected data, namely the discrepancies in the average value (i.e., the use of the average and median values) or the overall confidence of experts in their perceptions (i.e., the bias of the number of replies for each factor). Furthermore, it should be noted that weights should range from zero to one and the total weight sum should be one.

The final step aims at developing the condition models with the calculated weighting factors. The construction of models should take into consideration the positive or negative relationship of each weighting factor with the physical condition of water distribution pipes. This means that special attention must be given to the variation of the influencing factor and their contribution to the condition grade, through the knowledge gathered by the literature review.

2.3. Linear Regression Algorithm

Linear regression assumes that pipe deterioration has a non-random relationship with network characteristics that yield pipe failure. These failures can only be detected by water utilities during a pipe inspection or when a burst occurs, which is the most common type of failure history, as direct action needs to be taken when detected. As a result, this algorithm uses failure history as a dependent variable and aims to construct models that estimate this theoretical failure considering different independent variables related to physical, operational and environmental factors. The steps that are needed to complete this algorithm are the following:

- Development of a correlation matrix between network characteristics (i.e., independent variables) and failure variables (i.e., dependent variables).
- Construction and assessment of linear regression models.
- Validation of regression models.

The first step aims at developing a correlation matrix with the dependent and independent variables. The independent variables are the characteristics of water distribution pipes (e.g., year of installation, material, nominal diameter) and the dependent variables are the failure history. Preferably, the collected variables should be quantitative; this operation might require the conversion of categorical variables to numerical values. The construction of the correlation matrix allows us to identify the highest-correlation coefficients that best describe the relationship between dependent and independent variables. The Spearman's rank correlation coefficient is used to construct the correlation matrix, as it provides a nonparametric technique and measures the strength and direction of a non-monotonic relationship [22].

The second step consists of the construction of simple and multiple linear regression models and the assessment of the developed regression models through statistical analysis. Statistical analysis includes the calculation of the coefficient of determination for both simple (r-squared) and multiple regression analysis (adjusted r-squared) as well as the statistical significance of linear models by null hypothesis testing. The multicollinearity between explanatory variables (i.e., independent variables) is verified by the mathematical measurement of the variance inflation factor (VIF). Values higher than or equal to 10 are considered to have a high degree of multicollinearity and, therefore, are excluded from the models [23].

The third step corresponds to the validation of linear models by verifying the statistical dispersion of the collected data through the evaluation of the root mean square error, relative error and absolute error. The collected data must be divided into two subsets to carry out the validation: the training subset used for model construction, typically representing 80% of the whole dataset, and the validation subset used to validate the obtained results, representing the remaining 20% of the dataset. The goal of the validation subset is to perform cross-validation of the evaluated models and flag problems, such as overfitting and selection bias [24].

2.4. Support Vector Regression Algorithm

This subsection explores support vector regression (SVR) as an alternative to linear regression for predicting pipe failures. Unlike linear regression, which is based on a linear relationship between variables [25], SVR can effectively model non-linear and complex relationships [26] between network characteristics and failure occurrences. This characteristic makes SVR a potentially more suitable approach for scenarios where the deterioration process exhibits non-linear behavior, such as in aging pipe networks.

The objective of SVR is to find a hyperplane in the high-dimensional feature space that maximizes the margin between the hyperplane and the closest data points, also called support vectors, from each failure class:

$$w\varphi(x) + b = 0 \tag{2}$$

in which $w \in \Re^d$ is the weight vector, $\varphi(x)$ is the transformed input vector in the feature space and b is the bias term.

The process of finding the optimal hyperplane can be formulated as a convex optimization problem that minimizes the error of approximation. This minimization is also described as the ε-insensitive loss across all data points [26]. The ε-insensitive loss function penalizes deviations from the desired behavior and the model prediction for a certain input. Solving this optimization problem using appropriate algorithms allows us to obtain the optimal weight vector (w) and bias term (b) that define the decision function for classifying unseen data points. Prediction for a new data point involves projecting it into the high-dimensional feature space using the chosen kernel function and calculating the distance from its projection to the established hyperplane.

The SVR algorithm is applied to estimate the number of failures for each pipe by using the same network characteristics, as the ones used in linear regression. The classification of each pipe based on the number of failures is evaluated by using a confusion matrix, comparing the real number of failures with the estimated one. Furthermore, to compare the results with the linear regression algorithms, the determination coefficient is calculated.

3. Case Study

A water distribution network with a total length of approximately 85 km and serving 1787 houses with an annual water volume of 1,805,024 m^3 is studied. This distribution system includes three pumping stations and four water storage tanks. The network is located in low-density residential housing and the domestic consumers correspond, mainly, to detached houses, which are mostly used in the summer season. Thus, this utility is characterized by seasonal water consumption with high outdoor water use in the summer and four to five times lower water consumption during the winter.

A total of 1666 distribution pipes comprise the network with different materials, such as polyvinyl chloride (PVC), asbestos cement (AC), ductile iron (DI), steel and high-density polyethylene (HDPE). The most predominant pipe material is PVC, corresponding to 53% of the total network, followed by AC (27%) and DI (17%) (Figure 2a). The nominal diameter of distribution pipes varies between 50 and 600 mm, with the most common pipes, those with small nominal diameters (i.e., less than 250 mm), representing more than 75% of the total distribution pipes (Figure 2b). The distribution network was initially constructed in 1972; however, the largest expansion of the network took place between 1982 and 1992, in which 50% of the pipes were installed (Figure 2c).

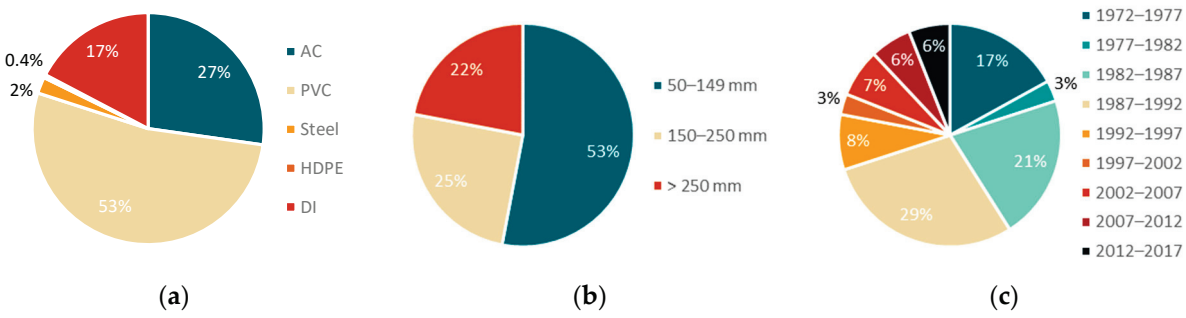


Figure 2. Water distribution network characteristics: (**a**) construction materials; (**b**) nominal diameter; and (**c**) construction year.

The studied distribution network presented 113 bursts during the observation period between February 2014 and February 2020. From a total of 113 bursts, 41 were classified as third-party interventions, while the remaining 72 bursts can be attributed to the natural process of pipe deterioration (2 of these bursts were not considered for further analysis due to being located in service connections). A total of 70 bursts, located in 49 different pipes, are considered for the present study.

4. Results

The proposed methodology is applied to the described case study to assess the physical condition of water distribution pipes, considering three different algorithms (i.e., heuristic, linear regression and support vector regression). A detailed description and discussion of the results are divided by the type of algorithm used and presented in the following sections.

4.1. Heuristic Algorithm

4.1.1. Development of a Survey on the Influence of Internal and External Factors on Pipe Deterioration

The perception of experts is collected through a survey, in which the influence of each factor already identified in Table 1 is evaluated. A total of 31 experts in the water supply sector, with professional careers of different maturity levels, were surveyed. All surveyed experts are engineers working for the public or private sector, including water utilities, academia and research. The distribution of their professional experience described by the duration of their professional career is presented in Figure 3. The number of experts in each experience group is similar, allowing us to obtain fairly distributed results throughout each group: eight experts with 0–5 years of experience (26%), seven experts with 5–10 years of experience (22%), seven experts with 10–20 years of experience (23%) and nine experts with more than 20 years of experience (29%).

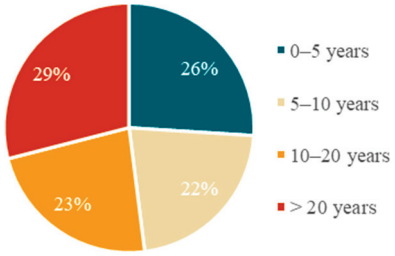


Figure 3. Distribution of the duration of the professional career of surveyed experts.

4.1.2. Processing and Analysis of the Survey Data and Calculation of Weighting Factors

The processing and analysis of the survey results allows us to obtain quantitative weights for each influencing factor. The mathematical formulas used to obtain the weights are presented in Table 2. Each weight aims to value a certain aspect of the collected data that allows for the comparison of each factor's influence. For example, the use of average- versus median-based weights allows us to evaluate the susceptibility to outliers in the collected data.

Table 2. Methods for obtaining factor weight attribution in the heuristic algorithm.

Factor Weight	Equation
Answer-based weights	$w_i = \frac{S_i}{\sum_{i=1}^{n} S_i}$
Number of replies and answer-based weights	$w_i = \frac{S_i \times A_i}{\sum_{i=1}^{n} S_i \times A_i}$
Median-based weights	$w_i = \frac{m_i}{\sum_{i=1}^{n} m_i}$
Number of replies and median-based weights	$w_i = \frac{m_i \times A_i}{\sum_{i=1}^{n} m_i \times A_i}$
Mean-based weights	$w_i = \frac{I_i}{\sum_{i=1}^{n} I_i}$
Number of replies and mean-based weights	$w_i = \frac{I_i \times A_i}{\sum_{i=1}^{n} I_i \times A_i}$

Notes: w_i is the weight of factor i; S_i is the sum of answers of factor i; n is the total number of influencing factors; A_i is the number of answers of factor i; m_i is the median value of factor i; and I_i is the average value of factor i.

Since the available data in the case study does not exist for all considered factors (see Table 1), only six factors were analyzed, namely pipe material, pipe age, pipe nominal diameter, pipe length, pipe roughness coefficient and average operating pressure (considered the same as the static pressure for this study). The diagrams with the obtained weights for each of the six factors using the different mathematical formulations (Table 2) are presented in Figure 4. The vertices of the diagrams represent the weight attributed by each expert experience group.

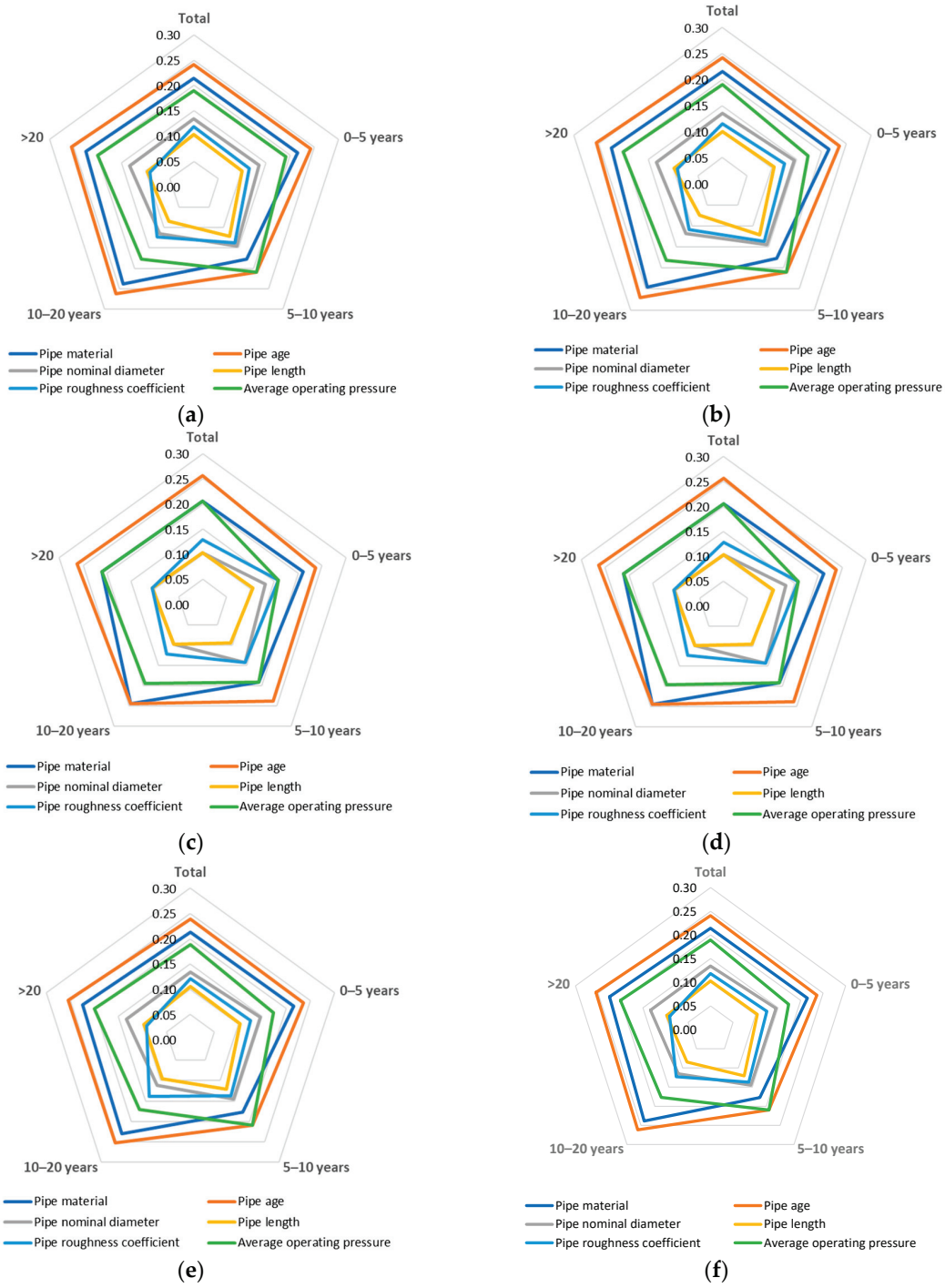


Figure 4. Obtained weight values for each influencing factor considering different weight formulations: (**a**) answer-based weights; (**b**) number of replies and answer-based weights; (**c**) median-based weights; (**d**) number of replies and median-based weights; (**e**) mean-based weights; and (**f**) number of replies and mean-based weights.

Pipe age is the most relevant factor in pipe deterioration. However, the group with 5–10 years of experience also considers the average operating pressure of pipes as an equally important influencing factor of deterioration when using most weight formulas. On the other hand, the evaluation of the weight associated with each factor is very similar throughout experience groups with the order of most influential to least influential factors: age, material, average operating pressure, nominal diameter, roughness coefficient and length. Although some variation of this order can be identified, mainly in Figure 4e, the overall consensus of the experts remains.

Additionally, it can also be concluded that the order of influence in the factors does not change with the different weight calculation methods. Furthermore, the multiplication of the number of replies did not significantly change the results, which can be explained by the recommendation for experts to avoid guesswork in the survey leading to potential outliers in the answers. Nevertheless, when analyzing the weights attributed by expert experience groups, different perceptions arise. While all expert experience groups agree that pipe age is highly influential, the group with 10–20 years of experience concludes that pipe material and pipe age are highly influential, while the experts with more than 20 years of experience attribute a higher influence to average operating pressure than pipe material.

Table 3 presents the results of the weight values using answer-based weights for the total expert group and the +20 expert group. These weights were considered for the subsequent analyses. Note that the summation of the weights equals 1.

Table 3. Obtained weights using answer-based weights for the total expert group and the +20 expert group.

Factor	Answer-Based Weights and Total Expert Group	Answer-Based Weights and +20 Expert Group
Pipe age	0.2407	0.2546
Pipe material	0.2142	0.2242
Pipe nominal diameter	0.1345	0.1333
Pipe roughness coefficient	0.1186	0.0909
Pipe length	0.1027	0.0970
Average operating pressure	0.1893	0.2000

4.1.3. Development of Condition Models

The development of a pipe condition model using the obtained weights requires the normalization of the properties of each pipe according to the following equation:

$$N_{n,i} = \frac{y_{n,i} - y_{\min,i}}{y_{\max,i} - y_{\min,i}} \times w_i \tag{3}$$

in which $N_{n,i}$ is the normalized and weighted influencing factor i for pipe n; $y_{n,I}$ is the value of the influencing factor i for pipe n; $y_{\min,i}$ is the minimal value for the influencing factor i; $y_{\max,i}$ is the maximum value for the influencing factor i; w_i is the attributed weight for the influencing factor i.

Finally, the sum of the weighted variables of each factor results in a non-dimensional value of physical condition for each pipe as follows:

$$C_n = \sum_{i=1}^{n} N_{n,i} \tag{4}$$

in which C_n is the condition value for the pipe n.

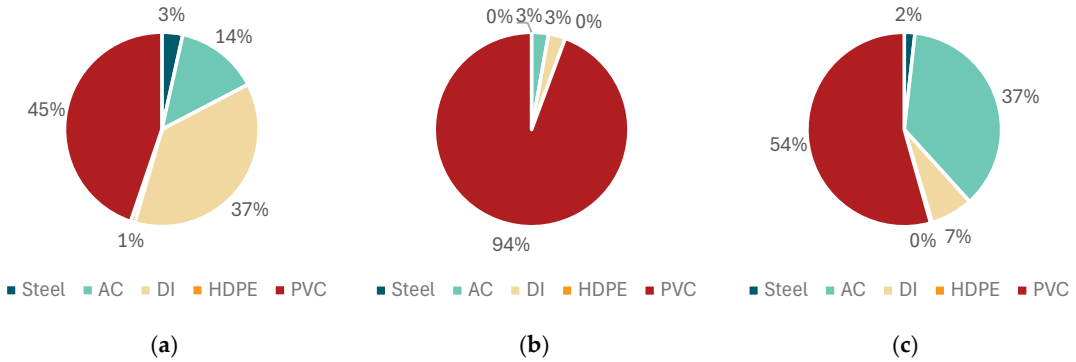
It should be noted that influencing factors do not present the same relationship (positive or negative) with pipe physical condition; thus, special attention must be given to the variation of the influencing factors and their contribution to the condition grade through the knowledge gathered by the literature review.

The pipe condition model is applied to the described case study considering the total expert knowledge (i.e., 31 experts) and the most experienced experts (i.e., over 20 years of experience) and using the answer-based weights. The condition scale presented in Figure 1a is used to classify the physical condition of pipes as good, average and unsatisfactory. The obtained results are quite similar for both categories of expert groups, classifying most of the network with an average condition (Table 4).

Table 4. Pipe condition results using a heuristic algorithm and considering answer-based weights for the total expert group and +20 expert group.

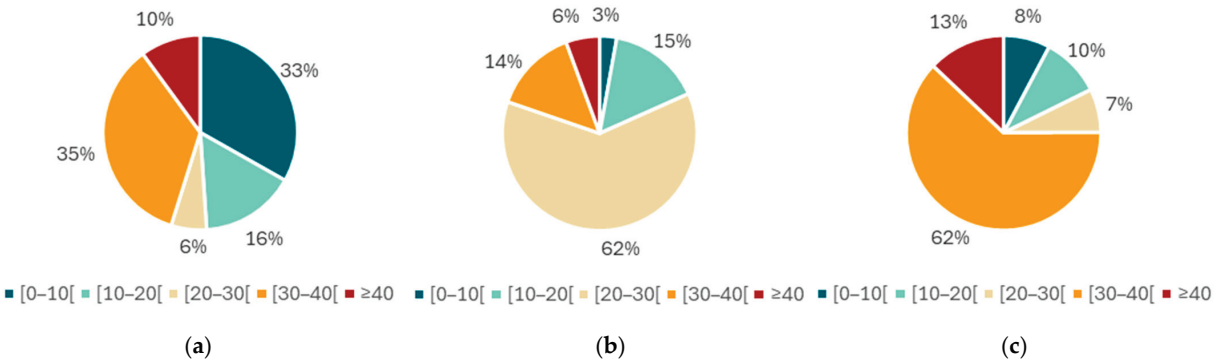
Condition Grade	Answer-Based Weights and Total Expert Group		Answer-Based Weights and +20 Expert Group	
	Number of Pipes	Relative Frequency (%)	Number of Pipes	Relative Frequency (%)
Good	370	22.21%	201	12.06%
Average	994	59.66%	1165	69.93%
Unsatisfactory	302	18.13%	300	18.01%
Total	1666	100%	1666	100%

Figures 5 and 6 present the pipe material and pipe age distribution for the three condition grades (i.e., good, average and unsatisfactory), respectively. The majority of the pipes classified as unsatisfactory condition are made of AC and PVC, which are the materials mostly installed between 1970 and 2000 (Figure 5). In terms of pipe age distribution, there is a tendency for more recent pipes to be classified as good condition (almost 50% of the pipes present an age between 0 and 20 years), followed by pipes classified as average condition and with an intermediate age (i.e., 62% of the pipes present an age between 20 and 30 years). Finally, the majority of the older pipes are classified as unsatisfactory condition, representing 75% of pipes with an age higher than 30 years (Figure 6).



(**a**) (**b**) (**c**)

Figure 5. Pipe material distribution: (**a**) good condition; (**b**) average condition; and (**c**) unsatisfactory condition.



(**a**) (**b**) (**c**)

Figure 6. Pipe age distribution: (**a**) good condition; (**b**) average condition; and (**c**) unsatisfactory condition.

4.2. Linear Regression Algorithm

4.2.1. Development of a Correlation Matrix between Network Characteristics and Failure Variables

As mentioned in the proposed methodology, this algorithm aims to use network properties as independent variables to model the failure history of the network (e.g., the number of bursts, rate of bursts, number of bursts per year). The regression models are developed through the use of linear regressions. A summary of the dependent and independent variables used is provided in Table 5. The variable distance to the tank (DT) is used as an indirect variable of pipe location in order to consider the influencing factors attributed to environmental factors (e.g., traffic, soil pH, road surface type, external loads).

Table 5. Summary of the dependent and independent variables used in the deterministic approach.

Type of Variable	Variable	Equation	Units	Abbreviation
Independent	Pipe material *	-	Years	*Mat5* or *Mat3* ***
Independent	Installation year	-	Year	*YI* or *YI_0*
Independent	Length	-	m	*Length*
Independent	Static pressure	-	m	*SP*
Independent	Distance to the tank	-	m	*DT*
Independent	Nominal diameter	-	mm	*DN*
Independent/dependent	Average pipe age when the burst occurred	-	Years	*AA*
Dependent	Number of bursts	-	no.	*Nburst*
Dependent	Number of bursts per year	-	$\frac{Nburst}{year}$	*NBY*
Dependent	Rate of burst per meter **	$AA03 = \frac{N_{Burst}}{l \times PO} \times 100km$	$\frac{Nburst}{year \times 100km}$	*AA03*
Dependent	Rate of burst	$RoB = \frac{N_{Burst}}{l \times PO}$	$\frac{Nburst}{year \times meter}$	*ROB*
Dependent	Rate of burst length non-dimensional	$ROBLND = \frac{Nburst}{l \times PO}$	$\frac{Nburst}{year \times meter}$	*ROBLND*

Notes: *PO*—period of observation; *l*—pipe length; * converted to defined services lives; ** defined by [27]; *** *Mat5*—material 5 unique values, Table 6 and *Mat3*—material 3 values, Table 7.

Table 6. Reference values of useful lives.

Pipe Material	Asbestos Cement (AC)	Polyvinyl Chloride (PVC)	High-Density Polyethylene (HDPE)	Steel	Ductile Iron (DI)
Established useful life (years)	40	45	50	60	70
	40		50		60

Table 7. Correlation matrix using Spearman's rank level correlation coefficient considering only pipes with bursts (n = 49).

Variables	*Mat5*	*Mat3*	*YI*	*YI_0*	*DN*	*Length*	*AV_T*	*DT*	*SP*	*NB*	*AA03*	*AA*	*ROB*	*ROBLND*	*NBY*
Mat5	1.00	1.00	0.60	−0.60	−0.13	−0.20	0.02	0.07	0.11	−0.38	0.06	−0.41	0.06	−0.38	−0.38
Mat3	1.00	1.00	0.60	−0.60	−0.13	−0.20	0.02	0.07	0.11	−0.38	0.06	−0.41	0.06	−0.38	−0.38
YI	0.60	0.60	1.00	−1.00	0.19	−0.13	−0.11	0.28	0.30	−0.51	−0.09	−0.45	−0.09	−0.51	−0.51
YI_0	−0.60	−0.60	−1.00	1.00	−0.19	0.13	0.11	−0.28	−0.30	0.51	0.09	0.45	0.09	0.51	0.51
DN	−0.13	−0.13	0.19	−0.19	1.00	0.18	−0.18	0.03	−0.04	0.12	−0.17	0.14	−0.17	0.12	0.12
Length	−0.20	−0.20	−0.13	0.13	0.18	1.00	0.03	0.13	−0.04	0.34	−0.91	0.09	−0.91	0.34	0.34
AV_T	0.02	0.02	−0.11	0.11	−0.18	0.03	1.00	0.02	−0.01	0.06	−0.05	−0.11	−0.05	0.06	0.06
DT	0.07	0.07	0.28	−0.28	0.03	0.13	0.02	1.00	0.84	−0.22	−0.25	−0.25	−0.25	−0.22	−0.22
SP	0.11	0.11	0.30	−0.30	−0.04	−0.04	−0.01	0.84	1.00	−0.35	−0.13	−0.38	−0.13	−0.35	−0.35
NB	−0.38	−0.38	−0.51	0.51	0.12	0.34	0.06	−0.22	−0.35	1.00	0.05	0.63	0.05	1.00	1.00
AA03	0.06	0.06	−0.09	0.09	−0.17	−0.91	−0.05	−0.25	−0.13	0.05	1.00	0.14	1.00	0.05	0.05
AA	−0.41	−0.41	−0.45	0.45	0.14	0.09	−0.11	−0.25	−0.38	0.63	0.14	1.00	0.14	0.63	0.63
ROB	0.06	0.06	−0.09	0.09	−0.17	−0.91	−0.05	−0.25	−0.13	0.05	1.00	0.14	1.00	0.05	0.05
ROBLND	−0.38	−0.38	−0.51	0.51	0.12	0.34	0.06	−0.22	−0.35	1.00	0.05	0.63	0.05	1.00	1.00
NBY	−0.38	−0.38	−0.51	0.51	0.12	0.34	0.06	−0.22	−0.35	1.00	0.05	0.63	0.05	1.00	1.00

Notes: *Mat3*—pipe material; *YI*—year of installation; *DN*—nominal diameter; *Length*—pipe length; *AV_T*—average water temperature; *DT*—distance to tank; *SP*—static water pressure; *NB*—number of bursts; *AA03*—rate of burst per 100 km; *AA*—average pipe age when the burst occurred; *ROB*—rate of burst; *ROBLND*—rate of burst length non-dimensional; *NBY*—number of bursts per year.

All collected pipe characteristics must be quantitative to develop the correlation matrix (Step 1) and the linear and quadratic models (Step 2). One of the independent variables that requires a transformation from a qualitative categorical variable to a quantitative variable is pipe material. This transformation is carried out based on reference values of useful lives for each pipe material (see Table 6). Although other associations can be made to develop this variable transformation, the decision to use the useful life is based on the known relationship between the useful life and the material durability. However, since useful lives are one of the most uncertain variables, additional useful lives aggregated for the type of material (i.e., concrete, plastic or metal) are also considered (Table 6). This aggregation is based on the known fact that some material types have similar useful lives given their composition and durability.

The construction of a correlation matrix aims at understanding, at a preliminary stage, the relationship between the pipe characteristics and the failure variables. The use of Pearson's product moment correlation coefficient (PPMCC) requires that variables must be continuous, normally distributed, have a paired value and be absent of outliers that can skew relationships [22]. Since some variables are discreet and only 3 of the 13 collected variables are normally distributed, the use of Spearman's rank order correlation coefficient (SRCC) is the most appropriate coefficient for the development of the correlation matrices.

The construction of the correlation matrix only includes pipes that have bursts during the period of observation. Accordingly, the dataset is composed of only 49 elements (i.e., pipes) as opposed to 1666, which is the total number of pipes in the network. This reduced number of data points is preferable to avoid the excess noise created by pipes that did not experience bursts during the period of observation. Finally, before the construction of the correlation matrices, it should be noted that the data entry points are pipes and not single pipe bursts. This algorithm aims at determining the physical condition of pipes and, therefore, the occurrence of multiple bursts in a single pipe is indicative of poor physical condition. The correlation matrix for a dataset of n = 49 is presented in Table 7. The color gradient is increasingly red for inverse correlation and increasingly blue for direct correlation values.

The analysis of the correlation matrix demonstrates that there is a strong direct correlation between the year of installation and the material type. This conclusion is unsurprising given that material choices are associated with the evolution of pipe material. A high correlation between the variables of distance to the tank and static pressure is observed,

which can be explained by the natural geography of the network, since the distribution tank is located on a hilltop and the network progresses towards the sea level. Other network properties did not present such a strong relationship.

Furthermore, the analysis of the correlation matrices demonstrated the existence of two groups of failure variables: Group 1 (*NB*, *NBY* and *ROBLND*) and Group 2 (*ROB* and *AA03*). This conclusion is not surprising given that the difference between the grouped variables is constant values. In the first group, the number of bursts is divided by two constants (year and length), while in the second group, the number of bursts is divided by different values of length. Variables from Group 1 present the highest correlation values with the network properties; thus, one of these variables should be considered the dependent variable. Since the differences between the variables of Group 1 are only constant values, the choice of the dependent variable is no longer a statistically based decision but a technical choice. Therefore, the number of bursts per year (*NBY*) was chosen as the dependent variable due to the easy interpretation of the results by the water utilities.

Finally, the obtained correlation matrix shows that the reduced number of data points is sufficient to establish some relationships between the independent and the dependent variables, namely between failure variables and pipe material (*Mat5*), year of installation (*YI*), pipe length (*Length*), distance to the tank (*DT*), static pressure (*SP*) and average pipe age when the burst occurred (*AA*).

4.2.2. Construction and Assessment of Linear Regression Models

Simple and multiple linear regression models were developed testing different combinations of explanatory dependent variables. The six best goodness-of-fit linear regression models are presented in Table 8, including the results for the r-squared values and adjusted r-squared values. Results show that the variable *AA* (average pipe age when the burst occurred) is present in all models and that this variable presents the highest correlation coefficient. This means that this variable can be considered as having high explanatory ability.

Table 8. Best goodness-of-fit linear and quadratic models.

Linear Regression Models	$\mathbf{R^2}$	$\mathbf{R^2_{adj}}$
$NBY = 0.3376 + 0.0072\ AA - 0.0057\ SP$	0.51	0.48
$NBY = 0.3587 + 0.0073\ AA - 0.0060\ SP - 0.00003\ Length$	0.52	0.48
$NBY = 0.4038 + 0.0069\ AA - 0.0013\ Mat3 - 0.0056\ SP$	0.44	0.48
$NBY = 1.5263 + 0.0069\ AA - 0.0006\ YI - 0.0055\ SP$	0.51	0.48
$NBY = 0.3567 + 0.0072\ AA + 0.00001\ DT - 0.0063\ SP$	0.52	0.47
$NBY = 0.4599 + 0.0070\ AA - 0.0019\ Mat3 - 0.0061\ SP - 0.00004\ Length$	0.44	0.47
Quadratic Models	$\mathbf{R^2}$	$\mathbf{R^2_{adj}}$
$NBY = 0.28 - 0.01\ AA + 0.00035\ AA^2$	0.50	-
$NBY = 1419 - 1.42\ YI + 0.00036\ YI^2$	0.33	-

Notes: *AA*—average pipe age when the burst occurred; *SP*—static pressure; *Mat3*—material type in 3 values; *Length*—pipe length; *YI*—year of installation; *DT*—distance to tank.

The possibility of a quadratic function existing that better fits the number of bursts per year is also analyzed. As the variables of average pipe age when the burst occurred and year of installation present promising correlation results for linear models, these variables are tested for polynomial fitting and the corresponding results are also presented in Table 8. When analyzing the obtained results versus the linear regression models, it can be concluded that no significant improvement is attained.

Following model construction, it is important to verify the statistical dependencies of the influencing factors. The variance inflation factor (VIF) is used to assess the degree of multicollinearity between the variables. A VIF value of 10 is considered a high degree of multicollinearity; consequently, variables that present values approximate to 10 are discarded. The VIF analysis shows that all variables can be used to model the relationship between the pipe properties and failure history.

Given the relatively small number of data points, the validation of the regression models will not be developed; however, in a larger dataset, this step is recommended.

The regression models were applied to the described case study considering the linear model with the variables of average pipe age when the burst occurred and static pressure ($NBY = 0.3376 + 0.0072\ AA - 0.0057\ SP$) and the quadratic model with that of average pipe age when the burst occurred ($NBY = 0.28 - 0.01\ AA + 0.00035\ AA^2$). Table 9 presents the distribution of the physical pipe condition into three ranking levels defined according to the condition scale presented in Figure 1b. The comparison of the results obtained by the two models shows that the linear model classifies more pipes as good condition than the quadratic model. However, both models classify almost 60% of the network as being in an unsatisfactory condition.

Table 9. Pipe condition results using the linear regression algorithm, including linear and quadratic models.

Condition Grade	Linear Regression Model ($NBY = 0.3376 + 0.0072\ AA - 0.0057\ SP$)		Quadratic Model ($NBY = 0.28 - 0.01\ AA + 0.00035\ AA^2$)	
	Number of Pipes	Relative Frequency (%)	Number of Pipes	Relative Frequency (%)
Good	476	28.57%	342	20.53%
Average	194	11.64%	346	20.77%
Unsatisfactory	993	59.60%	978	58.70%
Total	1666	100%	1666	100%

4.3. Support Vector Regression Algorithm

The SVR algorithm is applied to estimate the number of bursts for each pipe by using the following network characteristics: *AA*—average pipe age when the burst occurred; *SP*—static pressure; *Mat5*—material type in five values; *Length*—pipe length; *DN*—nominal diameter. The total number of pipes is randomly divided into 70% for training data and 30% for validation data.

The classification of each pipe based on the number of bursts is evaluated by using a confusion matrix that allows for the visualization of the performance of the SVR algorithm by comparing the real number of failures with the estimated one. Figure 7 presents the confusion matrix, where each row of the matrix represents the number of real bursts, while each column represents the number of bursts predicted by the algorithm. The diagonal entries of the confusion matrix (represented by the blue colour) indicate the number of pipes where the algorithm accurately predicted the real number of bursts. For instance, the SVR algorithm correctly predicted that 952 pipes had one burst during the observation period. On the contrary, the off-diagonal values represent cases where the algorithm misjudged the real number of bursts. For example, the algorithm erroneously predicted that 16 pipes had one burst when, in reality, there were two bursts. It is important to highlight that, despite these discrepancies, the algorithm successfully predicted the majority of burst occurrences.

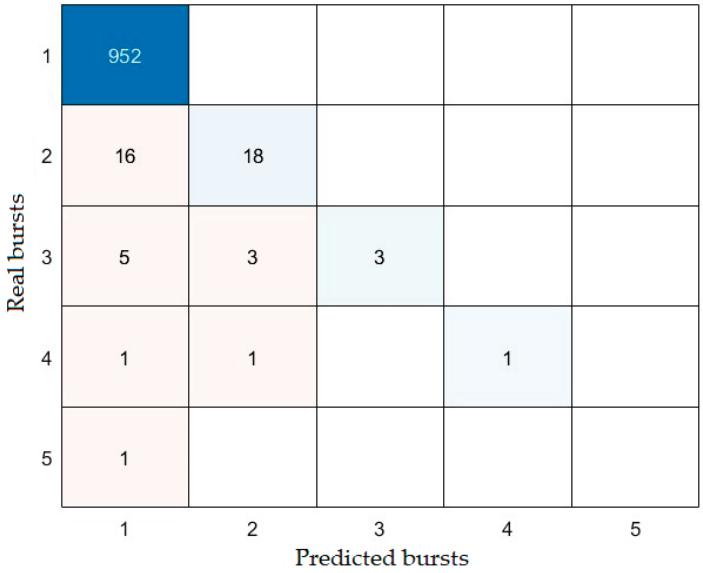


Figure 7. Confusion matrix for the SVR algorithm.

The determination coefficient is calculated, with values of 0.94 and 0.64, respectively, for the training and validation data. The determination coefficient results indicate a better performance for the SVR algorithm compared to linear regression. Table 10 presents the distribution of the physical pipe condition into three ranking levels defined according to the condition scale presented in Figure 1b for the SVR algorithm.

Table 10. Pipe condition results using the SVR algorithm.

Condition Grade	SVR Algorithm	
	Number of Pipes	Relative Frequency (%)
Good	687	41.24%
Average	976	58.58%
Unsatisfactory	6	0.18%
Total	1666	100%

5. Discussion

Results have shown that the linear regression algorithm tends to overestimate the pipe condition rating, classifying pipes with worse conditions than the heuristic and SVR algorithms. The application of the three algorithms to the described case study resulted in different overall classifications for the same pipe. While the heuristic algorithm classified 60% of the pipes as average condition and 18% as unsatisfactory condition (considering answer-based weight and the entire survey group), the linear regression algorithm evaluated approximately 60% of the pipes as unsatisfactory condition (considering the linear model with the independent variables of average pipe age when the burst occurred and static pressure). Finally, the SVR algorithm classified approximately 60% of the pipes as average condition and almost all the remaining pipes as good condition.

The assessment of the physical condition of water distribution pipes combining the well-known performance indicator of the ratio of useful life (RUL) and the results of the three developed algorithms is presented in Figure 8. Results have demonstrated the following: the ratio of useful life tends to distribute pipe classification more equally in the three classes; the heuristic algorithm classifies most pipes as average condition; and the linear regression algorithm classifies most pipes as unsatisfactory condition. The SVR algorithm stands out as the main classifier for identifying pipes in good condition when compared to other algorithms. Additionally, it indicates that most pipes are classified in average condition and it only assigns three pipes to the unsatisfactory condition category.

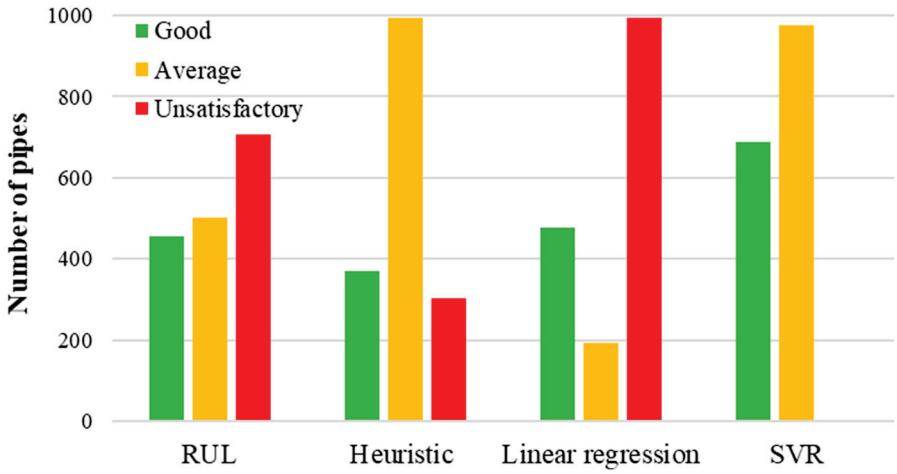
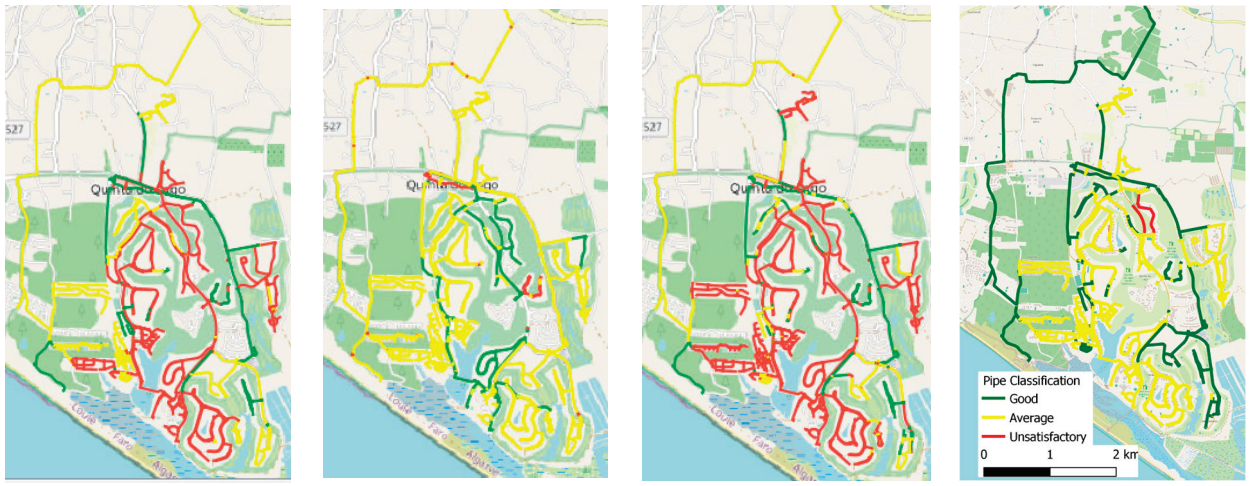


Figure 8. Distribution of pipe physical condition for the ratio of useful life and heuristic, linear regression and SVR algorithms.

Figure 9 depicts the condition assessment maps obtained by the abovementioned three algorithms and the RUL. The pipes classified in unsatisfactory conditions by the ratio of useful life and the linear regression algorithm are almost the same, though the SVR algorithm is less conservative with a higher number of pipes in good and average condition.



(**a**) (**b**) (**c**) (**d**)

Figure 9. Color map for: (**a**) ratio of useful life; (**b**) heuristic algorithm; (**c**) linear regression algorithm; and (**d**) SVR algorithm.

Although different results were obtained, the development of a rehabilitation plan for a water distribution network should ideally integrate the results of these three algorithms to priority assets for intervention, i.e., the pipes classified as unsatisfactory and average condition in all algorithms. The cross-referencing of these three algorithms is described in Table 11.

Table 11. Cross-referencing of three algorithms.

Same Condition Grade in the Three Algorithms	Number of Pipes	Relative Frequency (%)
Good	155	67%
Average	77	33%
Unsatisfactory	0	0%
Total	232	100%

The use of different algorithms for pipe condition assessment within water distribution systems has significantly improved the existing methods (i.e., RUL), since these allow for the inclusion of several factors that affect pipe deterioration as well as the use of advanced statistical tools and machine learning algorithms. The studied algorithms should be incorporated in the infrastructure asset management of urban water assets contributing to more informed and robust decision-making processes.

6. Conclusions

The prioritization of water distribution pipes for rehabilitation requires the assessment of the physical condition of assets. A methodology is proposed, including the following steps: data collection and validation, algorithm development and condition assessment. Three algorithms were studied and compared: the heuristic, linear regression and support vector regression algorithms. The proposed methodology allows for the assessment of the physical condition of assets without the need for extensive fieldwork or specific computational know-how, since it is based on the knowledge of simple infrastructure and operational data (e.g., pipe characteristics and operating conditions).

The application of the proposed methodology allowed for the assessment of the physical condition of a water distribution network located in Portugal. The results obtained from each algorithm were compared with a well-known performance indicator, the ratio of useful life. The results presented significant differences in their overall pipe condition classification. The linear regression algorithm allowed us to develop multiple linear regression models, considering different variables, such as the average pipe age when the burst occurred, the static pressure, the pipe material, the pipe length, the installation year and the distance to the tank. These models use the pipes with bursts during the period of observation as a training dataset. Consequently, the developed models include the notion that the structural condition of all other pipes will resemble the pipes that are presumably in worse condition (i.e., pipes that exhibited bursts during the period of observation). Therefore, this algorithm is considered to be highly penalizing in the classification of network pipes, classifying almost 60% of the network with an unsatisfactory condition.

On the other hand, the results from the heuristic and SVR algorithms were much less conservative, classifying the pipes as predominantly in average and good condition. In the heuristic algorithm, the following factors were considered: pipe material, pipe age, pipe nominal diameter, pipe length, pipe roughness coefficient and average operating pressure, pipe age being the most relevant factor in pipe deterioration. Different quantitative weights for each influencing factor were used; however, their order of influence does not change with the weights. In the SVR algorithm, different variables were used, such as the average pipe age when the burst occurred, the static pressure, the pipe material, the pipe length and the nominal diameter. The determination coefficients for the training and validation data were 0.94 and 0.64, respectively. These results indicate better performance from the SVR algorithm compared to linear regression.

Nevertheless, these three algorithms can be considered an improvement on the existing method of condition assessment through the use of the performance indicator ratio of useful life (RUL). This improvement is justified by the incorporation of several factors that influence pipe deterioration besides the asset age and its respective useful life. The application of the proposed methodology to a larger dataset with a higher period of

observation should be carried out as future work. This would allow for the achievement of more robust results, as well as testing of the proposed methodology. Furthermore, the obtained results should be included in the decision-making process for pipe rehabilitation.

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Article

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

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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

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.

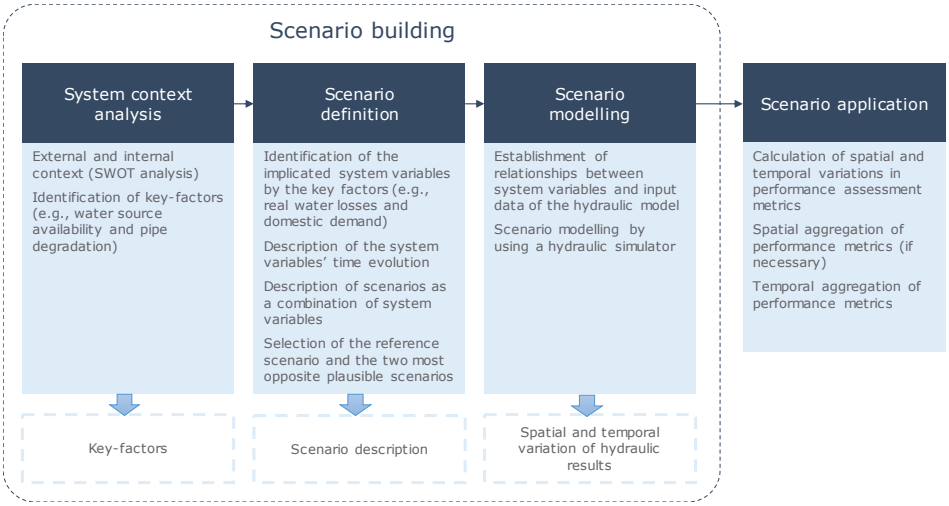


Figure 1. Proposed scenario-building methodology for urban water systems.

