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Enhancing reclaimed water distribution network resilience with cost-effective meshing

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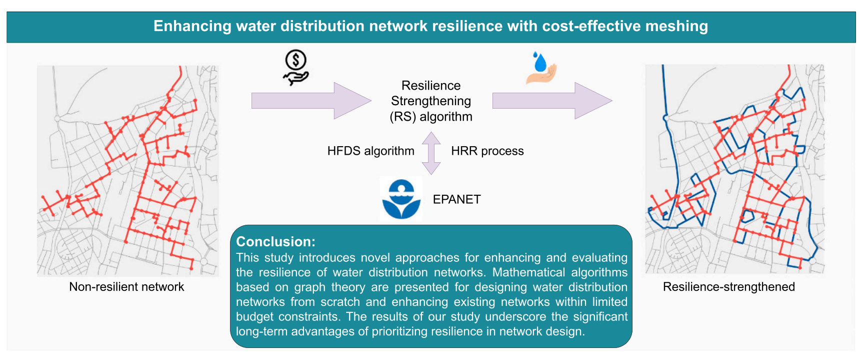
HIGHLIGHTS

- Novel algorithms for enhancing the resilience of water distribution networks
- Design of resilient and cost-effective networks in limited budget scenarios
- The Water Availability (WA) provides a comprehensive measure to evaluate resilience.
- Prioritizing resilience in network design demonstrated substantial long-term benefits.

GRAPHICAL ABSTRACT



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ABSTRACT

Water Distribution Networks (WDNs) are critical infrastructures that ensure a continuous supply of safe water to homes. In the face of challenges, like water scarcity, establishing resilient networks is imperative, especially in regions vulnerable to water crises. This study evaluates the resilience of network designs through graph theory, including its hydraulic feasibility using EPANET software, an aspect often overlooked. Novel mathematical algorithms, including Resilience by Design (RbD) and Resilience-strengthening (RS) algorithms, provide cost-effective and resilient network designs, even with budget constraints. A novel metric, Water Availability (WA), is introduced to offer a comprehensive measure of network resilience, thereby addressing ongoing discrepancies in resilience evaluation methods. Practical benefits are illustrated through a case study in which a resilient-by-design reclaimed water network is created, and an existing equivalent non-resilient network is improved. The resilient-by-design network demonstrates remarkably better results compared to the equivalent non-resilient design, including up to a 36 % reduction in the probability of service disruptions and a nearly 65 % decrease in the annual average unserved water due to service disruptions. These findings underscore the

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enormous advantages of a resilience-focused network design approach. When compared to the equivalent non-resilient design, the resilient-by-design network generated effectively safeguards up to a significant 91,700 m^3 of water from the impacts of water disruption events over a 50-year operational period. In addition, the resilient-by-design WDN solution incurs a subtle decrease in overall costs compared to consuming tap water from the drinking WDN baseline over a 50-year operational period. These findings highlight the cost-effectiveness of the approach, even offering financial benefits. This paper builds on our previous research by expanding its scope to include resilience considerations, providing algorithms that can be easily adapted from reclaimed to drinking WDNs. Ultimately, we contribute to the enhancement of water resource management and infrastructure planning in ever-evolving urban environments.

1. Introduction

Water Distribution Networks (WDNs) are critical infrastructures of modern urban life, ensuring the seamless flow of safe water from reservoirs to homes. It is paramount for households and essential industries and public services to have a consistent water supply, particularly within the context of drinking water networks that safeguard public health and support societal functions (Liu and Song, 2020). However, in light of growing challenges such as water scarcity and climate change, it has become imperative to also plan reclaimed water networks for non-drinking purposes (Kristensen et al., 2018). Regions around the world, especially those most susceptible to water scarcity crises, must develop and prioritize their reclaimed water networks as critical infrastructures (Domènech and Saurí, 2010; Vallès-Casas et al., 2016). Only by effectively ensuring the resilience of these WDNs (both drinking and reclaimed water) can we ensure the proper long-term functioning of these vital systems that play such a pivotal role in sustaining urban life.

The repercussions of WDN failures have broader implications involving both economic and environmental consequences. In the absence of proactive measures aimed at enhancing resilient network designs, the likelihood of such failures increases significantly, amplifying the potential for devastating outcomes. These may include compromising public health, disrupting essential services, and incurring substantial economic costs (Ahmad et al., 2023).

The debate over the definition of resilience is a recurring aspect in this field (Soldi et al., 2015; Piratla et al., 2016; Herrera et al., 2016). In this paper, we adhere to the definition of resilience as 'the capacity of a system to withstand stress and recover from failures' (Soldi et al., 2015; Piratla et al., 2016; Herrera et al., 2016), thus forming the foundational concept with which to address this challenge. Resilience defies a single performance indicator, instead it comprises multiple dimensions, including structural robustness and adaptive recovery considerations influenced by factors such as network topology, failure rates, recovery rates, and severity (Meng et al., 2018; Lindhe et al., 2009). This interdisciplinary issue offers a range of approaches that consider different hazard categories, methodologies, and enhanced measures.

In the literature, diverse metrics and approaches have been explored to evaluate the resilience of WDNs (Christodoulou et al., 2017; Cimellaro et al., 2016; Zhao et al., 2015). While some works offer insights into minimizing network disruptions during large-scale cascade failures such as natural disasters (McAllister, 2015; Chang and Shinozuka, 2004), they focus predominantly on evaluating resilience rather than providing preventive design solutions. In particular, Cimellaro et al. (2016) introduced a Resilience Index (R) for WDNs which focuses on parameters like the number of users temporarily without water, water tank levels, and water quality. Similarly, other studies have explored resilience evaluation measures like the Resilience Index (RI) and Network Resilience Index (NRI) (Baños et al., 2011; Todini, 2000; Tumula and Park, 2004). It is important to note that while both R and RI are named equally, they represent distinct measures. RI, for instance, aims to assess network resilience by ensuring demand satisfaction. However, these metrics frequently rely on operational data which is rarely available during the initial design stages. Furthermore, while RI and NRI excel at over-demand resilience analysis, they do not consider other crucial causes of such as failures and fail to provide specific design improvement measures to enhance network resilience.

This discrepancy highlights the need for a more comprehensive approach. Recent research by Taiwo et al. (2023) systematically analyzed the causes leading to network failures, categorizing them into three main categories: pipe-related, environment-related, and operation-related (Zhang et al., 2009), identifying a total of 33 distinct causes, and also providing a detailed table of relative weights of the causes of water pipe failure. These causes encompass a wide spectrum of elements, such as pipe age or diameter, some of which have not received attention in previous metrics.

While assessing the resilience of a network is crucial, it is equally important that the proposed designs conform to hydraulic feasibility constraints, an aspect that has received less attention in prior works (Yazdani et al., 2011; Herrera et al., 2016). In this regard, the EPANET software plays a pivotal role (Rossman et al., 2000), offering hydraulic simulation capabilities with which to assess the validity and performance of Water Distribution Networks (WDNs). Recent advances in the field have introduced the Water Network Tool for Resilience (WNTR), an EPANET-compatible Python package designed to simulate and analyze the resilience of WDNs (Klise et al., 2017b, 2018). While WNTR provides valuable insights into resilience analysis, it primarily focuses on evaluating resilience rather than offering concrete design improvement measures (Klise et al., 2017a).

The sole work offering resilience improvements through design and hydraulically validated for cost-effectiveness is, to the best of our knowledge, presented in Todini (2000). However, it has several limitations that warrant consideration. First, their study focuses on designing networks from scratch, i.e., neglecting the potential for enhancing existing systems. Moreover, its data and algorithms are outdated and inaccessible to the public. Additionally, the approach lacks automation, relying on an initial set of fixed diameters determined by the designer's experience. The study itself acknowledges the need for further investigation and development to create efficient and easy-to use tools.

Although there is an extensive body of literature on this topic, it is evident that this specific field of study lacks comprehensive improvement measures or strategies that would ensure resilience by design. Given this context, automating the process of water distribution network design through mathematical algorithms becomes feasible to provide both resilient and cost-effective networks. The contributions of this paper are the following:

1. Water Availability (WA): A novel metric is introduced, the Water Availability (WA), which serves as a comprehensive measure for assessing the resilience of water distribution networks. This metric is based on the concept of Network Availability (NA), which is commonly employed in the placement of controllers within telecommunication networks (Lu et al., 2019; Hu et al., 2014; Gaur et al., 2021; Rosenthal, 1977). NA is defined as the probability that all nodes can reach at least one controller with an operational probability of each link, which can be estimated using Monte Carlo simulations or computed precisely via a brute force algorithm. In cases where a single controller is present in the network, NA aligns with all-terminal reliability which is the probability that the network is

connected. To compute the exact value of all-terminal reliability, the path decomposition algorithm is recommended, particularly for medium-sized networks, due to its lower computational complexity compared to the brute force approach (Carlier and Lucet, 1996).
2. Mathematical Algorithms for Resilient Networks Design and Improvement: Not only cutting-edge mathematical algorithms are introduced for designing water distribution networks from scratch, but also several strategies are offered to enhance existing networks within limited budget constraints, which will provide resilient and cost-effective networks.
3. Hydraulic Feasibility with EPANET: An innovative and interactive process that integrates the developed algorithms with EPANET software (U.S. EPA, 2000) ensures that the generated network designs not only prioritize cost-effective resilience, but also adhere to hydraulic feasibility constraints. Something that is hardly found in the reviewed literature.

