Reliability Engineering and System Safety 219 (2022) 108248

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

A comprehensive framework to efficiently plan short and long-term investments in water supply and sewer networks

Cristóbal Ramos-Salgado [*], Jesús Muñuzuri, Pablo Aparicio-Ruiz, Luis Onieva

Organization Engineering Group, School of Engineering, University of Seville, Camino de los Descubrimientos s/n, 41092 Seville, Spain

ARTICLE INFO

Keywords:
Water distribution and sewer system
Infrastructure asset management
Risk management
Performance assessment
Long-term investment

ABSTRACT

Water supply and sewer networks are critical infrastructures that provide a basic service to society. However, these systems constantly age and degrade over time. In addition, since network infrastructures are so extensive in length, they require a significant investment in maintenance tasks. Hence, within the context of infrastructure asset management (IAM), accurately defining the most efficient investment planning possible is essential to ensure their long-term sustainability. This paper presents an original five-step comprehensive framework to successfully implement an infrastructure asset management strategy and plan long-term investments. Moreover, this methodology integrates innovative and relevant operational and convenience factors that, while provide the problem both with realism and practicality, have not been addressed so far. To illustrate the usefulness and applicability of this methodology, the case study of a large water company in Spain is presented.

1. Introduction

Water infrastructures that provide a basic public service are supposed to operate properly during their service life. However, they inevitably age and degrade, leading to inefficiencies, and choosing the right elements and time to replace is crucial. While appropriate maintenance requires important economical effort, public investment in these infrastructures is usually insufficient or not based on technical criteria. Thus, a proper renewal strategy of these degrading infrastructures to guarantee the future technical, social, economic, and environmental sustainability is a challenge that water companies and municipalities must face [1].

Therefore, the water utilities' objective is to plan and define efficient long-term investment strategies in order to maintain, if not enhance, these infrastructures' performance, whilst managing limited economic resources. And it is here where the infrastructure asset management (IAM) comes into play. According to Alegre and Coelho, the IAM methodologies in urban water networks "seeks that the infrastructure performance meets the service targets, risks are properly managed, and costs are as reduced as possible over time" [2].

In this sense, many countries have developed diverse water infrastructure asset management guides to aid the decision-making process for the rehabilitation and renovation of these systems [3–9]. Also, several decision-aid methodologies and software tools have been developed all over the world over the last two decades to facilitate water companies perform an appropriate management of their infrastructures. Some of them are KANEW [3], AQUA-WertMin [4], UtilNets [5], PRISM [6], PARMS-PLANNING [7], CARE-W [8], CARE-S [9], PARMS-PRIORITY [10], HYDROPLAN [11] and AWARE-P [12].

In addition, water companies are often of a public nature and have therefore to define their investment strategies abiding by factors that are not exclusively technical or economic, such as the convenience of simultaneously replacing two adjacent pipes, even if one of them has a lower priority of replacement because of operational reasons, or the establishment of predefined budget allocations according to other criteria. Nonetheless, while these criteria provide with practicality to the methodology and align the solution with the actual replacement strategies implemented by the utilities, they have not generally been taken into account, not even by the above-mentioned methodologies, as our literature review has shown. Furthermore, they often rely on evaluating predefined intervention alternatives or establishing the replacement of individual pipes, without generating actual work plans composed of practical interventions affecting several pipes at the same time.

This work addresses a comprehensive framework to produce effective infrastructure asset management methodologies. The ultimate intention of this methodology is to properly schedule replacement activities in both water supply and sewer networks and efficiently plan investment needs to guarantee their long-term sustainability. To align

---

[*] Corresponding author.
E-mail address: cramos7@us.es (C. Ramos-Salgado).

https://doi.org/10.1016/j.ress.2021.108248
Received 25 August 2021; Received in revised form 22 October 2021; Accepted 24 November 2021

these results with the actual water utilities replacement strategies, operational and convenience criteria, which have not been addressed so far, will be included to provide the methodology with an innovative and practical approach.