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).

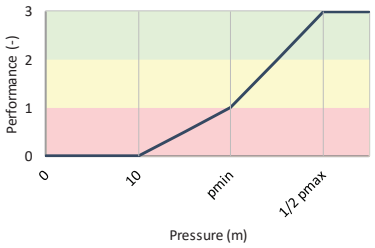
Public irrigation demand, private irrigation demand, and domestic demand evolutions (i.e., trends) are applied to the respective category demand patterns, in accordance with the scenarios described. The modelling of real water losses is more complex. Herein, it is considered that real water losses are 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 [-]	$NRI = \frac{\sum_{i=1}^{N} U_i Q_i \left(H_i - H_i^{req}\right)}{\sum_{r=1}^{Nr} Q_r H_r + \sum_{b=1}^{Nb} \frac{P_b}{\gamma} - \sum_{i=1}^{N} Q_i H_i^{req}}$ (1) being $U_i = \frac{\sum_{l=1}^{np_i} D_l}{np_i \times \max\{D_1,\ldots,D_l\}}$ (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.

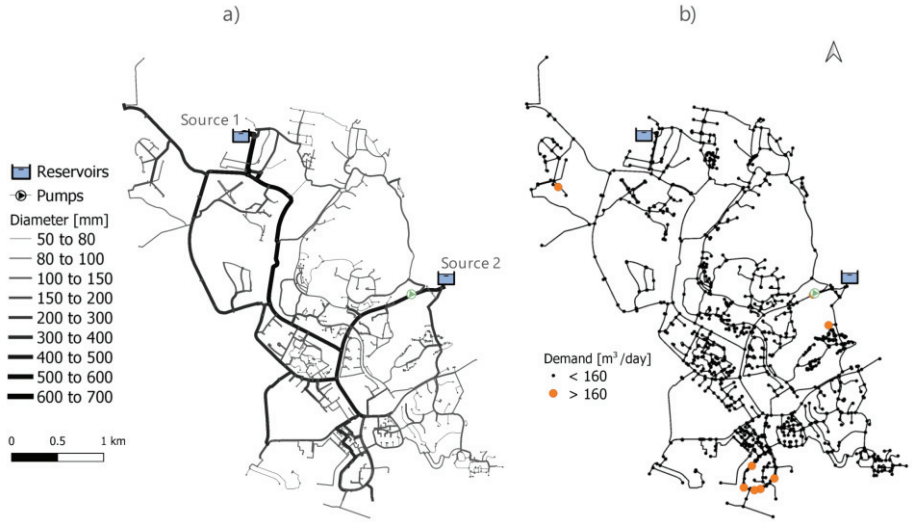


Figure 2. Schematic representation of the water distribution network: (**a**) pipe diameters and (**b**) location of large consumers.

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.

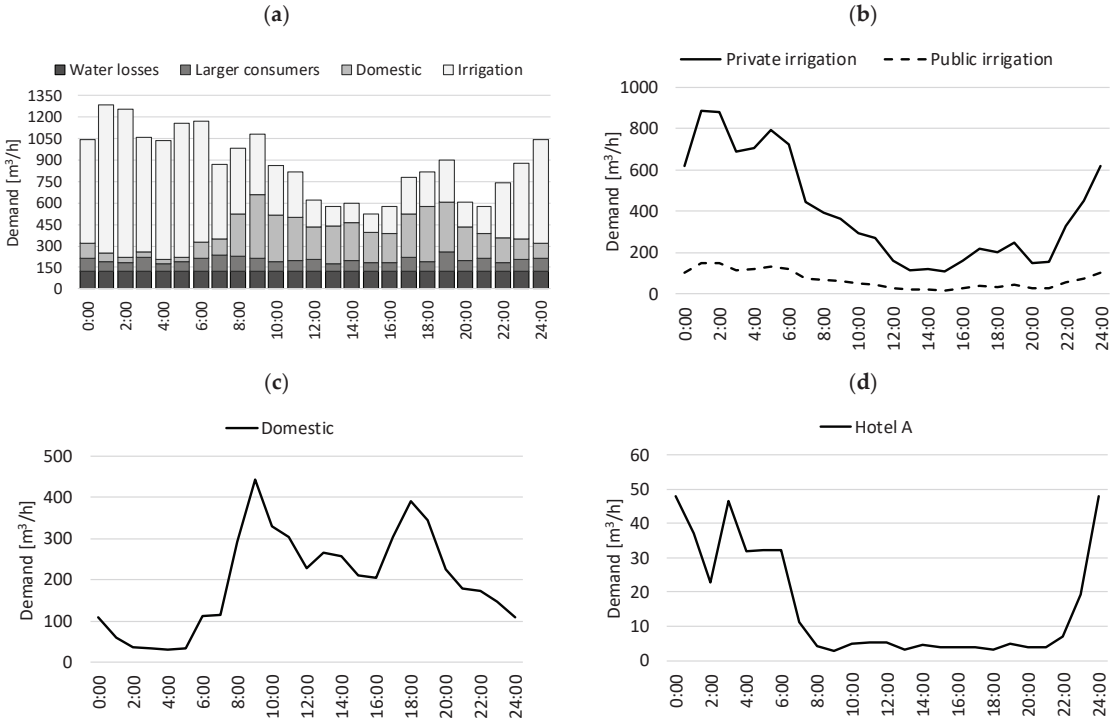


Figure 3. Summer period hourly pattern for (**a**) demand categories; (**b**) irrigation demand; (**c**) domestic demand; and (**d**) largest hotel consumer.

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.

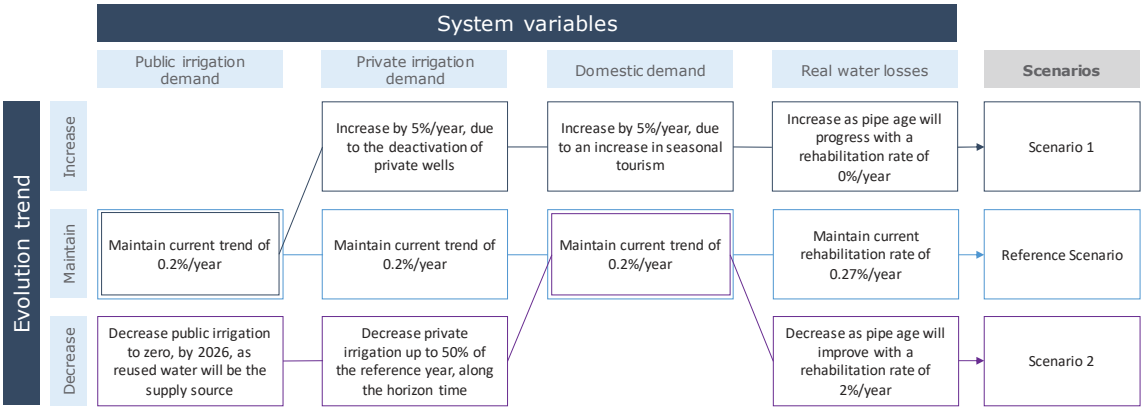


Figure 4. WDN variable trend conjugation to define the two most opposite plausible scenarios and the reference scenario.

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).

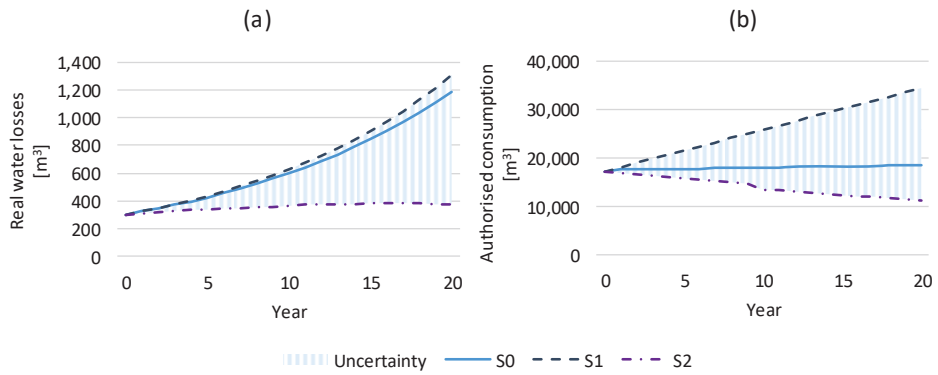


Figure 5. Time variation for the three scenarios of: (**a**) real water losses; (**b**) authorised consumption.

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.

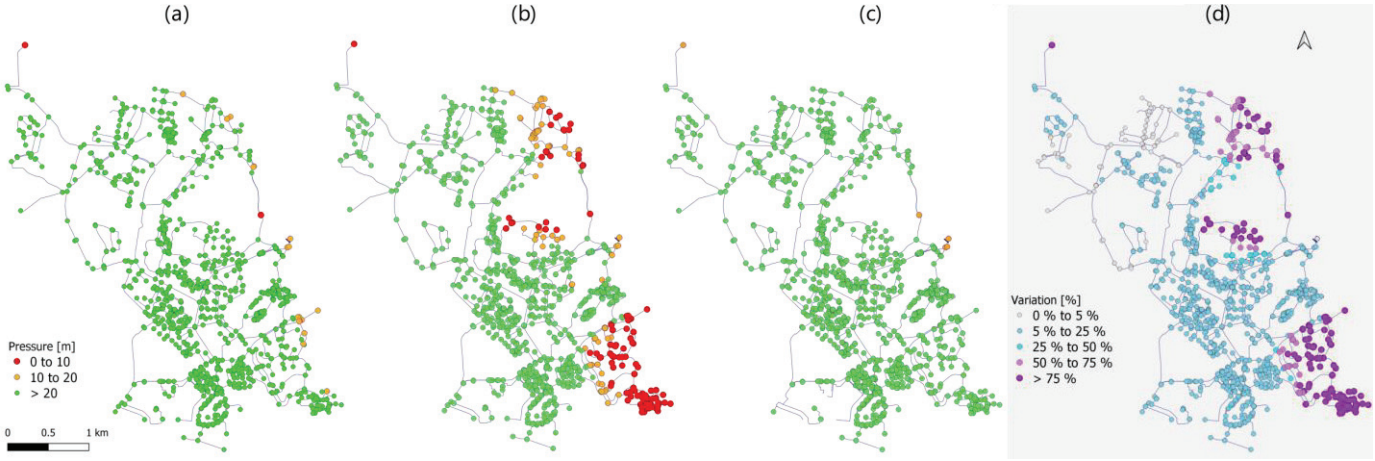


Figure 6. Spatial distribution of minimum pressures in nodes for year 20, at the peak-hour consumption (2 h): (**a**) Reference scenario; (**b**) Scenario 1 (demand increase and low rehabilitation rate); (**c**) Scenario 2 (demand decrease and adequate rehabilitation rate); and (**d**) Relative variation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

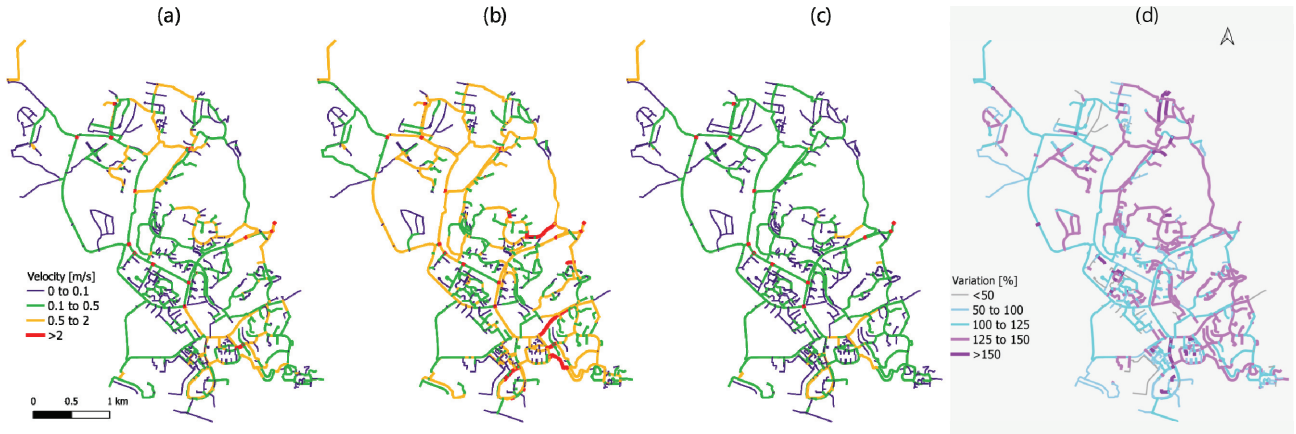


Figure 7. Spatial distribution of maximum velocities in pipes for year 20 at the peak-hour consumption (2 h): (**a**) Reference scenario; (**b**) Scenario 1 (demand increase and low rehabilitation rate); (**c**) Scenario 2 (demand decrease and adequate rehabilitation rate); and (**d**) Relative variation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

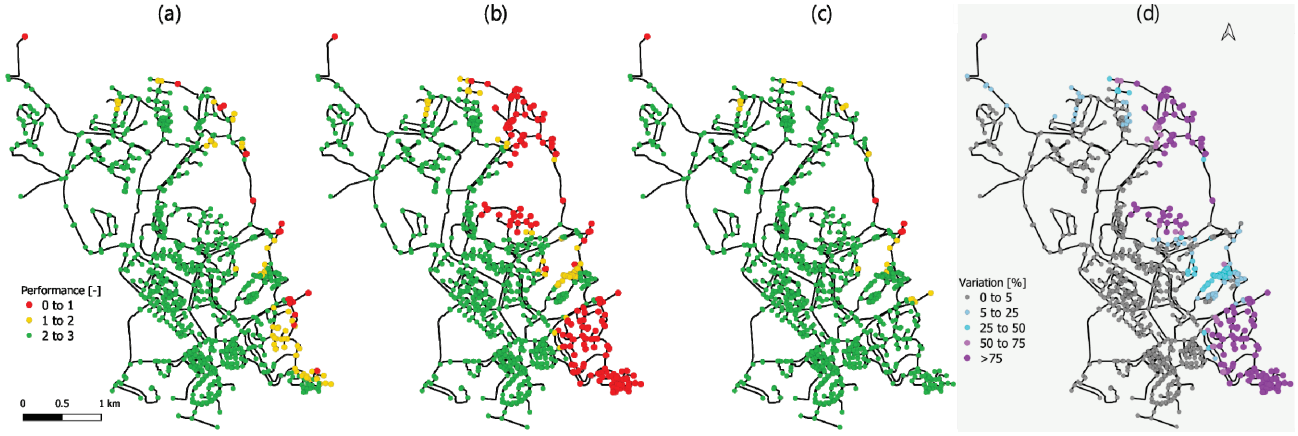


Figure 8. Spatial distribution of the minimum pressure index for year 20, at the peak-hour consumption (2 h): (**a**) Reference scenario; (**b**) Scenario 1 (demand increase and older pipes); (**c**) Scenario 2 (demand decrease and renewed pipes); and (**d**) Relative variation from Scenario 1 and Scenario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

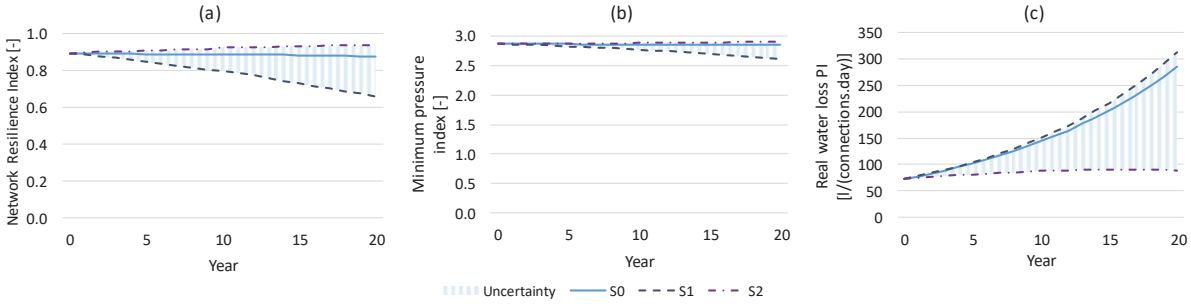


Figure 9. Evolution of the performance assessment metrics for the different scenarios: (**a**) network resilience index; (**b**) minimum pressure index; and (**c**) real water loss performance indicator.

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.

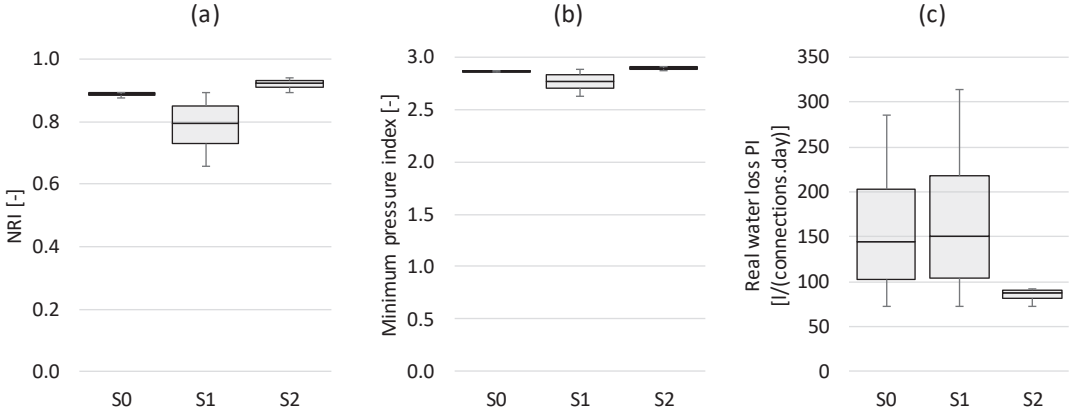


Figure 10. Resilience assessment metric box and whiskers plot of the temporal variation for each scenario: (**a**) network resilience index; (**b**) minimum pressure index; and (**c**) real water loss performance indicator.

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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Article

Water–Energy–Nutrients Nexus of Urban Environments

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Abstract: The objective of this article is to deepen knowledge about the existing connections, at the level of urban environments, between energy, water, and nutrients (or food). Energy and basic resources—water and food—are closely interconnected, which is why the water–energy–food nexus constitutes the essential integrated approach to ensuring the sustainable development of humanity. This nexus is also valid in urban environments and can be adapted for buildings, interconnecting, in this case, water, energy, and nutrients. This article is a literature review in this area, intending to highlight the strong connections between water, energy, and nutrients at the level of buildings, integrating the results obtained in different studies and showing the global importance of this nexus. The water–energy relationship in buildings is already well known in terms of the production of domestic hot water or building pumping, for example, but it turns out that it goes far beyond this interrelationship, also having implications for public networks. Regarding the water–nutrients nexus in urban environments, it can play an important role in terms of food security for humanity, especially regarding the possibility of recovering phosphorus in buildings.

Keywords: water–energy nexus; water–energy–nutrients nexus; net-zero buildings

1. Introduction

The increasing need for the sustainable use of energy and resources globally, as a result of population growth on our planet, economic development models, and, in some regions, climate change, requires a holistic and integrated approach as a guiding principle of development policies [1–5]. This principle is highlighted in the UN Agenda 2030, where it is stated that it is through this integrated approach that cross-connections can be promoted among social progress, economic development, and environmental protection [6–9].

Energy and basic resources—food and water—are closely interconnected, which is why the water–energy–food nexus constitutes the essential integrated approach to ensure the sustainable development of humanity. In general terms, water is crucial in most forms of energy production and energy is necessary for many uses of water, such as supplying populations or heating domestic hot water [10]. Energy and water are also closely linked to food. In the current conditions of the planet, with a growing global population, agriculture is responsible for 70% of total freshwater consumption [11], while food production and its distribution chain represent around 30% of all energy consumption [12].

This water–energy–food nexus can also be valid in urban environments [13–16] and can be adapted for buildings, particularly in their use phase [17]. In this case, this nexus must be seen concerning the interconnection between water, energy, and nutrients (or fertilizers).

It may be added that some authors, noting that urban agriculture is expanding rapidly to meet the growing demand for locally produced food, propose an intermediate concept,

dividing the "food" component in urban environments into nutrients and food, that is, considering a water–energy–nutrients–food nexus [18]. This extended nexus, however, is only of interest in the analysis of resource stocks and flows when there is urban agriculture, excluding other situations, such as the use of nutrients recovered in the fertilization of green roofs or urban gardens.

Due to sustainability concerns, net-zero-energy buildings (NZEBs) have already become a reality in many areas of the planet, and the next actions should be the design and dissemination of net-zero-water and net-zero-nutrients buildings. However, this approach should not be conducted independently. In fact, "net-zero-buildings" should be the constructive solutions of the future, but they should consider the intrinsic relationship that also exists in urban environments between water, energy, and nutrients.

The net-zero-building concept intertwines with the circular use of resources, but these concepts are not equivalent. In the case of energy, net-zero-energy buildings do not mean the circular use of the resource, but rather that the total amount of energy used by the building is approximately equal to the amount of renewable resources produced or available locally.

In relation to water, part of this resource can be used circularly, through water recycling, but alternative renewable sources, such as rainwater, can also be considered. In the case of buildings with zero nutrients, the use of resources can be circular [19], as some nutrients can be recovered and used as fertilizers in green roofs or urban agriculture, as is the case with phosphorus (P), as illustrated in [20–22].

When there is a centralized drainage system, the recovery of nutrients discarded in buildings can be performed downstream in wastewater treatment plants (WWTPs), for example [23–27]. For this solution, several technologies have been proposed over the last few years [28–35], which will be referred to later, although none of them have become widespread or have been recognized, to date, as being of obvious interest from a technical–economic perspective.

This article aims to highlight, at the level of urban environments, the strong connections between water, energy, and nutrients. Based on a review of some recent publications in this area, we intend to integrate the results obtained in partial studies related to each of these interconnections and to show the importance of the nexus between energy, water, and nutrients in buildings.

2. Materials and Methods

For the literature review, keywords related to the nexuses of water–energy, energy–nutrients, and water–nutrients in buildings were used, as well as keywords related to the global water–energy–food and water–energy–nutrients nexuses. Articles on "net-zero buildings" were also analyzed. It was found that the available literature on the relationship between water, energy, and nutrients in buildings is relatively restricted and focuses mainly on isolated analyses of each of these resources or the relationship between water and energy, specifically the production of sanitary hot water (SHW). The concepts of net-zero-water or net-zero-nutrients buildings have also been the subject of few studies. A search of the scientific literature centered on these concepts returned a relatively small number of articles, unlike net-zero-energy buildings (NZEBs), also called "nearly zero-energy buildings", where extensive references can be found.

However, it appears that most studies on NZEBs focus exclusively on solutions to reduce the energy needs of the network through better thermal insulation, self-production, increased efficiency in use, etc., without addressing the possible implications outside the building or interconnections with other resources, such as water, except for SHW production.

In this article, the links between water nutrients, energy nutrients, and water–energy will be analyzed separately. The latter will focus not only on the traditional approach to SHW production but also on reducing energy consumption in public water supply and drainage systems associated with greater efficiency in water cycle management for buildings.

3. Results

3.1. Water–Nutrients Nexus in Buildings

Regarding the water–nutrients nexus in buildings, toilets and urinals, when they exist, are essential components in the relationship between these resources. These devices have always played a key role in the context of the water–nutrients nexus and have high potential, in the future, to make important contributions to the promotion of solutions for the sustainable use of nutrients at the scale of buildings and their surroundings. In fact, nutrients recovered in buildings, from manure, urine, or domestic effluents, can be used in urban agriculture or the fertilization of public gardens or green roofs.

In early civilizations with sanitation concerns, such as Rome, some buildings were equipped with direct flush solutions, such as open seats over water lines. Pit latrines appeared later, usually in rural areas (Figure 1), and were improved and reinvented over time, allowing the recovery of nutrients and their subsequent use in agriculture with progressive health safety [36,37]. It can be said that these latrines thus constituted the first sustainability solution within the water–nutrients nexus in buildings and their surroundings. (Even in cases where they were not equipped with flushing devices for cleaning, water was always present, as it represents 95% of urine and 75% of feces).

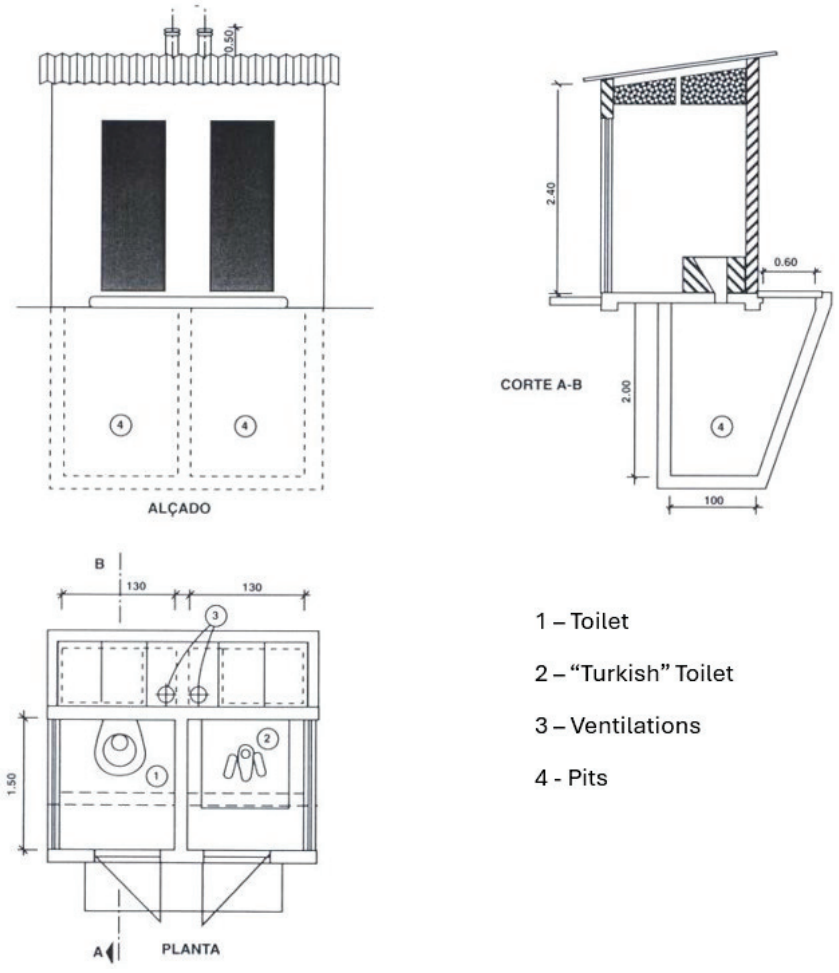

Figure 1. Pit latrine [38].

Recently, in parallel with concerns about water efficiency in toilets, the importance of resource recovery has resurfaced, leading to the development of solutions such as composting toilets. Examples of solutions of this type include the toilets installed in the Choi building at the University of British Columbia, which do not require water or the Aquatron system [37]. The latter system can operate with less than 3 L per flush

and allows the separation of solid and liquid waste, allowing the separate treatment of these two types of waste, with composting in the case of solid waste. More recently, the nanomembrane toilet, which is also a waterless solution, was developed by researchers at Cranfield University and promoted by the Bill and Melinda Gates Foundation [37].

Food production requires a total of seventeen elements, among which nitrogen, phosphorus, and potassium are considered the fundamental ones (macronutrients). These three elements can be found in human urine, which also contains some secondary micronutrients.

However, special attention must be paid to phosphorus and the possibility of its recovery. There are several warnings about the urgency and importance of this recovery, from, for example, the European Commission (Parliament statement of 24 May 2012 (§52)). Its scarcity could compromise humanity's food security, but population growth, wars, and the increase in global agriculture are intensifying the pressure on the finite reserves of this nutrient. About 90% of phosphorus reserves are in China, Russia, the United States, and Morocco, but it is estimated that the reserves whose extraction will be economically viable will be exhausted in the next 30–40 to 300–400 years. The wide range of this estimate arises from doubts regarding the volume and quality of reserves and uncertainties regarding future demand [20–22].

On the other hand, the discharge of domestic and industrial effluents rich in phosphorus into the water environment is the main cause of eutrophication, which is a very significant problem affecting the quality of freshwater bodies that has yet to be adequately resolved, at least in Europe. As the recovery of phosphorus is an emergency in the face of food safety and pollution problems, it appears that its elimination through urine is one of the main contributors to its dissemination in the environment and loss in the value chain. Indeed, urine contributes almost half of the total P load in wastewater.

An average adult excretes a significant amount of phosphorus through urine (around 1 g per day), but there are still no established solutions for its recovery in water bodies. Phosphorus recovery in urban wastewater treatment plants (WWTPs) is theoretically possible and has been the subject of several studies and pilot installations, proposing different technologies, such as infiltration–percolation processes [39], microalgae [40,41], membrane contactors [42], ion exchange processes [43], selective electrodialysis [44], simultaneous nitrification–denitrification [45], electrochemical pH modulation [46], and others [47–54]. However, recovery at source, that is, in buildings, presents clear advantages in reducing dilution and minimizing costs and energy consumption when compared to recovery processes in treatment plants.

Usually, urine recovered from buildings can be directly used as fertilizer without the need for a specific process of separation and recovery of phosphorus (or other nutrients). The biggest problem with using urine directly as a fertilizer, which should be avoided, is the possible presence of enteric pathogens. In general, human urine does not contain pathogens, but fecal cross-contamination can occur during the separation and collection process. Storing source-separated urine in sealed containers is considered the simplest approach to reducing the number of pathogens. Several studies have demonstrated that a storage time of a few months is sufficient to reduce the risk of transmission to below the acceptable limit [55]. During this maturation phase, urea is hydrolyzed into ammonia, which causes the pH to increase from approximately pH = 6 to pH = 9 after a few days or weeks. At this point, ammonia represents 90% of the nitrogen in stored urine, and it is this harsh chemical environment that allows the sanitation of source-separated urine [55]. In some specific situations, other problems may exist, particularly when the presence of medicines and other micropollutants in urine intended for fertilization applications is expected [56,57].

It can be noted that, on green roofs for example, fertilizations are typically performed twice a year. This periodicity is perfectly compatible with the periods necessary for urine maturation, which must be at least 2 to 3 months. Even if other fertilization periods are necessary given the type and age of the species, it does not appear that incompatibilities will arise in these applications.

The direct use of matured urine for agricultural purposes has already been the subject of pilot projects in several countries, such as South Africa, Germany, the Netherlands, Sweden, and China, which has already installed more than 700,000 urine-diverting toilets since the end of the last century [37,58].

In Sweden, urine diversion in toilet facilities has been considered a good solution for rural areas to reduce nutrient enrichment in natural waterways, with more than 135,000 urine diversion toilets installed. There are also specific recommendations for the use of urine collected in buildings [37]. In the Netherlands, the authority responsible for water management in the city of Amsterdam developed a pilot program for collecting urine in public toilets, estimating an annual production of 1000 tons of fertilizer, to subsequently fertilize public gardens and green roofs.

Although current efforts focus mainly on the recovery of urine and its direct use as fertilizer after maturation, technologies are also being developed for the direct recovery of phosphorus from urine at the source, based, for example, on physical separation processes with nanotechnological structures of alumina [59,60]. In any case, urine separation in buildings, whether or not one is aiming at the subsequent recovery of phosphorus, requires a revolution in current bathrooms, with the generalization of the installation of urine-diverting toilets and the generalization of the installation of urinals in residential buildings, including specific models for women. These measures may involve new designs for sanitary appliances and installations and, eventually, new sizing rules for building drainage networks.

The development of urine-diverting toilets has been ongoing for several years [61]. However, the acceptance of this type of toilet has been conditioned by problems not yet fully resolved related to the complex maintenance required to avoid the blockage of pipes caused by the precipitation of salts and minerals present in urine, which causes the formation of crystals [62,63].

One of the most recent projects in this context is being developed in Portugal and is in the final testing phase. It is a separating toilet with a traditional exterior design (Figure 2) but with an innovative solution for urine separation, which involves diluting the urine in a small volume of flush water. This condition required specific research on urine maturation to evaluate the efficiency of the separation process and health safety, in turn confirming the feasibility of the later use of matured urine as fertilizer. Through microbiological analyses already carried out, it was confirmed that, after a maturation period of 2 to 3 months, sanitary conditions compatible with the intended applications were achieved [55].



Figure 2. Urine-diverting toilet (OLI Company) [57].

From the perspective of the water–energy–food nexus, nitrogen and potassium are equally relevant although without the urgency for recovery that is attributed to phosphorus [64–68]. The contribution of buildings, in these cases, may not be as significant.

3.2. Energy–Nutrients Nexus in Buildings

Electric toilets, which use electricity to process waste for nutrient recovery, can be representative of the nutrients–energy nexus in buildings. This is the case, for example, of the composting toilets installed in the C.K. Choi Building, a demonstration building with innovative sustainable design features located at the University of British Columbia (Vancouver) [69].

Energy may also be necessary for the recovery of urine, its maturation, and its subsequent use as fertilizer, for example in pumping equipment. However, the nexus between energy and nutrients will be less relevant than the nexus between energy and water at the building level, in relative terms, given the smaller amounts of energy involved in the former.

In the context of the energy–nutrients nexus, it is interesting to note that the energy consumption for the industrial production of one kilogram of phosphate fertilizer is around 8 MJ, according to industry data. In the case of nitrogen fertilizers, the value is 40 MJ [70]. Furthermore, the fertilizer distribution chain (including processing, packaging, and transport) also consumes significant amounts of energy.

These values show that, in a global analysis, the simple recovery and use of nutrients in buildings and their surroundings can lead to significant reductions in energy consumption. In fact, the local use of urine as fertilizer in buildings or their surroundings only requires small pumps to transfer liquids between containers, and long-distance transportation is not necessary. In other words, energy consumption is negligible.

3.3. Water–Energy Nexus in Buildings

In the context of improving water efficiency in buildings, studies show that simply replacing traditional equipment with more efficient devices can lead to significant water savings in buildings, with rapid economic return [71]. This should, therefore, be the solution that should be implemented as a priority, due to its relatively low cost, the significant savings that can be obtained, and the effects it can also have on reducing energy consumption.

A relevant contribution to reducing energy consumption in buildings can result from the application of water efficiency measures, although this aspect is not generally perceived in the implementation of policies to improve energy efficiency in the built environment. Water efficiency has significant consequences in reducing energy consumption in buildings, by reducing energy needs for heating sanitary hot water (SHW) and for possible water pressurization, also reflecting on energy consumption in public networks and of water supply and drainage, by reducing the volumes abstracted, pumped, and treated [71].

A study by the Portuguese Association for Quality in Building Installations (ANQIP) carried out in Aveiro, a medium-sized Portuguese city (70,000 inhabitants), concluded that water consumption in the city could potentially be reduced by around 3.1×10^6 m^3 per year, compared to the current scenario, through the widespread application of more efficient devices in buildings (showers, taps, etc., with category "A" of the ANQIP labeling system for the water efficiency of products) (Figure 3). According to the same study, this reduction, which represents around 24% of the total water consumption in the domestic sector in the city, translates to a reduction in energy consumption of approximately 11.6×10^6 kWh per year, only concerning the production of SWH in buildings for taps and showers [71].

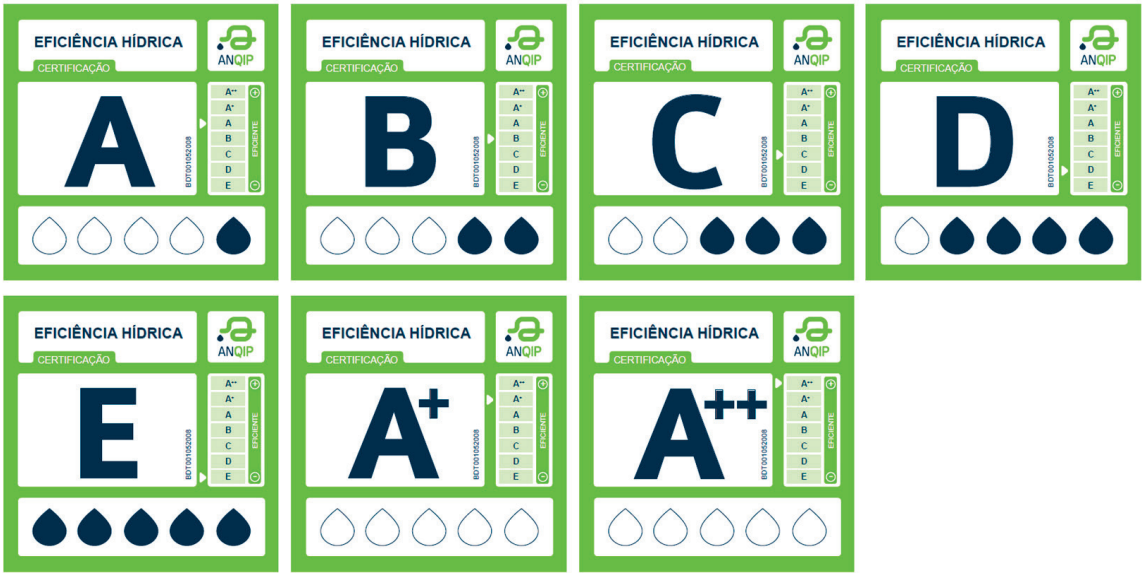

Figure 3. ANQIP labelling scheme for water efficiency of products.

According to the Aveiro Water Authority (AdRA), energy consumption is 1.156 kWh/m^3 in water production and distribution and 0.818 kWh/m^3 in wastewater drainage and treatment. Therefore, in addition to direct energy savings in SHW heating, reducing water consumption in buildings also implies reductions in energy consumption in public water supply and drainage systems (including treatment plants), which can be estimated at 4.4×10^6 kWh per year [71].

In total values, the potential for reducing energy consumption in the Municipality of Aveiro, as a result of applying simple water efficiency measures in buildings, is around 16×10^6 kWh per year. This amount reflects the relevance of the water–energy nexus in buildings.

Reducing energy consumption can also translate to a reduction in greenhouse gas emissions, mainly CO_2. In Aveiro, the form of energy used in public networks is electricity, which is also the form of energy used in the vast majority of buildings. Considering the indicator available at the time of the ANQIP study, which results from the energy mix used in electricity production in Portugal (≈270 g CO_2/kWh), it can be estimated that a reduction in water consumption in buildings of 2.24×10^6 m^3 per year will allow a reduction in emissions of around 4500 tons per year [71].

This result clearly shows the important link between water and energy that exists in buildings. However, this nexus can also be found in other installations or equipment in buildings, and not just in SHW heating or in the associated consumption in public networks. This is the case, for example, of water pressurization systems or vacuum drainage systems, when they exist.

Regarding water-using products (WuPs) in buildings, in addition to concerns about reducing flows or volumes, there has been a rapid evolution in recent decades in their designs, seeking to increase comfort, hygiene or sustainability parameters. This evolution has implied, in many situations, an increase in energy consumption in sanitary installations.

As an example, Table 1 presents a summary of the main recent innovations in toilets, according to manufacturers' catalogues (including smart toilets, which combine the function of a normal toilet with the cleaning functions of a bidet), indicating those that involve energy consumption. It can be observed that most innovations involve energy consumption.

Table 1. Recent innovations in toilets and energy needs.

Recent Innovations in Toilets with Energy Needs	Recent Innovations in Toilets without Energy Needs
- Touchless flush button; - Seat with motion-activated automatic opening/closing; - Heated seat; - Adjustable seat temperature; - Air purifier deodorization; - UV sanitizing nozzle; - Oscillating jet; - Adjustable water pressure; - Adjustable water temperature; - Air dryer; - Adjustable air dryer temperature; - "Hands-free" remote control; - "Touch screen" remote control; - Ambient lighting; - Multiple memorized profiles; - Speaker integration (radio, music, etc.); - Integrated sensors that alert you to possible leaks; - Seat height adjustment.	- Dual flush; - Discontinuous flush; - Tornado flush; - Rimless pan design; - Soft-close seat; - Self-cleaning nozzle; - Removable nozzle; - Rear cleaning nozzle; - Adjustable jet position; - Emergency flushing system during power outages.

The water–energy nexus in water-using products (WuPs) was also considered in the recent Unified European Water Label (UWL). According to studies by the European Commission (EC), replacing standard domestic devices (taps, showers, etc.) with water-efficient products will result in an overall reduction in annual domestic water consumption of up to 35% for taps and 11% for showers and 30% in associated energy. It should be noted that the Aveiro study is in line with these estimates [71].

The importance of these numbers is evident, considering that the total water withdrawal for use in taps and showers was estimated in the European Union (EU) to be around 25,000 Mm^3 in 2010, and the total energy demand associated with the use of taps and showers in EU countries was estimated at around 3000 PJ^3/year [72]. The total CO_{2eq} emissions related to annual EU primary energy demand from taps and showers were estimated to be around 160 Mton in 2010.

However, strong EU policies for water efficiency in buildings have not been promoted in the past, which is why several efficiency labels for water-using products (WuPs) have emerged in different European countries in recent years, generally for voluntary use, as is the case with the ANQIP label shown in Figure 3 [73,74]. In 2018, an agreement was reached with representatives from ANQIP, Water Label, Swedish Label, and Swiss Label to develop a unified European label for all WuPs. This agreement resulted in the creation of the Unified Water Label (UWL), which is represented in Figure 4.

The Unified Water Label Association (UWLA), the entity responsible for developing the UWL, considered that a single label covering water and energy efficiencies would be the best option for the market. Therefore, in addition to a color grid associated with water consumption, the UWL also has an energy icon on the base, which can be seen in Figure 4, to make consumers aware of the predicted annual energy consumption when using the product.

Energy consumption associated with water flow rates or volumes (water–energy nexus) is not yet considered in European Standards, so the UWLA has established a calculation based on basic physics principles:

$$E = m \times C \times \Delta T \quad (1)$$

where

E = energy [kWh];
m = mass [kg];

C = specific heat of water = 0.00116 kWh/(kg K);
ΔT = temperature difference [K].

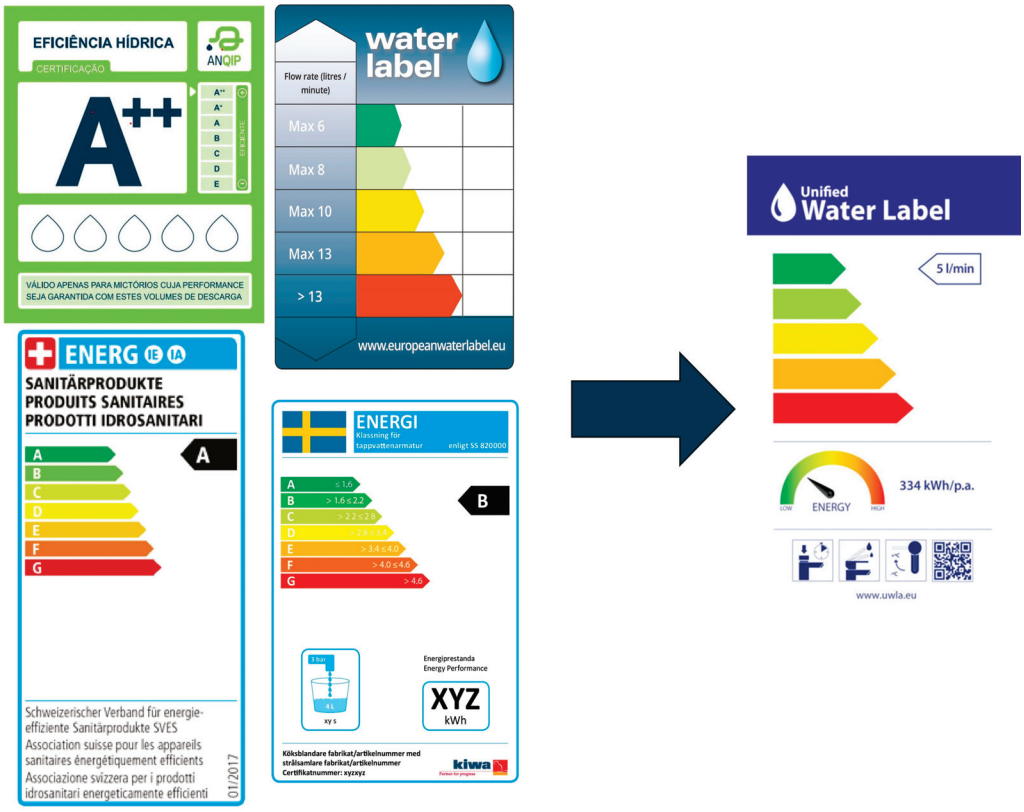

Figure 4. European Unified Water Label (UWL) [36].

With this basic calculation, together with average usage times, the expected annual energy consumption can be easily estimated. The average usage times to consider are as follows:

(1) For washbasin taps (and bidets): 1 min per use and five uses per person and per day;
(2) For kitchen taps: 1 min per use and five uses per person and per day;
(3) For showers: 7 min per use and one use per person and per day.

With regard to washbasin taps and showers, an average outlet temperature of 38 °C is accepted, while for kitchen taps, the average outlet temperature is considered to be 45 °C. In all cases, the average inlet temperature is set at 15 °C. The main calculation assumptions were taken directly from an EC study on taps and showers [73,74]. For bathtubs, the same calculation can be used to raise awareness of the energy costs associated with filling the bathtub.

The development of rainwater-harvesting systems and the reuse of gray water in buildings are constructive solutions that have had significant dissemination in several countries over the last few years. Therefore, the analysis of the water–energy nexus for these installations is also of interest.

Rainwater-harvesting systems in buildings obviously reduce water (and energy) consumption from public networks, as rainwater can be used for purposes that do not require drinking water. However, they often require a pressurization system in the building.

It can easily be seen that the energy consumption when these systems are installed is equal to or lower than that which occurs when the supply is made via the public network, given that the pressurization systems are dimensioned for the minimum pressures required in the building, which is not the case with the public network, where pressures seek to respond to the general needs of the entire urban area.

With regard to the use of graywater, it can be said that so-called compact installations, with a short retention period and simplified treatment (as is the case with devices available on the market that combine a washbasin and flush toilet), also lead to savings in energy. In fact, there is a reduction in water consumption from the public network in these situations, with an inherent reduction in energy consumption, as previously mentioned.

In the case of installations with long retention periods, with "conventional" treatment, the energy consumed in the treatment process makes the system "neutral" from an energy point of view. In fact, the energy required to treat graywater, around 1.8 kWh/m^3, is approximately equivalent to the energy saved in the urban water cycle. (In the study carried out by ANQIP in the city of Aveiro, energy consumption in public networks was precisely determined to be around 1.8 kWh/m^3 [71]).