The algorithms presented in this paper are based on applying graph theory (Kesavan and Chandrashekar, 1972) coupled with hydraulic validations to design the water distribution networks. Several previous works have used graph theory in water networks: Ahmadullah and Dongshik (2016) for designing drinking water networks; Calle et al. (2021) for wastewater sensor placement approaches concerning SARS-CoV-2 detection; and Meng et al. (2018) for proposing a comprehensive analytical framework for examining the resilience pattern of water distribution systems against topological characteristics (i.e., the correlations between resilience and topological features). The use of EPANET for hydraulic validations is also present in several previous studies (Soldi et al., 2015; Klise et al., 2017b; Todini, 2000).

2. Materials and methods

2.1. Generation of the initial graph

The REWATnet tool automates the generation of the initial graph, illustrating the paths of city streets for potential reclaimed water network designs. It achieves this by collecting data from diverse open sources. Subsequently, additional algorithms are then employed to develop resilient network designs based on this initial representation (Calle et al., 2023). The process of generating the initial graph involves 5 steps (see Table 1):

1. City Street Graph Acquisition: REWATnet utilizes OpenStreetMap to obtain the city street graph based on the city's name and source point (i.e., initial tank) coordinates. City's topography Digital Elevation Model (DEM) is gathered for node elevation required for hydraulic validations.
2. Land Plot and Building Data Retrieval: Cadastral data files are used to gather land plot and building data for the identification of water consumption destinations. Overpass API and Shapely library locate and determine the surface area of public gardens.
3. Construction Cost Retrieval: REWATnet utilizes its open database to provide available PE100 (HDPE) pipe diameters and associated costs for materials, labor, valves, and water tanks.
4. Water Use Consideration: A list of water uses is essential for estimating water demand. The full list of water uses considered for reclaimed water networks is available in Calle et al. (2023).
5. Graph Generation: REWATnet automatically generates the initial graph in standardized graphml format by processing land plot and building data and estimating their water demands. The estimated water demand for each land plot is then linked to the nearest node in the city street graph.

Table 1
Initial graph generation process.

Step	Data source	Description	References
1	OpenStreetMap API, IGN Digital Elevation Model (DEM)	Obtain city street graph and node elevations.	Bennett (2010); Boeing (2017); Instituto Geográfico Nacional (2023)
2	Cadastral data, Overpass API, Shapely	Gather land plot, building, and public garden data.	Pezoa et al. (2016); Olbricht et al. (2011); Gillies et al. (2007)
3	REWATnet database	Retrieve available pipe diameters and construction costs.	Christodoulou and Agathokleous (2012)
4	Water use list	Consider water uses for estimating water demand.	Calle et al. (2023)
5	REWATnet tool	Generate initial graph by processing land plot and building data and estimating their water demands.	Calle et al. (2023); GraphML (2001)

2.2. Resilience metrics and optimization algorithms

In brief, $\mathscr{G} = (\mathscr{V}, \mathscr{E})$ represents the solution of a resilient water network graph resulting from the computation of the algorithms, with a V-element set of nodes $\mathscr{V}$ representing the set of destination (water consumption) nodes, the water source node, and junction points, and an E-element set of links $\mathscr{E} \subset \mathscr{V}^{|2|}$ representing pipes. Additionally, r (where $r \in \mathscr{V}$) denotes the source node (i.e., the initial water tank), and $\mathscr{C}$ (where $\mathscr{C} \subseteq \mathscr{V}$) denotes a C-element set of consumption nodes. Table 2 specifies the full notation used for the algorithms.

2.2.1. Water Availability (WA)

While the concept of Network Availability (NA) has traditionally found its application in telecommunication networks, it seamlessly extends to serve as an ideal approach for assessing resilience in water distribution networks. In the context of water distribution networks, we introduce Water Availability "WA($\mathscr{G}, \mathscr{P}, r$)" as the probability that the initial water tank r can effectively supply water to all the destination nodes $\mathscr{V}$ within the network $\mathscr{G}$ while considering variable pipe failure probabilities for each pipe in the network $p(e) \in \mathscr{P}, \forall e \in \mathscr{E}$.

As a reference point for the pipe failure probabilities $p(e)$, we utilize a well-established criterion of a maximum of 0.4 failures per kilometer per year (MIMAM, 2000). This criterion, coupled with the average duration of a failure, known as the Mean Time To Repair (MTTR) measured in hours, is used in deriving the unavailability per pipe kilometer denoted as q. This q value represents the probability of pipe failures per kilometer

Table 2
Full notation concerning the algorithms.

$r, r \in \mathscr{V}$	Reclaimed water source node
$\mathscr{C}$	Set of water distribution consumption nodes; $\mathscr{C} \subseteq \mathscr{V}$
$\mathscr{D}$	Set of available pipe diameters, in ascending order (each one in mm)
s_{max}	Float constant indicating the maximum desired water flow speed (in m/s, 1 by default)
s_{min}	Float constant indicating the minimum desired water flow speed (in m/s, 0.6 by default)
$pr(c), c \in \mathscr{C}$	Float indicating the water pressure of destination node c (in m)
$t(c), c \in \mathscr{C}$	Float indicating the water travel time from the origin r to the destination node c (in minutes)
$m(c), c \in \mathscr{C}$	Integer indicating the consumption of destination node c (volume, in m^3)
$\mathscr{E}(a, c), c \in \mathscr{C}$	Set of edges forming the shortest path from the source node a to the destination node c; $\mathscr{E}(a, c) \subseteq \mathscr{E}$
$l(e), e \in \mathscr{E}$	Float indicating the length of the pipe link e (in m)
$w(e), e \in \mathscr{E}$	Float indicating the water flow of the pipe link e (in m^3/s)
$s(e), e \in \mathscr{E}$	Float indicating the water speed of the pipe link e (in m/s)
$v(e), e \in \mathscr{E}$	Integer indicating the valve diameter for pipe link e (in mm); 0 by default (i.e., no valve installed on link e)
$d(e), e \in \mathscr{E}$	Integer indicating the assigned diameter of the pipe link e; $d(e) \in \mathscr{D}$ (in mm)

within the network, as delineated in Eq. (1). The choice of MTTR is crucial and may vary depending on the scenario and the criticality of the network. For drinking water networks, a recommended MTTR value is 19 h (Darvini et al., 2020). Conversely, for reclaimed water networks primarily used for non-critical purposes such as public garden irrigation, a higher MTTR may be considered. Considering the criticality of reclaimed water networks for toilet flushing, we recommend a default MTTR of 24 h, easily modifiable as an input in the algorithms to accommodate different case-study scenarios. Assuming an MTTR of 24 h, which means the average down time per kilometer of pipe is 9.6 h per year, yields an approximate q value of 0.0011.

$$q = \frac{0.4 \times \mathrm{MTTR}}{(24 \times 365)} \tag{1}$$

Then, the estimation for each pipe unavailability can be written as Eq. (2), where $u(e)$ denotes the unavailability of pipe e with its length $l(e)$ transformed to kilometers. This formula is common practice in telecommunication (Mezhoudi and Chu, 2006), with values between 0 and 1, increasing as a function of the pipe length. The expression $u(e)$ goes to 1 if $l(e)$ goes to infinity, and for a $l(e) = 1000$, we retrieve $u(e) = q$.

$$u(e) = 1 - (1 - q)^{l(e)/1000} \tag{2}$$

While $u(e)$ serves as a valuable reference point for evaluating the overall likelihood of each pipe failure, assuming an average repair time of 24 h (i.e., the average duration of the failure), it does not fully capture the individual variability of each pipe. This is because each pipe has its own unique set of related features contributing to its failure. In water distribution networks, pipe failures can be attributed to three primary causes, each with its own distinct probability of incidence (Taiwo et al., 2023): (i) pipe-related (probability w_{pr}: 0.396), (ii) environmental-related (probability w_{er}: 0.413), and (iii) operational-related (probability w_{or}: 0.191). As we are approaching resilience from a network design perspective, only pipe-related attributes can be directly quantified, including pipe diameter (d) with a probability of w_d at 0.122; age (a) with a probability of w_a at 0.105; material composition (m) with a probability of w_m at 0.076; pipe length (l) with a probability of w_l at 0.066; and wall thickness (t) with a probability of w_t at 0.027. The sum of all the pipe-related attribute probabilities is equal to $w_{pr} = 0.396$.