For this purpose, the following section reviews the different water infrastructure replacement strategies and how they can result in effective long-term investment planning. In Section 3, the developed framework is the described. Then, to illustrate the procedure, an application to a case study company in Spain is presented in Section 4. Following this, Section 5 includes an in-depth discussion about the repercussion of including the operational and convenience factors in the methodology and their impact on the investment planning solution. Finally, conclusions are drawn in Section 6.

2. Literature review

In the literature there exist a great variety of works addressing the water infrastructure replacement needs and providing effective long-term investment planning. They can be classified into two main categories. The first one is based on a life-cycle cost analysis and consists of finding the moment in the asset's economic life where the expected future replacement and repair costs are balanced against one another. The second category relies on two sequential processes: 1) the establishment of a replacement priority for every network asset and 2) the definition and follow-up of key performance indicators (KPIs) to determine the future desired condition of the infrastructure and define specific action plans and long-term investment needs.

Within the first category, Engelhardt [13] completed a comprehensive review of the most relevant works up to the year 2000, with more recent approaches proposed by Kleiner et al. [14,15], Park and Loganathan [16], Mailhot et al. [17] or Hong et al. [18]. These earlier works seek the lowest life-cycle cost but "deal primarily with analytical solutions to single-pipe problems" [19]. More recent works take a more global network-scale perspective, like Dandy and Engelhardt [20] or Giustolisi et al. [21], who use different genetic algorithms to produce the economically near-optimal schedule for the replacement of the water supply pipes. Some later works also incorporate reliability [22,23], hydraulic [24,25] and performance [26] aspects. More recently, cumulative damage criteria have also been addressed [27]. Finally, other approaches consider cost reductions if multiple networks elements are replaced simultaneously, including quantity discounts [28–30], grouping optimization models [31] or adjacency criteria [32,33]. The main drawback with these grouping approaches lies in the fact that they require a vast processing capacity and computation time, and can therefore only be applied to small-size or sample networks.

This issue is overcome in the second category, that relies on the establishment of a replacement priority (index or score) for each element of the network. While this figure can be an estimation of a pipe's condition or failure's likelihood [34–38], most of the reviewed works combine both the probability and consequences of failure to compute a risk index. For this purpose, multi-criteria decision methods are commonly used.

Within this group of multi-criteria techniques, the most straightforward methodology is the risk matrix [39–44]. This is a double entry-matrix that integrates and scales both the probability and consequence of failures into categories. Then, a given pipe's risk of failure, i.e., replacement priority, depends on the matrix cell it is allocated to. Even though the risk matrix is a simple and powerful technique, it is not very practical for real-scale networks. When a large number of pipes have to be considered and assigned a risk index, too many elements are allocated to the same matrix cell and their replacement priority cannot be distinguished.

The second multi-criteria decision technique is the weighted sum model (WSM), that assigns to every pipe a risk score (calculated as the sum of scores for each factor weighted by its relative importance), which is equivalent to a priority index for its replacement. Examples of this approach can be found in [45–49]. The WSM is a very flexible technique that can also be used to compute intermediate risk calculations such as structural, environmental and hydraulic indices [50] or vulnerability and hazard ratings [51]. Lastly, this technique has also been used to prioritize not only pipe objects, but entire street sections including the coexisting road, sewer, and water assets [52,53] and sets of connected elements [54].

Given that the risk matrix and the WSM are both simple and efficient techniques, they have been widely used in the literature. Nonetheless, there exist other techniques to rank pipe objects for replacement such as the outranking methods ELECTRE [55,56] and PROMETHEE [57]. Also, to handle with the uncertainties related to the risk of failure, machine learning techniques [58], fuzzy-based methods [59–63] or Bayesian Belief Network models [64] have also been applied.