4. Conclusions

The water–energy–food nexus, to which some authors add climate, is the fundamental link for the sustainable development of humanity and human security. This nexus is valid globally but can also be considered on a regional or local scale or even applied in non-agricultural environments, such as cities or even buildings. In the latter cases, this nexus reflects the relationship between energy, water, and nutrients (or fertilizers).

With regard to the connection between water and nutrients, it should be noted that the recovery of phosphorus in buildings or urban environments will probably be a solution of the greatest relevance in the future. Phosphorus is a non-renewable element essential for food production, the lack of which can compromise humanity's food security, with its loss through urine being one of the main causes of losses in the value chain. Without prejudice to other applicable recovery technologies, for example in WWTPs, the installation of urine-diverting toilets and urinals in residential buildings and the generalization of urinals for women, for example, will probably be advantageous solutions for recovery in terms of energy and efficiency. The relationship between energy and nutrients in buildings is generally not very relevant. However, the global water–energy–nutrients nexus can be found in buildings at the level of some modern toilet composting solutions.

The relationship between water and energy is always very significant, and buildings are no exception. In addition to the important and well-known dependence that exists on the production of domestic hot water, there are many other aspects in which this connection is revealed in urban environments and buildings. This is the case, for example, for electricity consumption in public supply and drainage networks, which must, naturally, be associated with water consumption in buildings, and energy consumption resulting from pressurization needs in buildings or the existence of vacuum drainage systems. Furthermore, the rapid evolution in recent decades in the design of sanitary installations, seeking to increase comfort, hygiene, or sustainability parameters, has implied, in many situations, an associated energy consumption. Water labelling for water-using products (WuPs) must be encouraged, as, in addition to being an incentive for the installation of efficient devices, it in many cases incorporates information on the water–energy nexus, as is the case in the new European Unified Water Label (UWL).

Overall, the water–energy–nutrients nexus in urban environments and buildings is particularly relevant and, in some respects, may be essential for sustainable development and human food security. It should, therefore, be the subject of special attention, in parallel with the global and essential approach to the water–energy–food nexus.

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A Framework for Operational Management of Urban Water Systems to Improve Resilience

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Abstract: Optimizing the management of hydraulic infrastructures that support water supply, wastewater, and stormwater drainage can increase the efficiency of these systems. A framework for operational management of urban water systems allows for robust management, which contributes to the system's overall resilience. A methodology has been structured to support the decision-making process of managing entities. The methodology for the operational management of hydraulic infrastructures incorporates concepts of asset management, risk management, and technical management. It is organized into three operational areas (assessment, operation, and intervention) and aims to increase the efficiency of managing entities. Two cases were used to implement the aforementioned methodology—the Arouca Water Supply System (SAA-Arouca) and the Trofa Wastewater Drainage System (SAR-Trofa), both under the responsibility of Águas do Norte, S.A. In SAA-Arouca. There was a particularly significant reduction in the system input volume (purchased the first level) and the number of pipe busts observed in the subsequent period after the implementation of the methodology. Regarding the SAR-Trofa, the application of the methodology focused particularly on improper inflows (rainwater and others). The proposals for this system mainly aim at reducing the volumes collected by the drainage networks (in low-level infrastructures) and delivering them to different high-level infrastructures.

Keywords: operational management; hydraulic infrastructures; water systems' resilience; water supply; water losses; wastewater drainage; inflows

1. Introduction

The demographic evolution in the second half of the 20th century, particularly in the 60s, leveraged the construction of housing estates and public facilities, rising to the expansion of hydraulic infrastructures [1]. Currently, the increase in urbanization in concentrated hubs and the desertification of rural areas, the improvement of service and increased demand, the conclusion of new systems in a significant number of locations, the operation of aging systems, the assurance of performance levels with increasing efficiency, scenarios of resource scarcity, the strong availability of data and technological means to support management, and the need to preserve existing know-how and empower new human resources are aspects of the reality observed in the current context of hydraulic infrastructure management. On the one hand, this demonstrates the overall positive balance of recent decades. On the other hand, it highlights the need to reflect on current vulnerabilities and opportunities [2].

The increase in population and the consequent increase in consumption, in the context of climate adaptation, have been accentuating water scarcity in different regions of the world [3–6]. Currently, urban areas are consolidated and fully or partially infrastructured. The challenge for the management of hydraulic infrastructures is identified in this context: the renovation and adaptation of systems [7].

Alegre et al. [8] (2012) state that public water services represent a paradigmatic example, emphasizing that they are essential public services, although commonly undervalued.

The supporting infrastructures are of limited visibility and entail high construction costs and durability. Using water efficiently is to promote processes and technologies without compromising the efficacy. Some measures that can be considered, regarding public systems of water supply and water drainage are: the optimization of opportunities and processes, pressure and water losses reduction in supply systems, adequate taxes, and reusing treated urban wastewater [9].

The GPI (asset management) structures traditional management practices, integrating them into principles of objective management and continuous improvement and favoring new techniques of analysis, comparison, and communication. GPI balances performance, cost, and risk based on management, engineering, and information, planned strategically, technically, and operationally. It is mentioned that defining priorities and selecting intervention needs require knowledge of assets (infrastructures), and diagnosing the existing situation allows the assessment of residual life and the economic value of infrastructure [10]. An organic approach of asset management must include an analysis to rehabilitation and development of plans. These can be reinforced by evaluating interventions and considering alternatives [11].

Planning the rehabilitation of aged infrastructures needs a critical analysis on two main questions — How much investment is needed to maintain a sustainable service? – and — Which of the components are the priority? It should be noted that although the issues are closely linked, the analysis approaches are different, with the first relating to strategic infrastructure rehabilitation planning, which seeks to establish long-term investment strategies, and the second to medium-term tactical planning [12–14].

In the decision-making process, risk is approached as the inability to anticipate the structure, results, and consequences, including uncertainty and its outcomes [15]. Including risk in the decision-making process requires considering two factors: the probability of scenario occurrence and the probable consequences of scenarios. A decision that accounts for these is referred to as a decision informed by risk [16]. Regarding the technical applications of quantitative risk analysis, the general technical definition of risk is considered sound, starting from the hypothetical occurrence of an event with negative or positive consequences. Risk is determined by the product of probabilities and consequences [16]. It is suggested to use the general technical definition of risk because it is an expedient calculation methodology that can be based on real data and allows the use of risk from an operational, adaptive, and versatile perspective, informing decision-making. The efficient management of water distribution systems and the potential associated with telemetry systems as generators of consumption data are challenges related to a more in-depth knowledge of urban consumption. The use of this data in engineering applications is a long way off, given the demands that these applications place on the data collected [17].

Structurally, Almeida [18] (2017) mentions that most managing entities do not have organizational documents (such as water safety plans, loss reduction plans, or meter management plans) and emphasizes that experts identify these documents as one of the main details of “organizational causes", referred to as the second main cause of water losses, just after “infrastructural causes”.

The proposed methodology was developed by Jorge Cardoso Gonçalves. The Operational Management of Hydraulic Infrastructures methodology (GOIH, in Portuguese) is presented as an aggregating element of asset management, risk management, and technical management concepts, proposing a new organizational model detailed further in Section 2.2 in order to tackle the referred vulnerabilities and take advantage of the opportunities.

Water must be managed resiliently when responding to the challenges emerging from the exploration of water supply, wastewater, and rainwater drainage systems—water consumption and water treatment before discharge into receiver water bodies are matters to consider [19]. Urban and industrial development is demanding natural resources. Hence, it is necessary to promote water management policies to ensure the renewal of water resources, which can benefit future generations [20]. The efficiency of the water management sector depends on daily proactive measures [21]. A proper management

policy, along with the application of the most effective techniques, is the key to the success of this process. The positive results associated with water losses in supply systems are proportional to the economic and financial resources [22].

GOIH, presented in this article, aims for optimized management of water systems (supply and/or drainage), focusing on economically viable and environmentally sustainable solutions. Preservation of water sources, availability in scarcity scenarios, supply security, protecting the receptor water bodies, response to extreme phenomena, and adaptation to new contexts are some of the issues considered in this methodology [19]. This methodology is based on three main steps in order to reach the final proposed solutions to the managing entities: data analysis, the methodology itself (evaluation, exploration, and intervention, among other matters), and decision support, which are divided into several processes, as shown in Figure 1 [23].

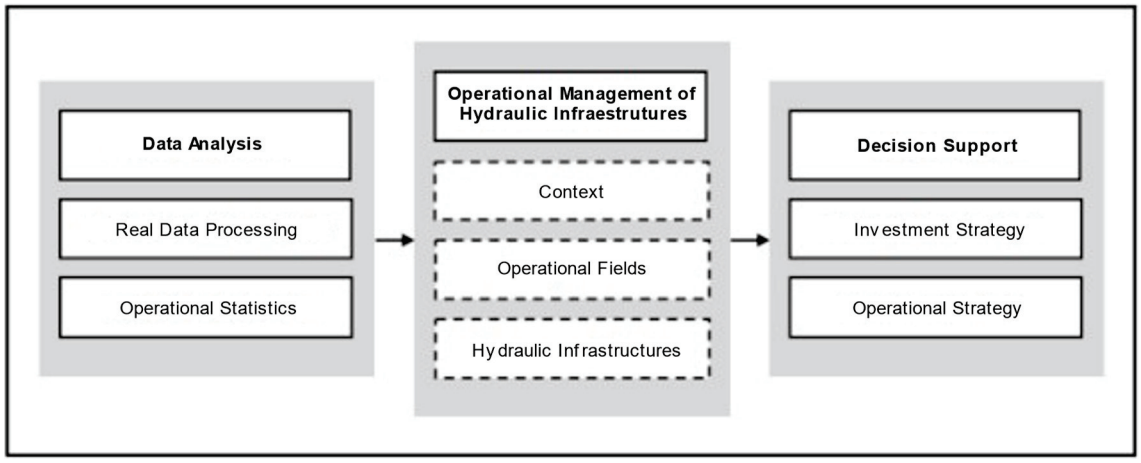

Figure 1. Organizational structure of the framework (adapted from [23]).

2. Operational Management of Hydraulic Infrastructures (GOIH)

Operational Management of Hydraulic Infrastructures is based on the management concepts of patrimony management—state, performance, costs, and risks; risk management—simplified calculation methods, real data, and management informed by risk; and technical management—operational and organizational concepts. It also considers the inherent challenges of the water service's management and the supporting hydraulic infrastructure. The methodology aims for the development of strategies that consider the environment (searching for environmentally sustainable solutions), society (considering people's need for effective water supply and wastewater and rainwater drainage), the economy (searching for efficient solutions with fewer financial resources that stimulate the market), and politics (involving decision-makers). It also considers science and innovation when trying to bring the academic community and managing entities closer and develop new solutions.

The GOIH methodology considers the challenges of the water system's management, which include an integrated perspective of the sector and society's several dynamics, the resilient management of water resources and their sustainable usage, adaptation to climate change consequences, and operational optimization. All of the proposed solutions must respond effectively to these challenges.

This methodology depends on political support, effective leadership, clear and attainable goals, and enough time to implement the proposed solutions. It also needs cross-border and broad communication with all the involved parties.

After establishing the context of the systems in study, further steps of the methodology take place (Figure 2).

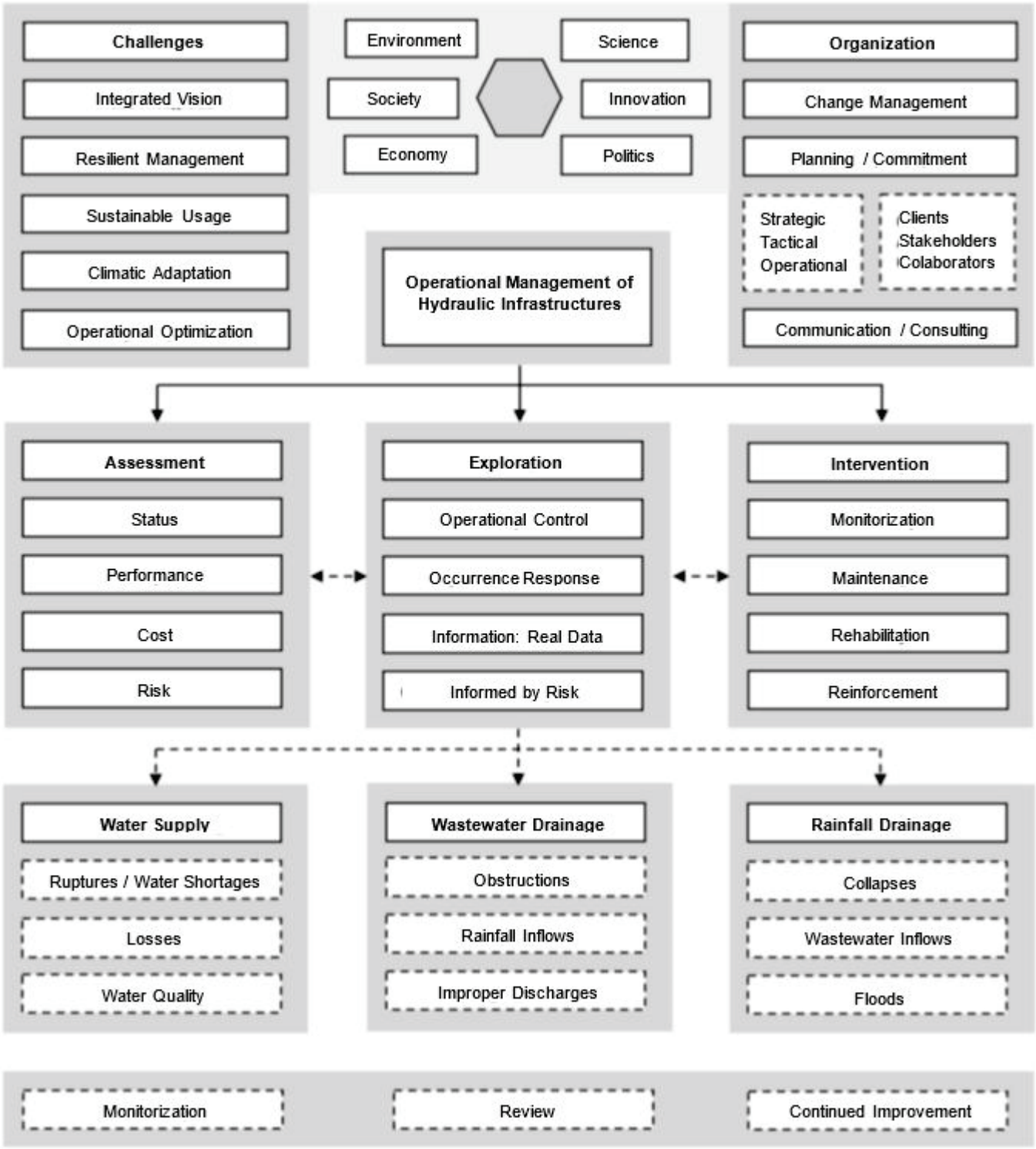

Figure 2. Organizational structure of the Operational Management of Hydraulic Infrastructures (adapted from [23]).

According to Figure 2, after context is established, the methodology follows the operational areas—assessment, exploration, and intervention.

2.1. Data Analysis

The process of data analysis (Figure 1) is sorted between the processing of real data and operational statistics.

Regarding the processing of real data, it starts with a primary analysis to identify the main peculiarities and eventual abnormal data—descriptive analysis. Following this comes *data systematization*, where data are sorted between data from the managing entity and data obtained throughout the present study. The data are also organized into three main categories:

Infrastructure data—concerning infrastructure characterization and inquiries into data regarding the state, performance, and risk of the infrastructure.

Exploration data—data that pertains to monitoring, occurrence records, intervention logs, and other operational data.

Management data—management reports, the system's performance, and commercial information.

The detection and deletion of abnormal data are carried out throughout the whole process, after the descriptive analysis and data systematization. Data normalization allows us to unify the collected information, which in turn allows for a comparison between the different data sets. Data reduction makes a long period of analysis possible by compacting the initial data volume.

After the real data has been processed, the statistical treatment of technical information is carried out—operational statistics. An empirical and rational approach is chosen over more sophisticated mathematical models or probabilistic models for scenario simulations. This step—operational statistics—consists of descriptive statistics, information organization, and a risk approach.

Descriptive statistics consists of the analysis of some statistical elements obtained from the collected data, such as the mean, standard deviation, range, and mode, among others.

When organizing the information, the collected and processed data should be converted into tables and graphs.

The risk approach is flexible, with variable complexity sustained in the data provided by the managing entity, to estimate the risk and support the decision-making process. The risk degree of an event is directly correlated with the probability of its occurrence and its consequences. The probability and consequence calculation as well as risk estimation can be sustained in three types of approaches:

Objective approach—sustained by real exploration data. A quantitative analysis of the probability of event occurrence is carried out through a ratio between the number of occurrences of one system and the total number of occurrences. As for the consequences of occurrences, these are measured according to the monetary consequences of the events. Lastly, risk is determined by the product of probability of the occurrence and consequences for isolated or associated events.

Subjective approach—based on inquiries to the managing entity. The probability of occurrence is assessed qualitatively, while the consequences are assessed empirically. Risk is assessed using a risk matrix.

Modelling-based approach—sustained in hydraulics modelling and risk and reliability analysis.

Finally, the value of the calculated risk is translated into a monetary value.

2.2. Infrastructure Assessment

The assessment of the infrastructure is sorted into four categories: status, performance, cost, and risk. Status, performance, and risk assessment establishes five categories for each assessment—from class 1 (very good, excellent, and very low, respectively) to class 5 (very bad, inefficient, and very high, respectively). Cost assessment is based on several factors, as shown in Figure 3.

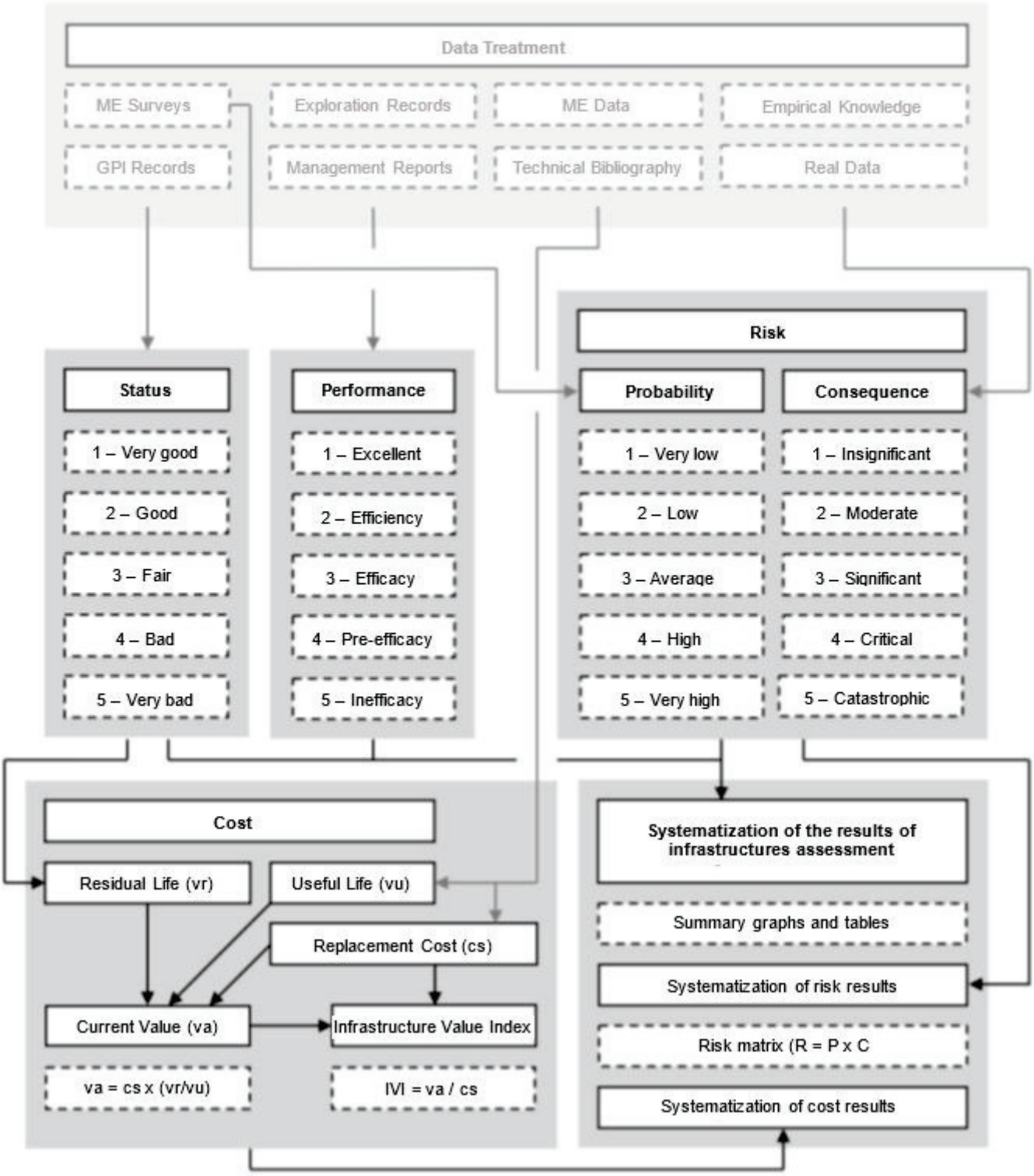

Figure 3. Infrastructure assessment method (adapted from [23]).

2.3. Exploration

This stage of the GOIH methodology is based on the data collected through the managing entities and is sorted in four steps that can be excluded or added according to the infrastructure under study:

- Operational control

This stage of *Exploration* consists of systematic recording (occurrences, monitoring data, anomalies, updates, and interventions); operating costs; human resources management (including structured operational routines, implementation of specialized teams, and action planning); and finally, real-time management (through monitoring and alert systems). Some of these are in common with Section 2.1. (Data Analysis) and Section 2.2. (Infrastructure Assessment).

- Response to occurrences

When occurrences take place, resolution depends on human resources and material means (prevention teams, external contractors, and operational storage), operational relevance index (IRO, in Portuguese), and prediction modeling for preparing preventive action.

Regarding IRO, this index is used for pre-positioning human and material means and for prioritizing operating actions. IRO translates the relevance of certain activities, infrastructure, or subsystems through the average weights of different indicators of the system.

- Information management

This focuses on the conversion of the collected information into knowledge about occurrences (number, type, time and space distribution, and locations with the most incidence) and performance information.

- Risk-informed management

This risk-informed management is based on risk calculation based on real data—calculation of probability (ration between occurrences associated with an infrastructure or subsystem and the total number of occurrences); consequences (operating costs associated with occurrences); and risk, which is the product resulting from probability and consequences. This type of management also depends on objective risk assessment and risk-informed decision-making.

2.4. Intervention

This stage of GOIH is divided into five categories to organize the interventions necessary in the different components of water systems, with the goal being prioritization, action planning, summarizing costs, and optimizing the operational management of hydraulic infrastructure. The four categories are as follows:

Monitorization;
Maintenance;
Rehabilitation; and
Reinforcement.

Of these four categories, Monitorization and Maintenance include the same steps: systematization of past, ongoing, and future actions; action planning (plans, routines, and actions); data summary; cost analysis; and future action definition. Rehabilitation and Reinforcement include the aforementioned systematization, investment planning, intervention summary, and future action definition.

2.5. Decision Support

Decision support for managing entities is associated with investment planning since financial resources must be managed carefully, directing them into solutions that result in larger gains and shorter return periods. This tool of the GOIH methodology is based on the data gathered in all the previous stages explained regarding the status, performance, cost, and risk of the hydraulic infrastructure.

Two types of investment can take place:

With operational return, it envisions performance improvement of the infrastructure. Its intervention aims to decrease occurrences and decrease outflows and inflows, among others. It is also analyzed based on its estimated return.

With strategic return, it focuses on interventions that are assessed based on the global interest of their execution from a system's evolution standpoint (to reinforce responsiveness, increase the coverage rate, or improve the service's security and quality).

The data attained in the above-mentioned stages is converted through decision support indexes—status evaluation index (IAE), performance evaluation index (IAD), risk assessment index (IAR), operational relevance index (IRO), risk management index, and context factors index (IFC). Directly resulting from the operational field of *Assessment* is cost assessment, translated into replacement costs, current value, and IVI (infrastructure value index); and resulting from the *Exploration* field are occurrence summaries and systematized operational costs.

The decision-making process will encompass a selection of interventions, the prioritization of interventions, and the estimated investment.

The decision support winds up at three levels:

- Investment strategy

This stage of strategy is based on indexes, which are based on the indexes aforementioned—the infrastructure investment index (III) and the operational investment index (IIO). This is a flexible methodology; hence, the decision does not need to use the totality of the indexes, and it may include others.

- Operational strategy

This strategy considers investments, gains, and return periods.

The annual gains are calculated considering the annual economic losses and the current economic gains. Similarly, it is also possible to calculate future economic gains. These economic losses may be deleted if a certain investment is executed.

The return period is dependent on the investment amount and the annual gain due to the investment. The higher the annual gain, the shorter the return period.

- Specific decision strategy

In this stage, the investments under analysis must not be only the monetarily measurable ones. At this stage, predictions of the evolution of the systems, medium- to long-term, can be included.

The gains associated with the chosen investments may finance a transformative process for the managing entities, along with gains for the stakeholders.

3. Case Studies

3.1. Water Supply System of Arouca

This system supplies the Arouca municipality, which has an area of 327 km^2 and approximately 24,000 inhabitants. Topographically, the area is rural with great altitude variations.

Regarding the supply system, the Water Supply System of Arouca (SAA-Arouca, in Portuguese) consists of a Main System (MS) and Autonomous Systems (AS). The MS is supplied through 6 Delivery Points (DP) provided by Águas do Douro e Paiva, S.A. (AdDP), and its 25 subsystems are additionally provided by 27 water catchments (information related to 2017, according to the managing entity) [23]. Figure 4 shows the distribution of the system in its Main and Autonomous Systems.

In the past, the SAA-Arouca was divided into 58 subsystems. This led to interruptions in the supply chain, especially during the summer. Because of this problem, a main pipeline at a higher level of the system was executed. With the several alterations done to the SAA-Arouca throughout, with a focus on the balance of supplied areas and the deactivation of autonomous sources, Figure 5 shows the supply areas in 2017.

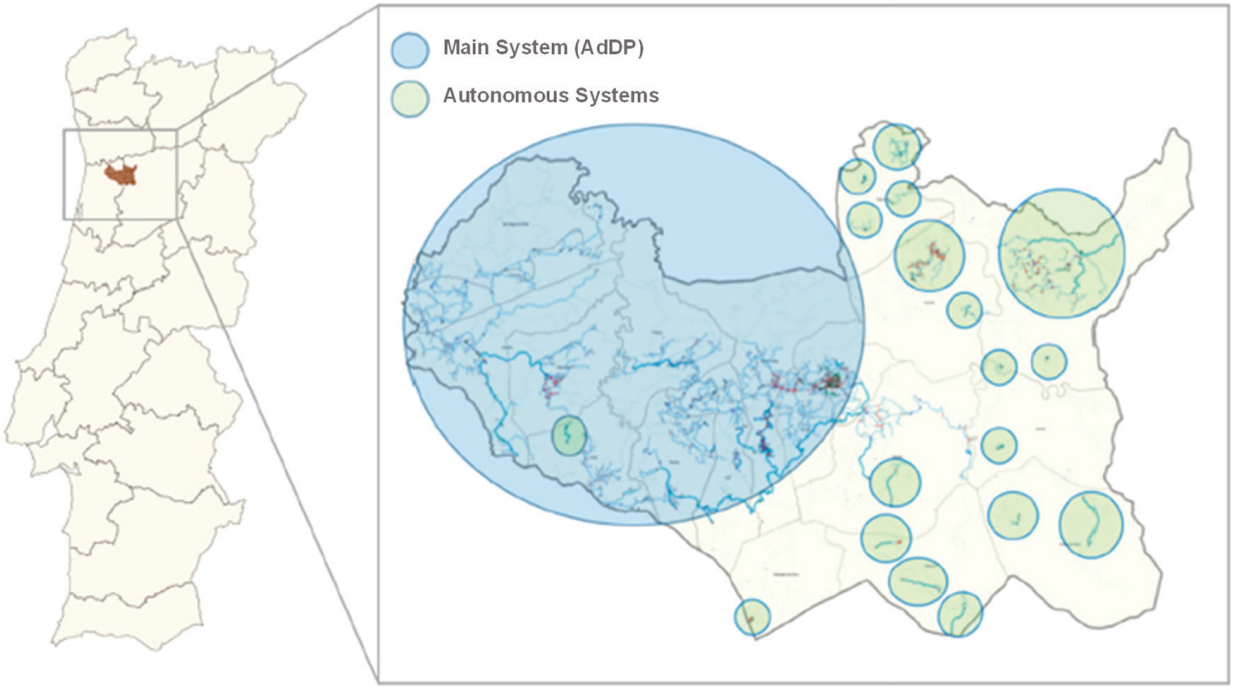

Figure 4. Representation of the subsystems of the SAA-Arouca (adapted from [2]).

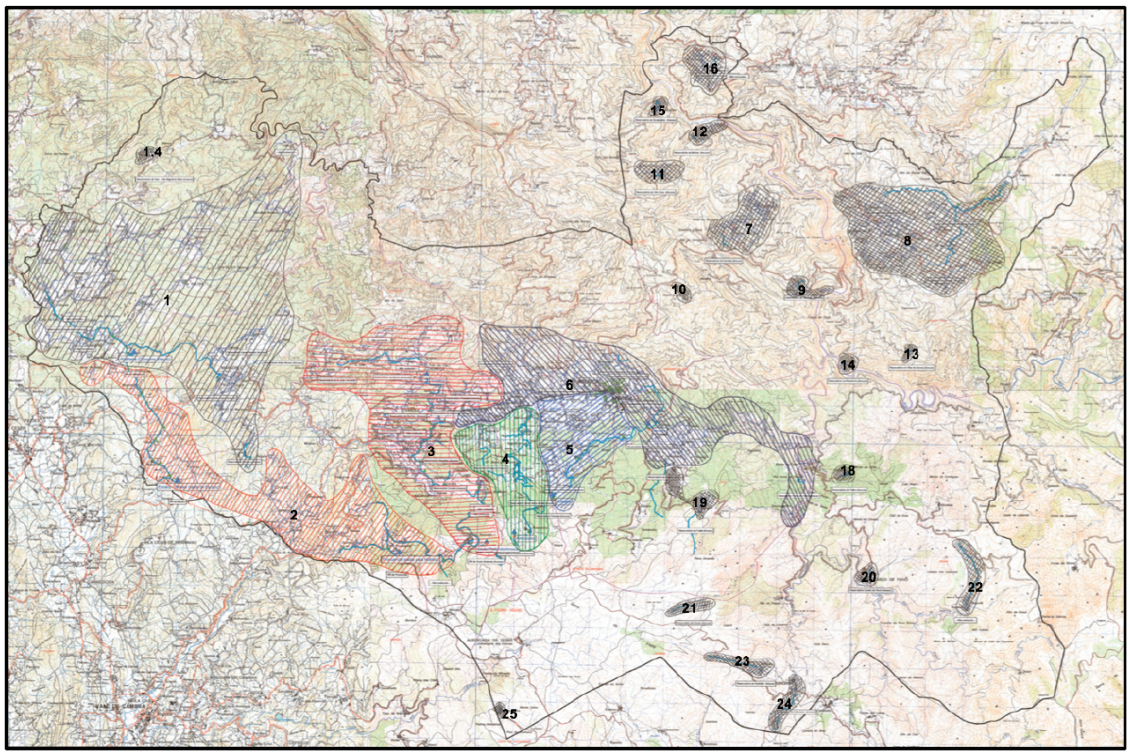

Figure 5. Supplied areas of the SAA-Arouca in 2017 (adapted from [23]).

Currently, the SAA-Arouca has 40 water catchments (13 out of service), 52 reservoirs (9 out of service), 27 pumping stations (7 out of service), 44 km of main pipelines, 17 water treatment plants, and 370 km of distributor pipelines.

In 2017, Arouca registered 10,695 houses, from which 7660 had available water supply (a coverage ratio of 72%), and from this portion, 6039 had effective water supply service (a subscribing ratio of 79%).

About 86% of the clients are domestic, followed by commercial/industrial/services with 8%. There was a pattern of evolution throughout the last 3 years, due to the number of clients, the execution of distributors, as well as substituting and installing water meters (thus ensuring better monitoring of the water volumes).

On this note, it is important to highlight that the age of the water meters may compromise the monitoring process of water volumes. Between 2016 and 2017, there was an improvement in the water meter fleet regarding the age of the equipment. This may have influenced, not solely, the improvements registered in Figures 6 and 7.

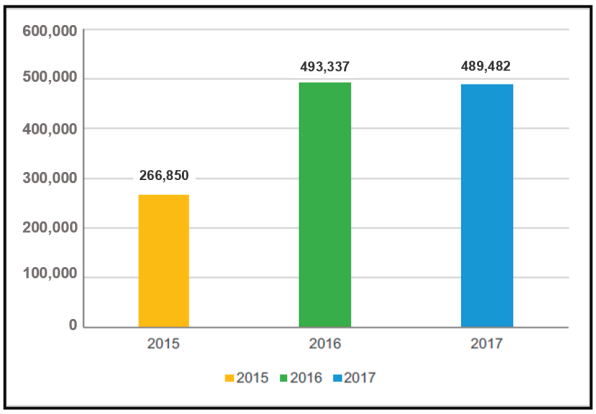

Figure 6. Volumes of water delivered in SAA-Arouca between 2015 and 2017 (adapted from [23]).

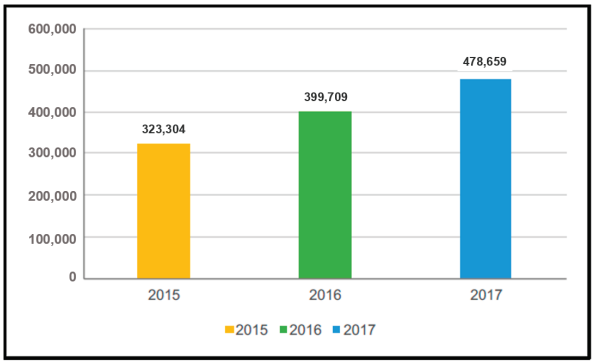

Figure 7. Volumes of water delivered in the MS between 2015 and 2017 (adapted from [23]).

Figures 6 and 7 reveal a difference between the volumes of water delivered in the SAA-Arouca globally and in the Main System only. In the latest, the volumes for the three years under observation are higher, and there is an increase in this indicator throughout the three years, while in the global analysis, there is an increase, though slight, between 2016 and 2017.

3.2. Wastewater Drainage System of Trofa

The Wastewater Drainage System of Trofa (SAR-Trofa, in Portuguese) drains the municipality of Trofa, which covers an area of 71.71 km^2 and with approximately 400,000 inhabitants. Regarding the year 2017, Trofa registered 15,583 houses. Of the 15,121 wastewater drainage options available (a ratio of 97% coverage), 9873 had effective service (a subscription ratio of 65%).

The Wastewater Drainage System of Trofa (SAR-Trofa, in Portuguese) is subdivided into two levels: the lower level, with 2 drainage basins, managed by the Northwest Region's Water System (SARN, in Portuguese), and the higher level, which is managed by TRATAVE (Tratamento de Águas Residuais do Ave, S.A.), responsible for SIDVA (translated to Depollution Integrated System of Ave's Valley).

SIDVA was developed to respond to the deterioration of water quality in the River Base of Ave's Valley (which has been aggravated since the 1980s). This system (SIDVA) encompasses four drainage fronts—Lordelo, Serzedelo, Rabada, and Agra. SIDVA is substantially exposed to groundwater and rainwater inflows because a substantial extension of the system is installed in the riverbed.

Regarding the SAR-Trofa organization, at the higher level of the system there are four interceptors—Trofa (managed by TRATAVE), Trofa Prolongamento, Covelas Poente e Bougado (all three managed by Águas do Norte, S.A.). At the lower level, there are drainage basins managed by Águas do norte, S.A., which connect to Trofa Interceptor. This Trofa Interceptor is then connected to the Ave Interceptor, which is included in the Multimunicipal System of Water Supply and Wastewater Drainage of Ave's Valley. There are a total of 11 drainage basins in the SAR-Trofa. Considering other infrastructure, there are 3925 connection branches, 99,251 m of collectors, interceptors, and outfalls, 2827 manholes, 3928 junction chambers, and five lifting installations. Figure 8 illustrates the organization of SAR-Trofa.

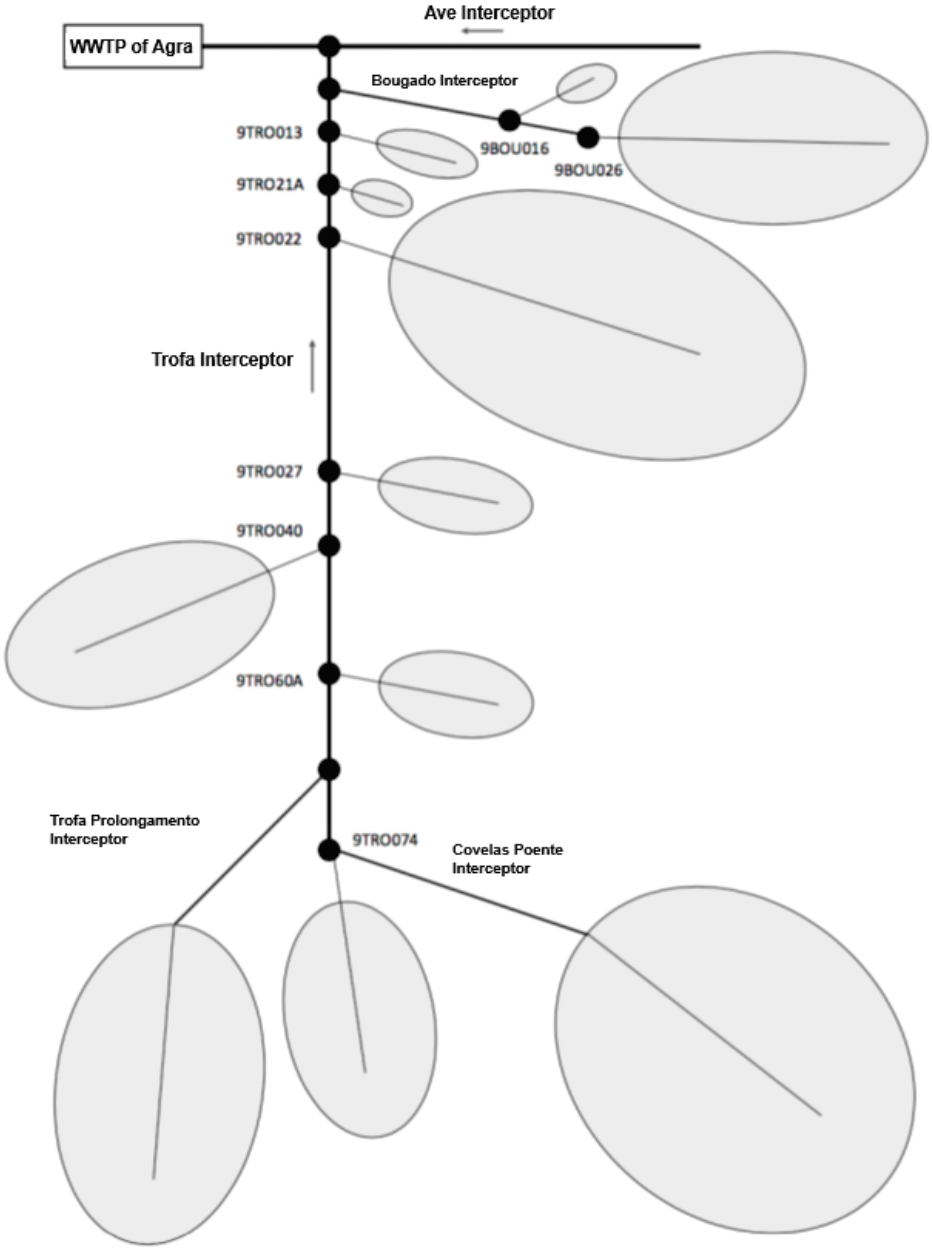

Figure 8. Schematic representation of the SAR-Trofa (adapted from [23]).

Service-wise, the coverage ratio has risen from 12% to 97% (year 2018) in the last 15 years; the number of clients rose between 2006 and 2018 to 6468, from a total of 4752 associated clients to 11,220—an approximately 58% increase.

The significant increase noted in Figure 9 between 2017 and 2018 was due to the installation of a flow meter in the drainage basin 9TRO022, making up a total of 2 flow meters in all of SAR-Trofa.

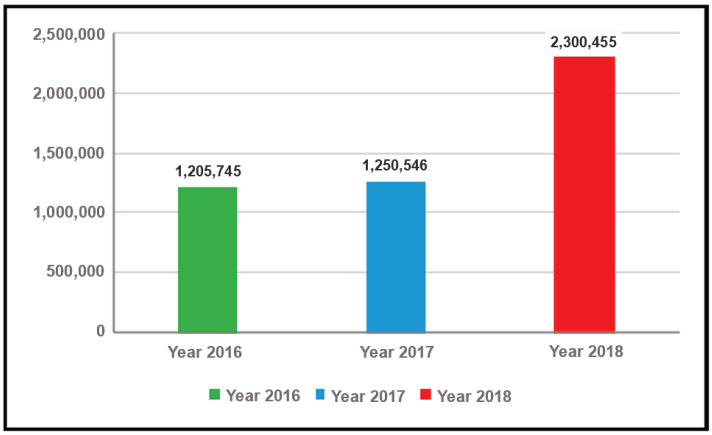

Figure 9. Volumes of delivered wastewater annually at the higher level by Águas do Norte, S.A., in Trofa, between 2016 and 2018 (adapted from [23]).

In 2018 (Figure 10), between 15% and 24% of the accounted volumes registered of TRATAVE were from industrial sources, which means that the volumes accounted are mainly domestic—850,032 m^3.

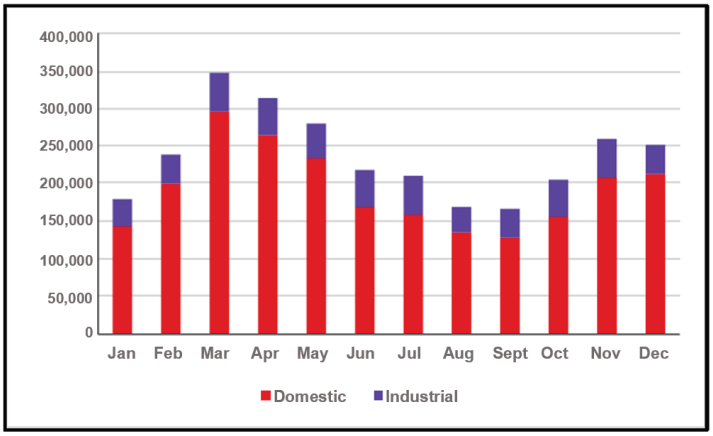

Figure 10. Graphic representation of monthly values accounted for by TRATAVE in Trofa in 2018 (adapted from [23]).

According to a study from Engidro e HIDRA (2006c), monitoring the Trofa interceptor on inflows showed this was the worst-performing interceptor (out of the four aforementioned) at the higher level. This interceptor showed that the flow from upstream to downstream nearly doubled (58 m^3/h and 111 m^3/h).

4. Application of the Methodology GOIH

4.1. SAA-Arouca

4.1.1. Assessment

Infrastructure status assessment is done at five levels—very bad, bad, fair, good, and very good. In 2018, the global status of SAA-Arouca was as follows:

Catchments—87% are in fair or bad status; 13% are in good status.

Pipelines and distributors:

Pipelines—mainly in fair or very good status (31% and 25%, respectively).

Distributors—mainly in fair status (77%).

Reservoirs (construction and equipment)—mainly in fair status (47% and 55%, respectively).

Treatment System—70% in fair status (in construction and equipment).

Pressure Reducing Valve—regarding construction, it is mainly in fair or good status (42% and 24%); regarding equipment, it is mainly in good status (71%).

Pumping Stations—77% in fair status (construction and equipment).

Regarding performance assessment, the same infrastructures in the Status Assessment, were established at five levels—ineffectiveness, pre-effectiveness, effectiveness, efficiency, and excellency. The results of the assessments were:

Catchments—regarding flow availability, between pre-effectiveness, effectiveness, and efficiency, with 26%, 43%, and 30%, respectively.

Pipelines and distributors:

Pipelines—functioning wise, they present a similar pattern to the Catchments, with 28% for pre-effectiveness, 47% for effectiveness, and 25% for efficiency.

Distributors—regarding functioning, these infrastructures are divided into pre-effectiveness (40%), effectiveness (24%), and efficiency (35%); as for accessory suitability, the registered status was mainly pre-effectiveness (50%) and effectiveness (46%).

Reservoirs—assessing reservation, level control, and watertightness, the main status level of each was effectiveness (40%), pre-effectiveness (68%), and pre-effectiveness (40%), respectively.

Treatment System—these were assessed regarding treatment capacity and functioning. Treatment capacity was assessed mostly by the level of effectiveness (70%). As for functioning, a more balanced assessment was registered between pre-effectiveness, effectiveness, and efficiency—40%, 24%, and 35%, respectively.

Pressure Reducing Valve—regarding pressure reduction, these devices were assessed with mainly efficiency (90%); as for flow availability, pre-effectiveness and effectiveness were balanced, with 42% and 45%, respectively.

Pumping Stations—these were assessed considering pumping capacity (41% effectiveness and 55% efficiency) and energetic efficiency (32% pre-effectiveness and 68% effectiveness).

Social Performance was also assessed, and, with one exception, all the indicators were predominantly effective or efficient when compared with the infrastructure assessment:

Image of the Management Entity—only 5% have a pre-effectiveness level; the remaining 95% are divided into effectiveness (37%), efficiency (53%), and excellency (5%).

Customer Service—like the above-mentioned indicator, 5% was attributed to a pre-effectiveness level; the remaining was subdivided into 42% effectiveness, 32% efficiency, and 21% excellency.

Invoicing Process—this indicator was the one exception that showed a higher pre-effectiveness level (47%), with the remaining divided among the three highest levels of the attribution scale.

Service Quality—regarding this, effectiveness and efficiency were predominantly registered, with values of 42% and 47%, respectively.

Occurrence Response—predominantly efficient, with 63% and 16% at the excellency level.

Problem Resolution—52% of effectiveness was assessed, and 32% efficiency.

Meters Installment—16% was found at the excellency level; the remaining was equally divided between effectiveness and efficiency.

Execution of Branches—mainly divided into effectiveness (42%), efficiency (37%), excellency (16%), and pre-effectiveness (5%).

Infrastructure Conservation Status—mostly assessed with the efficiency level (43%), followed by 32% with effectiveness, 11% with pre-effectiveness, and 5% with excellency.