Thus, it becomes feasible to adapt and normalize the probability of pipe-related failure causes w_{pr} for each individual pipe $w'_{pr}(e)$ through a table of normalized attributes (see Table 3). This table maps potential attribute values (within specified ranges) to their corresponding normalized values, falling from 0 to 1. In this normalized range, a value of 0 indicates the lowest severity, while a value of 1 represents the highest severity. Subsequently, the established probability of pipe-related failure causes w_{pr} is adapted for each pipe individually in $w'_{pr}(e)$, which is the weighted sum of these normalized attributes, as defined in Eq. (3). As the pipe unavailability $u(e)$ is calculated based on an established maximum number of failures, the adapted $w'_{pr}(e)$ results in a value between 0 and 0.396 (i.e., from lowest to highest-vulnerable pipe-related attributes), where a value of $w'_{pr}(e) = 0.396$ would represent a pipe e with the most vulnerable pipe-related features according to the table of normalized attributes (i.e., all the normalized values of pipe-related attributes are 1, therefore $w'_{pr}(e) = w_{pr}$). Importantly, it should be noted that the pipe unavailability $u(e)$ already incorporates the length of each individual pipe; therefore, the length is set as $l = 1$ in the equation.

$$w'_{pr} = (d \times w_d) + (a \times w_a) + (m \times w_m) + (l \times w_l) + (t \times w_t) \tag{3}$$

Given this context, the failure probabilities $p(e)$ for each pipe $e \in \mathscr{E}$ are calculated by multiplying the reference point of the overall likelihood of each pipe failure, $u(e)$, by the sum of the failure weights $w'_{pr}(e)$, w_{er}, and w_{or} (see Eq. (4)).

Table 3
Proposed table of normalized attributes for pipe-related failure causes.

Attribute	Value intervals	Normalized value
Pipe diameter (d)	0 to 90 mm	0
	90 mm to 250 mm	0.33
	250 mm to 560 mm	0.67
	More than 560 mm	1
Reference: Wilson et al. (2017)		
Age (a)	0 to 33 years	0
	33 to 67 years	0.33
	67 to 100 years	0.67
	More than 100 years	1
Reference: Zangenehmadar et al. (2020)		
Material (m)	HDPE (PE 100)	0
	MDPE (black)	0.33
	MDPE (blue), GI, LDPE (black), AC	0.67
	UPVC, DI	1
Reference: Christodoulou and Agathokleous (2012)		
Wall thickness (t)	More than 33.2 mm	0
	14.8 to 33.2 mm	0.33
	3.8 to 14.8 mm	0.67
	0 to 3.8 mm	1
Reference: Wilson et al. (2017)		

$$p(e) = u(e) \times \left(w'_{pr}(e) + w_{er} + w_{or}\right) \tag{4}$$

The annual volume of water affected by the pipe failures is also a crucial metric for assessing resilience. Initially, the volume of Average Unserved Water per service Disruption event (AUW/D) is computed by examining Water Availability (WA) during the Monte Carlo realizations. AUW/D represents the average volume of unserved water in each Monte Carlo realization that results in a water service disruption. Next, utilizing the computed WA value, a Mean Time To Repair (MTTR), and the Mean Time Between Disruptions (MTBD), the number of Average Disruptions per Year (AD/Y) is calculated, as demonstrated in Eq. (5), where the Mean Time To Repair (MTTR) is 0.002739726 (1 day converted to years). Finally, the volume of Average Unserved Water per Year (AUW/Y) is determined by multiplying AD/Y by AUW/D, as illustrated in Eq. (6). This comprehensive measure provides valuable insights into the impact of disruptions on the annual water supply.

$$\mathrm{AD/Y} = \frac{1}{\mathrm{MTBD} + \mathrm{MTTR}};\ \text{where}\ \mathrm{MTBD} = \frac{-\mathrm{WA} \times \mathrm{MTTR}}{\mathrm{WA} - 1} \tag{5}$$

$$\mathrm{AUW/Y} = \mathrm{AD/Y} \times \mathrm{AUW/D} \tag{6}$$

It is important to highlight that the formulation presented in Eq. (5) draws inspiration from a standard telecommunication Availability (A) formula, which is typically expressed as a function of the Mean Time to Repair (MTTR) and the Mean Time Between Failures (MTBF), as detailed in Calle (2004). In the context of this paper, this formula has been adapted to suit the specific needs of water networks. Here, the MTBF corresponds to what it is referred to as the Mean Time Between Disruptions (MTBD), as the calculations focus on service disruptions when computing Water Availability (WA).

2.2.2. *Hydraulic-feasible diameter selection*

To create resilient water networks, an algorithm is needed to efficiently select the optimal diameter for each pipe while simultaneously ensuring the hydraulic feasibility of the design. The Hydraulic-Feasible Diameter Selection (HFDS) algorithm (Algorithm 1) aims to initially predict water flows within pipes, considering destination demands and the pipe network design. Subsequently, it determines the optimal pipe diameters from a predefined set of available options (Calle et al., 2023), ensuring a suitable water speed according to the predicted flows.

The first phase of predicting water flows $w(e), e \in \mathscr{E}$ starts with the assumption that all water pipes in the network have similar speeds. As a result, the water flows from the initial tank to the farthest node while traversing the network and passing through nodes based on their respective distances. In accordance with this premise, the Breadth-First Search (BFS) exploration graph theory algorithm generates an ordered list of water destinations reflecting the sequence of the water's journey and the directional flow within the pipelines, with minor adjustments to prioritize same-level neighbor water destinations based on increasing pipe distances. Afterwards, the HFDS algorithm traverses this list in reverse order. For each evaluated water destination, it predicts the flow within its connected pipes based on the accumulated demand and the various sources from which water comes.

The second phase in determining pipe diameters involves iterating through each water pipe $e, e \in \mathscr{E}$ from the list of available pipe diameters $d \in \mathscr{D}$, arranged in ascending order, until an appropriate flow speed $s(e)$ is achieved based on the predicted pipe flow $w(e)$. The algorithm defines an acceptable speed range, denoted as $s_{min} \leq s \leq s_{max}$, typically falling between 0.6 and 1 m/s (Simpson and Elhay, 2008; MIMAM, 2000). Speeds lower than 0.6 m/s may lead to pipe sediment accumulation issues, while speeds higher than 1 m/s can cause vibrations. Importantly, this range remains consistent across various water qualities, making it applicable to both reclaimed and drinking water networks. When the algorithm identifies an evaluated diameter d resulting in an excessively low speed $s < s_{min}$, it selects the previous, smaller diameter, provided the prior velocity s_p is below the maximum threshold $s_p \leq s_{max}$. Otherwise, although the current diameter results in a low speed, it is chosen. It is crucial to avoid selecting diameters that result in speeds exceeding the maximum limit $s > s_{max}$, as this can lead to pipe failures due to factors such as vibration (Rezaei et al., 2015).

Algorithm 1. Hydraulic-feasible diameter selection (HFDS).

Step 1: Given a water network design $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, initialize the node r and sets $\mathcal{C}$; $\mathcal{D}$; m; $\mathcal{E}$. Initialize s_{min} and s_{max} to the desirable values. Create a new empty set of visited nodes $\mathcal{W} := \emptyset$.
Step 2: Create a new variable $f(v), v \in \mathcal{V}$, which is a float indicating the accumulated consumption of each node in the graph, and initialize to 0 $f(v) := 0, \forall v \in \mathcal{V}$.
Step 3: Order the nodes $c \in C$ by performing a reverse Breadth-First Search (BFS) traversal of graph G starting from node r while considering the weights of node neighbors based on pipe distances.
Step 4: For each consumption node $c \in C$:

(a) set a new variable that indicates the number of sources of node c, such that $o := 0$.

(b) add node c to visited nodes, such that $\mathcal{W} := \mathcal{W} \bigcup \{c\}$.

(c) for each neighbor n of node c:

  (i) if $n \notin \mathcal{W}$, then set $o := o + 1$.

(d) for each neighbor n of node c if $n \notin \mathcal{W}$:

  (i) set $f(n) := f(n) + ((m(c) + f(c))/o)$

  (ii) set current diameter as the smallest diameter in the list $d(\mathcal{E}(c, n)) := \mathcal{D}[0]$.

  (iii) set a counter $i := 0$ and previous speed $s_p := Inf$

  (iv) for every diameter $d \in \mathcal{D}$:

   - obtain the speed s of $\mathcal{E}(c, n)$ considering flow $((m(c) + f(c))/o)$ and diameter d.
   - if $s \leq s_{min}$ and $s_p \leq s_{max}$, then $d(\mathcal{E}(c, n)) := \mathcal{D}[i - 1]$
   - otherwise if $s \leq s_{min}$, then $d(\mathcal{E}(c, n)) := \mathcal{D}[i]$
   - set $s_p := s$ and $i := i + 1$

Step 5: $d(e)$ contains the assigned pipe diameter $\forall e \in \mathcal{E}$.