Once the replacement priority among all the network assets is known, it is necessary to define replacement strategies and plan short-, mid-, and long-term maintenance tasks. In this step, it is essential to select indicators (KPIs) that evaluate the performance of the infrastructure and to assign them long-term target values that will determine the required level of investment and define specific action plans. Different indicators have been proposed in the literature, related to natural resources (water supply) and environmental (wastewater), operational, personnel, physical, quality of service and financial aspects [65–69]. Widely used indicators are the Infrastructure Value Index (IVI), which is the ratio between the current value of an infrastructure and its replacement cost [70], and the Infrastructure Degradation Index (IDI) and the Infrastructure Histogram (IH), that complement the IVI and were developed by [71]. In recent years, vulnerability [72], resilience [73], sustainability [74,75] and leakage [76] performance indexes have also been proposed.

Within this second category, an efficient long-term investment planning is usually carried out through consolidated methodologies, often using the AWARE-P software [39,77-79]. These works, while interesting since they integrate numerous and diverse metrics, do not address the replacement of network pipes, but evaluate intervention solutions such as the extension of the network [77] or the construction of a new pumping station [78].

In contrast, Ferreira and Carriço [80] target the replacement of water and sewer network pipes according to a set of tactical objectives like achieving an adequate IVI value or reducing the energy consumption and water losses. The alternatives correspond to different investment strategy scenarios, so this approach cannot guarantee obtaining the best solution, given that it may not be among the set of predefined discrete investment alternatives. Other works define the required investments for the infrastructure to meet certain strategic objectives. For example, Large et al. [81] seek to guarantee that all pipes are in service at the end of the planning horizon. Given the strong impact of the discount rate in the long-term, three different scenarios for this parameter are evaluated. Similarly, Urrea-Mallebrera et al. [82] estimate the future investment needs to guarantee the sustainability of water infrastructures according to the IVI and the ASI, based this latter one on past maintenance activities. Brito et al. [83] use the IVI, the rehabilitation rate and the ratio of assets in service, while Cabral et al. [84,85] rely exclusively on the IVI.

After this comprehensive review and critical analysis of the existing literature, several gaps have been detected. To address them, we present a practical five-step IAM framework whose main contributions are the following:

- Regarding the existing replacement strategies, a widely used approach in the literature proposes a set of discrete alternatives, from which the most suitable one is chosen [39,77-80]. This perspective is not easily applicable to any other utility though. Thus, our work proposes a more versatile and practical methodology that consists in determining the required investments to meet certain strategic objectives established by the company. In this sense, we rely on the second category identified in the literature, i.e., the establishment of a replacement priority (index or score) for every network asset, using a WSM technique.

- Additionally, while most of the reviewed works define maintenance strategies on the basis of individual pipelines, these elements do not abide by the street's layout or other urban elements. In our work, we consider street sections between intersections to be the operational replacement unit. This perspective can help minimize the impact on society attached to every intervention.
- Furthermore, when producing the long-term investment planning, most of the works reviewed in the literature [80,81,83,84], as well as the most widely used IAM methodologies and commercial software, such as KANEW, CARE-W or AWARE-P, disregard the criteria related to the adjacency between elements and the convenience of their replacement at the same time. Instead, they estimate and plan the investment needs on the basis of individual pipes. However, this approach is not aligned with the actual water utilities replacement policies, since water utilities perform replacement activities on coherent aggregations of neighboring pipes. Similarly, restrictions on budget allocations by social and geographic criteria have not been previously addressed. Yet, these distribution criteria are essential to guarantee a fair distribution of the investment amount between districts and towns. Therefore, these criteria will be included in our methodology, not only because of their relevance to produce real and practical intervention strategies, but because their non-consideration may be deceptive, as it may result in insufficient estimations of investment needs and irreversible future infrastructure conditions.
- Some recent works propose varied and practical intervention strategies but, while thorough and well-founded, bring to light the strong dependence of the existing works on the IVI. However, this indicator, though simple and powerful, is not entirely reliable. This is due to its strong dependence on the estimation of the asset's service life, with a high degree of uncertainty. This is especially true for extensive planning horizons because new materials, whose long-term behavior is not known (since there exist no data on previous usage experience) are installed. Therefore, service life for these new assets can only be approximately estimated., to guarantee an overall and accurate estimation of the infrastructure condition. In our work, we use a combination of the following four indicators: the IVI, the average probability of failure, the average risk index and the average network age. These KPIs have been selected because, while their calculation and interpretation are straightforward and unambiguous, they can provide complete and diverse information on the network's performance. Additionally, the average network risk index is originally introduced in this paper as a novel metric that integrates all relevant factors in the decision-making process.
- Finally, to compute the necessary investment amount as efficiently as possible, we employ the mathematical bisection technique, which can help to reduce considerable computation time and effort.