Infrastructure Safety—42% of the system is at an efficiency level, and 37% is at an effectiveness level.

Global Assessment—globally, this system's social performance is efficient in 43%, effective in 37%, excellent in 12%, and pre-effective in 8%.

Cost assessment is summarized in the following tables (Tables 1 and 2), regarding infrastructure consumed, useful life, current value, and replacement cost:

Table 1. Infrastructure Cost Assessment of SAA-Arouca (2017)—Summary (adapted from [23]).

Infrastructure	Replacement Cost	Current Value	Infrastructure Value Index
Catchments	EUR 158,625	EUR 99,460	0.63
Pipelines	EUR 1,381,695	EUR 901,544	0.65
Reservoirs	EUR 2,353,779	EUR 1,425,292	0.61
Treatment System	EUR 60,800	EUR 35,760	0.59
Distributors	EUR 15,200,880	EUR 9,287,480	0.61
Pressure Reducing Valve	EUR 590,614	EUR 409,441	0.69
Pumping Station	EUR 99,000	EUR 61,100	0.62
Total	**EUR19,845,393**	**EUR12,220,077**	**0.62**

Table 2. Infrastructures Rehabilitation Estimated Cost of SAA-Arouca (2017)—Summary (adapted from [23]).

Infrastructure	Consumed Useful Life
Catchments	37%
Pipelines	35%
Reservoirs	39%
Treatment System	41%
Distributors	39%
Pressure Reducing Valve	31%
Pumping Station	38%
SAA-Arouca (Global)	**38%**

This infrastructure value index (IVI) of around 60% indicates that infrastructure is stable.

Risk was assessed based on a 5-level scale—very low, low, average, high, and very high:

Catchments—non-compliance is mostly at a high or average level of risk (43% and 48% respectively. Regarding safety, is between low risk (70%) and average (30%).

Pipelines and distributors:

Pipelines—risk was assessed based on the probability of water loss, rupture, and service interruption. For water loss and service interruption, the probability was mainly average (53% and 54%, respectively). Regarding rupture risk, the probability lies at a low level, at 45%.

Distributors—the same as abovementioned was assessed in distributors. Regarding the risk probability for water loss and rupture, it was registered at 39% and 38% of the average risk, respectively, followed by 45% and 42% at a high level of risk. As for service interruption, 54% were at the average level and 43% at the low level of risk.

Reservoirs—were assessed for water loss, contamination, and accidents. For these 3, the average level of risk represented 40% to 43%, followed by a high level of risk between 34% and 40%.

Treatment System—service interruption was at the base of the assessment, with 82% in average risk.

Pressure Reducing Valve—the parameters used to assess these devices have all been above 88% of low risk—water loss (93%), rupture (88%), and service interruption (92%).

Pumping Stations—the parameters used were water loss (59% in low risk level), contamination (41% in low risk level and 50% in average risk level), and accident (32% in low risk level and 54% in average risk level).

In the following table (Table 3) is a summary of the several assessments aforementioned according to SAA-Arouca's subsystems.

Table 3. Infrastructure Assessment of SAA-Arouca—Summary (adapted from [23]).

Assessment	Abelheira	Provisende	S. Redondo	Ameixieira	Forcada	Moldes	Autonomous Systems	Average
Status	2.49 (good)	2.45 (good)	2.64 (fair)	3.42 (fair)	2.82 (fair)	3.11 (fair)	3.36 (fair)	2.88 (fair)
Performance	2.20 (efficiency)	2.32 (efficiency)	2.70 (efficacy)	3.30 (efficacy)	3.27 (efficacy)	3.07 (efficacy)	3.30 (efficacy)	2.86 (efficacy)
Risk	6.07 (interme-diate)	4.38 (low)	8.02 (interme-diate)	7.81 (interme-diate)	6.22 (interme-diate)	8.13 (interme-diate)	8.69 (interme-diate)	7.77 (interme-diate)
Actions/interventions to consider	Pressure control	Sectioning valves and Landfills discharges	Pipeline replacement in São João reservoir	Pressure control and pipeline replacement in Fráguas reservoir	Connection execution from Forcada reservoir to Santo Aleixo	Pressure control and re-placement of part of the supply network	Pressure control, air valve installation, mine inspection, and deviation of part of the catchment's water	

4.1.2. Exploration

Concerning operational control, there is a summary of the proposed and implemented actions with the application of GOIH methodology. Several actions were proposed:

Reservoir monitoring.

Systematic registration and management of occurrences.

Structured management of various works.

Monitoring standpipes with autonomous sources.

Setting up and managing a Pressure Reducing Valves team.

Operational costs were slightly lower in 2018 when compared with the previous year (Figure 11).

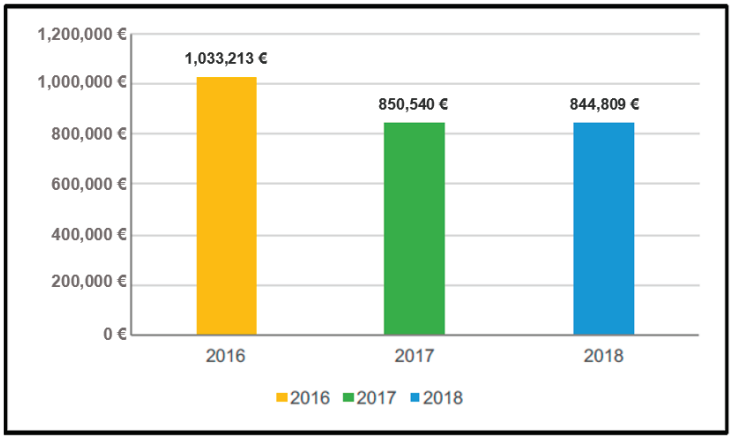

Figure 11. Graphic representation of the annual operational costs of SAA-Arouca between 2016 and 2018 (adapted from [23]).

Regarding human resources management, the proposed functional teams were designed to account for the main indispensable routines for adequate hydraulic infrastructure management:

System monitoring:
Water quality.
Volumes and consumption.
Energy consumption.
Verification of electromechanical equipment.
Prevention:
Response to occurrences.
Resolution of urgent problems.
Losses:
Operational optimization.
Active leakage control.
Night and day inspections.
Pressure Reducing Valves:
Monitoring, maintenance, replacement, and installation of.
Pressure management.
Ruptures:
Identification.
Repairment.
Monitoring of work carried out by external providers.
Reduction of response times.

The proposed actions in response to occurrences have the goal of promoting a timely and effective response to the different demands of managing SAA-Arouca. The proposal is as follows:

Reduction of response time through:
Optimizing the process of sending internal teams to identify incidents.
Systematic monitoring and control of external providers.

Management of the SAA-Arouca, accounting for the relevance of the subsystems, and enabling:

Continuity of service.
Data minimization.

The real data collected regarding the Main System shows an increase in water shortage, probably due to the supply network extension that happened in the network dependent on the delivery point of Souto Redondo (Figure 12), which can be associated with a lack of delivery capacity and ruptures on the pipeline of São João reservoir.

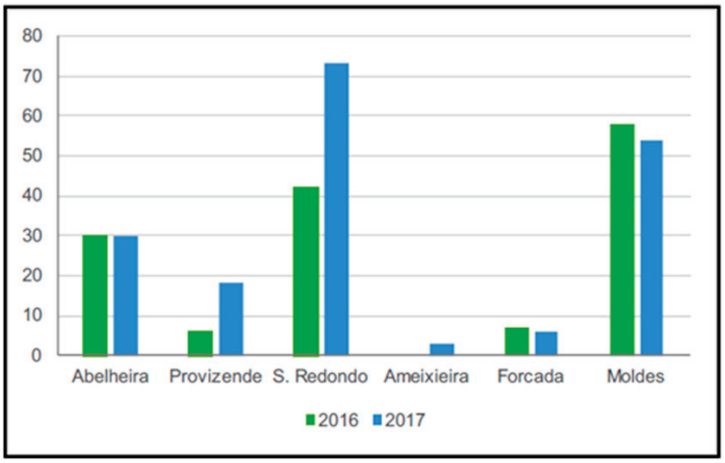

Figure 12. Graphic representation of water shortages in the Main System between 2016 and 2017 (adapted from [23]).

Water quality had non-conformities mainly in the Autonomous Systems (around 78% of the non-conformities), due to the treatment systems having less reliability when compared to the Main System.

In Figure 13, it is possible to note that a higher number of ruptures occurred between June and August, over 50% compared to the average monthly ruptures.

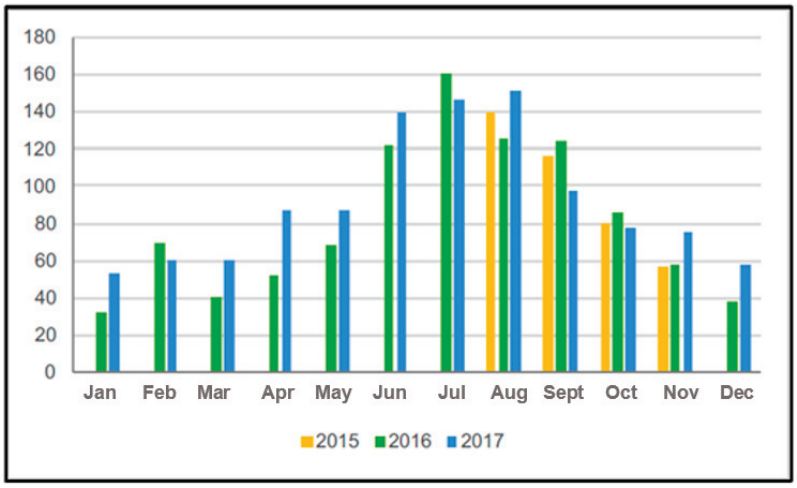

Figure 13. Graphic representation of ruptures that occur monthly in SAA-Arouca between 2015 and 2017 [23].

Risk management was translated by the rupture costs and real repair costs from 2015 to 2017. The ratio between the associated total costs and the number of ruptures that occurred allows the calculation of the average cost per rupture for each subsystem, being the subsystem of Moldes delivery point that presents the highest risk of rupture (Figure 14).

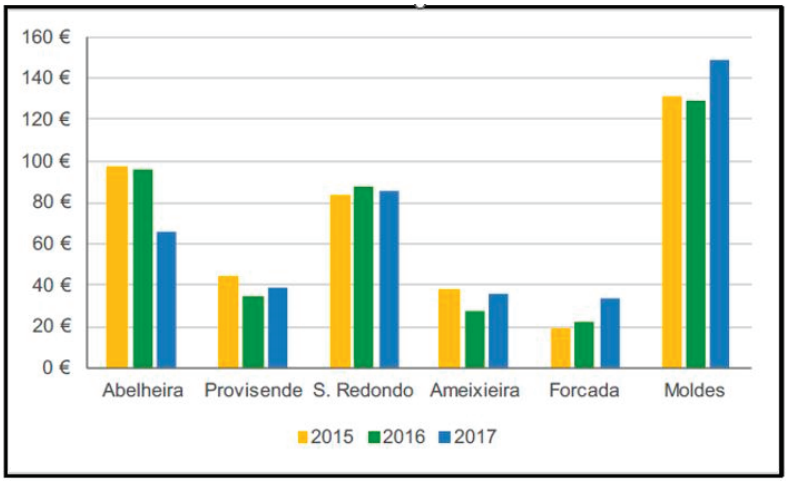

Figure 14. Annual rupture risk in the Main System by delivery point between 2015 and 2017 (adapted from [23]).

Figures 15–17 show the risks for ruptures, water shortages, and water loss, respectively, translated into associated costs. The subsystems of Moldes, Souto Redondo, and Abelheira are the ones with higher annual rupture risk (Figure 15), which can be translated into monetary values (Figure 15). There also appears to be a correlation between the rupture risk and water shortage, as Figure 16 shows a similar pattern to Figures 14 and 15. Figure 17 shows water loss translated into monetary values, and the same pattern seems to apply regarding these three more concerning subsystems.

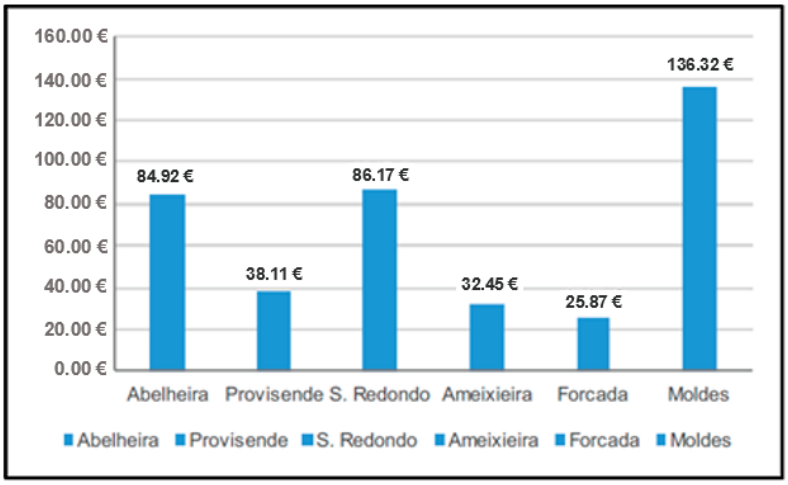

Figure 15. Annual rupture risk in the Main System between 2015 and 2017 (adapted from [23]).

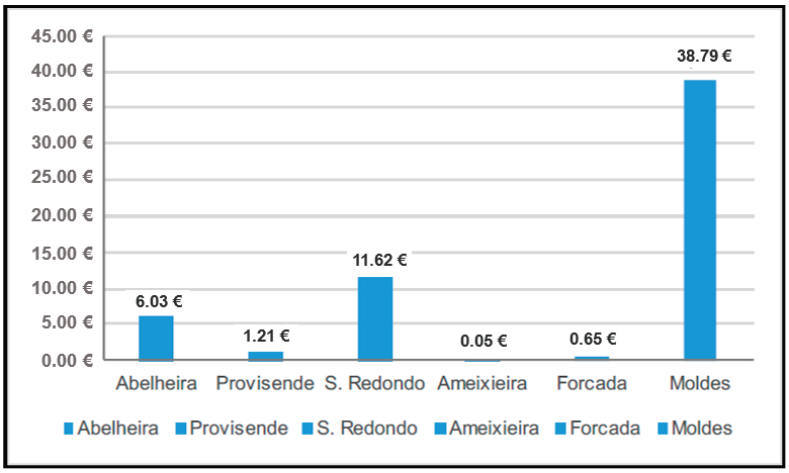

Figure 16. Risk of water shortage in the Main System between 2015 and 2017 (adapted from [23]).

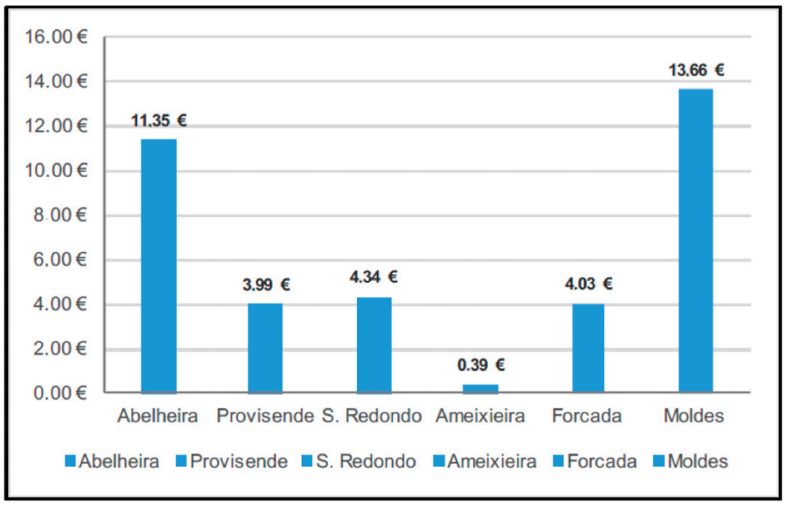

Figure 17. Water loss risk in the Main System between 2015 and 2017 (adapted from [23]).

In order to improve the problems of SAA-Arouca, several actions were proposed and developed.

The methodology ends up in the exploration section with several proposed actions for the future, focused on operational control and apparent losses, such as:

Reservoir monitoring and occurrence management with Aquafield;
Consumption monitoring;
Team planning and management;
Supplies management;
Reduction of losses due to measurement errors, not-accounted consumptions, and not-authorized consumptions.

The table that follows (Table 4) summarizes the costs of possible improvements for functional teams.

Table 4. Summary of means allocation and associated costs for functional teams of the SAA-Arouca (adapted from [23]).

Functional Teams	Human Resources		Vehicles		Supplies		Total Cost
	Allocation	Cost	Allocation	Cost	Allocation	Cost	
Prevention	30%	EUR 47,520	30%	EUR 5850	60%	EUR 12,000	EUR 65,370
Monitoring SAA	10%	EUR 15,840	30%	EUR 5850	5%	EUR 1000	EUR 22,690
Ruptures/Clearings	10%	EUR 15,840	10%	EUR 1950	10%	EUR 2000	EUR 19,790
Pressure Reducing Valve	20%	EUR 31,680	15%	EUR 2925	20%	EUR 4000	EUR 38,605
Loss/Infiltrations	30%	EUR 47,520	15%	EUR 2925	5%	EUR 1000	EUR 51,445
Total		**EUR 158,400**		**EUR 19,500**		**EUR 20,000**	**197,900**

Actions already implemented focused on combating real water losses by outlining the water loss prevention zone (ZCP, in Portuguese). Seven ZCPs were outlined and intervened through: maintenance, replacement, installation, and adjustment of pressure-reducing valves; network replacement; rupture repairment. In Table 5, it is possible to see the improvement of six in the ZCP after the interventions.

Table 5. Summary of the results of active water loss control in the Main System in 2018 (adapted from [23]).

ZCP	Period (2018)	Minimal Night Consumption			Annual Estimated Gains	
		Initial	Final	Decrease		
ZCP Pressure Reducing Valve	June—July	7.0 m^3/h	4.0 m^3/h	4.0 m^3/h (− 57%)	35,040 m^3	EUR 18,245
	November—December	3.5 m^3/h	2.5 m^3/h			
ZCP Vila Nova	September—October	11.0 m^3/h	3.0 m^3/h	8.0 m^3/h (− 73%)	70,080 m^3	EUR 36,491
ZCP São Pedro	November—December	7.0 m^3/h	1.0 m^3/h	6.0 m^3/h (− 86%)	52,560 m^3	EUR 27,368
ZCP Abelheira	November—?	* 20.0 m^3/h	* 18.0 m^3/h	2.0 m^3/h (− 10%)	17,520 m^3	EUR 9123
ZCP Provisende	November—?	7.0 m^3/h	6.0 m^3/h	1.0 m^3/h (− 14%)	8760 m^3	EUR 4561
ZCP Forcada	December—?	9.0 m^3/h	6.4 m^3/h	2.6 m^3/h (− 29%)	22,776 m^3	EUR 11,860
			Total:	**23.6 m^3/h**	**206,736 m^3**	**EUR 107,648**

Note: * The values of de Minimal Night Consumption of ZCP Abelheira include the continuing supply to the Reservoir of Cimo da Inha, with an intake of approximately 10 m^3/h.

The ZCP Canelas are not included in Table 5, but they showed improvement after the intervention in regard to pressure control, minimal night consumption, and rupture number. Figures 18 and 19 show this improvement. Actions to prevent water losses were implemented in the second semester of 2018, and these figures show a clear decrease in minimal night consumption (Figure 18) and a decrease in rupture number (Figure 19).

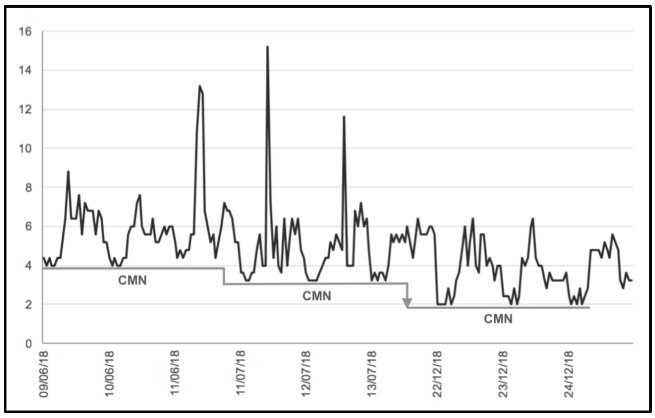

Figure 18. Minimal Night Consumption (CMN, in Portuguese) Evolution in ZCP Canelas (adapted from [23]).

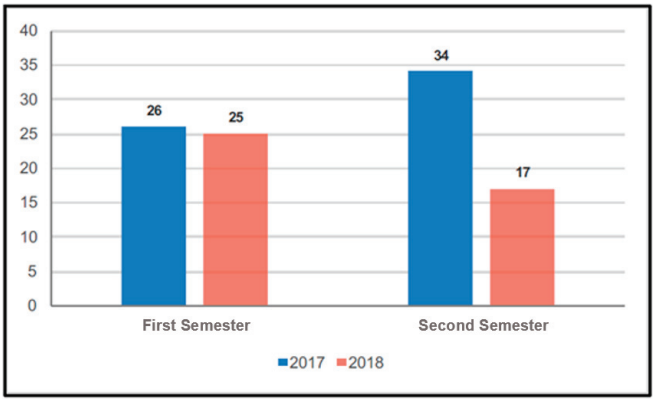

Figure 19. Rupture number evolution in ZCP Canelas (adapted from [23]).

4.1.3. Intervention

Regarding *Monitoring* interventions, they were focused on pressure-reducing valves (VRP, in Portuguese), reservoirs, water fountains with uncontrolled sources, and a systematic record of occurrences. VRP suffered pressure management, as shown on the following table (Table 6), and it is possible to note a total reduction of 18% downstream of the VRP, therefore pressure on the supply system overall. It is important to mention that the pressure reduction was done without detriment to the continuity and quality of the service.

Table 6. Summary of Pressure Management in SAA-Arouca (adapted from [23]).

Subsystem	VRP Number	VRP with Pressure Reduction	Pressure Reduction after Fase 1 on Pressure Management	
			(mca)	Final
Abelheira	33	17	8.5	26%
Provisende	14	10	7.0	23%
S. Redondo	40	12	4.2	13%
Ameixieira	11	4	5.7	18%
Forcada	15	7	4.4	12%
Moldes	30	11	6.7	19%
Total	**143**	**62**	**6.0**	**18%**

Maintenance was focused on VRP and reservoirs, emphasizing the Reservoir of Vista Alegre and the Reservoir of Cimo da Inha.

As for *Rehabilitation*, portions of the network and VRP were replaced with the costs presented in Table 7.

Table 7. Summary of Rehabilitation and Reinforcement actions (adapted from [23]).

Subsystems	Replacement Length	Replacement Cost	VRP Replacement Cost	Installation Length	Installation Cost	VRP Installation Cost
Abelheira	1660 m	EUR 24,827	EUR 21,000 *10 VRP were replaced*	1795 m	EUR 69,804	EUR 81,000 *3 VRP were installed*
Provisende	250 m	EUR 6520		285 m	EUR 3111	
S. Redondo	4014 m	EUR 88,927		2926 m	EUR 73,057	
Ameixieira	40 m	EUR 1600		70 m	EUR 2800	
Forcada	120 m	EUR 4800		386 m	EUR 6514	
Moldes	870 m	EUR 16,931		310 m	EUR 12,004	
Autonomous Systems	615 m	EUR 8370		300 m	EUR 5474	

As for *Reinforcement* measures, conducts and VRP were installed, as well as level controls in reservoirs and maneuvering chambers (costs presented in Table 7).

Interventions are expected to continue as progressive work that has already started, as follows (Table 8):

Table 8. Summary of the interventions carried out in SAA-Arouca between 2016 and 2017 (adapted from [23]).

Year	Rehabilitation		Reinforcement		Total
	Conducts	VRP	Conducts	VRP	
2016	EUR 83,235	-	-	-	EUR 83,235
2017	EUR 202,425	EUR 21,000	EUR 172,764	EUR 81,000	EUR 477,189
2018	EUR 101,663	EUR 25,250	EUR 109,597	EUR 57,500	EUR 294,010
Following	EUR 463,553	EUR 52,500	EUR 1,522,501	EUR 123,000	EUR 2,161,554
Total	**EUR 850,876**	**EUR 98,750**	**EUR 1,804,862**	**EUR 261,500**	**EUR 3,015,988**

4.1.4. Overview

The following figures show graphically the improvement of the Main System, which is also reflected in the SAA-Arouca, regarding rupture occurrences (Figure 20), system input volumes (Figure 21), billed consumptions, and non-revenue water (Figure 22). It is a clear improvement and successful implementation of the GOIH methodology, with important results for the efficiency and sustainability of this water supply system, as all of these indicators have evolved desirably.

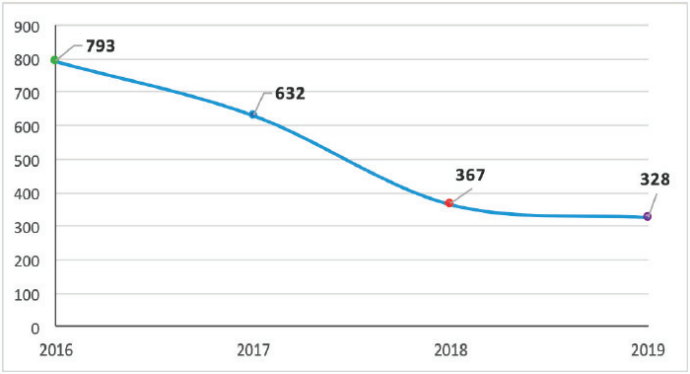

Figure 20. Evolution of the number of ruptures in the Main System between 2016 and 2019 (adapted from [2]).

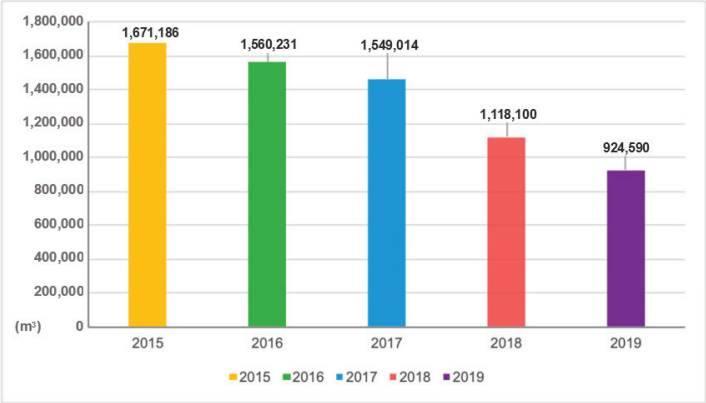

Figure 21. System Input Volumes the Main System of SAA-Arouca between 2015 and 2019 (adapted from [2]).

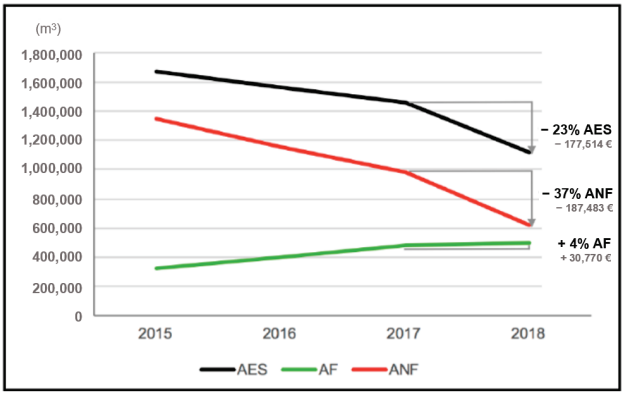

Figure 22. Evolution of water entering the system (AES), accounted water (AF), and not accounted water (ANF) in the Main System between 2015 and 2018 (adapted from [23]).

4.1.5. Decision Support

Nine investment scenarios were calculated (from no investment at all to an investment of EUR 626,020 with a return period of 20 years) in this analysis. Considering that accounted water remains constant, in Figure 23, it is possible to analyze three possible scenarios, from a more conservative one to the least conservative:

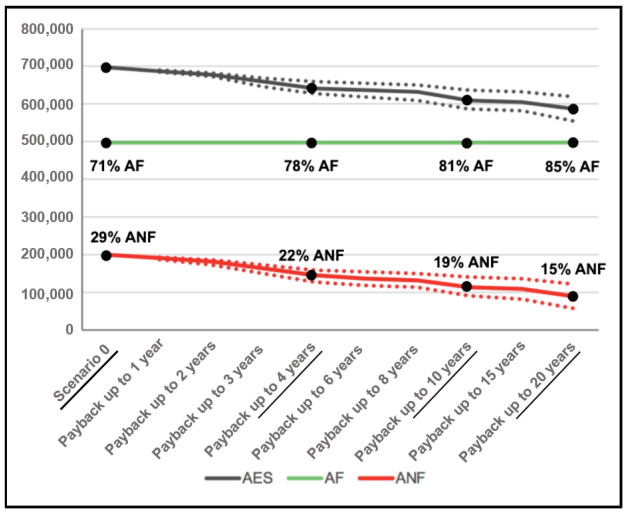

Figure 23. Prediction of the evolution of water entering the system, accounted water and not accounted water (adapted from [23]).

It is important to note that all the scenarios in Figure 23 ensure the quality of this service.
The suggested approximate investments with operational costs were as follows:
Investments for 2019:
Inventoried interventions—EUR 191,000.
Interventions in execution—EUR 94,000.
Operational teams—EUR 200,000.
Total investment—EUR 485,000.
Investments for the following years:
Inventoried interventions—EUR 300,000.
Operational teams—EUR 200,000.
Total investment—EUR 500,000.
Investments with a strategic return:
Improvement of the Main System—EUR 544,000.
Improvement of the Autonomous Systems—EUR 658,000.
Total investment—EUR 1,200,000.

The continued application of GOIH allowed for the continued improvement of SAA-Arouca (Figure 24), showing a 64% reduction in water input between 2015 and 2023.

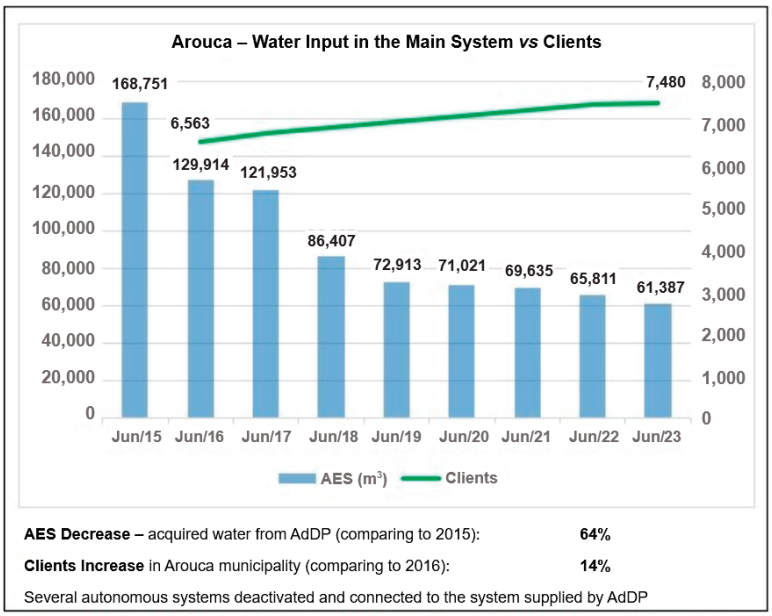

Figure 24. Evolution of water input in June between 2015 and 2023.

4.2. SAR-Trofa

4.2.1. Assessment

The status assessment registered that most of the connection lines were in good status (83%), 5% of them were in fair status, and the remaining 12% were in bad status. As for collectors and interceptors, 59% were in fair status, 35% were in good status, and finally, 6% were in bad status. In neither infrastructure were registered very good or very bad status.

Finally, manholes were, for the most part, in bad status (42%), 23% were in fair status, and the remaining 32% were in good status.

The performance assessment was done using a five-level scale (from worst to best—inefficacy, pre-efficacy, efficacy, efficiency, and excellency) and showed that all the indicators are within the levels of pre-efficacy and efficiency.

Connection Lines—regarding operation and suitability. A total of 66% of these infrastructures were at an efficacy level, and 34% were efficient.

Collectors and Interceptors—as for operation assessment, 18% were in pre-efficacy, 58% were in an efficacy level, and 24% were in an efficiency level. About accessory suitability, 17% were in pre-efficacy, 30% were in efficacy level, and the remaining 53% were efficient.

Manholes—these infrastructures were mainly at an efficacy level with 57% of the infrastructures; as for accessibility, 55% were efficient.

Lift Installation—these were assessed on lifting capacity and energy efficiency. As for lifting capacity, all the infrastructures were efficient (100%); on energy efficiency, 80% were efficient.

The cost assessment was based on the infrastructure's useful and residual life, replacement cost, current value, and the infrastructure value index, summarized in Table 9.

Table 9. Infrastructure Cost Assessment of SAR-Trofa (adapted from [23]).

Infrastructure	Replacement Cost	Current Value	Infrastructure Value Index
Connection Lines	EUR 834,064	EUR 619,624	0.74
Collectors and Interceptors	EUR 4,545,949	EUR 2,952,769	0.65
Manholes	EUR 1,413,500	EUR 819,100	0.58
Lift Installations	EUR 272,288	EUR 206,384	0.76
Total	**EUR 7,065,802**	**EUR 4,597,877**	**0.65**

Risk assessment was based on a 5-level scale—very high, high, fair, low, and very low.

Connection Lines—these were assessed on obstruction probability and inflow probability. As for obstruction, 67% were at a fair level of risk, and 33% were at a low risk level. About inflows, 36% are at a very high-risk level, followed by 41% at a high risk.

Collectors and Interceptors—in 58% of these infrastructures were at a fair risk level of obstruction, 27% at a low risk. As for inflows, 27% were at a very high-risk level, and 61% were at a high-risk level. Also, 44% were at a fair risk of collapse, and 41% were at a low risk.

Manholes—58% of the manholes were at a fair risk level of obstruction, 27% were at a low risk level, and the remaining 15% were at a high level of risk. As for inflows, 26% were at a very high-risk level, and 60% were at a high level. Finally, accidents related to the environment and safety probability were also assessed, with 47% at a fair risk and 27% at a high risk.

Lift Installation—regarding these infrastructures, the probability of service interruptions, as well as inflows and accidents related to the environment and safety. Service interruption presents a fair risk level in 60% of these infrastructures, with the remaining 40% presenting a low risk. There is a high risk of inflows in 20% of the assessed infrastructure, a fair risk in 40%, and a low risk in the remaining 40%. As for the accidents' indicator, 80% presented a fair risk level, and the remaining 20% presented a low risk.

4.2.2. Exploration

Regarding the *Operational control* stage of this section, the main scheduled operational routines are the systematic record of occurrences, monitoring of lifting installations, and checking of critical points of the systems.

As for *Occurrence response*, the sites with significant relevance can be indicated using the operational relevance index (IRO, in Portuguese), based on the network extension, number of clients, and system input volumes (VEA, in Portuguese). This is shown in Table 10 and Figure 25 for each drainage basin.

Table 10. Operational Relevance Index in the drainage basins of SAR-Trofa (adapted from [23]).

Drainage Basin	Operational Relevance Index (IRO)						
	Extension (km)		Clients (un)		VEA (m^3)		Global
BD 9BOU016	1734	0.02	219	0.05	6363	0.00	**0.02**
BD BOU026	14,850	0.15	524	0.13	398,801	0.24	**0.17**
BD 9TRO013	1379	0.01	12	0.00	2741	0.00	**0.01**
BD 9TRO21A	428	0.00	6	0.00	623	0.00	**0.00**
BD 9TRO022	26,891	0.28	2219	0.53	1,169,647	0.71	**0.51**
BD 9TRO027	1108	0.01	20	0.00	3979	0.00	**0.01**
BD 9TRO040	5385	0.06	104	0.02	12,918	0.01	**0.03**
BD 9TRO60A	1209	0.01	24	0.01	3793	0.00	**0.01**
BD Trofa Prolongamento	13,120	0.14	449	0.11	20,698	0.01	**0.09**
BD 9TRO074	5748	0.06	270	0.06	*12,151* *	0.01	**0.04**
BD Covelas Poente	24,059	0.25	344	0.08	*15,482* *	0.01	**0.11**
	95,911		**4191**		**1,647,196**		

Note: * Accounted volume (VEA) in these two delivery points are calculation jointly. The division was done with the proportion of the number of clients.

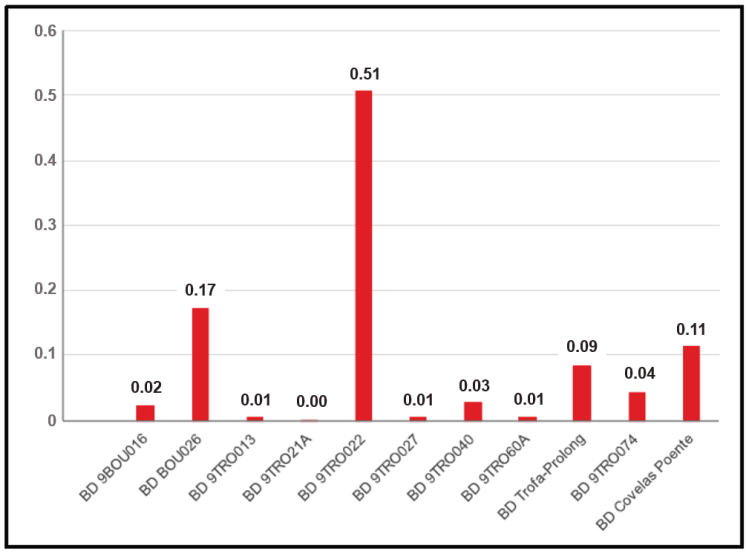

Figure 25. Graphic representation of the Operational Relevance Index of SAR-Trofa (adapted from [23]).

According to this, the drainage basin with the most operational relevance is BDTRO022, followed by BD BOU026, with a significant difference between the two, also notable in Figure 25.

As for *Information: Real Data*, energy consumption, obstruction, accounted volumes at high levels, and measured volumes.

In Figure 26, it is possible to note that the highest energy consumption is in BD TRO022. Regarding obstruction registered, Figure 27 shows no patterns in obstruction occurrences throughout the year or between 2017 and 2018.

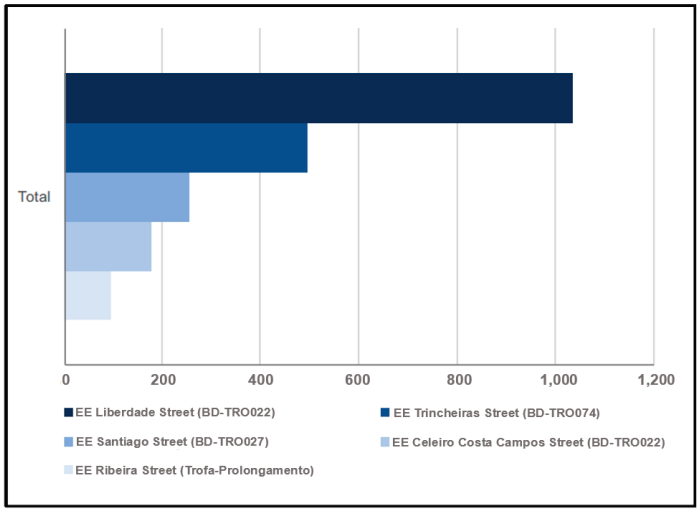

Figure 26. Annual Energetic Consumption (kWh) of Lift Installations of SAR-Trofa (adapted from [23]).

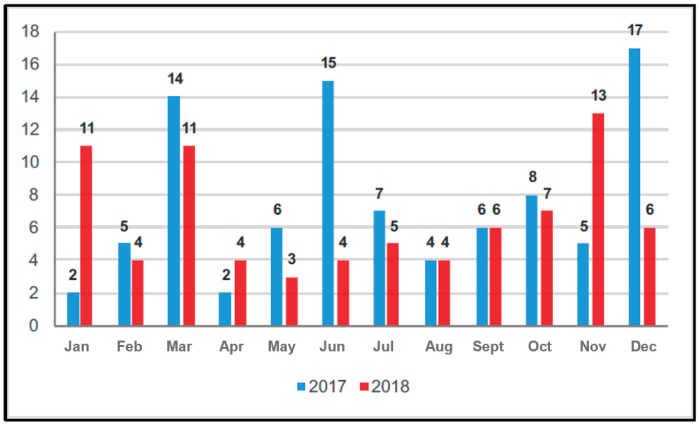

Figure 27. Monthly distribution of Obstructions occurrence in Trofa municipality between 2017 and 2018 (adapted from [23]).

As for volumes registered, the following figures (Figures 28–30) show a bigger similarity between Figures 28 and 30, which can indicate that basin BD 9TRO022 influences the whole system significantly.

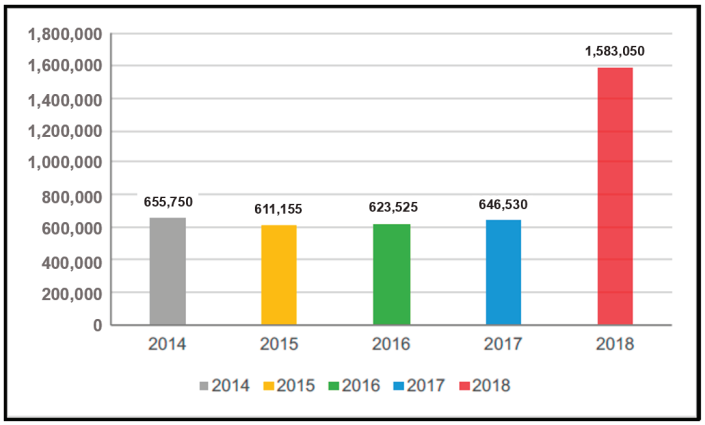

Figure 28. Quantified volumes in the drainage basins from 2014 to 2018 (adapted from [23]).

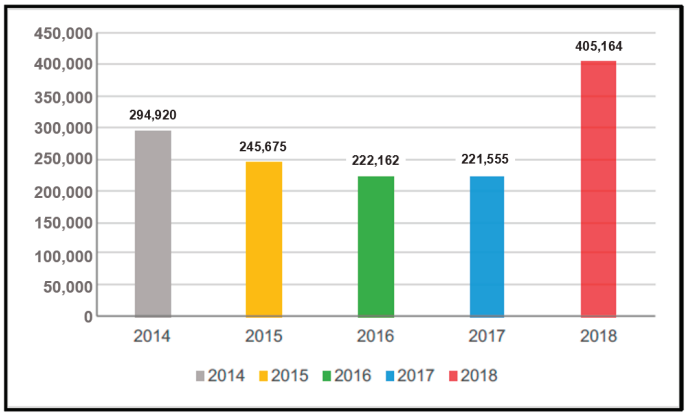

Figure 29. Quantified volumes in the drainage basin of the Interceptor of Bougado between 2014 and 2018 (adapted from [23]).

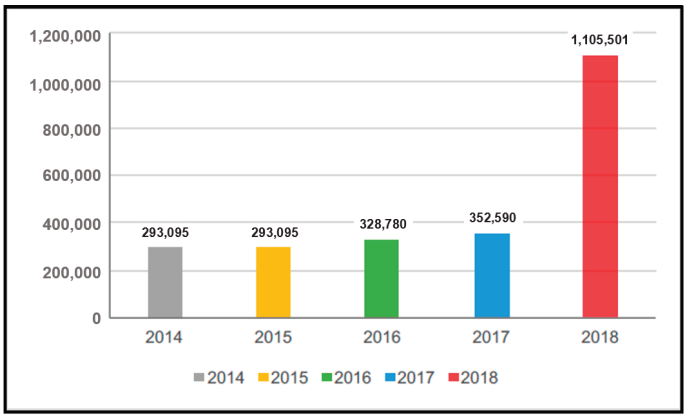

Figure 30. Quantified volumes in the drainage basin BD 9TRO022 (adapted from [23]).

Regarding *Informed by risk management*, obstruction risk was analyzed, and, similarly to the IRO graphic, basin BD 9TRO022 presents the highest value by a large difference (Figure 31).

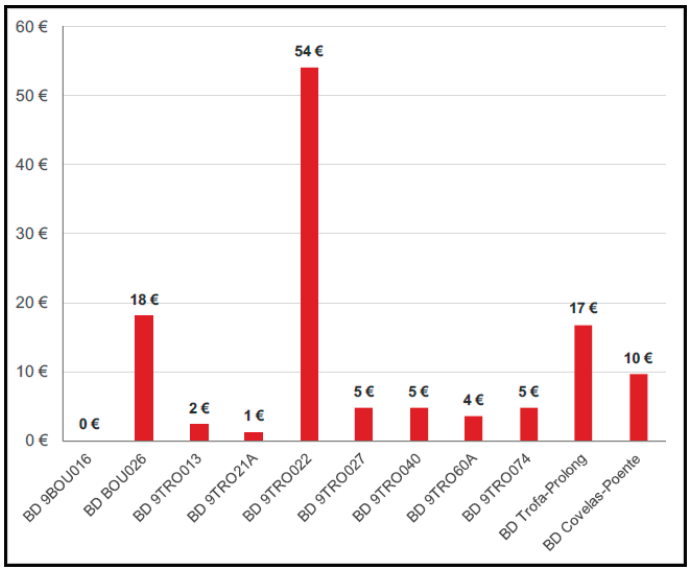

Figure 31. Obstruction risk in SAR-Trofa in 2017–2018 (adapted from [23]).

The methodology of GOIH proposes several actions according to each stage of the exploration section.

Operational control—inflows control; prevention planning; structuring functional teams; incorporation of all operational actions in one single tool.

Occurrence response—reduce response time (by optimizing the identification and verification process and with systematic monitoring and control of external providers); define an operational strategy, prioritizing service continuity and damage minimization.

Information: Real Data—robust databases and systematic analysis of the operational records.

Informed by risk management—treatment of exploration real data (risk of inflows, collapses, flooding, and service interruption); organization of actions and pre-positioning of operational teams according to the different risks of the drainage basins.

The particular focus of the exploration strategy is inflows. The following figure (Figure 32) shows the volume evolution for delivered water at high levels, accounted water and not accounted water, for the Trofa municipality, for SAR-Trofa, and for the 2 drainage basins that have flow meters available.