The HFDS algorithm is integrated into an interactive process with the EPANET software to perform hydraulic validation on the generated network designs, called Hydraulic Refinement Relay (HRR). For each design requiring hydraulic validation, the HFDS algorithm is initially executed to predict water flows and determine appropriate pipe diameters. Subsequently, the network design is automatically converted into an EPANET-compatible INP file and processed. EPANET then generates a result file, from which key output indicators are extracted. These indicators include whether the water supply meets the demands of all nodes, if node pressures $pr(c), c \in \mathscr{C}$ fall within the acceptable range (i.e., between 15 and 60 m (Desta et al., 2022; MoWR, 2006)), and if all water travel times $t(c), c \in \mathscr{C}$ adhere to a maximum residence time. A maximum residence time value of 72 h was determined based on a thorough survey encompassing more than 800 utilities across the USA. This duration is widely acknowledged as the accepted maximum, though actual residence times within a system may diverge considerably due to variations in design and usage patterns (World Health Organization, 2014). While no other references specifically address water reuse systems, a value of 72 h is recommended as a precautionary principle. However, it can be easily adapted as an input value depending on the specific case-study scenario. If any of these indicators fail, highlighting a potential issue with the network design, the HRR process takes specific corrective actions. Depending on which indicator has failed, adjustments are made to the acceptable range of flow speeds, denoted as an interval $[s_{min}, s_{max}]$. The following adjustments are made automatically:

1. If any speed within the network $s(e), e \in \mathscr{E}$ exceeds s_{max}, the HRR slightly reduces s_{max}.
2. If the water supply fails to meet the demands of all consumption nodes $m(c), c \in \mathscr{C}$, the HRR slightly reduces s_{min} while maintaining s_{max}.
3. If node pressures $pr(c), c \in \mathscr{C}$ fall outside the acceptable range, adjustments are made by slightly increasing s_{max} or reducing s_{min}.
4. If any water travel time $t(c), c \in \mathscr{C}$ exceed the required criteria, the HRR adjusts both s_{min} and s_{max} as necessary.

The modified design is then subjected to another round of validation through the EPANET software. The HRR process continues until a feasible hydraulic solution is obtained. However, if such a solution cannot be achieved due to the speeds $s(e), e \in \mathscr{E}$ not falling within absolute interval constraints (i.e., where the minimum speed s_{min} should not be lower than 0.4 m/s, and the maximum speed s_{max} should not exceed 1.2 m/s), the process is terminated because the hydraulic feasibility is unachievable for this design. This outcome may be attributed to factors such as an excessively large network or an insufficient initial tank elevation.

2.2.3. Resilience by design

Designing a resilient water distribution network from its inception can be an arduous challenge, particularly when faced with tight budget constraints. The Resilience by Design (RbD) algorithm offers an effective and automatic solution. It operates as a greedy algorithm, crafting network designs that enhance resilience within the confines of budget limitations. This approach takes advantage of both the HFDS algorithm and the HRR process to guarantee hydraulic feasibility throughout the design process.

The Resilience by Design (RbD) algorithm (Algorithm 2) starts with an initial setup that includes a starting point capable of gravity-based water distribution (i.e., an elevated initial water tank r without requiring water pumps) and a set of locations requiring water ($\mathscr{C}$). The operation of the RbD algorithm is illustrated as:

1. Building the Resilient Network: The RbD algorithm goes through a step-by-step process to construct a resilient network based on the initial graph (see Section 2.1). It evaluates each destination where water is needed, one at a time, until the budget is exhausted.
2. Ensuring Resilience: One of the key goals is to ensure resilience in the network. This means that every consumption point should have at least two independent paths to receive water (i.e., a meshed pipe network design). To achieve this, whenever a path to a consumption point is added to the network, the algorithm also looks for an alternative path to the same point.
3. Optimizing for Cost-Effectiveness: In each iteration, the algorithm selects the candidate destination that provides the most cost-effective solution. This is determined by looking at the water

consumption at each node along the path and considering the length of the path itself.

Algorithm 2. Resilience by Design (RbD) algorithm.

Step 1: Initialize the initial graph $\mathcal{I}(\mathcal{V},\mathcal{E})$, node r, the budget B, sets $\mathcal{C}$; $\mathcal{D}$; m, and current expenses $Z := 0$.
Step 2: Let $\mathcal{T}(\mathcal{V}',\mathcal{E}')$ be the resilient network design graph initialized with $\mathcal{V}' := \{r\}$ and $\mathcal{E}' := \varnothing$.
Step 3: Create an empty prioritized list $\mathcal{C}' := \varnothing$ of consumption node candidates $c \in \mathcal{C}$ to be added to $\mathcal{T}$.
Step 4: For each consumption node $c : c \in \mathcal{C}, c \notin \mathcal{V}'$:
(a) get the node $a \in \mathcal{V}'$ that minimizes the path to join $\mathcal{T}$ with c, such that:
$$\sum l(e), e \in \mathcal{E}(a,c) := \min((\sum l(e), e \in \mathcal{E}(v',c)), v' \in \mathcal{V}')$$
(b) if Z+min_cost$(\sum l(e), e \in \mathcal{E}(a,c)) \leq B$, then:
(i) compute profit $P := \dfrac{\sum m(v), (v,\_) \in \mathcal{E}(a,c)}{\sum l(e) \times 2, e \in \mathcal{E}(a,c)}$.
(ii) add node c to $\mathcal{C}'$ such that $\mathcal{C}' := \mathcal{C}' \bigcup \{c\}$, prioritized by profit P. Also store its a and $\mathcal{E}(a,c)$
Step 5: For each consumption node candidate $c : c \in \mathcal{C}'$ and its related node a and path $\mathcal{E}(a,c)$ ordered by descending profit:
(a) remove every $e \in \mathcal{E}(a,c)$ if it does not disconnect the initial graph $\mathcal{I}$.
(b) find an alternative shortest path $\mathcal{S} := \mathcal{E}(a,c)$ from c to a following the equation of Step 5(a).
(c) reinstate removed $e \in \mathcal{E}(a,c)$ edges to graph $\mathcal{I}$ from Step 6(a).
(d) add the two paths to the resilient network graph $\mathcal{T}$, such that $\mathcal{E}' := \mathcal{E}' \bigcup \mathcal{E}(a,c) \bigcup \mathcal{S}$.
(e) compute HFDS algorithm and HRR process to get pipe diameters $d(e), e \in \mathcal{E}'$ of network $\mathcal{T}$.
(f) if Z+cost$(\mathcal{T}) \leq P$, then:
(i) for each node $(v,\_)$ in $\mathcal{E}(a,c) \bigcup \mathcal{S}$, if $v \in \mathcal{C}$ then $\mathcal{C} := \mathcal{C} \setminus \{v\}$
(ii) set $Z := Z$+cost$(\mathcal{T})$.
(iii) go to Step 3.
Step 6: $\mathcal{T}$ represents the final water distribution network design $\mathcal{G}$.

In order to benefit from the resilient meshed design, the RbD algorithm places valves $v(e)$ on each pipe $e \in \mathscr{E}$ connected to nodes with more than one downstream branch. Valve placement is crucial since a failure on an individual non-valve pipe e can result in the service disruption of an entire network section until its flow is successfully isolated both upstream and downstream.

2.2.4. *Resilience strengthening*

In many cases, existing water distribution networks (WDNs) have already been established and are currently in operation but may lack the necessary level of resilience. If not addressed promptly, inadequately resilient networks can lead to substantial economic losses and service disruptions. In such scenarios, it becomes crucial to initiate projects aimed at enhancing the network's resilience. The Resilience Strengthening (RS) algorithm offers an effective solution to this challenge. RS is a greedy algorithm, and its primary purpose is to enhance the resilience of pre-existing network designs while working within predefined budget constraints. Similar to the Resilience by Design (RbD) algorithm (see Section 2.2.3), the RS takes advantage of both the HFDS algorithm and the HRR process to guarantee hydraulic feasibility. In this scenario, the HFDS algorithm is applied to pre-existing water distribution networks, where the original pipe diameters are fixed and cannot be altered. Adapted to the context of RS, the HFDS algorithm focuses on predicting flows and determining diameters only for the newly added pipes, while leaving the existing network layout unchanged.

The RS (Algorithm 3) starts with a pre-existing network design and its operation can be outlined as follows:

1. Enhancing resilience: The RS algorithm introduces additional pipes and valves to enhance resilience in the network. This means, in a similar way to the RbD algorithm, that every consumption point should have at least two distinct paths to receive water. To achieve this, the algorithm searches for alternative routes to the same destination based on the initial graph (see Section 2.1).
2. Optimizing for Cost-Effectiveness: In each iteration, the algorithm selects the candidate that provides the most cost-effective solution. This selection process considers the volume of water delivered to each node via at least two distinct paths, factoring in the additional length of the newly introduced pipes.