Table 1. shows a comparison of our proposed methodology with the main IAM-related works identified in the literature. Then, the following section describes our proposed framework in detail.

3. Proposed IAM framework

This section describes in-depth the IAM methodology developed to aid in decision making and efficiently plan the investment needs in water supply and sewer infrastructure. It corresponds to the second category identified in the literature: the establishment of a replacement priority for every network asset and the subsequent definition and monitoring of KPIs. This framework consists of five steps, as shown in Fig. 1.

It should be noted that the methodology we are proposing here has a general nature and could be applied to any water company. However, companies choosing to apply it could also choose to change some of its features. For instance, a certain company could decide to implement this methodology but use a different technique to determine renovation priorities, or to allocate budget, or a different set of KPIs.

Step 1. Establishment of the replacement priority for every network intervention unit.

The first step of this methodology is to determine the priority of replacement for every network pipe. It is necessary to calibrate the balance between a pipe's condition and criticality. This helps to answer questions such as whether it is more urgent to replace a pipe that has high probability of failure or another with a lower probability but supplies a relevant customer, like a hospital. To do this, multi-criteria techniques such as the analytical hierarchical process (AHP), outranking methods or weighted sum models allow to weigh the relative importance of each factor.

Even though any of these techniques could work well here, we have chosen the risk index developed by Muñuzuri *et al.* [49] to prioritize pipe objects for replacement. This index, calculated through a weighted sum model, integrates five different criteria. Two of them represent the pipe condition: probability of failure and supply pipe leakage flow, whereas the remaining three are related to the consequences of pipe failure:

Table 1
Comparison of IAM-based research works.

Reference	Replacement priority	Indicators	Adjacency, convenience criteria	Planning scope	Methodology
[39] Marques et al. (2012)	Risk matrix	Performance, risk and cost metrics	No	Small network, 5 years	AWARE-P. Selection among predefined alternatives
[46] Zayed and Mohamed (2013)	WSM	Breakage rate, pipe condition	No	Small network, 3 years	Selection among predefined alternatives
[77] Carriço et al. (2013)	ELECTRE III	Performance, risk and cost metrics	No	Specific installation	AWARE - Selection among predefined alternatives
[78] Cardoso et al. (2016)	Risk matrix	Performance, risk and cost metrics	No	Small network, 20 years	AWARE-P. Selection among predefined alternatives
[80] Ferreira and Carriço (2019)	N.A.	Performance, risk and cost metrics	No	Small network, 15 years	AWARE-P. Selection among predefined alternatives
[82] Urrea-Mallebrera et al. (2019)	IVI, ASI	IVI, ASI	No	Small network, 20 years	Aggregate network analysis
[84] Cabral et al. (2019)	Percentage of residual life	IVI	No	Small network, 35 years	Selection among predefined alternatives
[83] Brito et al. (2020)	N.A.	IVI, annual rehab rate, assets within expected service life	No	Large network, up to 70 years	AWARE-P. Selection among predefined alternatives
[85] Vieira et al. (2020)	N.A.	IVI	No	Small network, 20 years	Selection among predefined alternatives
This research	WSM	IVI, risk, probability of failure, age	Yes	Large network, 20 years	Building of best solution