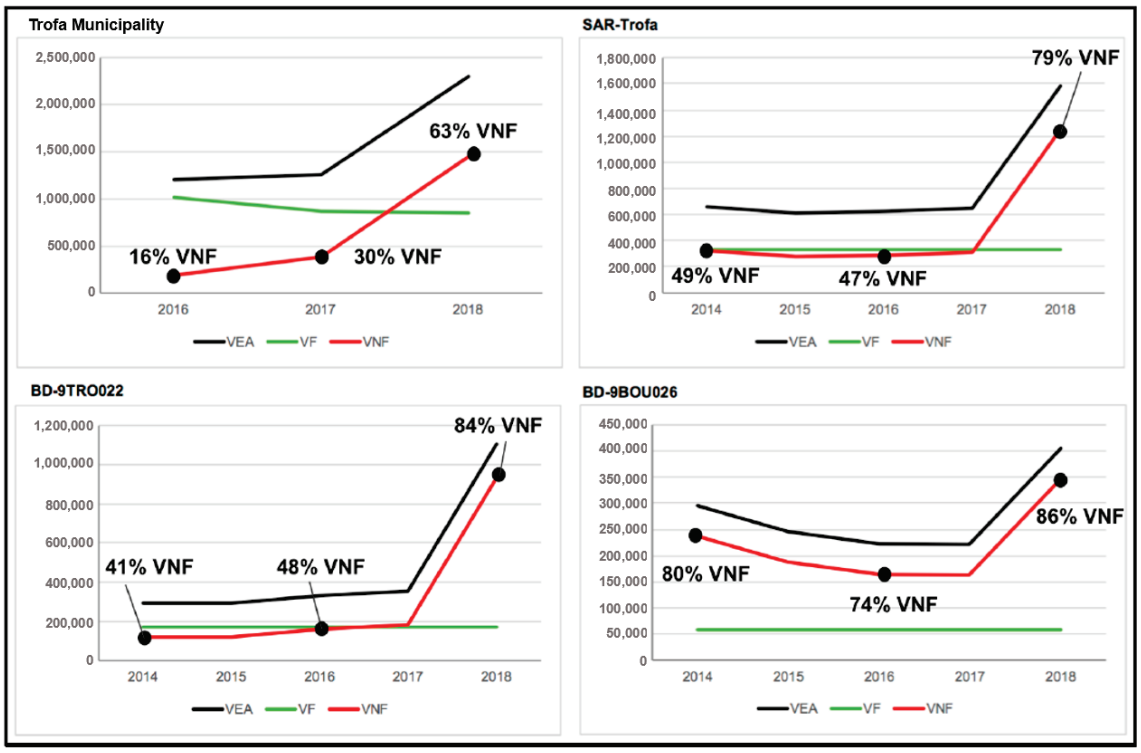

Figure 32. Annual variation of volumes delivered at high levels: Accounted Volumes and Not Accounted Volumes (adapted from [23]).

The difference between delivered wastewater and accounted volumes is notable, and in some cases, the first is 80% higher than the last. It appears that, even in a scenario that ensures an increase in accounted volumes, the best client's record, and more rigorous billing, the difference between delivered wastewater and accounted volumes would still be significantly high.

The delivered wastewater volumes can be influenced by rainfall volumes, and the following graphics show this. It is noticeable that the drainage basin BD 9BOU026 is specially influenced by these inflows because the delivered wastewater curve accompanies the precipitation curve very similarly (Figures 33 and 34).

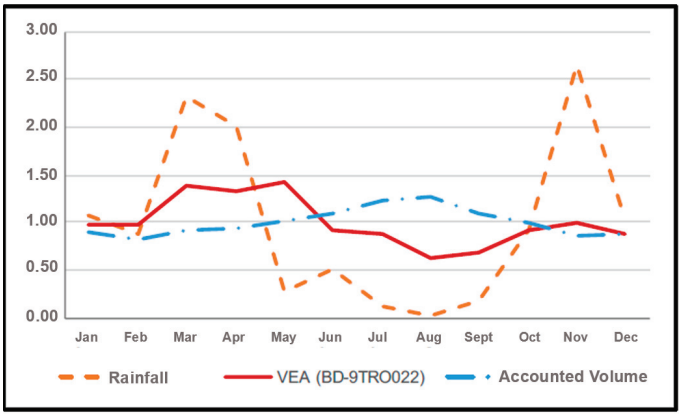

Figure 33. Monthly variation of delivered volumes (VEA), billed volumes (VF), and total precipitation in drainage basin BD 9TRO022 (adapted from [23]).

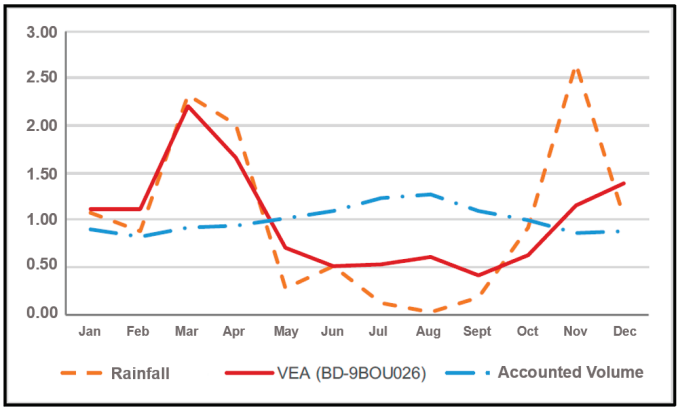

Figure 34. Monthly variation of delivered volumes (VEA), billed volumes (VF), and total precipitation in THE drainage basin BD 9BOU026 (adapted from [23]).

4.2.3. Intervention

Regarding *Monitoring* intervention actions, the following are suggested: lifting installations, critical sites of the system, volumes at existing measurement points, and gas measurement campaigns.

Maintenance is proposed for lifting installations and manholes.

As for *Rehabilitation* and *Reinforcement*, the methodology suggests small interventions of rehabilitation in collectors, contract work in different streets in Santiago do Bougado, and manhole rehabilitation. Organizing the data given by the management entity during these actions is part of the *Reinforcement* action.

4.2.4. Decision Support

This section is divided into three strategies:

Investment strategy—global investment to make in SAR-Trofa, by drainage basin, based on the assessment of hydraulic infrastructures and IRO.

Operational strategy—establishing investment scenarios, accounting for the operational return.

Specific decision strategy—analysis of specific situations related to the control of inflows.

Regarding the investment strategy, the real data available only allowed for the calculation of the risk of obstruction, so the index directly associated with risk (Risk Management Index) was not considered because it would have influenced the investment on one risk only (Table 11).

Table 11. Summary of assessment indexes for SAR-Trofa, relating to 2019 (adapted from [23]).

Drainage Basin	Status Assessment Index	Performance Assessment Index	Risk Assessment Index	Infrastructural Assessment Index
BD 9BOU016	0.08	0.07	0.06	0.07
BD BOU026	0.12	0.13	0.12	0.12
BD 9TRO013	0.08	0.07	0.08	0.07
BD 9TRO21A	0.11	0.12	0.08	0.11
BD 9TRO022	0.10	0.10	0.12	0.11
BD 9TRO027	0.08	0.09	0.09	0.09
BD 9TRO040	0.09	0.07	0.10	0.09
BD 9TRO60A	0.08	0.07	0.07	0.07
BD 9TRO074	0.09	0.08	0.10	0.09
BD Trofa Prolongamento	0.08	0.09	0.09	0.09
BD Covelas Poente	0.10	0.09	0.09	0.09

The operational strategy establishes hypothetical scenarios for the reduction of non-revenue volumes, analyzing:

Estimate the investment scheduled by the managing entity—EUR 54,749 for infrastructure rehabilitation and EUR 67,594 for reinforcement.

Estimate of the proposed investment through GOIH—EUR 100,000 for rainfall volume control and EUR 75,000 for reinforcement of human resources.

Annual gains simulation for different scenarios (Table 12).

Table 12. Summary of six hypothetical scenarios of VEA decrease in SAR-Trofa (adapted from [23]).

	Investment					Annual Gain	Return	
	Rehabilitation	Reinforcement	Volumes Control	Operational	Total	(Next Year)	(Years)	(Months)
↓ 40% VEA	EUR 54,749	EUR 67,594	EUR 100,000	EUR 112,500	EUR 334,843	EUR 374,932	0.89	11
↓ 50% VEA						EUR 468,665	0.71	9
↓ 60% VEA						EUR 562,398	0.60	7
↓ 70% VEA						EUR 656,131	0.51	6
↓ 75% VEA						EUR 702,998	0.48	6
↓ 80% VEA						EUR 749,864	0.45	5

Non-revenue volume simulation for different scenarios (Table 13).

Table 13. Summary of three scenarios of annual variation of delivered volumes and non-revenue volumes in Trofa (adapted from [23]).

Drainage Basin	↓ 60% VEA			↓ 70% VEA			↓ 80% VEA		
	VEA	VNF		VEA	VNF		VEA	VNF	
BD 9BOU026	159,520	117,100	73%	119,640	77,220	65%	79,760	37,340	47%
BD 9TRO022	442,200	270,432	61%	331,650	159,882	48%	221,100	49,332	22%
Total SAR-Trofa	680,469	348,429	51%	530,039	197,999	37%	379,608	47,568	13%
Total Trofa	1,397,874	547,842	39%	1,247,444	397,412	32%	1,097,013	246,981	23%

Estimate of the return on the operational strategy.

The control of undue rainfall may involve implementing rainfall detour solutions through the use of rainfall control chambers, discharge channels, float or guillotine flow regulating valves, or vortex valves.

The drainage basin BD 9TRO022 is relevant for the more efficient management of SAR-Trofa. An investment of EUR 50,000 in this basin could decrease VEA by 40% to 80% and would have a return period of 1 to 2 months.

Drainage basin BD 9BOU026 is also important to manage regarding these same inflows, and an investment of EUR 50,000 could decrease VEA by 40% to 80%, with a return period between 3 and 6 months.

5. Conclusions

Currently, urbanization is being established in concentrated centers, while rural areas are getting deserted. This influences the progress attained in the last few decades regarding the coverage of wastewater drainage systems, water quality in source and receptor media, and the adequate management of urban waters.

The methodology of GOIH is a strategic and broad approach to the existing patrimony, envisioning the optimization of water systems. Following a common methodology with different scope and transversality. It aims to be a process to boost an integrated transformation with fast results that can finance the project further.

SAA-Arouca showed improvement after the application of GOIH, and it is expected to continue to improve as the methodology continues to be implemented. Tackling water losses in the municipality of Arouca has been a clear focus in recent years. The proposed actions implemented with the use of decision support tools have resulted in a significant reduction of water losses in the Arouca Water Supply System (SAA-Arouca).

As for SAR-Trofa, the application of GOIH showed potential improvement if the suggested investment were to take place, particularly focusing on rainfall inflows, which are a significant concern in this system.

The study focuses on operational costs and gains. The main limitation to the study presented is the difficulty of including an integrated economic analysis that cuts across all areas of the hydraulic infrastructure management organization, which could also be a future development.

In the future, this methodology may continue to be tested and perfected, for example in wastewater treatment plants and submarine outfalls, as well as rainfall water drainage systems. And other methods can be added, such as water system modeling and geographical information systems.

To summarize the methodology presented, the work carried out, and the results obtained, these key observations are highlighted:

- The proposed methodology combines asset management, risk management, and technical management concepts and is organized into three main operational areas: assessment, operation, and intervention.
- The operational management strategy was designed with a focus on reducing operating costs, increasing service quality, and safeguarding the environment.
- It was applied to the case studies with the aim of evaluating the methodology and obtaining results to support operational management, particularly in terms of reducing water losses and controlling undue rainfall.
- The need to train human resources was identified as part of an integrated commitment to preserving existing know-how and continuous improvement.
- The pertinence of channeling operational gains into the enhancement of infrastructure and investment in innovation is highlighted.
- In a context of increasingly complex problems and ever more demanding challenges, the contribution of knowledge production in the area of GOIH could provide methodologies that help to ask the right questions, point out the appropriate paths, and facilitate the decision-making process.

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Article

Water Resources Carrying Capacity Based on the DPSIRM Framework: Empirical Evidence from Shiyan City, China

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Abstract: In this article, we construct an evaluation index system based on the DPSIRM framework to determine the water resources carrying capacity of Shiyan City. Then, we use an obstacle model to calculate and analyze the factors that constrain the improvement in the water resources carrying capacity in the city. The research results are as follows: (1) The water resources carrying capacity of Shiyan City was on the rise during 2011–2021, and the water resources carrying capacity of Shiyan City was continuously improved. (2) The management system is the primary obstacle subsystem, followed by the driving force system, the response system, the pressure system, the state system, and the influence system. (3) Among the specific factors, the top three obstacles are sewage treatment investment, the proportion of guaranteed harvest area in drought and flood, and the average annual fertilizer applied per unit of cultivated land. These primary factors restrict Shiyan City from improving its water resources carrying capacity. This study has important practical significance for understanding the resilience of the water system in Shiyan City; exploring the changes in the water resources carrying capacity and its obstacle factors; and guiding the development, utilization, and management of water resources in Shiyan City.

Keywords: water resources carrying capacity; DPSIRM framework; Shiyan; resilience

1. Introduction

Water is vital in crop production, economic activity, and sustainable ecological development [1]. Water resources are essential in supporting sustainable economic and social development and maintaining ecological balance [2], and they are irreplaceable in environmental and food security [3]. With the growth of the population and economic development, the problem of water shortages is becoming more and more serious, which is restricting the sustainable development of the region [4]. Water resources have become one of the most important resources in the process of economic and social development in the world. The carrying capacity of water resources directly affects the economic and social development of a region. The strength of a city's water carrying capacity reflects the resilience of the local water system. The stronger the carrying capacity of water resources, the higher the resilience of the water system. Evaluating the water resources carrying capacity of a region or city is of great significance for understanding the current situation of water resources in a region or city, understanding the resilience of a region's water system, and has a profound impact on how a city or region formulates water policies.

In order to conduct in-depth and quantitative research on the resilience of the water system in Shiyan City, this paper constructs the water resources evaluation index system of Shiyan City based on the DPSIRM framework. Then, by searching the data of the Shiyan Statistical Yearbook and Shiyan Statistical Bulletin, the entropy weight method,

comprehensive evaluation model, and barrier model were used to study the water resources carrying capacity of the city.

2. Literature Review

2.1. The Concept of Carrying Capacity

With the increasing contradiction between social development and resource shortages, the concept of the 'resource carrying capacity' was put forward by UNESCO in the early 1980s [5]. The carrying capacity refers to the maximum number, density, or biomass of people that a given area can support continuously [6]. Carrying capacity refers to the marginal capacity of a habitat or environment to provide the resources needed to sustain human life [7].The concept of carrying capacity of relative resources was first proposed by Huang and Kuang, which refers to 'calculating the relative resource carrying capacity of a research area based on the per capita resource occupancy or per capita consumption of the reference area and the resource stock of the research area based on one or more specific regions' [8]. Scholars generally believe that the concept of water resources carrying capacity was first proposed by the soft science research group of water resources in Xinjiang, China, in 1989. Some studies consider the water resources carrying capacity to be the capacity to sustain a society with a good standard of living [9]. A stable stage of socio-economic development, a good ecosystem, and a stable quality of life are supported by the maximum carrying capacity of water resources for human activities [10].

2.2. The Factors Causing Water Resource Overload or Water Shortages

The reasons for water shortage or overload have attracted widespread attention. Many scholars have researched this aspect. For example, factors that can overload the water resources carrying capacity are the quantity and quality of water resources [11,12], climate change [2,13], population size [14], urbanization [2], industrialization [2], economic structure [15,16], and human activities [13]. In addition, war, political instability, poor management, inadequate national environmental policy planning, poor administrative capacity, high investment needs, and a lack of environmental awareness all contribute to water overload or scarcity [17]. The analysis of the causes of water shortage can help solve practical problems and related research topics.

2.3. The Evaluation Method of Water Resources Carrying Capacity

(1) Some scholars use the single-index method to study the carrying capacity of water resources. For example, the carrying index (CI) and index of water supply–demand balance (IWSD) were used to study Tianjin's water resources carrying capacity. In this study, relevant data from 2004 to 2008 were used for research, and the results showed that the efficiency of water resource utilization in Tianjin is relatively low. It is predicted that after implementing water resource protection policies in 2010 and 2020, the trend of water resource utilization in Tianjin will become more reasonable, and the WRCC of Tianjin will exceed the national average [10]. (2) Some scholars have used scenario analysis to study the water resources carrying capacity of Beijing. In this study, using data from 1986 to 2002 and assuming a comprehensive domestic water consumption of 75 m^3/(person·year) in Beijing based on the water resources used in Beijing around 2002, Beijing's urban population carrying capacity was defined as 5–6 million people. By 2003, the total population of Beijing had reached 14.56 million, with an urban population of 11.51 million. The actual population size had exceeded its carrying capacity by nearly double. The population exceeding its carrying capacity is the fundamental reason for the severe water shortage in the region [14]. (3) Some scholars have used multi-index or comprehensive index methods in their studies, such as the fuzzy comprehensive evaluation method used by Zhou, Z. et al. By establishing the evaluation index system of medium water quality safety and using the analytic hierarchy process (AHP) to weigh the evaluation indicators, a fuzzy comprehensive evaluation model was established. The model was applied to the Liantang Water demonstration base in Shenzhen, and the results showed that the method

has a small error, avoids subjective randomness, and conforms to the actual situation [18]. Lv, A. et al. used the fuzzy comprehensive evaluation method to evaluate the vulnerability of the WRCC system in China, and the results showed that the risk of WRCC occurrence in North China was higher than that in South China, and that in developed areas, it was higher than that in developing areas. Among them, the Beijing–Tianjin–Hebei region is at the highest risk [2]. Wang, G. et al. combined the fuzzy comprehensive evaluation with the system dynamics model to study the carrying capacity of water resources, the results showed that if the current development model were continued, the carrying capacity of water resources in Changchun would continue to decline and remain at a lower 'normal carrying' level. The carrying capacity of water resources in Changchun City can be improved by changing the production mode and proportion of the national economy. The rational allocation of water resources and strengthening water ecological protection can significantly improve the carrying capacity of water resources and keep it in a 'positive carrying' state while maintaining stable economic and social development [19]. Wang, Y. et al. selected various indicators related to water resources, society, and the economy and established a comprehensive evaluation index system with multiple indicators. Research has shown that due to rapid development and population expansion, there is a serious shortage and overload of water resources in Wuhan. The future development of Wuhan is worrying, and the same concerns apply to Ezhou. Other cities in the Wuhan urban agglomeration, such as Xiaogan, Huanggang, Qianjiang, and Tianmen, have greater potential for carrying water resources [20]. (4) Wang, Y.F. et al., taking the Shendong mining area as the research object, used the gray prediction model to predict the water demand of the economy–society–ecosystem in the mining area from 2020 to 2030 under different scenarios, and the results showed that the allocation structure of water resources in the mining area needed to be further optimized, and the scale of water use in the mining area could not adapt to its carrying capacity [21]. (5) Yang, J.F. et al. constructed a water resources carrying capacity evaluation model based on the system dynamics model and used this method to evaluate the water resources status of Tieling in different scenarios. The results show that given the constraints represented by water resources, GDP growth is expected to trend to the s-curve growth model; rapid population growth may lead to earlier and more severe water resource constraints [22]. Hu, G.Z. et al. built a system dynamics model based on the five systems of population, ecology, water resources, water environment, and water ecology and studied the North Canal Basin's water resources carrying capacity. It is estimated that the water environment and resource carrying rate will fall to 2.60 and 0.94, respectively, in 2025, while the water ecological carrying rate will remain stable at 10.98 [23]. Sun, Y. et al. took the five subsystems of the economy—population, supply and demand, land resources, water pollution, and management—as macroeconomic factors affecting the sustainable utilization of water resources and then used the system dynamics model to build a feedback loop and inventory flow chart of the system to simulate the changes in the water supply and demand situation and the future supply and demand gap from 2005 to 2020. The results showed that the water use efficiency in China would be significantly improved compared with that in 2005. By 2020, the gap between water supply and demand will reach 220 billion cubic meters, 4.8 times that of 2005 [24]. Feng, L.H. et al. simulated the water resources carrying capacity of Yiwu using the system dynamics method. If the current water supply level is maintained, the water supply of Yiwu will not be able to meet the requirements in the near future [9]. (6) Weng, X.R. et al. combined the economic, social, and ecological characteristics of using 26 specific evaluation indicators and evaluated and analyzed the carrying capacity of water resources in Chongqing via principal component analysis. The results show that the carrying capacity of water resources in Chongqing was continuously optimized and gradually enhanced from 2003 to 2017 [25]. Wu, F. et al. selected 13 indicators from the four aspects of the economy, society, environment, and water resources and analyzed the water resources carrying capacity of Huai'an City via principal component analysis. The results showed that the water resources carrying capacity of Huai'an City declined year by year from 2013 to 2019 [26]. Scenario simulation: Yang,

Z. et al. designed five scenarios, conducted a simulation analysis of the water resources carrying capacity of Xi'an, and determined the city's social, economic, water supply and demand, and wastewater discharge development from 2015 to 2020. If the current social development pattern is maintained, WRCC (0.32 in 2020) will change from 'normal' to 'poor' [27]. Yang, J.L. et al. calculated the water resources carrying capacity of the Three Gorges Reservoir Area from 2005 to 2020 using the variable fuzzy evaluation method. From 2005 to 2020, although the population and GDP of the urban agglomeration increased, the water supply capacity first increased and then decreased. From 2005 to 2020, the carrying capacity of water resources in the Three Gorges Reservoir area showed an increasing trend [28].

2.4. Research Framework

At present, the driving force–pressure–state–impact–response (DPSIR) framework is the most widely used in environmental assessment. The DPSIR framework was originally developed by the European Environment Agency in 1995 to provide decision makers with information on environmental indicators in response to the European Environment Agency's proposal on how to develop an integrated environmental assessment strategy. DPSIR is an extension of the PSR framework, adding driving force (D) and impact (I). The PSR framework was originally developed by the OECD to organize its work on environmental policy and reporting. These five aspects are logically causally related, which is a very good analytical framework for exploring the relationship between environment and socio-economic activities. This analytical framework was initially a qualitative evaluation system, and scholars later used this evaluation system quantitatively.

Later, some scholars applied the DPSIR framework to environmental assessment, ecological security, water resources management, sustainable development, air pollution, and other fields. The representative studies on water resources security, water resources management, and water system risk using the DPSIR framework are as follows. Using the DPSIR (Drive, Stress, State, Impact, Response) method, Borja, A. et al. studied the ecological quality and risk of local water bodies in estuaries and coastal waters in the Basque country (northern Spain) [29]. Skoulikidis, N.T. examined the state of the environment of 15 major Balkan rivers within the framework of DPSIR, arguing that the wars, political instability, and economic crises of the previous decades, combined with administrative and structural constraints, poor environmental planning and inspections, and a frequent lack of environmental awareness, have put great pressure on the rivers [17]. Sun, S. et al. established an evaluation index of the sustainability of water resources use based on the driving force–pressure–state–impact–response (DPSIR) model. The sustainable change in the water resources system in Bayannur City was evaluated comprehensively using these indexes. The results showed that the driving force of local water consumption increases due to social and economic development and the change in residents' consumption structure. During the study period, the pressure on the water system increased due to the increase in driving indicators, while the status of water resources continued to decline [30]. Vannevel, R. embedded the DPSIR framework in The Pentatope Model for Environmental Analyses and used the Governance by Actor–Subject Impact Assessment (GASI) as the interface. A tool for water treatment of PTM-GASI-DPSIR was proposed [31]. Given the research of these scholars, we affirm the contribution of the DPSIR framework in water resources assessment. These studies teach the logical thinking needed to analyze such problems and determine the change characteristics and advantages and disadvantages of the research object from the two parts of the subsystem and the whole. This is very helpful for water resources planning and management.

However, with the deepening of the research on this kind of issue, the water resources carrying capacity in a region is not only affected by the difference in natural resource endowment and the driving force of water consumption but also affected by local management measures. The impact of management on the water resources system is omni-directional, and management affects the driving force, pressure, state, and response. The DPSIR frame-

work does not yet incorporate management systems in this analytical framework, and this does not reflect well on the role of government authorities in water management. Including the management system in this framework, from the perspective of scientific research, will increase management indicators from the evaluation system, broaden the evaluation of water system security and the water resources carrying capacity, and create a more comprehensive evaluation and more objective and accurate evaluation results. Moreover, it is of great value to further understand the internal relationship of each system of water resources and propose solutions to the problems of water resources management from the management perspective. Adding management elements to the DPSIR framework becomes DPSIRM.

Existing research literature on the water resources carrying capacity has provided many contributions in terms of research ideas and methods, and there has also been a lot of research on the constraints of the water resources carrying capacity. However, the existing research on water resources carrying capacity and constraints on the water resources carrying capacity are often studied separately rather than in combination. Therefore, this study will combine the evaluation of the water resources carrying capacity with the restrictive factors of the water resources carrying capacity to uncover the main factors affecting the water resources carrying capacity from all possible aspects. With respect to the research area, Shiyan City is the core water source area of the South-to-North Water Diversion Project. The carrying capacity of water resources in the core water source area is related to the safety of the local water system and the project's sustainability. A search of literature from the Web of Science shows that research on the water resources carrying capacity of the entire Han River basin where Shiyan City is located, from the perspective of water resources management, is scarce. In this study, DPSIRM is used to objectively uncover the state of the local water resources and help local water resources management. With respect to the research content, the specific index selection of this study draws on many academic research results and combines the actual situation of local indicators, which can provide a reference for the index selection of the same type of research.

3. Materials and Methods

3.1. Study Area

Shiyan City spans a northern latitude of 31°30′ to 33°16′ and eastern longitude of 109°29′ to 111°16′, about 200 km from east to west and about 195.5 km from north to south. Shiyan is located in the middle and upper reaches of the Han River in Central China and northwest of Hubei Province, the Hanshui Valley in the Qinling–Ba Mountains, the Qinling Mountains in the north, and the Bashan River in the south. Located in Hubei Province, China, Shiyan City is the only regional central city in the adjacent areas of Hubei, Henan, Shaanxi, and Chongqing. Danjiangkou Reservoir is the starting point of the middle route of China's South-to-North Water Diversion project, and the source of water for the project is located in the middle of Danjiangkou City in Shiyan, Hubei province. The construction of this important water conservancy project will have an influence on the distribution of water resources. Shiyan City is the main water source, so it is necessary to evaluate the water resources carrying capacity of Shiyan City to understand the water resources situation of Shiyan City objectively. The study area is shown in Figure 1.

3.2. Dataset and Source

This study involves the water resources data, ecological environment data, economy and industry data, and other data of Shiyan City derived from the 'Shiyan Statistical Yearbook' from 2012 to 2022, Shiyan City Statistical Bulletin. The basis of indicator selection, determination of positive and negative signs, and acquisition and calculation of indicator data are shown in Table 1.

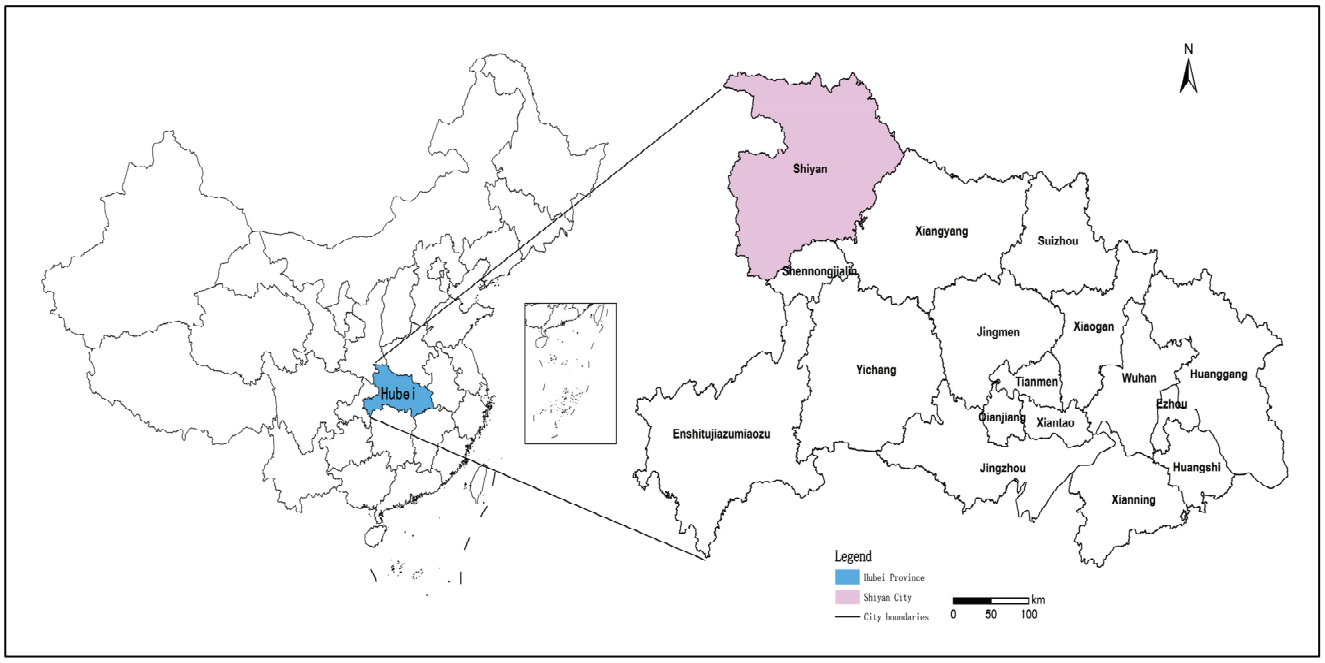

Figure 1. The study area covers parts of Hubei Province in China. Colored areas show the studied city.

3.3. Methods

3.3.1. DPSIRM Framework

The DPSIRM framework is the leading indicator system construction framework of current environmental assessment, which many scholars have recognized. The establishment of the DPSIRM framework has gone through a long development process, and the DPSIR framework is one of the original tools developed by the Organization for Economic Co-operation and Development (Paris, France) and the European Environment Agency for adaptive management of sustainable social environments (Copenhagen, Denmark) [32]. With the deepening of research in this field, some scholars have introduced the management subsystem based on DPSIR [33], from which the DPSIRM framework was gradually established and widely used. Based on Chai, N. and W. Zhou's research [34], combined with this study, the DPSIRM framework can be explained as follows.

The driving force subsystem (D) is the fundamental cause and initial driving force of changes in the regional water resources carrying capacity, mainly influenced by urbanization, economic and demographic changes, and development. The greater the driving force, the greater the risk of insecurity carried by water resources, and the greater the pressure and challenges faced by the resilience of water systems.

The pressure subsystem (P) refers to the pressure exerted on the water resources environment by intentional or unintentional human activities, such as the influence of the economic development level on water resources utilization, the change in water consumption of urban residents caused by urbanization development, and the discharge of industrial wastewater.

The state subsystem (S) refers to the actual changes and states of the regional water environment under pressure factors, mainly manifested as changes in the supply status, demand status, and water environment quality of water resources.

The impact subsystem (I) impacts the ecological environment, socio-economic, and other aspects, and the greater the impact, the less secure the regional water environment system.

Response subsystem (R) refers to the remedial actions that humans take to mitigate the negative impacts of the regional water environment, including responses to the treat-

ment of various pollution sources. The timelier the response, the safer the regional water environment system and the higher the resilience of the water system.

The management subsystem (M) represents people taking corresponding measures to control water resource management, such as formulating relevant policies and regulations and increasing financial investment in pollution control. Management is a proactive measure to enhance the carrying capacity of water resources and an important way to improve the resilience of water systems.

Based on the DPSIRM framework and considering the availability of data, an evaluation system of water resources carrying capacity in Shiyan City was constructed in this study, as shown in Table 1.

Table 1. Evaluation system of water resources carrying capacity in Shiyan City.

Criterion Layer	Indicator Layer	Properties	Calculation Methods	Reference
Driving force (D)	X_{D1} Per capita GDP (yuan)	Positive	From statistical data	[34,35]
	X_{D2} density of population	Negative	From statistical data	[34,35]
	X_{D3} urbanization rate	Negative	From statistical data	[34,35]
Pressure (P)	X_{P1} Wastewater discharge per unit of industrial output value (t/10,000 CNY)	Negative	Amount of industrial wastewater discharge/industrial output value	[35,36]
	X_{P2} Household water consumption (10,000 m^3)	Negative	From statistical data	[36]
	X_{P3} Average annual fertilizer application per unit cultivated land (kg/hm^2)	Negative	Amount of fertilizer application/cultivated area	[35,36]
Status (S)	X_{S1} Water resources per capita (m^3)	Positive	Amount of regional water resource/regional population	[34,35]
	X_{S2} Water resources per unit area (m^3/hm^2)	Positive	Amount of regional water resources/regional land area	[34,35]
	X_{S3} Annual precipitation (100 million cubic meters)	Positive	From statistical data	[37]
Impact (I)	X_{I1} Proportion of guaranteed harvest area of drought and flood in cultivated land (%)	Positive	Guaranteed harvest area in drought and flood/cultivated area	[38]
	X_{I2} Water quality in line with Class I~III standard proportion	Positive	From statistical data	[35]
	X_{I3} Forest coverage rate (%)	Positive	From statistical data	[38]
Response (R)	X_{R1} Sewage treatment rate (%)	Positive	From statistical data	[35,36]
	X_{R2} Length of drainage pipe (km)	Positive	From statistical data	[34]
Management (M)	X_{M1} Green coverage rate of built-up areas (%)	Positive	The annual built-up green cover area/green cover area	[34]
	X_{M2} Investment in wastewater treatment (10,000 CNY)	Positive	From statistical data	[36]

3.3.2. Index Weight Determination

The entropy method was used to determine the weights in this study. The main steps are as follows.

(1) Data standardization.

In order to eliminate the dimensionality of each index, data are standardized in this study. The formula for positive index processing is as follows:

$$\mathrm{MMS_x_{ij}} = \left(\mathrm{x_{ij}} - \mathrm{Min}\right) / \left(\mathrm{Max} - \mathrm{Min}\right)$$

The formula for negative index processing is as follows:

$$\mathrm{NMMS_x_{ij}} = \left(\mathrm{Max} - \mathrm{x_{ij}}\right) / \left(\mathrm{Max} - \mathrm{Min}\right)$$

(2) Calculate the entropy of the j-th index.

$$e_j = k\sum_{i=1}^{n} x_{ij}\ln(x_{ij})$$

Xij here is the normalized data.

(3) Calculate information on entropy redundancy.

$$d_j = 1 - e_j$$

(4) Calculate the weights of each indicator.

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$$

The calculation results of the water resources carrying capacity index weight are shown in Table 2.

Table 2. Index weight determination.

Indicator	Information Entropy e	Information Utility Value d	Weight Coefficient w
MMS_D1	0.8854	0.1146	5.90%
NMMS_D2	0.7822	0.2178	11.20%
NMMS_D3	0.8522	0.1478	7.60%
NMMS_P1	0.9059	0.0941	4.84%
NMMS_P2	0.8889	0.1111	5.71%
NMMS_P3	0.8307	0.1693	8.71%
MMS_S1	0.9437	0.0563	2.89%
MMS_S2	0.9456	0.0544	2.80%
MMS_S3	0.9064	0.0936	4.81%
MMS_I1	0.8663	0.1337	6.87%
MMS_I2	0.9387	0.0613	3.15%
MMS_I3	0.9477	0.0523	2.69%
MMS_R1	0.9163	0.0837	4.31%
MMS_R2	0.9007	0.0993	5.11%
MMS_M1	0.8322	0.1678	8.63%
MMS_M2	0.7128	0.2872	14.77%

Notes: MMS represents a positive indicator; NMMS represents a negative indicator.

3.3.3. Obstacle Degree Model

Step 1: Calculate F value. F value = W ∗ P (W is the weight of the criterion layer, P is the weight of the indicator layer), and SPSSAU will calculate the weight of the indicator layer corresponding to the criterion layer after normalization processing by default.

Step 2: Calculate the standardized value of R′. The formula for calculating the standardized value of R′ is: (X − min)/(max − min); that is, (a datum − the minimum value of this index)/(the maximum value of this index − the minimum value of this index).

Step 3: Calculate I value; I value = 1 − R′ standardized value.

Step 4: Calculate the O value of the index layer. The formula is as follows:

$$O_j = \frac{F \times I}{\sum_{j=1}^{m}(F \times I)}$$

In this formula, j represents the indicator number; there are m-many indicators in total.

$$U = \sum O_j$$

Here, j indicates the subsystem number.

4. Results

4.1. Change in Comprehensive Score of Water Resources Carrying Capacity in Shiyan City

After calculating the weight according to the entropy value method, the comprehensive score change chart of water resources carrying capacity in Shiyan City was calculated, as shown in Figure 2. As can be seen in the figure, the water resources carrying capacity of Shiyan City showed an upward trend from 2011 to 2021 as a whole, indicating that the water resources carrying capacity of Shiyan City was continuously enhanced from 2011 to 2021. The resilience of the Shiyan water system also increased. There was a downward trend from 2011 to 2012 and from 2017 to 2018 and an upward trend in other years. During this period, the year with the weakest water resources carrying capacity was 2018, with a comprehensive score of 0.3870. The highest water carrying capacity was in 2021, with a composite score of 0.6547.

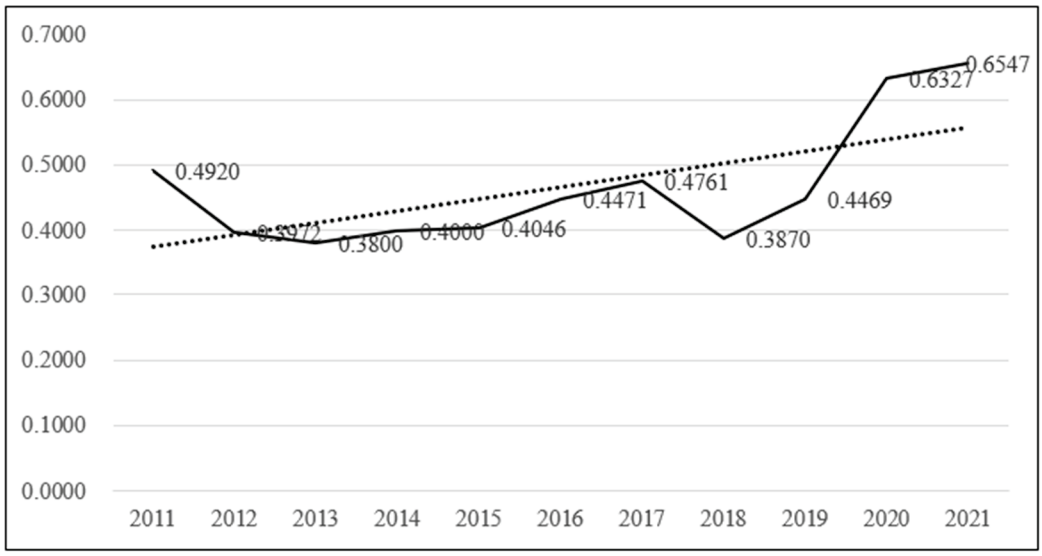

Figure 2. Change of water resources carrying capacity in Shiyan City. Note: The solid line is Comprehensive Score of Water Resources Carrying Capacity in Shiyan City; The dashed line is the trend line.

4.2. Analysis of Water Resources Carrying Capacity Obstacle Degree

4.2.1. Subsystem Obstacle Degree Analysis

The obstacle degree model formula was used to calculate the obstacle degree of each subsystem of the water resources system in Shiyan City from 2011 to 2021 (see Figure 3 and Table 3). As can be seen in Figure 2, there are obvious differences in the variation trend of the obstacle degree of each subsystem from 2011 to 2021. The subsystems of the driving force, state, and response showed a fluctuating downward trend, while the subsystems of pressure, influence, and management showed a fluctuating upward trend. Driving the subsystem down can promote the resilience of water resources in Shiyan City. The decline in the state subsystem indicates that the ability of the water resources system to support regional economic and social development in Shiyan City is weakening, which implies that the resilience of the water system has a declining trend. The decline in the response subsystem will hinder the improvement in the resilience of the water resources system in Shiyan City. The rise of the pressure subsystem and influence subsystem indicates that the pressure of the resilience improvement in water resources in Shiyan City is increasing. The rise of the management subsystem can improve the resilience of the Shiyan water system.

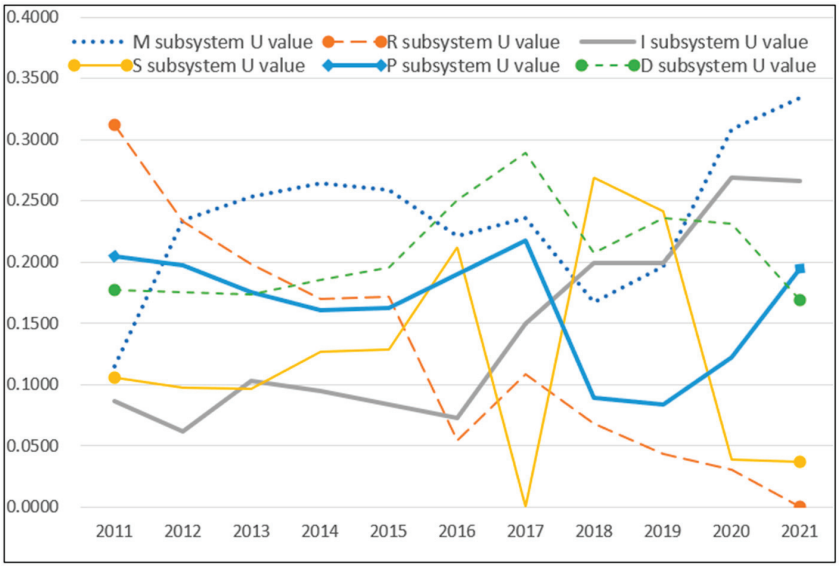

Figure 3. Trend chart of subsystem obstacle degree.

Table 3. Obstacle degree U value of each subsystem.

Year	M Subsystem U Value	R Subsystem U Value	II Subsystem U Value	S Subsystem U Value	P Subsystem U Value	D Subsystem U Value
2011	0.1149	0.3117 (I)	0.0861	0.1056	0.2043 (II)	0.1775 (III)
2012	0.2343 (I)	0.2329 (II)	0.0618	0.0978	0.1975 (III)	0.1757
2013	0.2533 (I)	0.1987 (II)	0.1028	0.0964	0.1757	0.1731
2014	0.2639 (I)	0.1695 (III)	0.0944	0.1264	0.1606	0.1852 (II)
2015	0.2592 (I)	0.1713 (III)	0.0834	0.1283	0.1621	0.1957 (II)
2016	0.2212 (II)	0.0542	0.0727	0.2117 (III)	0.1900	0.2502 (I)
2017	0.2361 (II)	0.1080	0.1492	0.0000	0.2173 (III)	0.2894 (I)
2018	0.1672	0.0679	0.1993 (III)	0.2690 (I)	0.0890	0.2077 (II)
2019	0.1963 (III)	0.0429	0.1997	0.2418 (I)	0.0838	0.2356 (II)
2020	0.3081 (I)	0.0301	0.2687 (II)	0.0390	0.1224	0.2317 (III)
2021	0.3342 (I)	0.0000	0.2658 (II)	0.0370	0.1942 (III)	0.1689

Notes: The parentheses indicate the ranking of obstacle subsystems, while (I), (II), and (III) represent the first, second, and third obstacle subsystems, respectively.

It can be seen in Table 3, under the DPSIRM framework, that the frequency of the occurrence of the top three subsystems of the obstacle degree of each subsystem under the overall framework from 2011 to 2021 is as follows: M system (nine times), D system (eight times), R system (five times), P system (four times), S system (three times), and I system (three times). The M subsystem was the first obstacle subsystem in 2012–2015, 2020, and 2021; the second obstacle subsystem in 2016 and 2017; and the third obstacle subsystem in 2019. This indicates that the management subsystem is the main constraining factor in improving the carrying capacity of water resources and the resilience of the water system in Shiyan City. In the future, further investment in water resource management is needed. The D subsystem was the first obstacle system in 2016 and 2017; the second obstacle system in 2014, 2015, 2018, and 2019; and the third obstacle system in 2011. This indicates that the population size, economic development level, and urbanization rate of Shiyan City from 2011 to 2021 are the factors that cannot be ignored when aiming to improve the water resources carrying capacity and enhance the water system elasticity of Shiyan City. The R subsystem was part of the top three obstacle subsystems from 2011 to 2015, with 2011 being the first obstacle subsystem, 2012 and 2013 being the second obstacle subsystem, and 2014 and 2015 being the third obstacle subsystem. After 2016, it was no longer part of the top three obstacle subsystems. This indicates that the response subsystem has undergone significant improvements in recent years, and it is recommended that Shiyan

City strengthen water resource management in its future development process. According to the characteristics of the local industrial structure of Shiyan City, it is important to adjust the water use structure, strengthen water-saving management, and improve the utilization efficiency of water resources.

4.2.2. Obstacle Degree Analysis of Each Factor

According to the obstacle degree model, the obstacle degree of the 16 influencing factors on the water resources carrying capacity of Shiyan City was calculated, and the top 3 obstacle degree factors were selected for statistical analysis. The results are shown in Table 4. The finding of the first obstacle showed that between 2011 and 2021, the M2 index appeared eight times, the R2 index appeared two times, and the D2 index appeared once. These results indicate that insufficient investment in sewage treatment was the main factor restricting the improvement in the water resources carrying capacity in Shiyan City from 2011 to 2021. According to the statistics of the second obstacle degree factor from 2011 to 2021, the I1 index appeared four times, the P3 index appeared two times, the R1 index appeared two times, the M2 index appeared once, the R2 index appeared once, and D2 index appeared once. This indicates that the I1 index is the second factor restricting the improvement in the water resources carrying capacity in Shiyan City, specifically referring to the proportion of guaranteed arable land in drought and flood. The guaranteed harvest area of droughts and floods refers to the effective irrigated area that can be irrigated in the case of a drought and discharged in the case of a flood. The higher the proportion of the guaranteed harvest area of droughts and floods, the lesser the impact of a change in the water resources carrying capacity on agricultural production. With regard to the second obstacle to improving the water resources carrying capacity in Shiyan, the proportion of the guaranteed area of droughts and floods is the most important restriction. According to the third obstacle, from 2011 to 2021, the P3 index appeared five times, the D2 index appeared once, the P2 index appeared twice, the S3 index appeared twice, and the M2 index appeared once. Regarding the third obstacle to improving the water resources carrying capacity in Shiyan, the average annual fertilizer application per unit of cultivated land is the most important. This shows that the agricultural fertilizer applied in Shiyan City has restricted the improvement in the water resources carrying capacity.

Table 4. Ranking of obstacle factors.