Algorithm 3. Resilience Strengthening (RS) algorithm.

Step 1: Initialize the initial graph $\mathcal{I}(\mathcal{V},\mathcal{E})$, node r, the budget B, sets $\mathcal{C}$; $\mathcal{D}$; m, and current expenses $Z := 0$.
Step 2: Let $\mathcal{T}(\mathcal{V}',\mathcal{E}')$ be the pre-existing network design graph.
Step 3: Create an empty prioritized list $\mathcal{C}' := \varnothing$ of consumption node candidates $c \in \mathcal{C}, \forall c \in \mathcal{V}'$ to be evaluated.
Step 4: For each consumption node $c : c \in \mathcal{C}$:
(a) remove every $e \in \mathcal{E}(r,c)$ if it does not disconnect the initial graph $\mathcal{I}$.
(b) find an alternative shortest path $\mathcal{S} := \mathcal{E}(r,c)$ from r to c, such that:
$$\sum l(e), e \in \mathcal{E}(r,c) := \min((\sum l(e), e \in \mathcal{E}(v',c)), v' \in \mathcal{V}')$$
(c) reinstate removed $e \in \mathcal{E}(r,c)$ edges to graph $\mathcal{I}$ from Step 4(a).
(d) if Z+min_cost$(\sum l(e), e \in \mathcal{S} \notin \mathcal{E}(r,c)) \leq B$, then:
(i) compute profit $P := \dfrac{\sum m(v), (v,\_) \in \mathcal{E}(r,c) \bigcup \mathcal{S}}{\sum l(e), e \in \mathcal{S} \notin \mathcal{E}(r,c)}$.
(ii) add node c to $\mathcal{C}'$ such that $\mathcal{C}' := \mathcal{C}' \bigcup \{c\}$, prioritized by profit P. Also store its $\mathcal{S}$.
Step 5: For each consumption node candidate $c : c \in \mathcal{C}'$ and its alternative path $\mathcal{S}$ ordered by descending profit:
(a) add every $e \in \mathcal{S} \notin \mathcal{E}(r,c)$ to $\mathcal{T}$.
(b) if Z+cost$(\mathcal{T}) \leq P$, then:
(i) for each node $(v,\_)$ in $\mathcal{E}(r,c) \bigcup \mathcal{S}$, if $v \in \mathcal{C}$ then $\mathcal{C} := \mathcal{C} \setminus \{v\}$
(ii) set $Z := Z$+cost$(\mathcal{T})$.
(iii) go to Step 3.
(c) otherwise remove every $e \in \mathcal{S} \notin \mathcal{E}(r,c)$ from $\mathcal{T}$.
Step 6: $\mathcal{T}$ represents the final water distribution network design $\mathcal{G}$.

3. Results and discussion

3.1. *Case study*

The usefulness of the methods and algorithms presented in this paper is illustrated in the city of Girona, Catalonia (northeast of the Iberian Peninsula). Girona, with its 102,666 inhabitants and 47,446 households (2.2 citizens per household), is a typical compact Western Mediterranean city (Statistical Institute of Catalonia, 2022). Its urban area extends 12.7 km^2 on a rivers' crossing, has a population density of 8,139 hab/km^2, an average slope of 5.1, and an altitude range (difference between the minimum and maximum altitudes) of 177 m. Within the results section of this paper, we present two scenarios:

(i) Achieving a cost-effective design of a new resilient reclaimed water network within a limited budget, ensuring hydraulic feasibility through the Resilience by Design (RbD) algorithm (Algorithm 2 and Section 3.2).
(ii) Enhancing resilience based on previous research regarding a non-resilient but cost-effective reclaimed water network design (Calle et al., 2023), using the Resilience-Strengthening (RS) algorithm (Algorithm 3 and Section 3.3).

Both scenarios share the same initial water tank location in the Fontajau neighborhood, situated at 111 m above sea level. The initial graph (see Section 2.1) encompasses Girona's entire urban area, including estimated reclaimed water demands for various public and private purposes (see Fig. 1), as detailed in previous works (Calle et al., 2023).

The results were obtained using an Ubuntu 20.04 LTS server (CPU: AMD Ryzen 5 5600X, 32GB RAM), executed within a Python notebook (Jupyter Hub, vanRossum (1995)). However, the tool is adaptable to other systems.

3.2. Resilient-by-design network

In scenario (i), a cost-effective and resilient network, named 'resilient-by-design', has been designed to ensure hydraulic feasibility within a limited budget of €1,500,000. The Resilience by Design (RbD) algorithm (Algorithm 2) was employed for this purpose. Fig. 2 illustrates the network graph created for this scenario, resulting in a 16-kilometer network. The 'resilient-by-design' network accommodates a total consumption of 1527 cubic meters per day, effectively serving 21.4 % of the city's total reclaimed water demand (Water served / total demand × 100). Remarkably, the algorithm demonstrated a rapid execution, completing its task within seconds.

Contrasting with prior research works (Yazdani et al., 2011; Herrera et al., 2016), the 'resilient-by-design' network not only conforms to a cost-effective, resilient layout consistent with the principles of the RbD algorithm, ensuring that each destination point is supplied by at least two distinct paths, but it also undergoes thorough hydraulic feasibility validation. This hydraulic feasibility assessment acts as a critical link between theoretical design and practical implementation.

The RbD algorithm integrates the Hydraulic-Feasible Diameter Selection (HFDS) algorithm (Algorithm 1) and the Hydraulic Refinement Relay (HRR) process. It utilizes the EPANET software to validate hydraulic feasibility at every stage of the reclaimed water network design process. The hydraulic simulation results for the 'resilient-by-design' are detailed in Table 4, presenting essential hydraulic output indicators categorized into three main groups: Water Service, Node Pressure, and Water Quality.

In the Water Service category, two vital aspects are assessed. First, a verification is conducted to check whether water can be effectively delivered to all destination points. Second, it is confirmed that water speeds remain below the established maximum limit of 1.2 m/s, thereby ensuring the correct functioning of the network.

Within the Node Pressure category, the focus lies on the distribution of node pressures to ensure that all node pressures fall within the acceptable range (i.e., between 15 and 60 m (Desta et al., 2022; MoWR, 2006)).

Addressing Water Quality concerns, especially in areas characterized by lower water speeds, we calculate the required travel time for water to reach each destination from the initial tank. This calculation is essential to ensure that water quality remains within acceptable limits. In this case study, the recommended maximum water age value of 72 h (World Health Organization, 2014) has been utilized (see Section 2.2.2). This analysis provides assurance that, despite lower speeds in some specific parts of the network (e.g., the smallest 32 mm pipes and distant endpoints with low demands), water quality is compliant and within acceptable limits.

In future works, we will explore incorporating pressure pumps within the water distribution network designs. This proactive approach ensures an uninterrupted water supply, even in scenarios where initial tank elevation alone may not be sufficient to serve water to all the destinations.

The resilience assessment of the 'resilient-by-design' network utilized the Water Availability (WA) metric, as outlined in Section 2.2.1. This assessment involved an extensive series of 1,000,000 Monte Carlo simulations. Remarkably, these simulations resulted in a Water Availability value of WA = 0.9949, indicating a substantial 99.49 % probability that the initial water tank can consistently fulfill the water demands of all destination nodes within the network. This translates to a mere 0.51 % chance of service disruption.

The Monte Carlo simulations conducted to evaluate WA also facilitated the computation of the Average Unserved Water per service Disruption event (AUW/D), which quantifies the average volume of water that cannot be served in the event of a service disruption, yielding a value of 512 m^3. Moreover, the Average Disruptions per Year (AD/Y) was computed using the Mean Time To Repair (MTTR) of 24 h and the Mean Time Between Disruptions (MTBD) derived from the Water Availability (WA) metric, as detailed in Section 2.2.1, yielding an average of 1.86 disruptions per year. Consequently, the Average Unsupplied Water per Year (AUW/Y) was determined to be a total volume of 952 m^3/year.

3.3. Resilience-strengthening of a current non-resilient network

In this section, scenario (ii), involving the resilience enhancement of a current 'non-resilient' network through the application of the Resilience Strengthening (RS) algorithm (Algorithm 3) is introduced. The 'non-resilient' network illustrates a cost-effective design for a reclaimed water network within the same city of Girona. This network's design is based in the same topology obtained by the algorithms introduced in Calle et al. (2023).

The original 'non-resilient' network design is not hydraulically feasible, as flows were predicted without the EPANET validation. Thus, before the application of the Resilience Strengthening (RS) algorithm (Algorithm 2), the network's pipe diameters have been adapted to ensure hydraulic feasibility, thus facilitating a fair comparison of resilience and cost output indicators. Consequently, the adapted 'non-resilient' network, illustrated in Fig. 3, represents a tree-based topology characterized by hydraulic feasibility, 10 kilometer pipe length, and the same 1527 m^3/day volume of transported water as the 'resilient-by-design' network in scenario (i), effectively serving 21.4 % of the city's total reclaimed water demand. The adapted pipe diameters resulted on a total construction cost for the network of €1,135,000.

The application of the RS algorithm over the current 'non-resilient' network resulted in the 'resilience-strengthened' design, as illustrated in Fig. 4. The 'resilience-strengthened' design evolved to a meshed topology characterized by hydraulic feasibility, 20 kilometer pipe length, and maintaining the same 1527 m^3/day volume of transported water. The added pipes resulted in an extra 10 km and a construction cost of €742,000, which results in a total cost of €1,880,000. In the figure, the original pipes of the 'non-resilient' network are illustrated in red, while the new pipes extension are in blue.

3.4. Comparative analysis of key output indicators

This section provides a comprehensive comparative analysis of key output indicators among the following networks: the current 'non-resilient' network, the 'resilience-strengthened' network enhanced through the application of the Resilience Strengthening (RS) algorithm (Algorithm 2) to the 'non-resilient' network, and the 'resilient-by-design' network created in scenario (i), as presented in Table 5. In the context of this study, it becomes evident that while the daily reclaimed water volume remains constant, notable variations emerge in the output indicators of the three network designs.

Beginning with the 'non-resilient' design, it is apparent that its construction cost is the lowest at €1,135,000, primarily attributed to its limited pipe length of just 10 km. As expected, this design exhibits the least favorable Water Availability (WA) at 99.20 %, resulting in a 0.80 % probability of service disruption. Furthermore, it registers the highest values for Average Unserved Water per Disruption (AUW/D), Average Disruptions per Year (AD/Y), and Average Unserved Water per Year (AUW/Y), culminating in a substantial volume of 2786 m^3/year affected by service disruptions. To ensure the sustained and reliable operation of these critical networks over the long term, it is imperative to minimize

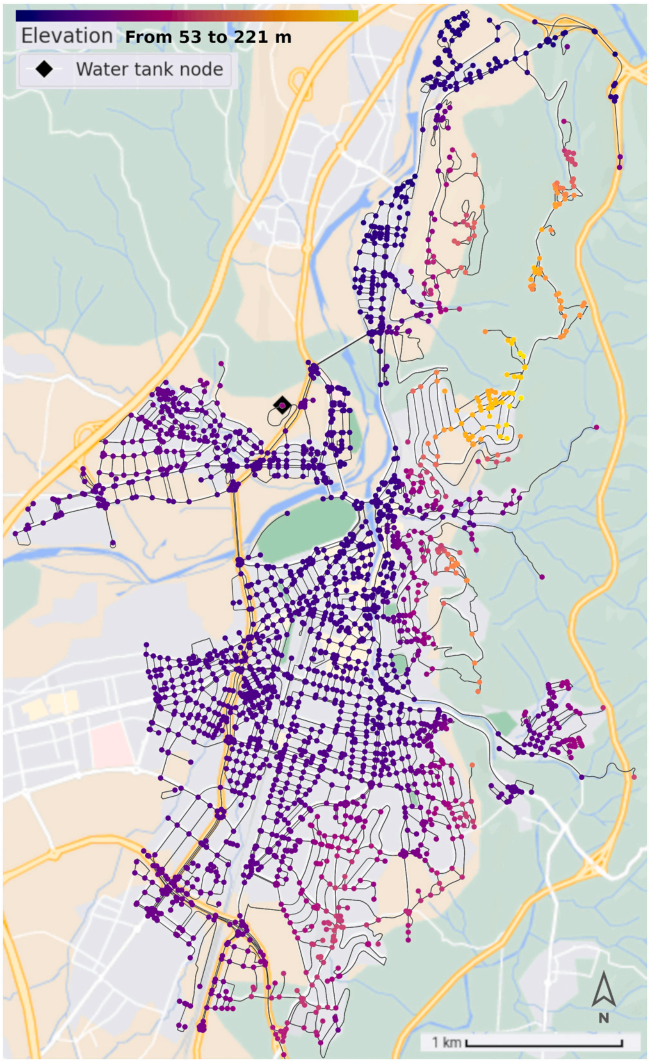

Fig. 1. Visualization of the Girona case study area, highlighting nodes color-coded by elevation, and indicating the placement of the initial water tank.

both the probability of service disruptions (SD) and the impact on water service in the event of such disruptions as much as possible (AUW/D). Concerning additional costs, the AUW/Y cost amounts to €1530 and the cost of D/KY rises to €9980, marking them as the highest among the three designs, reflecting the low resilience of the network.

The enhanced 'resilience-strengthened' design presents a network expansion of 20 km, which is almost twice the length of the pipe network compared to the original 'non-resilient' design. The total construction cost of the network is the sum of the cost of the original 'non-resilient' design (i.e., €1,135,000) and the cost of the expansion resulting from the RS algorithm (i.e., €742,000), which results in €1,877,000. Thus, the required investment to enhance resilience represents 65 % of the initial construction cost of the 'non-resilient' network. While this initial financial commitment is substantial, it yields significant improvements in resilience. The 'resilience-strengthened' design achieves a Water Availability (WA) of 99.30 %, translating to a noteworthy 12.5 % reduction in service disruptions (SD). Furthermore, it reduces the Average Unserved Water per Year (AUW/Y) to 1656 m^3, constituting a nearly 65 % reduction in the impact of water service disruptions. Notably, despite the 'resilience-strengthened' design featuring nearly twice the pipe length of the original 'non-resilient' network, the Average Disruptions per Year (AD/Y) also decrease by 11 % (from 2.92 to 2.56). This reduction underscores the effectiveness of the RS algorithm's strategy, which enhances network resilience by meshing the

Fig. 2. Visualization of the 'resilient-by-design' €1,500,000 reclaimed water network in Girona (highlighted in red) overlaying the Girona street graph (in grey).

infrastructure and ensuring multiple distinct water paths from the initial tank to all destinations, alongside efficient valve placement. Regarding additional costs, the AUW/Y cost of this design amounts to €910, which marks a 40 % decrease compared with the 'non-resilient' design, reflecting its improved resilience. Although the cost of D/KY decreases to €9530, it only represents a 5 % reduction, underscoring the trade-off between network resilience and maintenance expenses.

Notably, it is worth emphasizing that, to the best of our knowledge, there are currently no other cost-effective solutions available in existing research that offer comparable enhancements to the resilience of pre-existing network designs. By employing RS, organizations can address the critical issue of network resilience within the limitations of available resources, thereby reducing the potential for economic losses and service interruptions while maximizing the resilience and functionality of their water distribution systems.

In the context of planning the new design of water distribution

Table 4
Summary of hydraulic feasibility indicators provided by EPANET ('resilient-by-design', scenario (i)).

Indicator	Result
Water service	
- All destination points are fully supplied	Yes
- Water speed remains within the maximum (<12 m/s)	Yes
Node pressure	
- All nodes present adequate pressures (in meters)	Yes
- Quartiles [Q1, Q2-Median, Q3]	[33.3, 36.5, 40.5]
- Minimum and maximum values	[29.9, 44.5]
Water quality	
- Water age is acceptable (in minutes)	Yes
- Quartiles [Q1, Q2-Median, Q3]	[60.5, 75.5, 90.6]
- Minimum and maximum values	[6.7, 363.3]

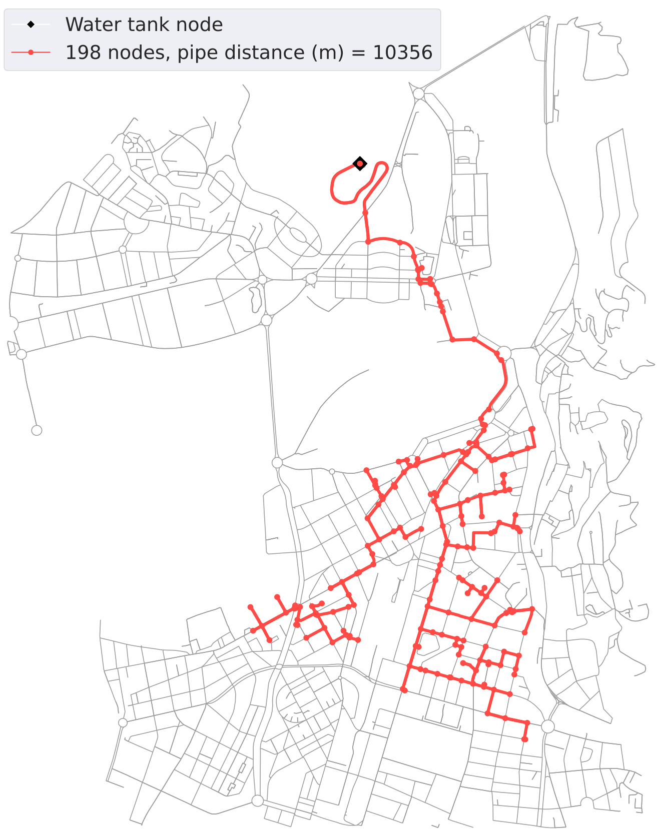

Fig. 3. Visualization of the 'non-resilient' current reclaimed water network in Girona (highlighted in red) overlaying the Girona street graph (in grey).

networks (WDNs), particularly in newly developed neighborhoods, it becomes essential to compare 'non-resilient' and 'resilient-by-design' networks. This comparison aids in determining the overall prioritization strategy, which can either emphasize solely the cost-effectiveness of the design or take into account both resilience and cost-effectiveness indicators.