Year	Category	No. 1 Obstacle	No. 2 Obstacle	No. 3 Obstacle
2011	obstacle factors	R2	R1	P3
	obstacle degree	0.1691	0.1426	0.1169
2012	obstacle factors	R2	M2	P3
	obstacle degree	0.1437	0.1403	0.1301
2013	obstacle factors	M2	R2	P3
	obstacle degree	0.1631	0.1339	0.1212
2014	obstacle factors	M2	P3	D2
	obstacle degree	01715	0.1127	0.1101
2015	obstacle factors	M2	R1	P3
	obstacle degree	0.1640	0.1237	0.1133
2016	obstacle factors	D2	P3	M2
	obstacle degree	0.1452	0.1233	0.1142
2017	obstacle factors	M2	D2	P3
	obstacle degree	0.2325	0.1679	0.1230
2018	obstacle factors	M2	I1	S3
	obstacle degree	0.1638	0.1454	0.1232
2019	obstacle factors	M2	I1	S3
	obstacle degree	0.1963	0.1623	0.1201
2020	obstacle factors	M2	I1	P2
	obstacle degree	0.3063	0.2490	0.1224
2021	obstacle factors	M2	I1	P2
	obstacle degree	0.3240	0.2658	0.1627

Further increasing investment in water resources and sewage treatment of Shiyan City is the primary measure to further improve the water resources carrying capacity of Shiyan City. The guaranteed harvest area of droughts and floods reflects the strength of the water resources irrigation system and drainage system in a region, and the improvement in the guaranteed harvest area of droughts and floods reflects the improvement in the water resources management system capacity in a region. The guaranteed harvest area is the area of farmland that can still produce a high and stable yield in case of a drought or flood disaster. It is a necessary measure for environmental protection and water resource protection to reduce the annual average fertilizer applied per unit of cultivated land.

5. Conclusions

The DPSIRM framework was used to study water system security from the perspective of water resources carrying capacity. From 2011 to 2021, the carrying capacity of water resources in Shiyan City gradually improved, as well as the safety of the water system. The resilience of the water system in Shiyan City also increased. The management system is the main obstacle subsystem, followed by the driving force system, the response system, the pressure system, the state system, and the influence system. Among the specific factors, the top three obstacle factors are sewage treatment investment, the proportion of guaranteed harvest area in drought and flood, and the average annual fertilizer applied per unit of cultivated land. These are the main factors restricting Shiyan City's water resources carrying capacity improvement.

In conclusion, although our study objectively evaluated the trend of changes in the water resources carrying capacity in Shiyan City, we also identified factors that constrained the further improvement in the resilience of the water resource system in Shiyan City from the perspectives of subsystems and specific factors. However, we did not fully consider the cross-regional spillover effects on water resource management in surrounding cities. Future research should expand the research area and further study the interactions and impacts between cities. In the selection of indicators in management, because there are no corresponding statistical data and no public multi-year data, only two dimensions were selected during the selection of indicators. This needs to be further enriched and perfected in future research.

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Stormwater Harvesting Potential for Local Reuse in an Urban Growth Area: A Case Study of Melton Growth Area in the West of Melbourne

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Abstract: Integrated urban water management approaches (IUWM) are implemented to address challenges from increases in water demand as a result of population growth and the impact of climate change. IUWM aims to utilize all water resources (stormwater, wastewater, and rainwater) based on fit-for-purpose concepts. Here, a local water utility in Melbourne's Melton growth area explored the availability of stormwater as an alternative water resource for water service planning for a proposed residential development in an existing greenfield area of 13,890 hectares for 160,000 new houses by 2040. A methodology was developed for assessing the stormwater quantity and quality under land use change and different climatic conditions considering the availability of stormwater from the proposed urban development. The modelling results indicated that the amount of annual stormwater generated in the region increased by nearly four times to 32 GL/year under the 2040 full urban land use with high climate change. The provision of constructed wetlands in proposed development blocks was found to be efficient at removing TSS, TP, and TN, and able to retain over 90% of TSS, 77% of TP, and 52% of TN in all scenarios. Harvested stormwater, if treated to potable standards, can meet nearly 40% of water requirements for residential area needs.

Keywords: stormwater harvesting; water quantity; water quantity; urban water demand; integrated urban water management; runoff modelling

1. Introduction

Urbanisation, population growth, and climate change have a significant impact on fresh water resources, in particular for rapidly growing urban developments around the world [1,2]. The increasing conversion of natural landscapes into impervious areas is a common phenomenon in most parts of the world. With urbanisation, pervious surfaces dominated by vegetated surfaces such as agricultural lands, greenfields, and forests are replaced with impervious areas such as roads, rooftops, and paved areas including parking lots. Urbanisation involves expansion associated with high population growth and rural exodus. The current world population is 8 billion and is projected to increase by 21% in 2050 [3]. The state of Victoria, Australia, also follows an upward trend, as the population increased from 1.9 million in 1960 to 6.7 million people today. This figure is expected to reach between 10.1 million and 14.5 million by 2066, according to the Australian Bureau of Statistics [4]. It is predicted that the gap between water supply and demand is most likely to increase in the future due to population growth, thereby putting an additional load on water supply systems.

Existing pressure on water resources can also be exacerbated by climate variability. Global greenhouse gas concentrations have been trending upwards since the mid-19th

century. Local temperature trends in Victoria, Australia, over a similar period are of a similar magnitude to global trends [5]. Increased greenhouse gas concentrations and associated changes to the global climate system have resulted in changes in the behaviour of Victoria's climate, with obvious reductions in rainfall in the cool season, i.e., April to October, in past decades [6]. CSIRO used global climate models (GCMs) to predict anticipated changes in climate of Victoria's river basins for the year 2040. The results of the GCMs indicated that Victoria will become hotter and drier under increased greenhouse gas concentrations. Under the high climate change scenario, for example, the average daily temperature is predicted to rise by 1.6 °C by 2040. The overall reduction and increase in annual average rainfall and potential evapotranspiration are projected to be 12.1% and 5.6% by 2040, respectively [7]. There is thus a fundamental concern that ongoing global greenhouse warming will put pressure on water resources due to reductions in water availability [6]. Hotter and drier conditions increase the water demand for intended end-use applications, i.e., non-potable uses [8] and potable uses [9].

The projected population growth due to urbanisation, increased water demand, and concerns about future climate variability have highlighted the need to manage water resources in a more sustainable way [10]. Stormwater harvesting, i.e., capturing runoff from urban areas to provide a source of non-potable, and in some cases potable water supply, is now acknowledged as a valuable resource to urban development areas, where a set of resilient urban water supply sources is needed [11,12]. Stormwater runoff is drained directly to streams via man-made drainage systems and is also a major source of a wide range of pollutants, and is thus identified as a primary degrader that stresses receiving waterbodies [13–15]. Hence, mitigating stormwater pollution is essentially required in urban water management to transform cities and towns into the most resilient and liveable in the world. Water sensitive urban design (WSUD) approaches are now implemented to minimise stormwater runoff and pollutant loads into the receiving environment [16].

Inamdar et al. [17,18] developed a GIS-based screening tool for locating and ranking suitable stormwater harvesting sites in urban areas and for the evaluation of selected stormwater harvesting sites using multi criteria decision methodology. Such approaches can be used to prioritise decentralised stormwater harvesting projects based on demand and supply considerations. Sapkota et al. [19] further developed a methodology for integrated evaluation of hybrid water supply systems. Sharma et al. [20] conducted a study to use alternative water resources based on a fit-for-purpose concept for a 3060-hectare urban development planned for a population of 86,000. Based on the study, it was assessed that nearly 28% of freshwater could be saved by using locally harvested stormwater for toilet flushing and garden watering. The savings could be increased further if the end usages can be extended, thus improving the treatment processes. Overall cost and raw stormwater storage size are known challenges to such systems due to seasonal variability in stormwater flows.

Sanciolo et al. [21] conducted a literature review for potential uses of harvested stormwater, with a focus on potable reuse applications, stormwater quality, and the requirements to treat stormwater to potable standards. The microbial and chemical quality of stormwater treated using two typical potable reuse treatment trains was modelled and compared with stormwater log-reduction targets from the literature and to drinking water guidelines. The cost of these treatments for current and expected future stormwater volumes was also estimated based on the literature costings.

Urban stormwater runoff quality statistics are essential for planning any treatment process for potable and non-potable applications based on a fit-for-purpose concept. Nature-based and engineered treatment processes alone or in combination can be planned for the desired degree of water quality treatment. Various researchers have investigated urban stormwater pollutants, their sources, and pollutant processes [22–24]; however, catchment-specific stormwater quality statistical information (e.g., 95th percentile data) would be required for the planning and design of the treatment processes. This is a major challenge, as stormwater's spatio–temporal variability necessitates monitoring a large number of pollutants over an extensive period to ensure the capture of a full range of

events, such as a heavy rainfall event or sewer overflow, which could lead to an increase in the individual pollutant level. This challenge is exacerbated by the need to also take into account contaminants of emerging concern. These are contaminants that are not commonly monitored, making the task of meaningful statistical analysis of their level in stormwater difficult without further extension of the monitoring period and detailed investigation.

A methodology is presented here for assessing the stormwater quantity and quality under land use change and different climatic conditions for the availability of alternative water resource for water services planning for new developments. It is hoped that this publication will help water professionals in assessing alternative water resources for similar regional developments across the globe for water resources services planning.

2. Case Study Area

The growth area boundary was provided by the local water utility "Greater Western Water", and encompasses the entire area of urban precincts included in the Melton-Rockbank Precinct Structure Plan (PSP) (Figure 1). The entire area in PSP was included in the modelling to provide an indication of the maximum stormwater harvesting potential from this area. The urban growth area was split into six urban blocks (blocks 1–5, with block 1 further split into blocks 1A and 1B (Figure 1)). The specified urban growth blocks nominated by the water utility were included in the model at the 2040 development level, assumed as 100% urban land use. Blocks 1A and 4 were located within the natural Werribee River catchment and thus stormwater from these areas was gravity-fed into the Werribee River. Nearly 62% of the total catchment of block 1B also drained naturally to the Werribee River via Toolern Creek, whereas the remaining 38% drained to the Kororoit Creek, which is outside of the Werribee River catchment. Blocks 2, 3, and 5 were not within the natural stormwater catchment of the Werribee River and thus scenarios that included stormwater from these blocks assumed that additional stormwater runoff harvested from these blocks would be pumped into the nearby Merrimu Reservoir (not shown) based on onsite treatment level. The vision for this stormwater harvesting scheme investigation was to explore availability of alternative water resources for water planning of the proposed development. An assessment is required for stormwater quality and quantity from the proposed area once it is fully developed. The urban blocks were considered based on the Melton-Rockbank Precinct Structure Plan (PSP) [25].

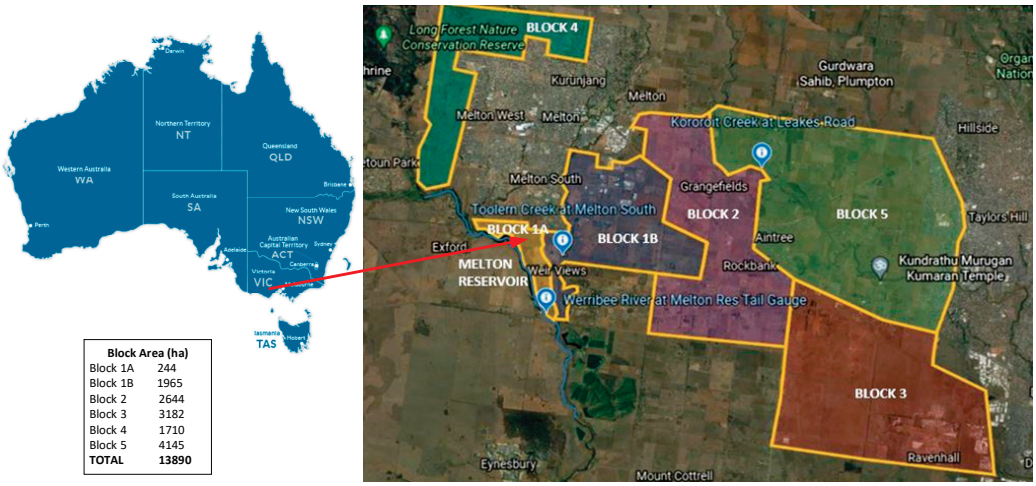

Figure 1. Melton-Rockbank Precinct Structure Plan (PSP) (West of Melbourne region) overlaid with urban block boundaries modelled as part of the current investigation (modified from [25]).

3. Proposed Methodology for Assessing Stormwater Harvesting Potential and Associated Water Quality

A literature review was conducted to investigate the current methodologies for the stormwater harvesting from an upcoming urban development. Various water systems and service-associated assessment methodologies are available in the literature [20,26–28]. These approaches mainly cover the integration of various analyses and design methods specific to urban water services. A conceptual diagram of the stormwater harvesting and potential reuse is depicted in Figure 2 below.

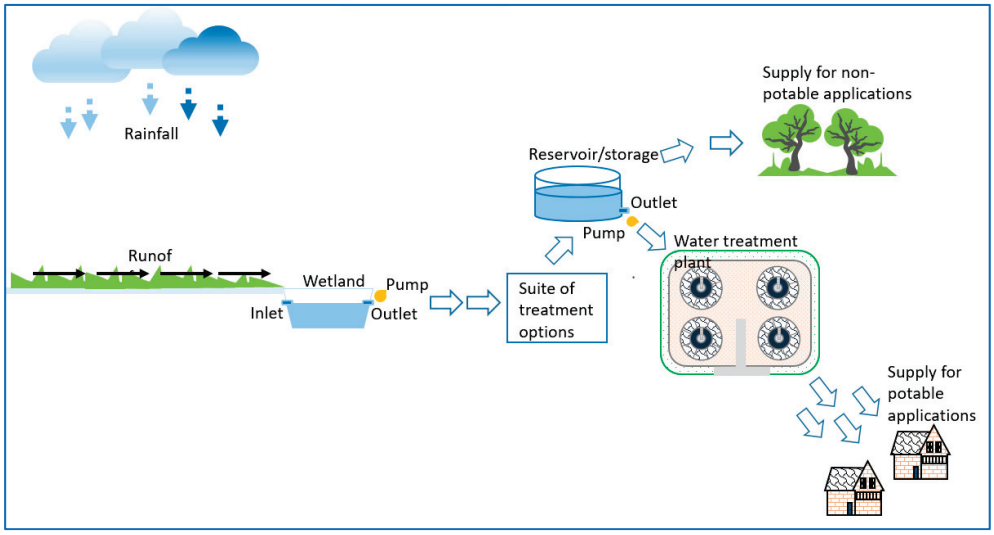

Figure 2. Conceptual diagram showing stormwater runoff generation and treatment.

Considering the varying nature of urban developments in greenfield areas and learning from existing literature, a generalised methodology for the assessment of the stormwater harvesting potential and associated water quality for treatment needs was developed, as depicted in Figure 3. The methodology is described in the following steps:

(1) ***Understand Specific Development Area Conditions and Environment:*** This step involves the collection of development-specific information for planning and executing the study. This will include, but not be limited to, existing development, if any, in the proposed area and the nature of existing land use, development plan and its area, number of blocks or sub-divisions and their areas, current and future climate data, local soil properties, household occupancy rates, industrial and commercial developments in the area, stormwater treatment/disposal options and constraints, and regulatory policies and guidelines. Engagement with project-specific stakeholders, e.g., local water utility, local government, and environmental agencies, should be made for information on the development of specific policies and guidelines, including establishing study objectives.

(2) ***Establish Development-Specific Study Objectives in consultation with local stakeholders:*** Study-specific objectives should be developed in consultation with stakeholders. These are generally based on site specific constraints such as the availability of limited fresh water resources, disposal of stormwater, and wastewater limitations in the area. These objectives can be quantitative or qualitative in nature. For example, the reduction in annual stormwater flow by 40% from the development is a quantitative objective, while minimizing stormwater flow from the development is qualitative. Some examples of objectives for the new development area can be maximizing application of local alternative water resources, minimizing the pressure on the freshwater resources, low or minimum impact on existing natural environment, minimizing waste/contaminants to natural environment, and low cost to community and wider social acceptance of the development specific objectives for the proposed

study. Local project objective-specific guidelines should be considered for developing qualitative and quantitative objectives.

(3) ***Develop Planning Horizon and Study Analysis Period:*** This will include understanding the planning horizon of the proposed development, timeline of development phases, and associated development sizes including nature of development (residential, commercial, industrial, and recreational). The study analysis period will be decided based on the overall development plan and timeline of development phases over the planning horizon.

(4) ***Estimate Water Demand for the Proposed Development:*** The proposed nature of development (residential, commercial, industrial, and recreational) should be used to estimate the annual water demand over the planning horizon and development timelines based on local water consumption guidelines for various intended usages. The breakdown between potable and non-potable demand should also be conducted to estimate the potential for alternative water source applications.

(5) ***Select Suitable Modeling Tool for Analysis:*** The selection of the most appropriate modeling tool is generally dependent on model capabilities for intended applications to meet study objectives, professionals' preferred models at geographic locations and data requirements, ease of availability, and associated cost.

(6) ***Establish Scenarios for Stormwater Runoff Quantity and Quantity Assessment:*** The scenarios for modeling stormwater runoff and associated water quality are developed considering existing land use, provision of water-sensitive urban design approaches, future urban land use, climate change impacts (low, medium, and high), and natural/manmade flow of stormwater from various blocks (sub-catchments) to the receiving environment.

(7) ***Model Set-up:*** The selected modeling tool is applied for developing a model for the development area based on the development plan, soil characteristics, drainage flow paths, stormwater-receiving environment, and proposed WSUD approaches.

(8) ***Assess Scenarios Applying Modeling Tool:*** The selected scenarios are modelled using the selected tool for the estimation of stormwater runoff as the maximum harvesting potential under various climatic conditions and scenarios. The stormwater quality is also modelled under various scenarios.

(9) ***Establish Stormwater Quantity and Quality from the Proposed Development:*** Check stormwater harvesting potential under various scenarios as water resources for the proposed urban development for water services planning and associated water quality to develop appropriate treatment trains.

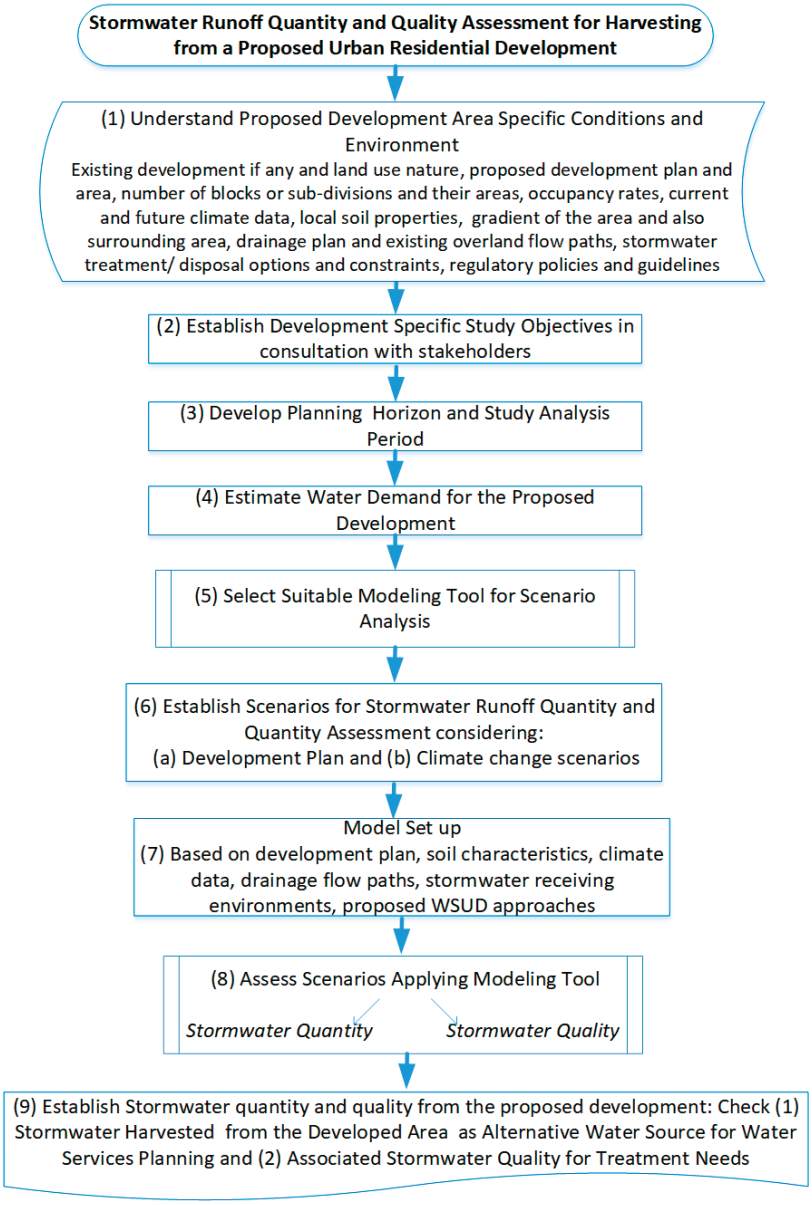

Figure 3. Proposed methodology flow diagram for stormwater quality and quantity assessment.

4. Application of Assessment Methodology

The application of the developed methodology for the assessment of stormwater quantity and quality is conducted in this section and the results are presented.

4.1. Understanding of Development Area Specific Conditions and Environment

The data and information collected about the planned urban development in a greenfield area are documented in this section for modelling purposes.

4.1.1. Existing Land Use and Proposed Urban Development

The proposed urban development area is shown in Figure 1. The total area of the proposed development is 13,890 hectares. The block-specific areas of the proposed development are provided below in Table 1.

Table 1. Melton-Rockbank Precinct planned urban block areas.

Blocks	Area (Hectare)
Block 1A	244
Block 1B	1965
Block 2	2644
Block 3	3182
Block 4	1710
Block 5	4145
Total	13,890

The development area and stormwater flow paths from various blocks have been described in detail in Section 2 (case study area). The existing use of land was primarily for dry land grazing and cropping.

4.1.2. Climate Data

The recent 22-year record of daily rainfall and potential evapotranspiration (PET) data (2000–2021) from the Little River Station (station no: 087033) taken from Scientific Information for Land Owners (SILO) (https://www.longpaddock.qld.gov.au/silo/about/ assessed on 25 March 2023) is shown in Figure 4. The average daily rainfall depth and PET were 1.25 mm and 3.91 mm, respectively.

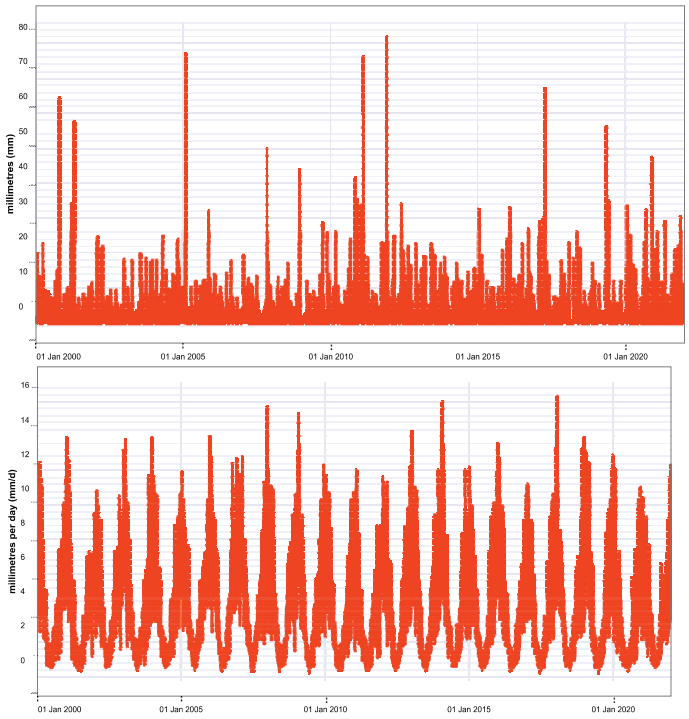

Figure 4. Time series of the 2000–2021 rainfall (**Top**) and PET (**Bottom**).

Various climate change impact scenarios for rainfall and PET were considered for the modelling, as listed below, in accordance with the DELWP guidelines [6]:

- Low-impact climate change: current rainfall and PET factored up by 2.2% and 2.9%, respectively
- Medium-impact climate change: current rainfall factored down by 2.7% and PET factored up by 4.7%.
- High-impact climate change: current rainfall factored down by 11.7% and PET factored up by 5.9%.

DELWP [6] provides guidance for long-term temperature, potential evapotranspiration, rainfall, runoff, and recharge to be used across Victoria to assess the impact of climate change on water supplies. Three representative climate change projections (low, medium, and high impact) were selected from the range of possible climate futures anticipated by 42 different global climate models (GCMs).

4.1.3. Soil Type: Soil Parameters for Modeling

The area is on the Keilor–Werribee plain, which is part of a lava plain. The texture of the soil is mostly basalt-derived cracking clay that has a poor drainage rate. The soil becomes water logged in wet weather and dries in the warm weather [29]. A soil storage capacity of 120 mm and field capacity of 50 mm was adopted for stormwater runoff estimation, as per the Melbourne Water Guideline [30].

4.2. Establishment of Development Specific Study Objectives in Consultation with Stakeholders

The aim of this study was to investigate stormwater harvesting potential from the proposed development for planning the reuse of this resource under integrated urban water management approaches to reduce the load on fresh water resources. The impact of climate change on the stormwater harvesting potential was also an important factor to investigate. It is also required to investigate stormwater quality from harvested stormwater through modelling for the development of appropriate treatment trains for intended use in future research.

Thus, the objectives of this research are as follows:

(a) Investigate the stormwater harvesting potential under current and future land use changes as well as low, medium, and high climate change impacts without and with the planed provisions of wetlands in each of the development blocks.
(b) Investigate the stormwater quality parameters under various conditions as mentioned in (a) for future investigation on the treatment train to treat water for fit-for-purpose applications.

These study objectives were developed in consultation with the main stakeholder (local water utility) and regular fortnightly meetings were organised for ongoing input during the execution of the project with the water utility.

4.3. Development of Plan Timeline and Analysis Period

It is expected that the planned urban area will be fully developed by 2040. Thus, for modelling purposes, the base case (current land use) analysis was planned for 2022 and for 2040 for the fully urban developed condition.

4.4. Estimation of Water Demand for Proposed Development

Melbourne Water Utilities are now running a program on water conservation called "Target 150", which is a voluntary water conservation initiative by the Victorian Government. It aims to encourage people to be mindful of our precious resource of water and to reduce our average daily water use to below 150 litres per person (https://www.water.vic.gov.au/liveable/using-water-wisely/t150 assessed on 26 March 2023). The Department of Sustainability and Environment, Victoria, Australia [31], also published a document for achieving target 155. This target did not apply to recycled, reclaimed, rain, or grey water, except where supplemented by drinking water [32]. The average occupancy rate in Melbourne was 2.6 person for a 2019–2020 reference period (https://www.abs.gov.au/ assessed on 26 March 2023). As the development plan was in the initial stages, only the approximate residential water demand for fully urban development could be estimated. Considering the proposed 160,000 homes in the area, occupancy rate of 2.6 person per home (total residential population 416,000) and per person daily water requirement of 150 litres, the water demand per year could be estimated as 23 GL/year at the fully developed stage. The water demands for commercial, industrial, and recreational

purposes in the development area were difficult to estimate at this stage and thus were not included.

4.5. Selection of a Suitable Tool for Hydrological and Water Quality Modeling

The search for a suitable modelling tool was conducted, considering the aims of the study. The stormwater harvesting potential, once the proposed development was fully developed, and the associated water quality parameters were investigated under various climate impact scenarios. Devi et al. [33] conducted the review of various hydrological models and briefly discussed the variable infiltration capacity model (VIC), TOPMODEL, HBV, MIKESHE, and soil and water assessment tool (SWAT) model. This review was mainly focused on agriculture land use and indicated that each model has its own unique characteristics and respective applications. There was not a single valid model fitting every purpose [34]. Beven and Young [35] highlighted that the model should not be more complex than necessary and should be fit-for-purpose. Elga et al. [36] conducted a review of 43 selected modelling approaches, including MUSIC v1.10 software dealing with urbanization at the catchment scale or city scale. MUSIC continuously simulates catchment runoff for a given rainfall and evapotranspiration time series at a user-defined time step from 6 min to 24 h [37]. Imteaz et al. [38] conducted a study on the accuracy of MUSIC estimations for different stormwater treatment options used in Australia and abroad. Data on several field measurements on different constructed stormwater treatment systems (bioretention, grass swale, and porous pavement) in Australia, Sweden, New Zealand, and Scotland were collected from the literatures. In general, they found that MUSIC could simulate flow conditions with good accuracy; however, MUSIC's predictions on the removal efficiencies of total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) were varying. Since then, eWater Australia recently released a new version of MUSIC software (as MUSICX) (https://ewater.org.au/musicx-v1-10/ assessed on 15 November 2021) with enhanced capabilities around data analysis and results interpretation. Moreover, Melbourne Water [30] developed guidelines for MUSIC modelling approaches and input parameters for the local area, including case study development. Shahzad et al. [39] recently verified the ability of MUSIC to represent the catchment runoff peak flow and volume in a satisfactory manner with appropriate parameters in an urban case study development.

eWater MUSICX software (https://ewater.org.au/musicx-v1-10/ assessed on 15 November 2021) was finally selected for this study considering its wider application for stormwater quality and quantity modelling, and the availability of local guidelines for the model's application and input parameters developed by Melbourne Water [30].

4.6. Establishment of Scenarios for Stormwater Runoff Quality and Quantity Assessment Considering Development Plan and Future Climate Change Impacts

The scenarios comprised an analysis of the current and future (2040) land use conditions in the growth area, as well as climate change scenarios according to the global climate models proposed by the Department of Environment, Land, Water, and Planning, Victoria, Australia [6]. Modelled stormwater quality was also included in the investigations to assess the potential risks associated with the diversion of stormwater from wetlands to the reservoir under various scenarios. The scenarios for stormwater quality and quantity modelling are listed in Table 2. These scenarios are based on the following current and future development conditions:

- Current agricultural land use and climate with and without the impacts of wetlands where stormwater from specific agricultural blocks flowed naturally into the Melton Reservoir with no stormwater being harvested and diverted to storage from some of the other blocks.
- Future (2040) fully urbanised land use with the impact of climate change scenarios in the absence and presence of wetlands, where additional stormwater from specific urban blocks was also captured and piped into the Melton Reservoir.
- The current climate data are based on a 2000–2021 time series and its modification to reflect climate change impacts are described in Section 4.1.2.

Table 2. Summary of scenario description and MUSICX model inputs.

Scenario	Scenario Description	Analysis Year	Land Use	Climate Change Impact	Wetlands	Stormwater Flow
S 1	Current land use and climatic conditions and no wetland in blocks	2022	100% agricultural use–10% Imperviousness	No climate impact Use 2000–2021 climate data	None proposed	Blocks 1A and 4 flows naturally into the Melton Reservoir (MR)
S 2	Current land use and climatic conditions and wetland in blocks	2022	100% agricultural use–10% Imperviousness	No climate impact Use 2000–2021 climate data	Proposed in blocks 2% of block area	Blocks 1A and 4 flows naturally into the MR
S 3	Future 100% urban land use and low impact climate and no wetland in blocks	2040	100% urban land use–75% Imperviousness	Low climate impact	None proposed	Blocks 1A and 4 flows naturally into the MR while stormwater from block 1B, 2, 3, and 5 is captured and pumped to MR
S 4	Future 100% urban land use and low climate impact and wetland in blocks	2040	100% urban land use–75% Imperviousness	Low climate impact	Proposed in blocks 2% of block area	Same as for Scenario 3
S 5	Future 100% urban land use and medium climate impact and no wetland in blocks	2040	100% urban land use–75% Imperviousness	Medium climate impact	None proposed	Same as for Scenario 3
S 6	Future 100% urban land use and medium climate impact and wetland in blocks	2040	100% urban land use–75% Imperviousness	Medium climate impact	Proposed in blocks 2% of block area	Same as for Scenario 3
S 7	Future 100% urban land use and high climate impact and no wetland in blocks	2040	100% urban land use–75% Imperviousness	High climate impact	None proposed	Same as for Scenario 3
S 8	Future100% urban land use and high climate impact and wetland in blocks	2040	100% urban land use–75% Imperviousness	Medium climate impact	Proposed in blocks 2% of block area	Same as for Scenario 3

4.7. MUSIC Model Set-Up

4.7.1. Development Area Representation in MUSICX Model

MUSICX was used to simulate stormwater runoff volume, total suspended solids (TSS), and nutrient loads, e.g., total nitrogen (TN) and total phosphorus (TP), from the defined urban growth area, under current (assumes 100% agricultural land use) and future fully urbanized land use conditions and climatic variability. Details of the general scenario setup are provided in Table 2. Two examples of the model configuration in MUSICX are also shown in Figure 5.

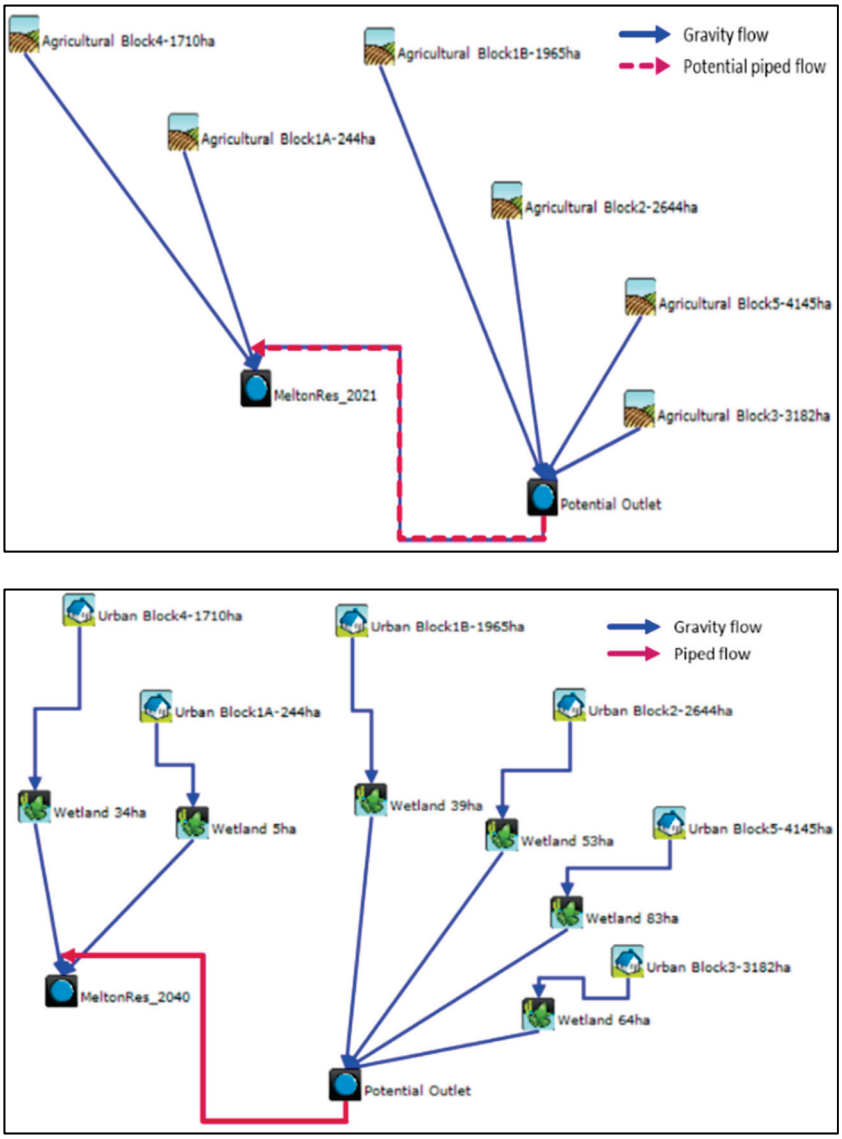

Figure 5. MUSICX model configuration of the Melton growth area under existing agricultural land use in the absence of the wetlands (**top**) and future urban development in the presence of the wetlands in 2040 (**bottom**).

Stormwater from blocks 1A and 4 flows was assumed to flow naturally into the Melton Reservoir. The additional stormwater generated in 2040 from Blocks 1B, 2, 3, and 5 is assumed to be piped and pumped to the Melton Reservoir or another suitable reservoir for subsequent treatment and reuse. Each wetland is assumed to have an area of 2% of the corresponding sub-catchment area based on a previous study [25].

The MUSICX model was developed for stormwater quality and quantity modelling in this study, with some key updates and amendments based on recent Melbourne Water

MUSIC guidelines [30]. These corresponded to key parameters around rainfall-runoff and impervious land fractions, as shown in Table 3. For all sub-catchment areas defined as urban land use, an average impervious land fraction of 0.75 was adopted in the model based on standard residential densities (lot size). Table 1 above shows the sub-catchment area of urban blocks for MUSICX modelling. As there were no local streamflow data available for proposed development to conduct calibration of a hydrlogical model, stormwater modelling parameters were selected from MUSIC software guidelines developed for the Melbourne area [30].

Table 3. Rainfall-runoff parameters and impervious fractions [30].

Rainfall-Runoff Parameters	MW Guidelines, 2022 [30]
Soil storage capacity (mm)	120
Field capacity (mm)	50
Zone description	Normal range
Large Residential (Lot size 601–1000 m^2)	0.5–0.8
Standard densities (Lot size 300–600 m^2)	0.7–0.8
High densities (Lot size < 300 m^2)	0.8–0.95

A range for future climate conditions, for the 'low', 'medium', and 'high' impact climate scenario, were selected from climate change guidelines [6] to estimate expected future conditions. All of these scenarios were investigated in the absence and presence of wetlands.

4.7.2. Wetland Parameters for Modelling

The MUSICX model used wetlands as a treatment option to meet the stormwater quality objectives, as defined in the Urban Stormwater Best Practice Environment Management Guidelines (BPEMG) [40]. The objectives include the following:

- 80% retention of the typical urban annual load for total suspended solids (TSS).
- 45% retention of the typical urban annual load for total phosphorus (TP).
- 45% retention of the typical urban annual load for total nitrogen (TN).

The area of the wetlands was estimated to be 2% of the total sub-catchment area for each block to meet the BPEMG target of urban nutrient load reduction [25]. The notional detention time was greater than 72 h. MUSICX outputs were generated, demonstrating that wetland treatments achieved BPEMG for stormwater treatment. The wetland parameters configured in the MUSICX model are shown in Table 4.

Table 4. Wetland parameters configured in the MUSICX model [25].

Wetland Design Parameter	Block 1A	Block 1B	Block 2	Block 3	Block 4	Block 5
Low flow bypass (m^3/s)	0	0	0	0	0	0
High flow bypass (m^3/s)	100	100	100	100	100	100
Inlet pond volume (m^3)	5000	39,000	53,000	64,000	34,000	83,000
Surface area (m^2)	50,000	390,000	530,000	640,000	340,000	830,000
Extended detention depth (m)	0.35	0.35	0.35	0.35	0.35	0.35
Permanent pool volume (m^3)	20,000	156,000	212,000	256,000	136,000	332,000
Initial volume (m^3)	20,000	156,000	212,000	256,000	136,000	332,000
Exfiltration rate (mm/h)	0	0	0	0	0	0
Evaporative Loss as % of PET	125	125	125	125	125	125
Equivalent Pipe Diameter (mm)	220	600	700	775	575	875
Overflow Weir width (m)	3	3	3	3	3	3
Notional Detention Time (h)	73	76	76	75	73	77

4.7.3. Stormwater Quality Parameters for Modeling

No amendments were made to the constituent MUSICX model parameters for TSS, TP, and TN as no field testing had been implemented to estimate the build-up and wash-off parameters. Default values for pollutant loadings were used in MUSICX, as shown in Table 5.

Table 5. Default pollutant loading concentrations for different land use and constituents.

Land Use	Event	Concentration (mg/L)					
		TSS		TP		TN	
		Mean	St. Dev	Mean	St. Dev	Mean	St. Dev
Agricultural	Base flow	25.12	1.35	0.13	1.35	1.18	1.35
	Storm flow	199.53	2.04	0.54	2.00	3.89	1.82
Urban–mixed	Base flow	12.59	1.48	0.15	1.55	2.09	1.32
	Storm flow	158.49	2.09	0.35	1.78	2.63	1.55

Various model parameters were selected based on the local guidelines for MUSIC modelling [29], as listed in Tables 3–5. As there were no stream flow data available at this stage to calibrate and validate the model, local guidelines were considered suitable for the model parameters at this stage.

4.8. Assessment of Options–Stormwater Runoff Quantity and Associated Quality

4.8.1. Stormwater Runoff Quantity from Various Scenarios

The annual average stormwater runoff volume for six blocks was estimated for different existing and future scenarios in the absence and presence of the wetlands, as shown in Table 6. Some of the key results are stated below:

- The volume of stormwater was proportional to the size of the blocks, with a larger area resulting in a greater stormwater volume. The runoff volume was lowest for the smallest block 1A and highest for the largest block 5 (see Tables 1 and 6).
- All future urban development scenarios resulted in a higher stormwater runoff volume due to increases in the impervious surface compared with the existing agricultural land use. For instance, stormwater runoff increased by nearly four times to be 32 GL/year under the 2040 full urban land use with high climate change (most conservative scenario) compared with 8.39 GL/year of stormwater generated today, assuming there were no wetlands built out there.
- The volume of stormwater available in the region decreased after the construction of wetlands, mainly due to ET losses in the wetlands under various scenarios.

Once rainfall and PET were rescaled in line with the DELWP guidelines for climate change for future scenario analysis [6], the runoff from the region changed to the following:

- Assuming no wetlands are constructed in the region, annual average stormwater volume increased to be 38.62 GL under the 2040 full urban land use with the low-impact climate. This decreased by 6% and 17% to 36.25 and 32 GL with the medium and high-impact climates, respectively.
- With the construction of wetlands in each block, annual average stormwater volume increased to 33.53 GL under the 2040 full urban land use with low-impact climate. This decreased by 7% and 20% to 31.08 GL and 26.78 GL with the medium and high-impact climates, respectively.
- The 8.39 GL/year of stormwater available today (if completely harvested) contributed to meeting the required amount of potable and Class B recycled water (7.5 GL/year,

reported by Greater Western Water), which is mainly used for irrigation of open spaces in the Melton growth area. Here, 26.78 GL/year stormwater generated under the 2040 full urban land use with a high-climate impact and the provision of wetlands was sufficient to meet residential potable water demand of 23 GL/year if 100% stormwater is captured and treated for potable standard.

Table 6. Water balance for each block under various land use (existing agricultural and future urban development) and climate conditions (low, medium, and high-impact climates).

Description		Water Balance (ML/Year)						
		Block 1A	Block 1B	Block 2	Block 3	Block 4	Block 5	Total
Existing Agricultural and climate scenarios 1 and 2	(S 1) Total outflow without wetlands	147.46	1187.56	1597.91	1923.06	1033.45	2505.05	8394
	ET Loss from wetlands	73.43	579.45	784.72	946.41	504.78	1229.36	4118
	(S 2) Total outflow with wetlands	74.03	608.11	813.19	976.65	528.67	1275.69	4276
Future Urban Development, Low Climate Impact Scenarios 3 and 4	(S 3) Total outflow without wetlands	678.45	5463.75	7351.74	8847.67	4754.72	11,525.32	38,622
	ET Loss from wetlands	91.41	713.61	969.80	1171.17	622.00	1518.95	5087
	(S 4) Total outflow with wetlands	578.04	4750.14	6381.94	7676.50	4132.72	10,006.37	33,526
Future Urban Development, Medium Climate Impact Scenarios 5 and 6	(S 5) Total outflow without wetlands	636.87	5128.88	6901.15	8305.39	4463.30	10,818.93	36,255
	ET Loss from wetlands	92.91	725.52	985.98	1190.66	632.35	1544.33	5172
	(S 6) Total outflow with wetlands	543.96	4403.36	5915.17	7114.73	3830.95	9274.60	31,083
Future Urban Development, High Climate Impact Scenarios 7 and 8	(S 7) Total outflow without wetlands	562.18	4527.36	6091.77	7331.33	3939.84	9550.08	32,002
	ET Loss from wetlands	93.72	731.95	994.69	1201.09	637.94	1558.02	5217
	(S 8) Total outflow with wetlands	468.46	3795.41	5097.08	6130.24	3301.90	7992.06	26,785

The stormwater runoff from each block under is summarised in Table 6 and depicted in Figure 6. There could be around 50% ET losses for the total runoff with the provision of wetlands in scenario 2 considering the current development condition. However, this was reduced to 15% of the total runoff when the area was fully developed (Table 6). Overall, the ET losses were of the order of 4–5.2 GL/year due to wetlands for all the scenarios.

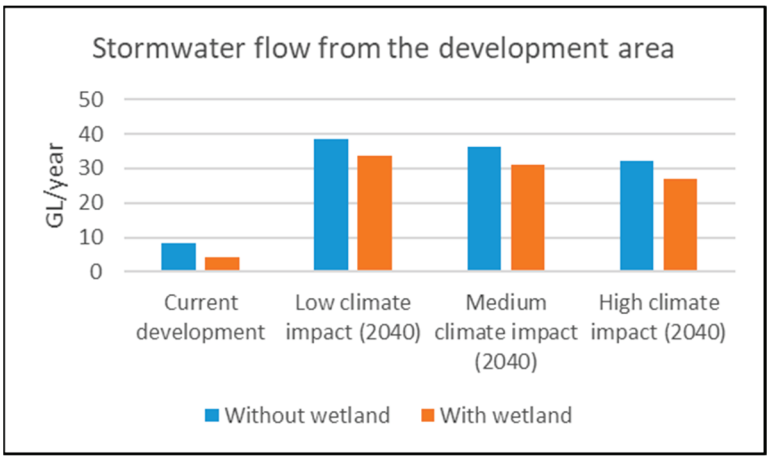

Figure 6. Stormwater runoff quantity from the development under various land-use development and climate change conditions.

4.8.2. Stormwater Pollutant Load from Various Scenarios

The MUSICX model also estimated the loads of TSS, TP, and TN from six blocks for different scenarios in the absence and presence of wetlands from stormwater runoff. Some of the key results are stated below:

- As expected, the loads of pollutants generated were proportional to the size of the blocks, with a larger area resulting in greater pollutant loadings. The pollutant loading was lowest for the smallest block 1A and highest for the largest block 5 (see Tables 1 and 7).
- The annual average loads of TSS were found to increase by over four times under the 2040 full urban land use with high climate change (most conservative scenario) compared with that of today. The same increasing trend occurred for both TP and TN, with larger loads of over three times in future urban development for the high-climate scenario compared with the existing agricultural land use (Figure 7a,b). This is likely due to the very high rate of stormwater runoff generated in all future cases than the default initial concentrations of the pollutant loads for current and future land uses. Even though the initial mean storm flow concentrations of the pollutants were higher for agricultural land use compared with urban-mixed land use (Table 5), higher pollutant loadings are expected for future urban scenarios as a result of the significantly higher stormwater volume generated in the future.
- The wetlands were found to be efficient at removing TSS, TP, and TN and were in line with the objectives of the Urban Stormwater BPEMG [40] with target removal percentages of 80% for TSS, and 45% for nutrient loads for TP and TN (see Table 7). It can be observed from this table that wetlands, at worst, were able to retain over 90% of TSS, 77% of TP, and 52% of TN in all scenarios. The sizes of wetlands in blocks could be reduced from 2% of the block area to meet best practice stormwater management current guidelines.