Notably, the 'resilient-by-design' network incurs an initial cost that is 32 % higher, primarily due to the requirement for a more interconnected and meshed topology. However, it is worth noting that, despite the higher initial cost, the 'resilient-by-design' approach still offers a cost reduction of 20 % compared to making an already existing network resilient. This upfront investment yields significant benefits, including a 36 % reduction in the probability of service disruption and a nearly 50 % decrease in the average unserved water volume per disruption. Consequently, the annual average unserved water drops from 2786 to 952 m^3, representing a substantial 65 % reduction. In terms of additional costs, the 'resilient-by-design' approach demonstrates significant advantages. In particular, it shows the lowest AUW/Y cost of €520, indicative of its maximal resilience. Furthermore, the cost of D/KY amounts to €6770, marking a notable 32 % reduction from the cost observed in the 'non-resilient' design at €9980. This decrease in disruption repair costs per kilometer per year, despite a considerable increase in the network's pipe length, underscores the effectiveness of the 'resilient-by-design' network. It indicates that despite the infrastructure's significant expansion, the associated disruption repair expenses have notably decreased, demonstrating the cost-effectiveness of resilience-focused strategies. This reaffirms the efficacy of the resilient-by-design approach, highlighting its capacity to mitigate disruptions while efficiently managing maintenance expenditures.

Fig. 5 illustrates the progression of Average Unserved Water per Year (AUW/Y) over a 50-year operational period. When extending our perspective to this extended timeframe, opting for a 'resilient-by-design'

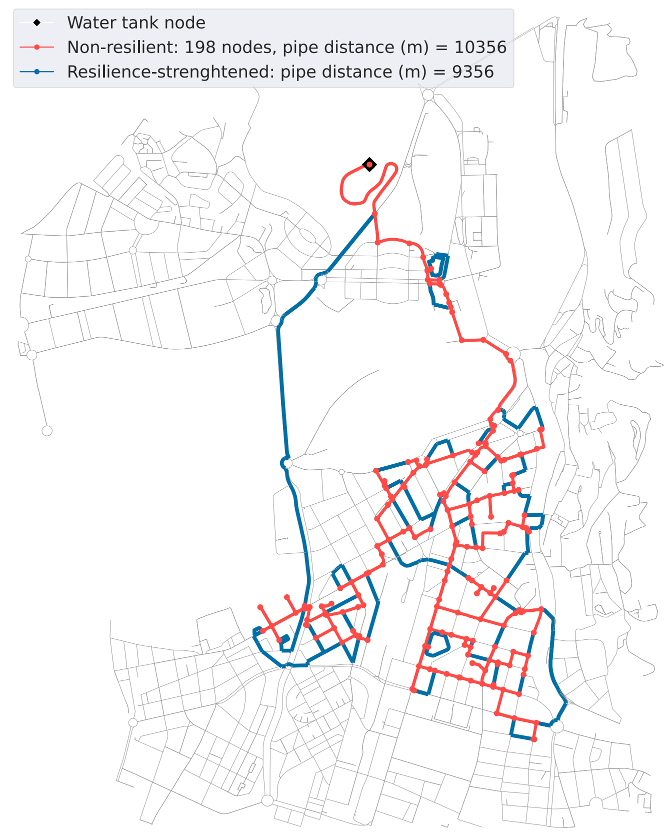

Fig. 4. Visualization of the 'resilience-strengthened' network extension in Girona (highlighted in blue) over the 'non-resilient' network existing pipes (highlighted in red).

Table 5
Comparative analysis of key output indicators across 'non-resilient', 'resilience-strengthened', and 'resilient-by-design' network designs.

	Non-resilient	Resilience-strengthened	Resilient-by-design
Length (m)	10,356	19,712	16,113
Cost (k€)	1135	1877	1500
WA (%)	99.20	99.30	99.49
SD (%)	0.80	0.70	0.51
AUW/D (m^3)	954	647	512
AD/Y	2.92	2.56	1.86
AUW/Y (m^3)	2786	1656	952
Cost AUW/Y (k€)	1.53	0.91	0.52
Cost D/KY (k€/km)	9.98	9.53	6.77

WA (%) – percentage of Water Availability; SD (%) – percentage of Service Disruption (SD = 1 - WA); AUW/D (m^3) – volume of Average Unserved Water per Disruption; AD/Y – number of Average Disruptions per Year; AUW/Y (m^3) – volume of Average Unserved Water per Year; Cost AUW/Y (k€) – cost of the AUW/Y, derived from the mean price per cubic meter of €0.550502; Cost D/KY (k€/km) – cost of disruption repairs per kilometer per year, derived from the mean price of disruption repairs of the WA Monte Carlo realizations, the AD/Y, and the length of the network (based on the cost of entire pipe replacements in the events of disruptions).

network would effectively shield up to a substantial 91,700 m^3 of water from the impact of water disruption events, in stark contrast to the 'non-resilient' network. Even when factoring in the subsequent resilience enhancement of the RS algorithm for the 'non-resilient' network, resulting in the 'resilience-strengthened' design with notable improvements, the associated costs would still be 25 % higher, and the annual average unserved water volume would remain 76 % higher. This underscores the long-term benefits of integrating resilience into the initial design considerations (i.e., resilience by design).

3.5. Cost analysis: reclaimed network vs. tap water baseline

In addition to evaluating the effectiveness of the 'resilient-by-design' network solution, we conducted a comparative cost analysis against a baseline scenario using tap water. In this baseline scenario, the supply of all water relies solely on the drinking water distribution network as no reclaimed water network exists. Upon implementing the 'resilient-by-design' network, 1527 cubic meters per day of reclaimed water are now supplied, reducing the reliance on the drinking water network for this portion of water demand.

To assess the benefits of this transition, we compared the cost savings of water originally provided by the baseline drinking water network, calculated using a price of €1.09 per cubic meter. This baseline scenario's cost is calculated from the mean price per cubic meter of drinking water in Spain in 2022 (AEAS-AGA, 2022).

On one hand, the reclaimed WDN includes the costs extracted from the algorithms and methods (i.e., design phase), which include construction costs, the cost of disruption repairs per year, and Water Availability (WA) costs; WA costs represent the expenses associated with the Average Unserved Water per Year (AUW/Y), which during disruption events would otherwise be supplied by the original baseline drinking water network.

On the other hand, the reclaimed WDN costs also encompass the adequate wastewater treatment to obtain the appropriate reclaimed water quality for specified water usages, the construction of the supplying WDN from the wastewater treatment plant (WWTP) to the reclaimed WDN initial tank, and operation costs of the pressure pump needed for the supplying WDN. These costs have been manually calculated for our case study. Construction costs of the supplying WDN include expenses for pipes, valves, and an additional water tank with the same capacity as the reclaimed WDN initial tank placed at the WWTP site. These costs have been meticulously computed utilizing the same REWATnet database as the construction costs of reclaimed WDNs. Additionally, the operational costs of the pressure pump essential for the supplying WDN have been determined based on an average water pumping energy consumption of 0.475 kWh/m^3 (Yerri and Piratla, 2019), and the final average energy price in Spain during 2023, standing at 0.0996 €/kWh (Statista, 2024).

The costs associated with wastewater treatment at the WWTP have been derived from the Suggereix tool (Catalan Water Agency, 2021), specifically designed to streamline access to information and resources concerning reclaimed water in Catalonia. This tool aids in decision-making processes regarding the costs of water regeneration and reuse procedures. It has been used in conjunction with the Spanish guide for the application of R.D. 1620/2007 (Spanish Ministry of Environment and Rural and Marine Affairs, 2010), which proposes the following wastewater treatment train: conventional activated sludge system with biological nutrient removal, including a secondary clarifier + coagulation/flocculation process + sand filter + microfiltration or ultrafiltration membrane + final disinfection (using Cl_2). This treatment train is recommended for achieving the best water quality, fully eliminating *Escherichia coli* concentrations, which is necessary for the water uses selected in our case study, including public and private garden irrigation and toilet flushing. The expenses linked to this wastewater treatment train, encompassing both construction and operation and maintenance (O&M) costs, for the water volume of 1527 m^3/day for 50 years have been calculated as €1100/day.

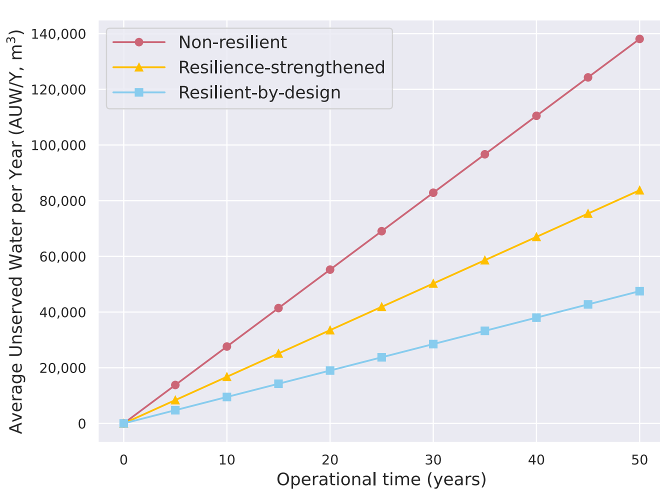

Fig. 5. Evolution of Average Unserved Water per Year (AUW/Y) over a 50-year operational period.

Table 6
Cost analysis of the 'resilient-by-design' reclaimed WDN, including the supplying WDN and wastewater treatment costs, considering a 50-year operational period.

Metric	Cost (k€)	Cost (%)
Construction	1500	5.12
Disruption repairs	5453	18.62
Tap water served during disruption events	26	0.09
Supplying WDN construction	906	3.10
Supplying WDN operational costs	1318	4.50
Wastewater treatment at WWTP	20,075	68.57
Total	29,278	100

Table 6 outlines the cost analysis of the 'resilient-by-design' reclaimed WDN over a 50-year operational period, providing a comprehensive assessment of its cost-effectiveness. The total cost of the reclaimed WDN for this period amounts to €29,278,000 (€1.05 per cubic meter), compared to €30,375,848 (€1.09 per cubic meter) for the tap water baseline, showing that they are both in the same level of magnitude. In addition to the slightly 3.67 % cost decrease, the reclaimed WDN saves up to a remarkable 27,820,150 cubic meters of water from the drinking water network. Significantly, the complex wastewater treatment train emerges as the primary expense, comprising up to 68.57 % of the total cost of the reclaimed WDN. This underscores the substantial investment required to treat wastewater to a quality suitable for reuse in our case-study scenario.

It is noteworthy that Spain's pricing model for drinking water does not fully account for all associated costs, including operational, infrastructure maintenance, renovation, and quality assurance measures (AEAS-AGA, 2022). In contrast, these associated costs, which are integral to ensuring water quality and service reliability, are fully integrated into the cost analysis of our reclaimed WDN solution. Therefore, taking these factors into account, the potential cost savings offered by our reclaimed WDN solution could be even more significant compared to the conventional tap water baseline.

While the 'resilient-by-design' reclaimed WDN demonstrates cost-effectiveness over a 50-year operational period, an initial investment is required to build the infrastructure (i.e., construction costs). Given the current drought emergency in our case study region, it becomes imperative to seek public aid initiatives aimed at promoting water reuse. Such subsidies are crucial in incentivizing water reuse practices, especially considering the severe strain on water resources. These initiatives not only yield significant ecological benefits but also promise substantial long-term cost savings.

At present, the methodology outlined in this paper does not include pressure pumps in the algorithms generating reclaimed WDN designs, thus omitting direct consideration of operation and maintenance (O&M) costs from the initial elevated tank to the consumption destinations. In our specific case study, the deliberate absence of pressure pumps aligns with the geographical reality of Girona, where an elevated location with pre-treated reclaimed water readily available for designated purposes eliminates the need for additional pumping. Future research will incorporate pressure pumps and O&M costs directly into the reclaimed WDN design phase, allowing for the evaluation of additional case studies that necessitate their use. This advancement will build upon insights from relevant literature, such as studies by Khurelbaatar et al. (2021) and Friesen et al. (2023), which provide valuable frameworks for integrating such considerations.

3.6. Final thoughts

While there exists a substantial body of literature on water network resilience and its evaluation, it becomes evident that this specific field of study has been lacking comprehensive measures or strategies for ensuring resilience through design. This paper addresses this gap in the literature by presenting algorithms and metrics that are well-suited for integration with existing approaches and tools, thus offering practical solutions for enhancing reclaimed WDN resilience. Notably, our work serves as an ideal supplement to the Water Network Tool for Resilience (WNTR) (Klise et al., 2017a, 2018). In addition to its primary function of resilience assessment, our algorithms offer cost-effective solutions for enhancing resilience in two key scenarios: the initial design of a network (RbD algorithm), and the optimization of resilience in existing operational networks (RS algorithm).

The figures showcased in the results section of this paper are automatically generated and exported as high-quality PDF vector maps. This ensures that their clarity and detail are preserved even when zooming in. Additionally, the network designs and hydraulic feasibility outputs are parsed into interactive HTML maps, a valuable resource for network operators when evaluating results and making informed decisions (Crickard III, 2014). Specifically, our Hydraulic Refinement Relay (HRR) process extracts key data from the EPANET output indicators, including node pressures, water supply, pipe velocities, and flow rates. This interactive presentation of information offers a comprehensive understanding of the network's performance, enhancing decision-making capabilities.

In contrast with the majority of the evaluated literature, all algorithm definitions, implementations, and output indicator results for the case study, including numerical, on-map, and graphical data visualizations, are available on a dedicated public repository (Martínez, 2023). This transparency and accessibility underscore our commitment to fostering collaboration and enabling wider application of our research findings in practice. All these algorithms and data will be available to municipalities, empowering them to utilize our work as needed. Given that the design and planning phase of water distribution networks is known to cost up to 10 % of the initial investment (Khurelbaatar et al., 2021), our work not only facilitates decision-making but also potentially saves significant financial resources.

4. Conclusions

This study fills a critical gap in the existing literature by introducing novel approaches for enhancing and evaluating the resilience of reclaimed water distribution networks. We have presented mathematical algorithms for both designing resilient water distribution networks from scratch and enhancing existing networks within limited budget constraints. These algorithms not only prioritize resilience but also optimize cost-effectiveness. Remarkably, the Resilience by Design (RbD) algorithm (Algorithm 2) guarantees both cost-effective and resilient water network designs, even with limited budgets. Additionally, the Resilience-strengthening (RS) algorithm (Algorithm 3) demonstrated excellent performance by significantly enhancing resilience output indicators within an existing non-resilient network design.

Furthermore, we introduced a novel metric, Water Availability (WA), providing a comprehensive measure to evaluate network resilience. Our innovative and interactive process seamlessly integrates these algorithms with the EPANET software validations, ensuring cost-effective resilience while adhering to hydraulic feasibility constraints in network designs. This holistic approach reshapes the way we evaluate and design resilient water distribution systems.

In practical terms, our study demonstrated substantial benefits in prioritizing resilience in network design. Comparing a resilient-by-design network to a non-resilient counterpart, we observed a 36 % reduction in the probability of water service disruption and a significant 65 % decrease in the annual average unserved water due to service disruptions (AUW/Y). Notably, not only is the AUW/Y significantly reduced, but the cost of disruption repairs per kilometer per year (D/KY) also decreases by a significant 32 % compared to the non-resilient design, highlighting its cost-effectiveness. These findings underscore the long-term advantages of resilience-focused network design, with our case study effectively safeguarding up to a significant 91,700 cubic meters of water from the impact of water disruption events compared to an equivalent non-resilient design.

Our cost analysis also revealed a 3.67 % decrease in costs over a 50-year operational period for our 'resilient-by-design' reclaimed water distribution network (WDN) solution compared to the baseline of using the conventional drinking WDN, highlighting its cost-effectiveness. Additionally, a remarkable amount of 27,820,150 cubic meters of clean water can be saved by our reclaimed WDN solution, especially meaningful in light of the ongoing drought emergency present in our case study region.

Overall, our research not only addresses a crucial gap in the literature by focusing on reclaimed water distribution networks but also illustrates its applicability to other WDN systems with minimal input data adaptation. Our work provides valuable insights and practical tools for the resilient design of water distribution networks, significantly contributing to the advancement of water resource management and infrastructure planning.

CRediT authorship contribution statement

David Martínez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sergi Bergillos:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Lluís Corominas:** Conceptualization, Resources, Visualization, Writing – review & editing. **Joaquim Comas:** Conceptualization, Resources, Visualization, Writing – review & editing. **Fenghua Wang:** Conceptualization, Methodology, Resources, Writing – review & editing. **Robert Kooij:** Conceptualization, Resources, Writing – review & editing. **Eusebi Calle:** Conceptualization, Resources, Supervision, Visualization, Writing – review & editing.

Declaration of competing interest

There is no conflict of interest.

Data availability

The data, algorithms, and code implementations that support the findings of this study are openly available in "Enhancing resilience of water distribution networks with cost-effective meshing" at https://doi.org/10.5281/zenodo.8398703, reference Martínez (2023).

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