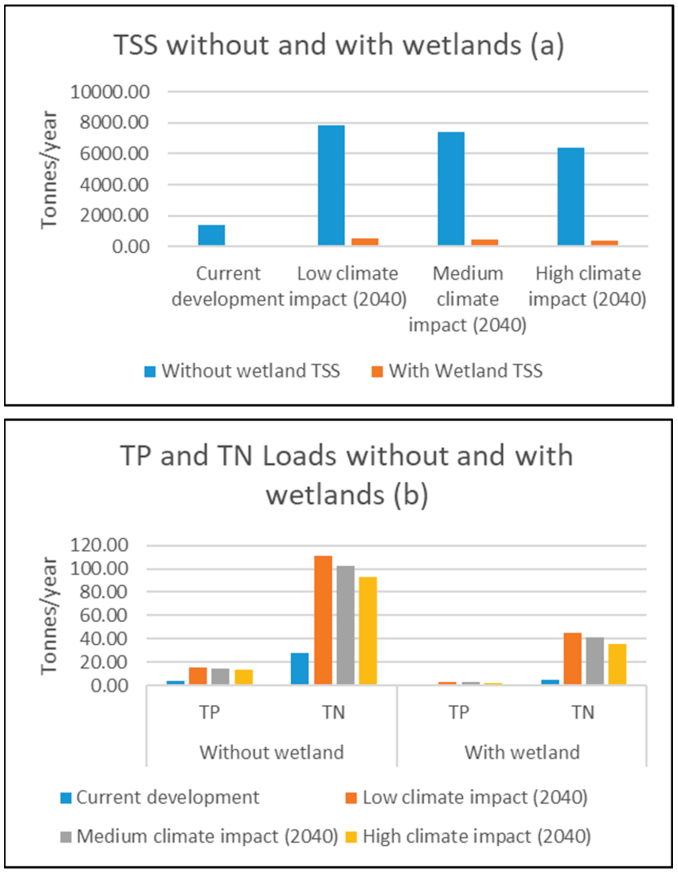

Figure 7. (**a**,**b**) Stormwater runoff quality TSS (**a**), TP, and TN (**b**) from development under various land use and climate change conditions.

Table 7. Annual average pollutant loadings for each block under various land-use and climatic conditions in the absence and presence of the wetlands, with their removal efficiency.

Development Condition & Climate Impact and Blocks (B)		TSS (Tons/Year)			TP (Tons/Year)			TN (Tons/Year)		
		Load without Weland	Load with Wetland	% Removal	Load without Wetland	Load with Wetland	% Removal	Load without Wetland	Load with Wetland	% Removal *
Existing Agricultural	B 1A	25.6	0.5	98.04	0.06	0.004	92.97	0.49	0.08	84.23
	B 1B	203.8	3.8	98.11	0.58	0.037	93.55	4.00	0.66	83.47
	B 2	240.7	5.1	97.87	0.75	0.050	93.32	5.19	0.85	83.68
	B 3	321.6	6.1	98.09	0.86	0.060	93.03	6.13	1.01	83.45
	B 4	172.7	3.4	98.05	0.47	0.032	93.00	3.51	0.56	83.91
	B 5	406.8	8.0	98.04	1.14	0.078	93.12	8.38	1.33	84.06
Future Urban Development—Low-Impact Climate Scenario	B 1A	131.7	12.4	90.55	0.28	0.06	77.53	1.89	0.90	52.33
	B 1B	1048.4	79.9	92.38	2.23	0.44	80.44	15.89	6.64	58.21
	B 2	1468.8	91.2	93.79	2.95	0.55	81.48	21.72	8.98	58.64
	B 3	1736.4	106.6	93.86	3.63	0.66	81.81	25.54	10.27	59.78
	B 4	954.3	73.2	92.33	1.91	0.38	80.18	13.26	5.59	57.80
	B 5	2484.3	134.5	94.58	4.58	0.83	81.90	32.90	13.07	60.29
Future Urban Development—Medium-Impact Climate Scenario	B 1A	128.29	12.1	90.60	0.25	0.06	77.57	1.84	0.85	53.97
	B 1B	1045.5	76.9	92.64	2.09	0.39	81.18	14.83	6.03	59.36
	B 2	1451.7	92.5	93.62	2.81	0.52	81.38	19.45	7.72	60.33
	B 3	1668.7	93.8	94.37	3.44	0.60	82.54	23.63	9.37	60.32
	B 4	904.7	60.5	93.32	1.77	0.33	81.35	12.71	5.19	59.14
	B 5	2186.0	134.2	93.86	4.42	0.76	82.84	30.41	12.07	60.28
Future Urban Development—High-Impact Climate Scenario	B 1A	112.8	8.7	92.24	0.23	0.04	80.12	1.66	0.72	56.56
	B 1B	918.4	56.2	93.87	1.93	0.34	82.53	13.07	5.09	61.03
	B 2	1160.8	63.1	94.56	2.55	0.43	83.05	17.92	6.85	61.80
	B 3	1510.3	78.8	94.78	2.92	0.48	83.39	21.28	8.05	62.18
	B 4	803.3	55.5	93.09	1.65	0.28	82.78	11.51	4.48	61.06
	B 5	1878.3	91.3	95.14	3.97	0.62	84.49	27.32	9.90	63.77

Note: (*) % removal of pollutant by wetlands is based on the loads with and without wetland provision in the blocks.

5. Conclusions

The overall objective of this investigation was to determine stormwater quantity and quality as an additional source for non-potable/portable applications in the Melton growth area under integrated water management approaches to meet the water demand of a newly planned development. The investigation explored a number of scenarios under changing land-use and climate conditions with and without the impact of the constructed wetlands. The stormwater quality investigations were limited to Urban Stormwater BPEM guidelines. Detailed investigations of wider water quality parameters are required for water treatment system design.

Modelling was based on 2040 conditions, considering full urban development of the Melton urban growth area and low, medium, and high-impact climate change scenarios. The conversion of land use from its existing agricultural use to a fully urbanised areas resulted in a remarkable increase in stormwater volume generated in the region. This increase in stormwater runoff volume was offset to some extent after the construction of wetlands due to significant ET losses happening in the wetlands. The hydrological modelling was based on local guidelines for various parameters due to the absence of catchment-specific stream flow data for model calibration and validation.

The modelling highlighted that the 8.39 GL/year of stormwater available today (if completely harvested) can contribute to meeting the required amount of potable and Class B recycled water (7.5 GL/year, reported by Greater Western Water). Under 2040 full urban land use and high climate impact, the provision of wetlands and 100% stormwater capture and treatment can generate 26.78 GL/year of potable water, which is more than the expected potable water demand of 23 GL/year.

The modelling with the provision of wetlands resulted in a considerable reduction in nutrient loads (minimum above 90% for TSS, 77% for TP, and above 52% for TN) compared with the untreated raw stormwater. It is suggested that the wetlands should be incorporated in the stormwater treatment train. To meet the water demand forecast at the Melton growth area and surrounding areas, the available stormwater in the region needs to be effectively captured, treated to an equivalent quality, and then pumped to the storage before

usage. Moreover, harvested stormwater would require treatment through the combination of natural/engineered processes and appropriate advanced treatment trains to produce water reaching potable standards.

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Review

How Scale Influences the Resilience of Urban Water Systems: A Literature Review of Trade-Offs and Recommendations

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Abstract: Climate change severely affects urban water systems (UWSs). Infrastructure historically designed for milder conditions cannot manage growing water demands and extreme events. To obtain a resilient water sector, adaptation and mitigation strategies must address rising water challenges while striving for net-zero emissions. Researchers have noted that extreme decentralization is positively associated with closing cycles while reducing transport costs. However, part of the scientific community defends centralized schemes due to economies of scale. The objective of this systematic review is to understand the trade-offs associated with the adoption of different scales at UWSs design and how this impacts system resilience. This process includes identifying different scale trade-offs and unique environmental aspects that influence the optimal scale suitability. A clear distinction was made in terms of scale concept and classification, considering different design levels. That is, considering the UWS at the city level and water management units (WMUs) at the local level. Similarly, a classification of different scales for each level, covering all water streams—supply, wastewater, and stormwater—was introduced. We defined the key environmental aspects that influence the optimal scale and location suitability: ten at the city-catchment level and eleven at the site-neighbourhood level. Scale impacts three major UWSs functionalities that have repercussions on urban resilience: net energy, net water, and ecosystem services (ES).

Keywords: urban water systems; resilience; planning; scale; suitability; urban water management; water-energy nexus

1. Introduction

Urban areas can be considered metabolizing organisms; they import flows from other ecosystems and (re)circulate them among users, while part of it leaves city boundaries as multiple forms of waste [1,2]. Cities account for 78% of all carbon emissions and 60% of residential water use [3]. This usage is impacted by changes in climatic conditions. For example, water scarcity affects approximately 11% of the EU population and, by 2030, will likely affect half of Europe's river basins [4].

The provision of water to cities, the subsequent wastewater treatment, and storm management require three main subsystems within the UWS: the water supply system (WSS), the wastewater system (WWS), and the urban drainage subsystem (UDS). These subsystems interact with each other and with the hydrological natural subsystems (Figure 1) to form the urban water cycle (UWC) [5–9]. For instance, the UDS is affected by the atmosphere via evapotranspiration and rain; soil and underground water sources can influence water supply; and infiltration processes can reduce stormwater flow to pipes. Usually, the UWC includes external water inputs from larger river basin resources. In

coastal cities, it may also interact with marine water bodies, through outfalls and desalinization plants [10–12]. They include networks, treatment plants, green infrastructure, and hybrid green-grey solutions, which are organized as centralized or decentralized water management units (WMUs), offering options for circular loops [13,14]. The spatial scope of this review is the UWS.

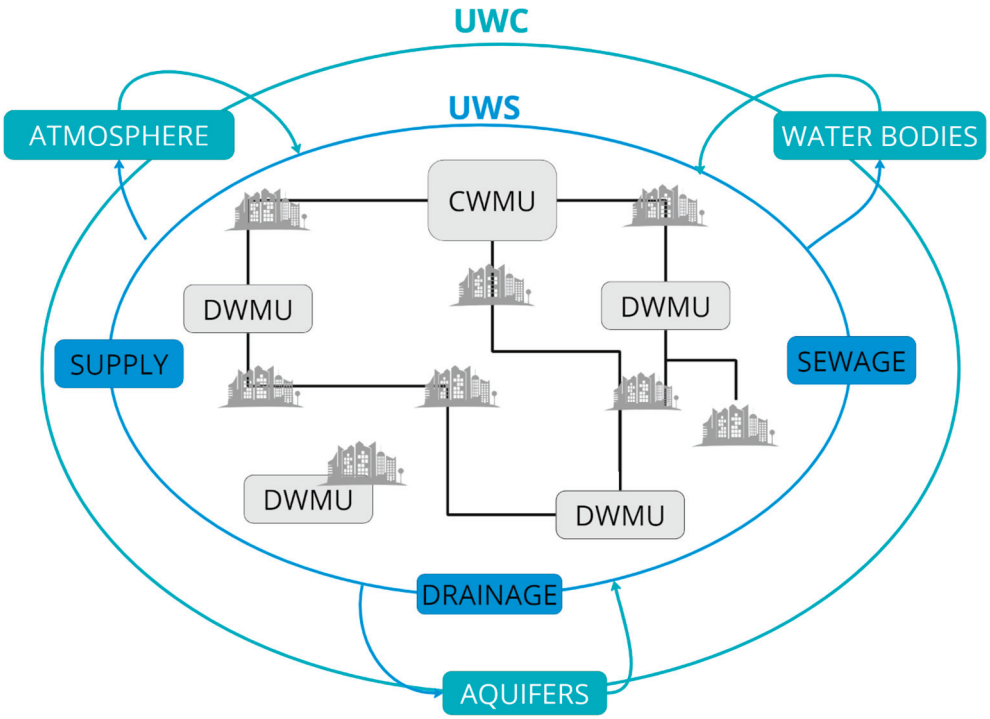

Figure 1. Urban water system (UWS) within the urban water cycle (UWC). Acronyms: DWMU: decentralized water management units; CWMU: centralized water management units.

In general, UWS resilience refers to the system's ability to anticipate variability, absorb disturbances and reduce damage, adapt to changing conditions, maintain functionality within a certain range over long periods, and recover back to acceptable functioning levels after disruptions, ensuring services now and in the future, while nature is still protected [15–17]. Analogous to the UWC, which can present multiple dimensions [7], resilience is multifaceted and has been referred to as having a wide variety of economic, social, organizational, environmental, and technical dimensions [18].

In this study, drawing on seminal work on resilience [15,17,19], we consider that three capacities can describe the resilience of UWS: **(i)** Absorptive, which involves absorbing and minimizing the consequences; **(ii)** Adaptative, which refers to the ability to adapt to changing operational conditions and recover quickly from stress while maintaining a minimum level of functionality. **(iii)** Restorative: rapidity of the system's return to an acceptable level of serviceability. It involves repair, replacement, or other recovery efforts. Common parameters used to measure the resilience of UWSs include water storage, water quality for safe use, flood, overflow, and runoff volume, baseline water stress (the total withdrawals related to the available renewable water supply), the return flow ratio, the drought index, the flood index, the city heat island index [5], network redundancy, the inflow-demand reliability indicator, and system energy surplus [17]. When assessing resilience, it is important to consider the various functions of a system and the trade-offs that exist between them. This systemic approach can effectively enhance the overall resilience of UWSs [17].

Thus, a full understanding of scale interactions and trade-offs can help optimize UWS design to enhance resilience properties. The definition of suitability recommendations for different scales can be translated into actions tailored to local water needs and demands [20].

Scale issues substantially impact how UWSs are designed and implemented, and a detailed understanding of these issues requires analyses that take a whole-of-system approach [21].

The objective of this literature review is to synthesize information for promoting best planning practices in the arrangement of UWSs, particularly in the context of how different scale scenarios impact UWS resilience. Scale is a theme discussed by researchers, but these discussions usually limit themselves to only one approach (decentralization vs. centralization), and their analyses often consider only one of the three subsystems (WSS, WWS, and UDS); thus, potential trade-offs and synergies across these sectors are missed.

There is a need to go beyond extremes and study how the optimal scale varies among WMUs and UWSs. How does the scale of each WMU impact the final scheme of the UWS? There are many trade-offs when transitioning from small to large scales. Usually, to gain a benefit, other aspects of the UWS are negatively impacted. How does this dynamic function? How is scale affected by urban conditions? Which scale is more appropriate under certain conditions? Is it possible to simplify the problem by grouping environmental conditions into two hierarchical analysis levels? How is scale related to UWS resilience, and what are the main impact routes of scale on increasing urban resilience?

The authors considered variables related to the suitability of different environments in the context of defining different scales at each WMU and at UWSs; they also accounted for the possible impacts of scale intertwined with other metabolic flows within the water–energy–food and ecosystem (WEFE) nexus. The key objective was to develop a greater level of understanding focused on scale trade-offs, especially across the water-energy nexus, considering the three subsystems within UWSs. Then, the feasibility of different scales of the WMU and the overall schemes of the UWS at both the city and site levels were studied to determine the optimal scale.

The optimal scale definition is proposed to be a function of a two-level hierarchical analysis:

1. The scale of the UWS is defined as a function of the environmental catchment and city-level variables and thus varies according to city typologies.
2. The scale of the WMU, considering neighbourhood and site conditions, varies across the urban fabric according to hydro-social variables.

A better comprehension of the relationships between different scales and environmental urban conditions can help decision-makers enhance the UWS scheme and increase the services of WMUs, especially under climate-stress conditions. Moreover, identifying clearer routes through which scale impacts urban resilience is important when determining which performance metrics should be considered when planning and operating UWSs.

The findings and contributions of this review relate to the proposal of a comprehensive scale conceptualization, establishing a clear distinction between scale classifications for UWSs and WMUs, and incorporating a nomenclature that covers all three subsystems (WSS, WWS, UDS). Additionally, scale trade-offs were listed, specifying the UWS resilience properties and affected subsystem(s). Finally, the environmental aspects influencing optimal scale and location suitability were defined at the city-catchment (CC) and site-neighbourhood (SN) levels.

2. Materials and Methods

The literature related to urban water cycle technologies was retrieved from the Web of Science (WOS) database and considered English articles worldwide. A total of 6225 published articles were obtained for all years (keywords used are shown in Appendix A). The screening process was conducted at two levels: the title and abstract and the full-text level. The preliminary criterion used was article classification according to the number of citations. Different citation number thresholds were set according to the publication period. Furthermore, articles from funding projects related to the review scope were included when the number of citations was greater than 25. Complementary articles related to the theme were retrieved through the machine learning web tool "connected papers" (Figure A1, in Appendix A), which enabled the collection of highly cited papers related to

the articles found through the keyword screening from WOS. Finally, reports and national and international guidelines on the review subject were also considered. The screening process involved reviewing titles and abstracts, followed by selecting articles specifically addressing the scale of UWSs. This process resulted in 51 scientific articles and 6 grey documents, which were further examined. Overall, a total of 57 articles, reports, and norms were thoroughly reviewed (Figure 2).

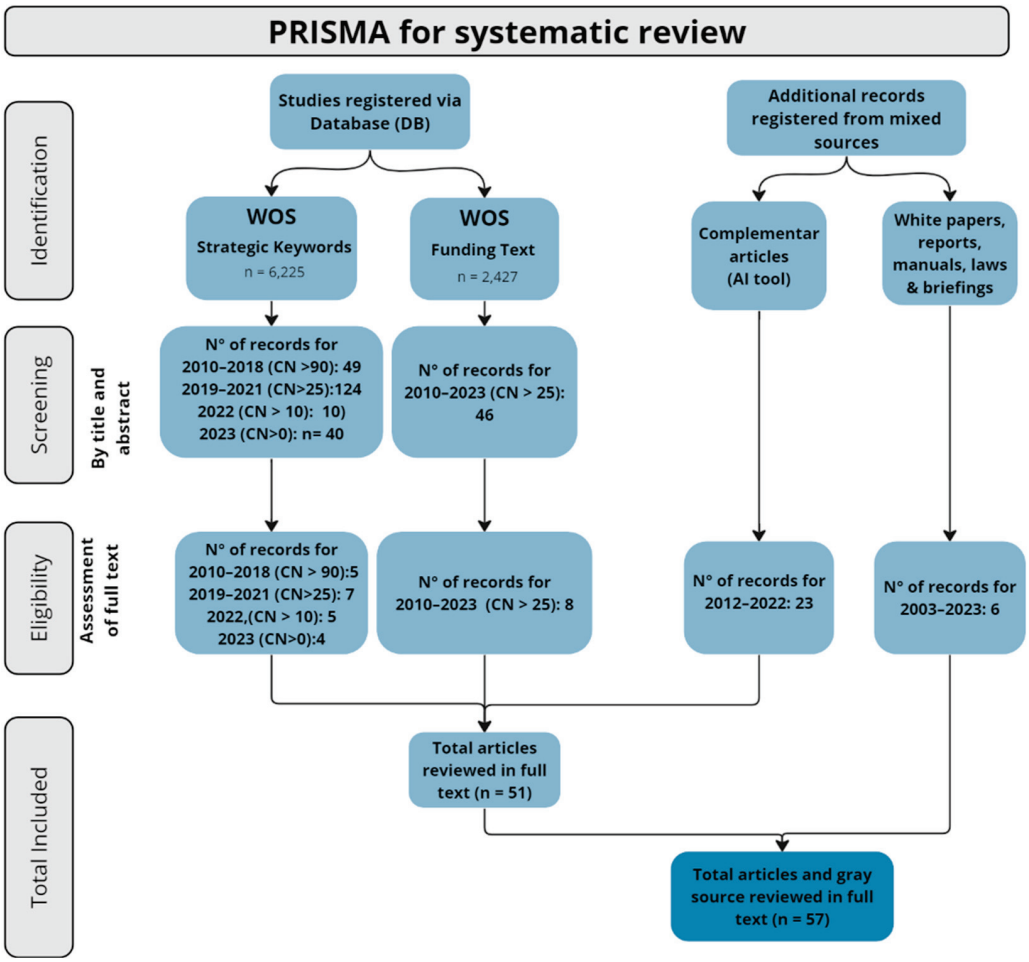

Figure 2. Methodology for the review following the PRISMA concept.

The selection of strategic keywords was guided by the study's goals and the similarity between key terms, resulting in seven keyword groups. These groups encompassed various aspects: the study context, including variations in terminology used in cities; the resources under investigation, such as different water streams and their word variations; frameworks related to UWS design and scale selection, such as decentralization and Integrated Water Management; technological approaches associated with UWSs scale; keywords related to the research approach, valuable for characterizing the technologies encompassed by UWSs design; keywords referring to assessment methods, such as systematic reviews, life cycle analysis, and suitability assessments; and keywords related to general interests addressing the social perspective of scale design implications on UWSs resilience, beyond technocratic considerations. Another keyword group, related to research projects that address studies about UWS design, was also retrieved. All the keywords used are shown in Appendix A.

3. Results

From the total of 57 articles and grey documents, 35 discussed sewage, 30 discussed supply, and 20 discussed urban drainage.

3.1. UWS Scale Definition

Scale definition depends on the concepts of centralization and decentralization. The literature has not made a clear distinction between the scale concept at the system or unit level (Figure 3). The UWS scale refers to the magnitude of water flowing through the system managed by centralized or decentralized WMUs, which are the elements that compose this system. The UWS can rely entirely on centralized treatment plants for all types of water streams (supply, wastewater, or stormwater) or can present distributed WMUs covering a diverse range of scales [22–28].

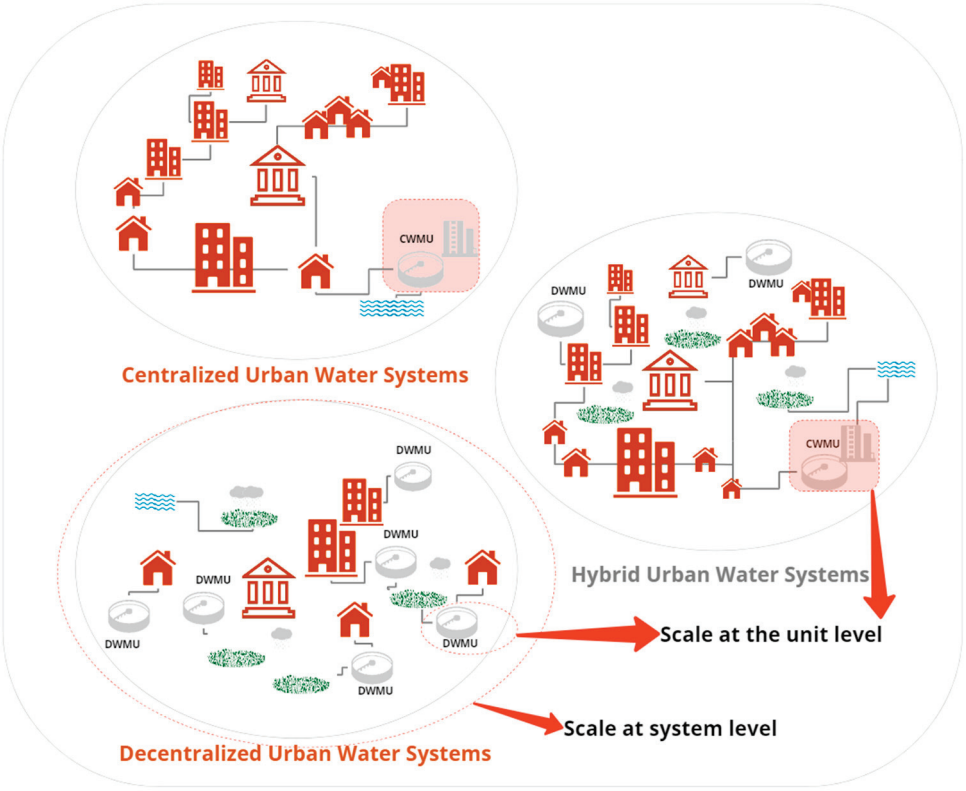

Figure 3. Urban water systems scale conceptualization.

Centralized urban water systems (CUWSs) consist of large treatment plants, distribution networks, collection pipelines, and drainage infrastructure carrying water far from the point of origin [22]. CUWSs usually assume a linear design, from freshwater abstraction to wastewater and stormwater discharge on water courses. Centralized WMUs include large treatment plants and storage water tanks in the supply subsystem to guarantee flow continuity at adequate pressure for water users [23]. Additionally, drainage systems (frequently combined with sewage) can rely on underground tanks to accumulate water during wet weather [24]. This design can prevent floods and overflows to water courses, as well as operational flow disturbances that affect treatment performance in wastewater treatment plants [25–30].

In the past years, the planning and design of decentralized systems have gained traction within the concepts of Integrated Urban Water Management (IUWM) and Water Sensitive Urban Design (WSUD) [21,22]. Both concepts focus on the coordinated management of water supply, wastewater, stormwater, and urban planning. They utilize locally available water sources such as rainwater tanks, stormwater harvesting, grey-

water reuse, and recycled water. According to those management paradigms, DWMUs are mostly emphasized in the literature when associated with technologies designed for water reuse [12,21,22,25,31–38]. As a result, schemes are better capable of diversifying water sources through closed loops centred on nonpotable reuse (NPR) [21,22,39]. Decentralization is also associated with distributed facilities and spaces that mimic nature to manage stormwater through green infrastructure (GI) [13,27,28,40]. GI is referred to in this document as any nature-based solution (NBS), green-(blue), or hybrid green and grey asset [41] of the system that mimics nature and contributes to the water cycle restauration. A decentralized UWS consists of overlapping small- and medium-sized facilities for water storage, distribution, and collection that occur at multiple spatial scales and can duplicate water pathways for potable and nonpotable water. As a result, decentralization enhances fit-for-purpose reuse of nonconventional water sources [31]. Decentralization places a strong emphasis on environmental functions, such as water reuse and reduced bulk water transfer, allowing for a wide range of technological options to be customized based on the intended purpose [22].

If decentralized, UWSs are composed of distributed WMUs working independently from each other. However, in urban environments, WMUs are ideally integrated into the centralized network, thus complementing the existing system rather than requiring a total system overhaul. This configuration involves service backup in case of failure and is referred to as a hybrid urban water system (HUWS) [22,39,42]. WMUs within a HUWS can be organized into larger managed cluster areas [39]. The clusters are managed at hierarchical network levels. The proposed HUWS combines decentralized onsite and middle-scale distributed treatment and reuse facilities to supply both potable and nonpotable water for various purposes (commercial, residential, green spaces, and industrial) and to manage stormwater through WSUD [21,27]. In summary, HUWS constitute a synergetic combination of centralized and decentralized WMUs, based on the circularity principle for water, designed to provide cascading, reuse, and recycling of multiple locally available water sources (rainwater tanks, stormwater harvesting, greywater reuse, and recycled water), to create new patterns of interaction and complexity and realize the value of water [31,39,41].

3.2. Scale Classification

The scale classification at system and unit levels varies among authors, and the literature does not clearly distinguish between the two. The classification also assumes different nomenclature for each subsystem within the UWS—supply, wastewater, and drainage. Considering the whole UWS, the literature terminology usually classifies systems as centralized, decentralized, or a combination of both, constituting hybrid systems [8,21,36,39,43]. A novel nomenclature classification distinguished UWSs as nongrid, small-grid, hybrid, or grid-dominated systems [44]. Nongrids include systems without pipes between individual buildings. Small grid systems present pipes between a small number of individual buildings. Grids are constituent elements of today's centralized systems. Hybrid systems integrate nongrid and small-grid solutions into grid-dominated systems. The interesting aspect of this classification is that it allows us to categorize UWSs considering the scale of the WMUs and the degree of interconnectedness through the network (grids).

WMUs within the UWS have been previously classified based on the number of people served or drainage area and range from centralized to intermediate levels of decentralization (urban cluster facilities) to complete decentralized facilities (onsite or individual solutions). Water supply and wastewater subsystems are often classified similarly; for example, the scale classification proposed by [45] states that units are decentralized at the household scale (<379 m^3/day flow rate), semi-centralized at the community scale (379–19,000 m^3/day) and centralized for plants at the city scale (3800 to 57,000 m^3/day or larger). In another study [46], the following classification was proposed: small-scale classification for onsite units serving up to 40 persons; medium-scale satellite sand urban cluster units (population ranging from 20 to 47,000), and large-scale classification for centralized city-scale units (serving populations of 9090 or greater). Additionally, the classification

proposed by [22] introduces three different scales for decentralized water and wastewater units: an onsite scale for individual properties; a cluster or development scale serving two or more dwellings, for which a local water supply, sewage collection and treatment are operated using a common ownership model; and a distributed system scale that provides services for large developments of 100 properties or more and is operated by water utilities.

For the drainage subsystems, the scale classification of WMUs was performed in the realm of sustainable urban drainage. A review by [47] revealed that the term "source control" can include three categories: urban best management practices (BMPs), which are housekeeping practices used to avoid pollutants coming in contact with runoff; site control units, which are used for areas of less than 2/3 hectares; and structural area or regional controls (which are often end-of-pipe solutions), which are appropriate for areas above $\frac{3}{4}$ hectares. First flush control drainage measures [48] were also classified according to the control implementation stage into source control, process control, and terminal treatment. NBSs have also been classified on different spatial scales. For example, ref. [49] grouped them into micro/neighbourhood or building scales, meso/district scales, and macro/city scales, while [50] categorized them into urban regions, cities/metropolises, neighbourhoods and building blocks.

3.3. Scale Trade-Offs

Centralization and decentralization present advantages, disadvantages, and trade-offs (Table 1), reflected in system functionalities (energy surplus, water storage, sustainable drainage capability, governance, and many more), which, conversely, influence the backbone components of the three main resilience capacities (absorption, adaptation, and restoration). The literature has cited many components of resilience capacities, of which four are considered key for UWSs: **(i)** Reliability, which consistently meets the goal; **(ii)** Robustness, which is the ability of the system to address a broad variety of contaminants and resist catastrophic failures; **(iii)** Redundancy (flexibility, connectivity), which is the ability to satisfy operational obligations using alternative components and strategies beyond minimum requirements to ensure that treatment goals are more reliable; **(iv)** Learning and investment ability, which relates to the degree of society cohesion, governance alignment, and investment capability to be able to change and retrofit to more sustainable paradigms while avoiding anthropic disruptions [15,17,19,51]. Therefore, an analysis of the impact of scale on UWS resilience was performed by evaluating the interactions between the scale trade-offs and the components of resilience capacities (resilience properties). This trade-off ultimately affects system functionality.

Table 1. Scale trade-offs impacting UWS resilience in different subsystems.

System Functionality	Resilience Property	Scale Trade-Off	Subsystem of Impact and Intensity *
Water storage (Diversification of water portfolio with climate-independent water-sources)	Reliability, Redundancy	Fit-for-purpose supply is more convenient at small-scale systems due to the proximity to the point of reuse. For example, nonpotable reuse to irrigate green DWMUs. On the other hand, the larger it is the scale, the greater the flow stability, allowing more security of the demand concerning reclaimed water generation [21,22,25,27,31,39]	WSS WWS UDS
Water Storage (Diversification of water portfolio)/Energy surplus/Governance	Reliability	Increasing the number of decentralized circular facilities increases the buffer capacity against scarcity and vulnerability. On the other hand, water reclamation and monitoring at these facilities will demand additional energy, with lower economies of scale for treatment than at larger units [21,31,44,52,53].	WSS WWS UDS
Water Storage (WMUs interconnections)	Reliability, Redundancy	Decentralized schemes intertwined with each other at the cluster/district level, or the whole system intertwined through smart water grids differ from extreme decentralized schemes composed of autonomous DWMUs. The higher the interconnectivity, the higher the flexibility (redundancy of those systems). On the other hand, risks of cascading effects or cyber-attacks that can reach a greater number of facilities is increased [51,54].	WSS WWS UDS

Table 1. *Cont.*

System Functionality	Resilience Property	Scale Trade-Off	Subsystem of Impact and Intensity *
Energy surplus	Reliability	Smaller-scale units generally reduce energy requirements for distribution, collection, and conveyance, while larger treatment facilities present, per volume, a lower carbon footprint, energy demand and cost for treatment, due to economies of scale [31,36,42,46].	WSS WWS UDS
Target water demand	Redundancy	Circular distributed smaller-scale units hold the ability to mitigate peak water demand and, thus, reduce the need for capital investments to increase the treatment capacity of existing supply facilities, while relieving pressure on central treatment plants and reducing wastewater pumping costs. On the other hand, each unit holds a smaller storage capability, being easily affected by external disturbances (more failures per time) [31,33,42,51,55].	WSS WWS UDS
Governance (Operation and monitoring)	Reliability, Redundancy	Larger-scale systems suppose less complexity to monitoring than operating multiple smaller units. This arises from fewer points to control in a larger-scale system. On the other hand, if anomalies are detected, is necessary a greater effort to recover, since the potential damage affects higher volumes rapidly; additionally, if one CWMU fails, the potential disruption damage (service covered area and people reached) is higher [32,39,52,56].	WSS WWS UDS
Governance (river basin discharge control), Sustainable Drainage a	Reliability	Large scale water collection and treatment sites alter natural hydrological systems leading to stream depletion, shoreline erosion, contamination, and other negative biological outcomes. On the other hand, high discharge flows in arid river basins are frequently responsible for maintaining minimal ecological flows and water quantity for unplanned reuse by downstream systems [12,31].	WSS WWS UDS
Water Storage (water cycle restoration), Sustainable drainage	Redundance, Robustness	Smaller-scale green-DWMUs facilitate local management and reduce the volumes of rainfall converted into runoff, avoiding piping overflow while protecting headwaters. On the other hand, they present a lower return period design capability, being unable to store a great amount of rain. Especially during extreme rainfall events, flow efficiency management is reduced. Thus, larger-scale facilities are needed for managing stormwater when dealing with high return periods [24,40,48,57].	WSS WWS UDS
Water storage (Leakage loss reduction through conveyance systems)	Reliability, Learning and investment capability	Systems based on a higher decentralization degree have lower water loss, due to leakages in water supply distribution, and soil contamination, by occasional exfiltration. On the other hand, monitoring demand-side management (DSM) is more complex. DSM hopes to evaluate human behaviour, detect water losses, and reduce consumption patterns based on data-driven measures. As some of the supply comes from different sources (ex: households' water micro-trading), other than from the central utility plant, this task will become more challenging [43,54].	WSS WWS UDS
Sustainable drainage, Governance	Redundancy, Learning and investment capability	Sustainable drainage is based on distributed small scale GI management units. They can deliver ecosystem services across the city. On the other hand, the footprint is higher than when employing grey infrastructure; and maintenance requirements are usually more complex since their backbone is a living ecosystem body [25,58].	WSS WWS UDS
Energy surplus Water quality	Reliability, Redundance	Large UWSs with CWMUs, obligated to remove phosphorus from wastewater, demand higher energy requirements due to longer aeration period; this prompts stream separation at the source; source separation could employ hybrid schemes designed to harvest energy/nutrients from black water at DWMUs, while lower carbon concentrations flows are treated at CWMUs. On the other hand, conventional centralized facilities hold higher operational security, lower complexity of phosphorus removal, and lower water quality problems due to malfunctioning risks [59,60].	WWS WWS UDS
Water quality	Robustness, Reliability	HUWS encompasses the integration of DWMUs and CWMUs. The centralized network functions as a background multi-barrier system for wastewater and/or stormwater. On the other hand, interactions of centralized and decentralized units, like increasing solids and other contaminants concentration in the wastewater pipes could increase corrosion and sedimentation problems [8,21]	WWS WWS UDS

Table 1. *Cont.*

System Functionality	Resilience Property	Scale Trade-Off	Subsystem of Impact and Intensity *
Governance	Learning and investment capability	Decentralization lowers capital intensity and shortens the construction timeline, through modular implementation. This avoids unutilized infrastructure in the beginning years or the risks of assuming population projections that may not reach the expected size. Moreover, decentralized schemes hold greater reconfiguration and retrofitting capability than centralized ones. On the other hand, the frequency of investment cycles will increase, requiring more retrofitting for additional units [8,31,61].	WWS WWS UDS
Governance	Reliability, learning and investment capability	Management of smaller-scale facilities favours the cohesion and synergies between local actors. On the other hand, larger WMUs count with a supportive legal framework and a greater acceptance by the water sector, with a deep understanding of operation and maintenance procedures. Thus, avoiding possible disturbances of changing the management paradigm. Complementary, society engagement demands greater effort from institutional parties to put in agreement multiple actors, which must receive adequate training and maintain continuous commitment during long periods [12,25,32,39,46,56,59,62].	WSS WWS UDS
Water justice	Redundancy, Learning and investment capability	Decentralized water units can augment resources and provide deeper, long-term cost savings to residents in underserved neighbourhoods by replacing or fixing water infrastructure closer to its source, showing an inherent ability to improve water service equity and greater adaptability to local contexts. On the other hand, facilities maintenance can be forgotten by authorities, and not get the adequate investment or structure because low-income communities usually provide no profits [31].	WSS WWS UDS
Governance (operational and monitoring capability)	Redundancy, Reliability Learning and investment capability	Smaller-scale units favour effluent separation at the source, improving nutrients and energy recovery. On the other hand, operational costs, and complexity to recover are higher. There is a greater experience of resource recovery practices at larger-scale units. Centralization also favours an increase in the total load to recover, even though materials are more diluted [31,32,36,46,59].	WSS WWS UDS
Energy harvesting	Availability of Energy surplus	Harvesting thermal energy for hot water energy savings is more advantageous when closer to the source, at smaller WMUs, due to higher efficiencies and reduced heat losses to the environment during conveyance. On the other hand, the total energy load to be harvested is lower than in larger systems with higher flows; and flows must exceed a minimal threshold to achieve economic availability [38,46].	WSS, WWS UDS

Notes: * Grey intensity in the table: White represents no impact; Lighter grey represents lower impact intensity in the subsystem; Darker grey indicates a greater impact intensity in the subsystem.

Decentralized systems present a greater ability to utilize a diversified portfolio of water sources and increase system buffer capacities through the NPR closer to the source and user. Therefore, it reduces potable water demands [22,31,36,37,39,42,55]. According to [31], water savings promoted by closed-loop decentralized systems reduce the energy demand and ecological footprint of UWSs. For example, past studies of onsite greywater or combined greywater and rainwater treatment have achieved system-level energy savings of more than 50% and reduced consumption by 75% compared to conventional systems. Decentralized solutions are frequently composed of green-blue or grey-green solutions, especially when the enhancement of urban land water management capacity through WSUD is considered [21,27,62]. NBSs can be a beneficial addition to decentralized water systems, acting as a prefiltration step for drinking water treatment, a polishing step for wastewater treatment, or a comprehensive runoff treatment zone for water before its re-entry into the watershed [14,58]. Nevertheless, the potential for adequate retention of stormwater is greater at small scales [40], although, during extreme events, their ability to manage flows decreases due to adverse hydrogeological conditions, such as fast saturation of the first soil layers [24,40,48,57]. By extracting and reclaiming wastewater from upgradient locations, decentralized treatment can minimize the need to pump reclaimed water back to users [55]. This could be accomplished through DWMU based on sewer mining techniques [63] to

serve downstream areas. Decentralized water technologies can secure preferable business conditions for urban industries, alleviate disproportionate access to urban water services, increase the energy efficiency of compact and mixed-use developments, and address local issues through community involvement [31]. Linking the potential of decentralized water infrastructures with the broader urban development agenda can both attract more financial resources and create opportunities for intersectoral collaboration [31]. Considering spatial characteristics, under the scope of global analysis, particularly in developing countries without old and established water conveyance systems, decentralized water treatment and distribution allows flexibility in addressing water access and sanitation in a modular treatment network [39,44,58,59]. Modularity can flex with the expanse or sparsity of a dynamic population, improving redundancy through smart-water grids [39,54]. Distributed plants may also be more resilient to wilful attacks, as they limit the impacts of system failures to smaller areas [31,42]. Conversely, the risks of cascading effects and cyber-attacks increase at higher levels of network interconnectedness between distributed WMUs [51,54]. In the case of malfunction, decentralized systems, particularly residential ones, pose challenges as technicians may take longer to address issues. These systems require efficient instrumentation for automating their operations and for triggering alarms in central water-control units based on high-tech solutions [39,43,53,54]. The flexibility of decentralized systems presents trade-offs, especially concerning the greater sensitivity to variable flows throughout the water system and the increased management complexity. Subsequently, they can be seen as less reliable [31,58]. The latter is one of the reasons for selecting WMUs at the cluster scale [39,46,52,55].

Centralized WMUs offer greater service reliability for water reuse than do smaller-scale WMUs when considering consistent and continuous flow rates and improved water quality monitoring. Monitoring water quality is simpler at centralized systems due to fewer sampling points and the presence of instrumentation and skilled personnel right next to the WMU, thus reducing costs and operational complexity [43,52]. These systems benefit from specialized teams and companies with appropriate management experience. Due to the added capital and operational costs associated with high network complexity requirements, centralized configurations discourage fit-for-purpose water supplies and favour quick residual and rainfall water removal to central treatment plants. Frequently, the operating costs for collection/distribution networks in centralized reuse systems counterbalance economies of scale in treatment [42,46,55]. For example, water reuse in centralized systems would require more pumping energy because facilities at these schemes are typically located at low points in collection systems. In water-stressed regions such as California and San Diego, the conveyance energy can be 20 to 39.5 times greater. In the US, 80% of electricity in the water sector is used for conveyance [42].

Within the WEFE nexus, scale affects the capacity for nutrient recovery. The closer the material is to the source, the greater its concentration [46]. Treatment proximity to the source also influences the amount of energy required to extract and recover materials from wastewater [49]. Thus, mixing resources should be avoided during the recovery stage of WMUs. For example, there is a reduction in losses to the atmosphere during pipe transport and storage, which can account for 50% of the potential nitrogen that needs to be recovered [49]. The treatment of urine from NoMix toilets has shown higher recovery rates [46,49]. Decentralized scenarios also require smaller investments in piping infrastructure for stream separation and would be easier to implement for new buildings and development areas [31,36]. With all that in mind, it is reasonable to assume that nutrient concentrations can be even lower under wet conditions; consequently, recovery would demand more effort due to dilution and added contamination from runoff and carried materials. The trade-off is that additional local infrastructure is needed since more energy and operational complexity are required to separate and recover materials. Furthermore, the total load of resources to recover, even though they are more diluted, increases at larger scales [46,49,60,64]. Thus, the optimal scale is defined based on the specific context of the location and the selected technology [46,49].

Recent studies and reports support the adoption of middle-scale DWMUs at HUWS. Hybrid systems can exploit multiple-scale approaches, in which decentralized units return residuals to centralized treatment systems downstream for further treatment [36,39,41,46]. Hybrid systems, with coexisting centralized and decentralized treatment plants, handle freshwater, water reclamation, and resource recovery; furthermore, they receive concentrated fractions of wastewater and biosolids from smaller treatment facilities for further reclamation [21,22] or vice versa [59]. This approach exploits the decentralized approach, reducing supply expenses to treat water to potable standards for nonpotable uses, the transport distances, and associated energy costs [39], while benefiting from economies of scale at the middle scale and larger units [36]. The existing infrastructure is maintained to guarantee high-quality standards and adequate monitoring for potable supply. HUWS also allows for profit from the existing infrastructure and avoids future retrofitting at pipelines or centralized units due to increasing water flow. While integrating DWMUs into the current centralized system offers numerous benefits, the interactions between CWMUs and DWMUs present complexities that could cause unintended long-term negative consequences [21]. For example, reduced flows and increased solids concentration in wastewater pipelines could escalate corrosion and sedimentation issues [21,31]. Retrofitting UWSs for the transition to hybrid schemes is challenging due to limitations such as potential high costs and scarce availability of land, different investment cycles compared to centralized solutions, and governance barriers [8,61,65]. Managing the increased complexity will require a new approach at smaller-scale units, potentially involving private actors, and the creation of new responsibility roles to ensure water quality and safety [8].

3.4. Scheme Suitability

What is the optimal scale of water schemes for the UWS and WMUs? This seems to be a straightforward question. However, the answer depends on many factors, ranging from the actual state of the UWS [42,52,59] to the surrounding environmental conditions [8,21,36,38,61] including managers' and society's values, which influence the selection of the most adequate option [66,67] according to the priorities established by behaviour trends. The analysis of environmental conditions can be performed at two hierarchical levels. First, variables at the catchment-city level must be considered. This level embraces the characteristics of the river basin and city location within the basin, which, combined, generate many city typologies, namely, city hydrological typologies, since the aim is to improve UWS design based on strategies that consider cities' hydrological categories. Similarly, the second level of analysis refers to understanding how site and neighbourhood characteristics vary across the urban fabric. The comprehension of a city typology helps identify factors that influence macro aspects of the UWSs. For example, the main water sources and characteristics of the CWMU and the total flow amount should be preferably treated by decentralized and centralized facilities. Moreover, site characteristics are fundamental for defining each unit's optimal scale and selecting priority sites that are most appropriate for DWMUs. Thus, this review aimed to identify not only the relationships between those conditions at both levels, but also the most suitable schemes for UWSs at the macro level and the best scale approach for WMUs considering local conditions. Many variables at the city-catchment (CC) level influence city hydrological typologies. Ten attributes considered pivotal for defining the scale of the UWS were selected. When considering site-neighbourhood (SN) conditions, eleven variables were considered for setting WMU scales. Some of the selected variables were analysed together since they present effects on WMU scale selection that are highly linked to each other, making it hard to evaluate them separately. All variables, at CC and SN, and their effects on scale recommendations are shown on Table 2.

The CC variables influencing the UWS scale include the following: **(i)** sea proximity (coastal or inland) refers to the city position within the river basin, whether upstream or downstream, and whether the catchment outlet is a river or ocean; **(ii)** freshwater source characteristics refer to the user's proximity and quality of freshwater resources, expenses

required for transport and treatment, and added environmental costs; **(iii)** climate and water for (non)consumptive uses refer to the rainfall pattern and available freshwater, which characterize the allowed dependency degree of the city on natural water sources; **(iv, v)** city human density and economic profile are related to the citizens' water consumption pattern, as well as population distribution and density impact, especially on the energy demand for supply distribution and wastewater collection; **(vi)** topography expresses the degree to which topographical variations impact the pumping demand of the whole system; **(vii)** the energy matrix source/electrical grid represents how clean, or carbon-based, energy used in the UWS affects greenhouse gas (GHG) emissions; **(viii)** social awareness reflects citizens' behaviours and political strategies and the commitment level of a city to improving resilience; **(ix)** water quality requirements refer to the legal framework under which utilities and users are subjected to supply water and discharge; and **(x)** the actual state of the UWS refers to the need to expand the system's coverage and retrofit existing WMUs and networks that interconnect them. Planning the scale must consider the baseline conditions to take better profit from the already-made investments. Additionally, the utility experience with smart sensor networks will impact the available database, which is necessary to understand supply demand and wastewater generation patterns and could help in the transition to a more decentralized UWS.

Concerning the scale and site suitability of WMUs, considering SN conditions, **(i)** water quality requirements affect scale differently across the urban fabric. This influences the selection of appropriate sites for installing autonomous DWMUs, which need to discharge some portion of the water (either a reclamation facility or water/wastewater/stormwater management unit) to aquifers or watercourses next to the facility. A contamination risk assessment must be considered; **(ii)** the actual state of the UWS also influences the optimal scale of WMUs across the city differently. This is related to the economies of density when placing DWMUs. When the goal is to promote the transition to a circular and more decentralized UWS, the density of DWMUs must be considered. For example, findings on the tasks carried out by specialized external contractors who travel to treatment plants, empty residuals, or assist with repair and monitoring, indicate that costs would be very high in the case of low-density adoption of distributed systems, and average economies of density diminish for values equal to 1.3 DWMUs/km^2 or above [52]. This suggests that priority must be given to the modular adoption of DWMs, where incentives are provided at the neighbourhood scale, to avoid the sprawl effect, which can increase costs. Therefore, the placement of DWMUs should define target areas to avoid sprawling those treatment facilities; **(iii, iv, v)** growth pattern, land use, and building type refer to the varying interactions between citizens, their activities, and how water consumption/generation patterns vary at land parcels due to different building types [31,37,38]. For example, considering land use scenarios, three main types of land use represent intense occupation patterns that favour decentralized systems, namely, underserved residential neighbourhoods, mixed-use development, and industrial areas [31]. Underserved low-income areas are considered because decentralized systems that replace or fix the actual water infrastructure closer to its source could provide long-term cost savings. Mixed-use development is a more compact urban design that can exploit surplus residential greywater and commercial deficits. Consequently, it requires shorter water networks and offers a greater opportunity to adopt sewage heat recovery and enhance greywater treatment efficiency. Additionally, the industrial water demand can frequently be satisfied by lower-water quality from stormwater harvesting and greywater for the NPR; **(vi)** the percentage of impervious surface: SN conditions that present a high portion of the sealed area and the low presence of green draining DWMUs exhibit greater runoff production entering the drainage subsystem. Furthermore, areas with stormwater connections to pervious land, here understood as green-DWMUs, can maintain better ecological conditions than those directly drained to pipes. Therefore, areas with low to moderate urbanization levels, which have impervious surfaces of up to 25%, present diverse water ecological statuses [40] in the face of the presence of buffering pervious areas; **(vii, vii, ix)** social vulnerability, human density, and green infrastructure coverage:

these variables should be considered when placing green-DWMUs to manage water while promoting distributive green social justice. Higher-density areas are a priority because a greater number of citizens would benefit. Moreover, areas with greater societal challenges related to social vulnerability are a priority for equitable justice, reducing the vulnerability of the most needed areas. Additionally, these areas present lower land prices for installing DWMUs. Above all, green coverage must be considered; that is, sites considered uncovered due to their location being very distant from green-blue spaces should be considered a priority. Other aspects related to ecosystem services (ESs), such as urban heat island reduction, should be considered when placing green-DWMUs [20,68,69]; **(x, xi)** Hydrological draining zone and elevation profile: DWMUs for local source control are more effective options if the intention is to reduce water flooding before runoff enters the drainage systems; they help to minimize pluvial flooding, protect headwaters, and promote aquifer recharge, while larger WMUs, such as ponds or underground water tanks, are a much more effective option if the intention is to reduce flooding in downstream areas and mitigate fluvial flooding [70]. The consideration of those variables depends on the purpose of the WMU.

In summary, to determine the scale of WMUs for drainage, different strategies must be implemented, considering the alignment between urban-subcatchment requirements (SN conditions) and the overall CC needs [47], since the latter governs the main goals desired for the specific UWS being designed. SN conditions can help define scale suitability and priority sites for DWMUs or CWMUs, while CC variables help to define the total amount of flow treated by centralized or decentralized facilities, which produces macro implications over the whole UWS.

Table 2. Scale recommendations for establishing different UWS schemes considering the environmental aspects at two hierarchical levels (city-catchment and site-neighbourhood).

EA [1]	EHL [2]/Ref.	Scale Recommendation
Sea proximity	CC [5,12,71,72]	The scale of WMUs for circularity purposes must consider keeping ecological river flow downstream at inland cities, while coastal cities should avoid discharge since costs and energy demand for desalination are greater than treatment to reuse. Coastal cities can associate reuse and desalination in CWMU for cost efficiency, while inland cities are optimal for various scales, considering discharge implications in the river flow quantity downstream for ecological reasons and possible unplanned water reuse.
Freshwater source characteristics	CC [5,71,73,74]	Diversifying scale for circularity purposes is more advantageous the more distant and deeper are freshwater sources that feed the centralized scheme, due to its increased costs with infrastructure and energy (pumping and piping). Likewise, lower quality of water sources (such as seawater) requires higher costs for treatment. Therefore, encouraging scale diversification to promote circularity.
Climate	CC [5,37,75,76]	The more severe the climate conditions are, the higher the need for scale diversification to close water loops. Cities with high water stress must avoid water storage reliance on rainfall behaviour. This can be achieved through the diversification of the water portfolio (many waters at many scales), prioritizing reuse and the right water for the right use and avoiding energy expenses to a higher quality than needed. Moreover, green-DWMUs can deliver ES and promote adaptation to heat island effects. The latter, during droughts, to continuously deliver ES needs irrigation, only sustainable when based in DWMUs for local nonpotable reuse.

Table 2. *Cont.*

EA [1]	EHL [2]/Ref.	Scale Recommendation
City human density and economical profile	CC	City human density influences the portion of the system flow that should be treated by CWMUs or DWMUs. Lower-density cities increase costs in conveyance, tending towards an increase in DWMUs. Human density has shown a greater effect than topography on the optimal scale. Moreover, population impact projections of future water needs. Complementary, the city's economic profile (e.g., industrial, tourist-oriented, or next to agriculture fields) influences the presence of certain users that demand high water flows per capita. This leads to the existence of CWMUs with low serving areas, avoiding conveyance costs while maintaining economies of scale.
	[32,37,38,52,77,78]	
Topography (steep or flat)	CC	Higher pumping costs due to terrain conditions (such as steeper cities) encourage the adoption of HUWS with larger flows being treated by DWMUs. This will reduce conveyance distances and, consequently, the pumping due to high topographic complexity.
	[36–38,42,71,73]	
Energy matrix source/Electrical grid	CC	The optimal scale must consider water needs and energy demand for running the whole UWS and each WMU. In the case of a low carbon-based energy matrix, systems can afford higher energy-intensive transport and treatment systems since they do not implicate high environmental impact due to GHG emissions. Moreover, systems should select the best technology alternative to expand the energy recovery capacity both at small (ex: thermal energy recovery) and larger scales, as well as increase green-infrastructure carbon storage capability. Since the energy demand for circular loops is clean, the optimal scale selection will favour the reduction in other resources withdrawal,
	[76,79–82]	
Social awareness	CC	Attitudes towards setting system scales are shaped by various factors, including awareness of water scarcity, perception of risks and costs, trust in science, and the social influence of relevant agents. Society engagement and implication are also important when managing DWMUs and defining responsibility roles.
	[66,67]	
Water quality e requirements	CC/SN	Water quality requirements vary according to the legal framework, and water sensitivity to discharges. For example, high discharge standards or higher requirements for centralized supply systems increase treatment baseline costs and energy requirements, subsequently lowering the required additional costs for water reuse. Emphasis should be placed on low and medium-scale nonpotable reuse (NPR) facilities, which can lower pumping costs through dual piping systems and treatment expenses compared to potable reuse facilities. This context variable has not only macro implications at the city scale but also at SN. That is because autonomous DWMUs need to discharge some part of the treated wastewater/stormwater to aquifers or watercourses next to the facility. For example, green-DWMUs must consider the risk of contaminating aquifers, as well as avoid shallow underground water.
	[5,12,31,36,39,71,72,83]	

Table 2. *Cont.*

EA [1]	EHL [2]/Ref.	Scale Recommendation
Actual state of the UWS	CC/SN [42,52–54,59]	System scale for circularity purposes is largely determined by existing infrastructure. HUWSs should take advantage of retrofitting investments due end of central WMUs' lifespan or piping restorations. Additionally, considering the SN level, the management of DWMU presents economies of density. Therefore, the placement of DWMUs for the water/wastewater subsystems should be sectorized through planned target areas, to reduce operational costs. Moreover, HUWS should consider the adoption of smart-water networks to increase redundancy. The utility baseline conditions of the sensors network and. high-tech infrastructure experience not only influence the ability to adopt smart water grids but also provide the database to assist the transition to higher decentralization levels of the system. For example, historical data on water demand, wastewater generation or rainfall overflows, through sensors at strategic points of the network, would allow to structure cluster zones to be served by DWMUs areas.
Growth pattern (compact, sprawl), land use (socioeconomical activities) and building type	SN [31,32,36–38,59]	In suburban, sprawl-occupied areas, individual solutions and other smaller-scale solutions are more appropriate, while in dense areas, the benefits of economy of scale increase, tending to larger-scale WMUs. Mixed-use development requires shorter water networks and offers a greater opportunity for heat recovery, and industrial water demand is frequently satisfied by lower-quality standards. High-rise buildings could employ middle-scale DWMU with lower treatment unit costs than single dwellings. These aspects influence the water-energy (WE) nexus, by finding the optimal scale in between extremes, where the total costs of conveyance and treatment are the lowest. To reduce operational and energy costs to reach water quality requirements, mixing must be avoided before coming into treatment. Therefore, decentralization in areas with specific contaminants generation should be considered. For example, industrial polygons are a priority to reduce mixing with urban wastewater.
Percentage of impervious surface	SN [40,77,84]	Runoff flow pressure in the drainage subsystem is affected by total impervious surfaces, turning areas more vulnerable to extreme rain events. To reduce runoff pressure at the drainage subsystem it is important to promote permeable DWMUs while reducing resident impervious surface footprint. Furthermore, reducing the portion of impervious surfaces indirectly connected to underground pipes, using buffer green-DWMUs (small sized green zones), would also reduce total runoff.
Social vulnerability, human density, and green-infrastructure coverage	SN [20,68,69]	To improve distributive environmental justice, green-DWMUs should be promoted where the population is living far from recreational green spaces, using as criteria the maximum walking distance to green patches suggested by authorities. Additionally, priority must be given where a greater number of citizens (higher sector human density) can be benefited. Moreover, cost benefits are higher in low-income areas. This can be attributed to lower land prices for installing GI and vulnerability reduction where societal challenges are higher.
Hydrological draining zone and elevation profile	SN [30,58,69,85]	Soil drainage capability, erosion vulnerability, hillslope stability, and the hydrological zone should be considered when placing green and/or permeable WMUs. The scale at upstream and middle zones should be smaller, while downstream areas require larger-scale facilities

Notes: [1] EA: Environmental aspect; [2] EHL: environmental hierarchical level, city-catchment (CC), site-neighbourhood (SN).

3.5. Optimal-Scale Studies

As seen, the optimal system scale depends on the costs and energy demands of treatment processes and context variables, such as local topographic, demographic, and hydrologic characteristics; energy conveyance requirements; water demand projections; and baseline investments in centralized systems [22,36,38,42,76]. Many studies that define optimal scales are based on life cycle analysis (LCA) [33,37,45,55], techno-economic assessment [59,86], sustainability index of different scenarios [87], and optimization models [36,38,42,52,61]. In these studies, a central-scale trade-off is highlighted; while centralization favours economy-of-scale treatments, it requires much investment in capital and operational costs for pipelines to meet conveyance needs, especially for the reuse of reclaimed water [32,33,39,42,55,88].

For example, ref. [55] compared four different scales and concluded that reclamation and reuse of greywater at the cluster level was the best option among the three reuse options, although middle and extreme decentralization scale alternatives were more socially beneficial. Compared to the other two centralized alternatives, the main advantages of the cluster level were water savings, community engagement, and urban landscaping. [37] assessed the location and scale of NPR and discovered that for high-elevation areas far from centralized treatment plants (2000 m^3/day), decentralized NPR (20 m^3/day) could lower energy use by 29%, but in low-elevation areas close to centralized treatment plants, decentralized reuse could increase energy demand by up to 85%.

The technoeconomic assessment of three different scale approaches (a centralized, hybrid scheme based on decentralized treatment of black water, together with centralized treatment of greywater, and decentralized treatment of grey and black water) showed that extending sewage connections to a distant treatment facility is less costly than doubling the pipeline at the household level. Results highlight that pipelines govern economies of scale. The decentralized configuration has just been shown to be advantageous (5% less expensive) once the potential energy offset derived from biogas production was included in the analysis [59].

Technoeconomic feasibility was evaluated for five different technology schemes applied at six different scales ranging from 2.3 inhabitants to 300 inhabitants in high-rise housing decentralized configurations. The total cost ranged as a function of the treatment technology and the scale. The most expensive of the presented decentralized systems is shown to be competitive with the cost of water in wealthier regions if more than 100 inhabitants are served [86].

The sustainability of four wastewater management alternatives was compared using a composite indicator that included total annual equivalent costs, carbon emission intensity, eutrophication, and resilience [87]. The four alternatives are two centralized schemes based on different technologies (activated sludge and membrane bioreactor), a decentralized scenario, and a hybrid alternative, which treats black water locally and sends greywater to a central plant. The decentralized and hybrid alternatives showed better performance in terms of carbon emission intensity and resilience, but had higher overall costs associated with source separation and eutrophication potential.

The effects of three different scales on 27 scenarios were studied [38], considering different topographies and human densities, and it was concluded that higher topographic complexity also favoured decentralized systems, while higher human density reduced energy demand in both centralized and decentralized arrangements, generating a greater impact on the cost curve than did topography. However, when accounting for hot water energy savings, the model indicated that the unit water cost did not increase significantly until plant service areas fell below 100 to 1000 homes. The optimal scale increased with human density, reaching 3333 homes per treatment plant. The results also showed that direct potable reuse (DPR) was too expensive for low-density populations and more appropriate for urban settings serving more than 100 residences, especially when considering potential energy savings from recovering hot water. Ref. [42] developed cost functions for both the capital and O&M costs of different water technologies and contrasted them with

those of ten DPR plants, revealing economies of scale for many treatment units. The study highlighted how operating costs for collection/distribution networks counterbalanced these economies in centralized systems, citing that in the US, 80% of the sewage energy demand is for conveyance, which consumes on average four times the energy of treatment. Conveyance can reach 39.5 times the energy needed for treatment if regions that suffer from water stress are considered.

To find the optimal scale, ref. [61] developed a heuristic model based on the shortest path and agglomerative clustering algorithm; the findings were that the optimal degree of centralization decreased with increasing terrain complexity and settlement dispersion, and the effect of the latter exceeded that of topography [33]. LCA was used by [33] to compare resource recovery through a centralized scenario and a hybrid scenario where black water was managed in a decentralized facility and greywater was managed for fertilizer production in a centralized unit. For all LCA categories, the total loads of the hybrid scenario were lower than those of the centralized scenario. The major reductions ranged from 66.7 to 74.8% and were shown for fossil resource scarcity, followed by terrestrial, marine, and freshwater ecotoxicity.

On the other hand, ref. [45] reported that centralization benefited resource recovery by reducing energy demand and the carbon footprint. However, the community scale was shown to have the lowest eutrophication potential. A review on the same topic by [32] concluded that economies of scale were largely present in the processing of wastewater and biosolids; however, the redistribution of reclaimed water exhibited diseconomies of scale as water networks increased in service size. When averaged and categorized by scale, the greenhouse gas emissions for large-scale water reclamation systems were significantly lower than those for medium- and small-scale systems. For reclaimed water distribution, her review revealed that decentralized systems exhibited lower (three articles), similar (two articles), or higher (two articles) distributions. The main conclusion of the review is that a centralized arrangement is preferred when higher flow rates of reclaimed water are transferred over shorter distances to fewer end users, and diseconomies of scale are exhibited when the distribution covers a large service area.

Overall, a potable water supply, such as DPR, is less recommended than NPR for decentralized systems, primarily due to its higher treatment costs, operational hurdles, risks of system failure, and potential water quality concerns [23,38,46,89]. Nevertheless, intermediate-scale systems, such as cluster-level setups with qualified personnel that are managed by specialized companies, can be suitable for potable water reuse depending on the surrounding environmental factors [39].

Based on many studies of the optimal scale and accounting for the unique attributes of each case, some scale approaches are more adequate for certain environmental conditions or technology techniques than others. The results indicate that economies of scale apply to many unit processes. However, capital and operational costs related to scale can change as a function of the techniques and technologies applied by the WMU. Thus, based on previous findings, some recommendations are presented in Table 3.

Table 3. Recommended optimal scale considering certain environmental and system scheme conditions.

Scale	Environment Condition/Technology Technique	References
MS [2]/D [1]	Adequate for NPR at high-elevation areas far from the treatment plant designed for water supply. Smaller-scale systems are usually preferred at NPR systems. Additionally, smaller-scale systems present more advantages due to the lower costs and resources necessary to reach desired reuse standards	[37,46]
MS/C [3]	Low-elevation areas close to the treatment plant	[36]
MS/C	High human density favours both approaches, although it increases the optimal scale	[38]

Table 3. *Cont.*

Scale	Environment Condition/Technology Technique	References
MS/C	More adequate for DPR due to higher energy requirements for treatment and greater treatment economies of scale impact while not requiring dual pipe system to water supply distribution	[42,89]
MS	More appropriate for hot water savings at DPR systems	[38,46]
D	Adequate for thermal energy recovery in cold climates due to residential energy demand reduction, resulting in low payback time	[46]
C	High flow rates transfer over short distances	[46]
D	For water distribution or collection covering large and distant service areas	[46]
MS/D	Recommended at more scarce regions that must ensure a more diversified water portfolio and where usually high amounts of freshwater sources are far located from end users	[80]
C	More adequate for hydropower generation that requires high flow rates and elevation drop and for biogas production through biosolids management	[46]
D	For urine source separation, technologies have exhibited higher recovery rates and lower environmental and economic impacts compared to conventional large-scale treatment	[46]
MS/D	Adequate for NPR at high-elevation areas far from the treatment plant designed for water supply. Smaller-scale systems are usually preferred at NPR systems. Additionally, smaller-scale systems present more advantages due the lower costs and resources necessary to reach desired reuse standards	[37,46]
MS/C	Low elevation areas close to the treatment plant	[36]
MS/C	High human density favours both approaches, although it increases the optimal scale	[38]
MS/C	More adequate for DPR due to higher energy requirements for treatment and greater treatment economies of scale impact while not requiring dual pipe system to water supply distribution	[42,89]
MS	More appropriate for hot water savings at DPR systems	[38,46]
D	Adequate for thermal energy recovery in cold climates due to residential energy demand reduction, resulting in low payback time	[46]

Notes: [1] D: Decentralized, [2] MS—Middle Scale, [3] C—Centralized.

4. Discussion

Scale classification (either at the system or unit level) varies among authors. The classification should serve all subsystems of the UWS—WSS, WWS, UDS—avoiding multiple classifications and providing greater comprehension between professionals when transferring knowledge from one to another. This article introduces a new method of classifying scales, differentiating the scale for the entire UWS and the scale of each WMU itself. (Figure 4). When considering the whole system, UWSs can be classified as *centralized*, if the total flow entering the system is managed by large central plants; *decentralized*, when all the flow is managed by autonomous DWMUs (with zero interconnectedness between facilities); and *hybrid*, when part of the flow is managed by CWMUs and the rest by DWMUs. Concerning the unit level, the scale of each WMU was classified (Table 4), considering thresholds defined by the scientific literature and the European wastewater proposal from 2022. Thus, WMUs are categorized in terms of inhabitants (inh.), people equivalent (p.e.), flow (m^3/s) or area of drainage (Ad) in hectares (ha), as follows:

(i) **Onsite individual decentralized units:** serving $1 \leq$ p.e ≤ 40 inh./p.e.; On-source drainage—Ad < 2/3 ha

(ii) **Urban cluster/medium-scale decentralized units:** serving 40 < inh./p.e. < 1000; Conveyance control drainage—2/3 ha < Ad < 3/4 ha

(iii) **Small urban agglomeration decentralized units:** serving 1000 $\leq$ inh./p.e < 10,000; End-of-pipe urban drainage and satellite facilities: 3/4 ha < Ad < 10 ha

(iv) **Medium-scale centralized units:** serving 10,000 $\leq$ inh./p.e. < 100,000; and drainage in between 10 ha < Ad < 8.5 km^2

(v) **Large-scale centralized units:** serving inh. or p.e. $\geq$ 100,000; drainage area with Ad > 8.5 km^2

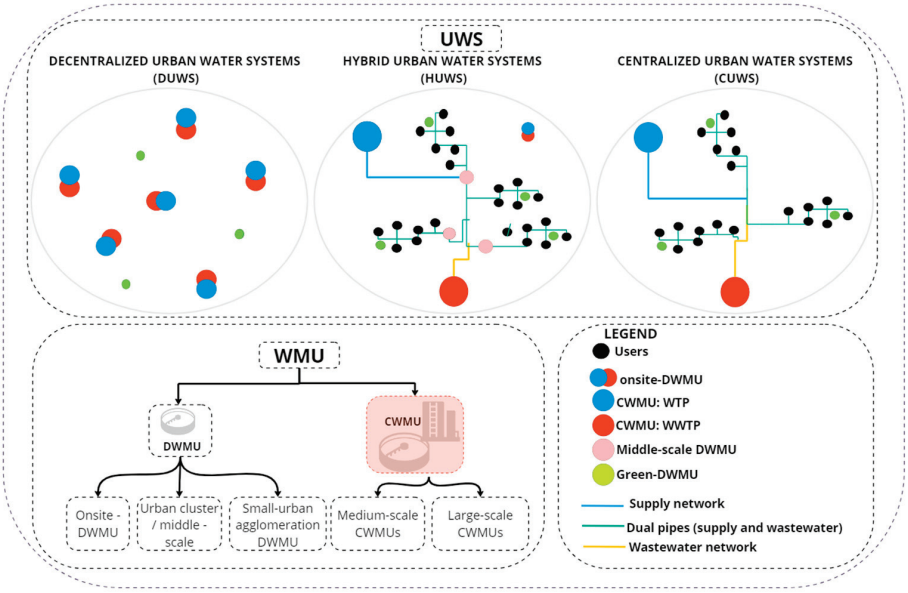

Figure 4. Scale in terms of WMU and UWS.

Table 4. Scale classification of urban water management at the macro (UWS) and micro (WMU) levels.

Scale Level	Scale Classification		Coverage of Service (inh./p.e./Area of Drainage)
Scale of UWS (based on CC conditions at the macro-level)	Centralized Urban Water Systems (CUWSs)		The total flow entering the system is managed by large central plants; The system is designed considering that each user must be connected to a central network that diverts the flow to or from CWMUs
	Hybrid Urban Water Systems (HUWSs)		Part of the flow is managed by CWMUs and others by DWMU; some users are connected through smaller networks and others are connected to networks of greater extent, which connect distant users to larger CWMUs.
	Decentralized Urban Water Systems (DUWSs)		The flow is managed by autonomous DWMUs (with zero interconnectedness between facilities);
Scale of WMU (based on SN conditions at the micro-level)	CWMU	Large-scale CWMUs	Serving inh. or p.e. $\geq$ 100,000; drainage serving Ad > 8.5 km^2
		Medium-scale CWMUs	Serving 10,000 $\leq$ inh./p.e. < 100,000; drainage serving 10 ha < Ad < 8.5 km^2
	DWMU	Small-urban agglomeration DWMU	Serving 1000 $\leq$ inh./p.e. < 10,000; End-of-pipe urban drainage or satellite facilities: 3/4 ha < Ad < 10 ha
		Urban cluster/middle-scale DWMU	40 < inh./p.e. < 1000; Conveyance control drainage: 2/3 ha < Ad < 3/4 ha
		Onsite DWMU	Serving 1 $\leq$ p.e. $\leq$ 40 inh./p.e.; On-source drainage: Ad < 2/3 ha

Decentralization has emerged as a pivotal strategy for harnessing multiple water sources while also enabling the recovery of materials embedded in water and reducing the energy demand associated with water conveyance over long distances. City priorities related to the promotion of circular WMUs for NPR, DPR, IPR, or even unplanned reuse must be very well understood to define which scale is optimal. The transition to decentralized systems is justified by their ability to provide a diversified and climate-independent water resource portfolio, by closing water loops next to the origin and source. Additionally, smaller-scale systems are associated with the greening of cities. The use of green and blue spaces increases the water exchange among urban landscapes, groundwater, and the atmosphere instead of facilitating quick drainage to underground pipes. As a result, the natural compartments of the UWC can be restored.

Nevertheless, centralization is more readily accepted by water managers. It reduces flow disturbances within WMUs and typically results in a lower energy footprint for treatment. This approach presents greater reliability because it is managed by water utilities, which decreases possible public health concerns and flow disturbances; furthermore, centralized schemes are usually preferred for potable water supply due to greater monitoring reliability. CWMUs are also needed for managing stormwater when dealing with high return periods. Conversely, conventional CWMUs supply water for different purposes through the same network. Thus, water is treated to meet drinking water standards, even for nonpotable demand, requiring more energy than it should. The distribution and conveyance costs of circular CWMUs can be reduced when it is possible to deliver high quantities of reclaimed water or recovered material to small areas. In this scenario, larger-scale units are preferred. This can occur in the presence of certain customers who generate and/or consume high amounts of flow. High-flow consumers are related to the city's economic profile and can be situated in urban or peri-urban areas, for example: industries, farmers, hotels, or recreation parks.

The adoption of different scales can potentially influence energy use and circularity loops for water reuse and/or water-embed resource harvesting [80]. Synergies from the interactions between the optimal scale design and the adequate circularity strategy can improve climate change resilience and reduce the depletion of water resources, either by increasing the water portfolio or reducing nonconsumptive uses of low-quality discharge flows. Optimal-scale studies usually point to middle-scale WMUs as the most appropriate solution because they benefit from economies of scale for treatment but are not subject to the larger distances and terrain irregularities that increase conveyance costs.

Since the optimal scale of WMU varies with site and city conditions, the co-occurrence of a diverse range of scales in the same UWS is better than relying on just centralized or decentralized facilities. The combination of both approaches facilitates water management closer to the source and promotes adequate source separation and treatment for NPR while providing high-quality water to treatment plants supplied for potable uses. This raises the concept of HUWS, a strategy that exploits centralized and decentralized WMUs. The HUWS allows the establishment of optimal performance scenarios that can count with multiple waters, local recovery, and usage in the DWMU, while the CWMU serves as a backup treatment for the DMWU, offering more security in the case of failure and an end-of-pipe treatment multi-barrier facility to manage residuals from the DMWU. This multi-barrier approach increases the system's robustness. HUWSs are associated with the concept of multiple waters, as they provide cities with a wide range of water sources and qualities in a sustainable water-secure system [41,43].

This review evaluated trade-offs between different scales of selection for UWSs resilience, by analysing the impacts of scale on the components of resilience capabilities (redundancy, availability, robustness, and learning and investment ability), as well as which UWS functionality (ies) could be involved in the trade-off. Considering the existence of UWS resilience metrics, future studies should focus on the quantitative assessment of these trade-offs, to better evaluate how UWS resilience curves vary at different scale

designs. Scenario assessments varying not only in scale design but also in the circularity approach could generate important insights.

The scale of WMUs and the degree to which UWSs rely on decentralized and centralized facilities are important not only for adapting to water-related risks but also for improving the efficiency of measures to mitigate GHG emissions. The reduction in GHG emissions can be achieved by decreasing energy consumption and recovering energy from wastewater for other uses. To make impactful changes, UWSs must go beyond net-zero and reach surplus energy by improving circularity at many scales in the whole system. Future water services will need to integrate multiple sources, such as freshwater, reuse water, stormwater, groundwater, and seawater, at multiple scales through both centralized and decentralized services.

To evaluate how scale affects UWS resilience, three system metrics that express UWSs functionalities related to resilience were selected. The metrics are net energy, net water, and ecosystem services (Table 5). The scale effect on net energy comes from its impact on the energy demand for pumping, piping, extracting, treating, and recirculating water and its recovery from wastewater, as well as the energy recovered or used to take full advantage of water embedded-materials. Scale also impacts the system's net water, as it influences the location and quantity of discharge flows from WMUs, reduces freshwater withdrawals through fabricated water sources at multiple scales, and affects downstream water quality through distributed or localized discharges (when combined with circular units); scale also impacts rainfall storage capability; and UWS's scale influences the ability to provide system functionalities beyond water services. These functionalities refer to ES capable of improving human well-being, the biological function of cities, or natural source restoration through nature-based WMUs.

Table 5. UWS resilience metrics and description of the impact of scale on UWS functionalities.

UWS Resilience Metrics	Description of UWS Scale Impacts on UWS Functionalities
Net Energy	A scale must be set to optimize UWS energy consumption. Minimal energy consumption based on clean energy should be preferred to reduce GHG emissions.
Net Water	The scale should be set to promote reuse and increase the water portfolio while decreasing water withdrawal. At the same time, the total discharge load decreases, reducing nonconsumptive uses.
Ecosystem services	Nature-based WMUs can provide ecosystem services across the urban fabric and distributed green units, which can be an instrument to provide equitable justice at vulnerable sites while enforcing community cohesion.

The full comprehension of the implications and relationships of scale and its surrounding conditions will usually provide WMUs with different optimal scales across the UWS. Thus, future water schemes should be based on hybrid configurations that include many technologies, ranging from green to grey [14]. These units are designed for water treatment and to improve urban metabolism by reusing water, restoring the water cycle, and recovering resources. All these processes must be facilitated by remote and predictive control based on digital and/or AI-powered solutions. Moreover, the inclusion of socioeconomic and subjective variables ensures that policy recommendations are not only environmentally sound but also socially acceptable, promoting community engagement and improving social justice across cities.

Scale, as a design variable, is constantly associated with other characteristics of UWSs. For example, the need to diversify the water portfolio or recover materials associated with the recovery of other urban metabolic flows refers to the scale of circularity, and in our research, 38 documents from a total of 57 papers would talk about scale in association with circularity. The urgency to provide ecosystem services in cities, to reduce climate

effects while managing water more sustainably, and to recover natural parts of the UWC is associated with scale diversification in drainage subsystems and the transition to higher implementation of greening strategies in UWSs. In our review, 22 documents would relate scale to greening. Finally, the need to provide coordination and efficient management between WMUs and smart water grids requires a central control facility supported by a smart sensor network distributed along pipes and the many WMUs that would cover the system, allowing greater redundancy and robustness of the system. In this case, scale diversification demands another improvement in the design of UWSs, which is the digitalization of the system. Our review revealed six documents related to scale and the increased use of digital technologies. Thus, we consider that, if resilience measures need to address multiple functionalities for trade-offs between competing aspects [17], or, further, possible synergies between system functionalities, to improve the comprehension of UWS resilience capacity, future work should focus on four design variables of UWSs, namely: ***scale***, ***circularity***, ***greening***, and ***digitalization***.

5. Conclusions

Scale is crucial in UWS design. Our study underscores the significance of identifying and implementing optimal scales that recognize the trade-offs between centralized and decentralized approaches and how they are affected by the environmental conditions of each city and different locations across urban areas. This article proposes a novel approach for choosing the optimal scale of urban water management and infrastructure, offering a classification at two levels of analysis: the system and the unit level. Then, a qualitative approach was used to reveal the trade-offs between different scales in terms of UWS functionalities; the interplay between scale, system functionalities, and the four selected components (reliability, redundancy, robustness, learning and investment capacity) of resilience capabilities (absorptive, adaptative, and restorative) was also analysed. To understand which is the optimal scale, we divided the analysis into two hierarchical levels: city-catchment and site-neighbourhood. The first level of analysis aims to support the optimal scale definition for the whole system. The second analysis level considers eleven site-neighbourhood environmental aspects to determine the scale and location of each WMU within the system. Considering city-catchment variables allows a full comprehension of the hydrological interactions of a city's metabolism and the river basin where the city is located. Moreover, the second level of analysis allows us to prioritize which city sectors/sites present greater advantages for decentralization and which zones should remain connected to the main central plant. This comprehension also provides insights into future schemes, which could be designed based on resilience metrics that reflect estimations of energy, environmental, economic, and social system performance. The optimal scale definition is a multicriteria decision problem. Therefore, the consideration and weight of each variable for deciding "which scale" depends on the purpose of each WMU, which must be aligned with the more urgent needs of the UWS, and ultimately, it reflects city water needs.

Previous research underscores the significance of understanding the interactions among different system components and functionalities to develop more effective strategies. Therefore, UWS resilience measures need to address multiple functionalities in order to account not only for trade-offs between competing ones but also for possible synergies that arise from the design of the system. For that, future studies are encouraged to delve deeper into understanding the interactions between scale, circularity, greening, and digitalization, which collectively constitute the primary design strategies of UWSs.

Intermediate scales of systems and units, when set to be optimal, have the potential to minimize energy and other resource consumption while enhancing ecosystem services. Decision-makers are urged to integrate elements of both centralized and decentralized approaches into the same system, fostering a HUWS that is designed to achieve net-zero emissions and facilitate circular resource flows beyond water. Optimal configurations must be as dynamic as the problem they aim to solve. Ultimately, the adoption of a low-carbon

energy matrix is crucial in the pursuit of net-zero emissions, thereby contributing to broader efforts to effectively address the WEFE nexus and climate change.

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Abbreviations

NPR	Nonpotable Reuse
SN	Site-Neighbourhood
UDS	Urban Drainage Subsystem
UWC	Urban Water Cycle
UWS	Urban Water Systems
WMU	Water Management Units
WSUD	Water Sensitive Urban Design
WSS	Water Supply System
WWS	Wastewater System
CC	City-Catchment
CWMU	Centralized Water Management Units
DWMU	Decentralized Water Management Units
DPR	Direct Potable Reuse
HUWS	Hybrid Urban Water Systems
IPR	Indirect Potable Reuse

Appendix A

Table A1. Keywords used for the QUERY 01, that considered queries for Context AND Resource AND Framework, AND Technology, AND Methods.

AND Query Layers	Layers Keywords
Context	"urban" or "cities" or "city" or "green cit*" or "circular cities" or "Urban greening" or "municipality"))
Resource TS	("Water supply" or "stormwater" or "water reuse" or "reclaimed water" or "residual water" or "sewer" or "runoff" or "wastewater" or "potable water" or "drinking water" or "surface water"
Framework TS	=("Water management" or "Integrated Water Management" or "water-food-energy" or "flood management" or "socio hydrology" or "hydrosonical" or "hydro social" or "stormwater management" or "urban water management" or "Digitalization NEAR/15 water" or "circular economy" or "resilience NEAR/15 water" or "climate change NEAR/15 water" or "risk management" or "climate adaptation NEAR/15 water" or "transition" or "sustainab* challenges" or "water schemes" or "adaption" or "mitigation" or "Social-Ecological Systems" or "Scarcity" or "Social injustice" or "resource depilation" or "Human Well-being" or "Sponge Cit*" or "Collaborative planning" or "urban planning"

Table A1. *Cont.*

AND Query Layers	Layers Keywords
Technology TS	"Water systems" or "system*" or "solution*" or "infrastructure" or "technolog*"or "control" or "sewer network" or "sewer Systems" or "Integrated water systems" or "urban water network" or "urban water systems"))
	"hybrid" or "circular" or "green" or "blue" or "grey" or "conventional" or "green-blue-grey" or "BGI" or "Blue-green" or "smart" or "digital" or "digital twin*" or "Water-sensitive urban design" or "Sustainable urban water management" or "sustainable urban drainage" or "SUDS" or "LID" or "low impact development" or "reuse" or "combined sewer overflow" or "CSO" or "drainage solution*" or "Nature-based solution*" or "NBS" or "*centralized" or "*centralised" or "green-blue" or "gray" or ("Resource recovery" and "wastewater") or "high tech" or "high touch" or "green urban infrastructure" or "GUI" or "information and communication Technology" or "ICT" or "resource recovery" or "circularity" or "renaturization" or "BMPs" or "whud"))
Research Approach TS	("environmental" or "social" or "hydrogeological" or "water quality" or "land") and ("*benefit*" or "impact" or "performance" or "need*" or "requirement*")) or "challenges" or "Key performance indicators" or "KPI" or "indicators" or "risk reduction" or "efficiency" or "ecosystem services" or "Effectiveness" or "hazard" or "index" or "TRL" or "Technology Readiness Levels" or "CAPEX" or "OPEX" or "scale" or "MCDA" or "GIS" or "spatial footprint" or "footprint" or "advantages" or "disadvantages" or "design" or "location" or "unit cost" or "cost" or "stakeholder* perception*" or "social value"))
Methods TS	"systemic" or "review" or "integrated method*" or "planning tool" or "planning-support tool" or "Cost effectiveness" or "Cost-benefit*" or "CBA" or "life cycle assessment" or "LCA" or "assessing" or "impact asses*" or "analysis" or "comparison" or "impact" or "performance" or "evaluat*" or "State-of-the-art" or "suitability" or "decision support system" or "analytic hierarchy process" or " life cycle costing" or "barriers" or "opportunities" or "trade-offs" or "synergies" or "co-benefit*" or "modelling" or "Planning support systems" or (("site" or "solution" or "technology" or "place*") and ("prioritization" or "ranking")) or "pathways" or "scenario*"))"
General Interest * TS	=(("health" OR "well being") AND ("review" OR "overview") AND ("urban") AND ("green justice" OR "green spaces" OR "Socio-environmental justice"))

Note: * OR layer.

Research Query of the Main Review

(((((((TS = ("urban" or "cities" or "city" or "green cit" or "circular cities" or "Urban greening" or "municipality")) AND TS = ("Water supply" or "stormwater" or "water reuse" or "reclaimed water" or "residual water" or "sewer" or "runoff" or "wastewater" or "potable water" or "drinking water" or "surface water")) AND TS = ("Water management" or "Integrated Water Management" or "water-food-energy" or "flood management" or "socio hydrology" or "hydrosonical" or "hydro social" or "stormwater management" or "urban water management" or "Digitalization NEAR/15 water" or "circular economy" or "resilience NEAR/15 water" or "climate change NEAR/15 water" or "risk management" or "climate adaptation NEAR/15 water" or "transition" or "sustainab* challenges" or "water schemes" or "adaption" or "mitigation" or "Social-Ecological Systems" or "Scarcity" or "Social injustice" or "resource depilation" or "Human Well-being" or "Sponge Cit*" or "Collaborative planning" or "urban planning")) AND TS = ("Water systems" or "system*" or "solution*" or "infrastructure" or "technolog*"or "control" or "sewer network" or "sewer Systems" or "Integrated water systems" or "urban water network" or "urban water systems")) AND TS = ("hybrid" or "circular" or "green" or "blue" or "grey" or "conventional" or "green-blue-grey" or "BGI" or "Blue-green" or "smart" or "digital" or "digital twin*" or "Water-sensitive urban design" or "Sustainable urban water management" or "sustainable urban drainage" or "SUDS" or "LID" or "low impact development" or "reuse" or "combined sewer overflow" or "CSO" or "drainage solution*" or "Nature-based solution*" or "NBS" or "*centralized" or "*centralised" or "green-blue" or "gray" or ("Resource recovery" and "wastewater") or "high tech" or "high touch" or "green urban infrastructure" or "GUI" or "information and communication Technology" or "ICT" or "resource recovery" or "circularity" or "renaturization" or "BMPs" or "whud")) AND TS = ((("environmental" or "social" or "hydrogeological" or "water quality" or "land") and ("*benefit*" or "impact" or "performance" or "need*" or "requirement*")) or "challenges" or "Key performance indicators" or "KPI" or "indicators" or "risk reduction" or "efficiency" or "ecosystem*

services" or "Effectiveness" or "hazard" or "index" or "TRL" or "Technology Readiness Levels" or "CAPEX" or "OPEX" or "scale" or "MCDA" or "GIS" or "spatial footprint" or "footprint" or "advantages" or "disadvantages" or "design" or "location" or "unit cost" or "cost" or "stakeholder perception*" or "social value")) AND TS = ("systemic" or "review" or "integrated method*" or "planning tool" or "planning-support tool" or "Cost effectiveness" or "Cost-benefit*" or "CBA" or "life cycle assessment" or "LCA" or "assessing" or "impact asses*" or "analysis" or "comparison" or "impact" or "performance" or "evaluat*" or "State-of-the-art" or "suitability" or "decision support system" or "analytic hierarchy process" or " life cycle costing" or "barriers" or "opportunities" or "trade-offs" or "synergies" or "co-benefit*" or "modelling" or "Planning support systems" or (("site" or "solution" or "technology" or "place*") and ("prioritization" or "ranking")) or "pathways" or "scenario*")) OR TS = (("health" OR "well-being") AND ("review" OR "overview") AND ("urban") AND ("green justice" OR "green spaces" OR "Socio-environmental justice"))*

Table A2. Keywords used for the QUERY 02, that considered queries for Funding Source AND Research interest.

AND Query Layers	Layers Keywords
Funding FT	"NATURANCE" OR "ThinkNature" OR "EKLIPSE" OR "OPPLA" OR "UNaLAB" OR "RCC-BrownMON" OR "UrbanGreenUp" OR "GrowGreen" OR "NATURVATION" OR "Nature4Cities" OR "ClimateKIC ACT on NBS" OR "EU Smart Cities Information System" OR "SCIS" OR "COST Action Circular City" OR "CLEaN-TOUR" OR "Closing material flows by wastewater treatment with green technologies" OR "UFR" OR "Urban health cluster" OR "Phusicos" OR "CRC for water sensitive cities" or "RCC-BrownMON: Urban Water Cluster" or "Clean & Circle Project" or "HYDROUSA" or "KURAS" or "C2C-CC" or "NICE" or "UK Natural Environment Research Council"or "US National Science Foundation" or "National Science Foundation Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure")) AND TS = ("stormwater" OR "wastewater" OR "urban" OR "cities" OR "flood" OR "city" OR "nature-based solutions" or "NBS" OR "SUD" OR "LID" OR "BMP" OR "WSUD" OR "information and communication Technology" OR "smart grid*" or "smart NEAR/15 water" or "water near/15 reuse" or "reclaimed water" or "potable water" or "drinking water"
Research Interest TS	"stormwater" OR "wastewater" OR "urban" OR "cities" OR "flood" OR "city" OR "nature-based solutions" or "NBS" OR "SUD" OR "LID" OR "BMP" OR "WSUD" OR "information and communication Technology" OR "smart grid*" or "smart NEAR/15 water" or "water near/15 reuse" or "reclaimed water" or "potable water" or "drinking water"

Note: asterisks denote a truncated version of the keywords used.

Funding Research Query

(FT = ("NATURANCE" OR "ThinkNature" OR "EKLIPSE" OR "OPPLA" OR "UNaLAB" OR "RCC-BrownMON" OR "UrbanGreenUp" OR "GrowGreen" OR "NATURVATION" OR "Nature4Cities" OR "ClimateKIC ACT on NBS" OR "EU Smart Cities Information System" OR "SCIS" OR "COST Action Circular City" OR "CLEaN-TOUR" OR "Closing material flows by wastewater treatment with green technologies" OR "UFR" OR "Urban health cluster" OR "Phusicos" OR "CRC for water sensitive cities" or "RCC-BrownMON: Urban Water Cluster" or "Clean & Circle Project" or "HYDROUSA" or "KURAS" or "C2C-CC" or "NICE" or "UK Natural Environment Research Council"or "US National Science Foundation" or "National Science Foundation Engineering Research Center for Reinventing the Nation's Urban Water Infrastructure")) AND TS = ("stormwater" OR "wastewater" OR "urban" OR "cities" OR "flood" OR "city" OR "nature-based solutions" or "NBS" OR "SUD" OR "LID" OR "BMP" OR "WSUD" OR "information and communication Technology" OR "smart grid" or "smart NEAR/15 water" or "water near/15 reuse" or "reclaimed water" or "potable water" or "drinking water")*

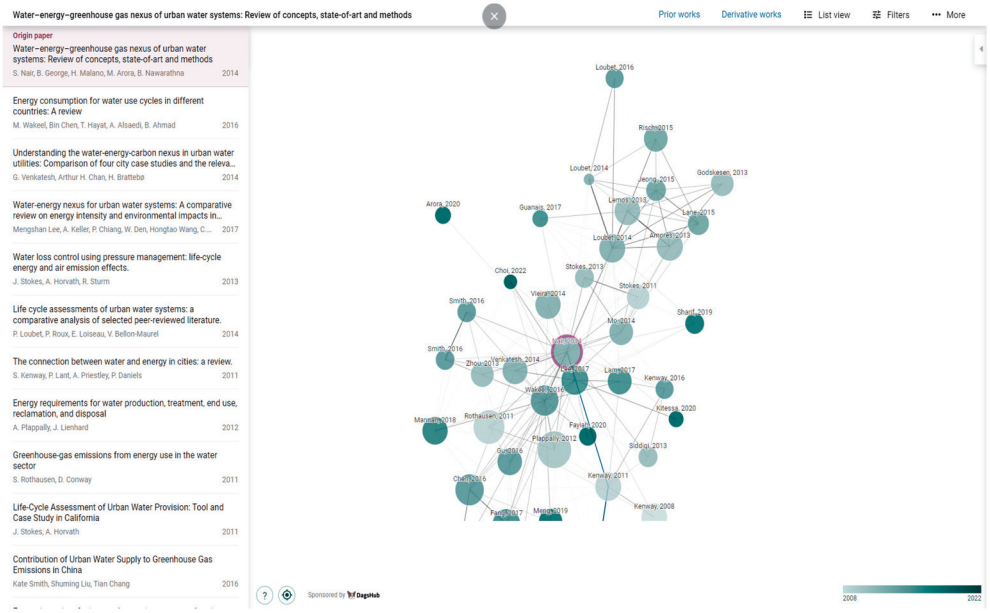

Figure A1. Research tool used for retrieving complementary articles. Access on https://www.connectedpapers.com/ (accessed on 23 October 2023).

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