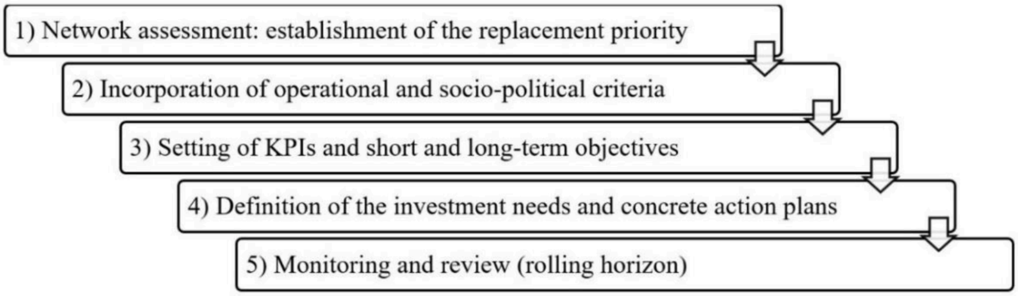


Fig. 1. Framework to produce an infrastructure asset management methodology.

demand for supply pipes, maximum evacuation flow for sewer pipes and pipe relevance (being relevant those pipes that supply potentially exposed to water related risks users or are critically located). Moreover, this index is particularly useful and versatile since it computes a replacement priority for all pipes, regardless of the network type they belong to, e.g., arterial, collector or secondary network. Thus, this model allows to directly compare the priority of replacement indistinctly among all the pipes of a given network infrastructure.

Furthermore, another issue should be taken into account. Most of the previous works rely on individual water and sewer pipes to addresses maintenance strategies. However, since pipelines might not be in consonance with the street's layout, this hydraulic element constitutes a theoretical or ideal concept, rather than practical. Instead, the definition of a workable intervention unit abiding by urban elements is helpful to establish realistic maintenance strategies, minimize the impact on traffic and pedestrians and boost the possible coordination of their replacement with other infrastructures maintenance projects. To contribute to this respect, this methodology proposes street sections between the two nearest intersections to be the functional, i.e., smallest replacement unit. Thus, if a certain section, hereinafter "street section", is to be intervened, then all the infrastructure elements within that section, i.e., geographically coincident, will be affected. Following our methodology, the risk index value for each street section is computed as follows [86]:

- The probability of failure for a street section is calculated as the weighted average of every inner pipe's probability of failure. The weights correspond to the length of the pipe that falls inside the street section, as pipes may belong to more than one.
- The leakage flow, demand and maximum evacuation flow for each street section are equal to the maximum existing value for each factor of all the existing pipes in the street section.
- A street section is considered relevant when it contains a relevant supply or sanitation pipe.

Finally, once all the five attributes have been characterized, the risk index can be computed for the whole street section.

Step 2. Incorporation of operational and convenience criteria.

Once every infrastructure unit is ranked for replacement, operational and convenience factors are introduced in the methodology. Regarding the first criterion, adjacency and grouping considerations should be integrated. Sometimes, it may be convenient to simultaneously replace two adjacent pipes (or street sections), even if one of them has a lower priority of replacement, than two others that are far apart from one another. In this process, given the numerous combination and aggregation possibilities, optimization techniques are necessary.

Again, other work-planning procedures could be applied here, but we have chosen the methodology proposed by Ramos-Salgado et al. [86], that groups neighboring pipes to form coherent and practical works. This approach integrates a diverse set of parameters that provides the methodology with high operational configurability. Besides, the best parameters configuration is obtained through an optimization process that adapts the resulting work configurations to the water company's strategic policy, know-how and experience, making it suitable to any water utility.

Additionally, the model integrates multiplicity of technical, geographical and economic factors, and also ensures that all the sections within the same work program have a similar replacement priority. Therefore, the previously defined risk index, or any other replacement priority indicator used, plays a fundamental role in this step as well. It has to be noted that, while this methodology is versatile and easily applicable, a calibration process to adapt the model to a given water utility is required.

Other aspects integrated are related to social and convenience criteria. Water companies are usually public organizations and cannot plan their investment needs relying exclusively on technical or economic factors. Generally, predefined budget distribution restrictions are considered. In this sense, the proposed methodology allows to previously set the available budget distribution according to 1) the network type, e.g., main and secondary networks or supply and sanitation networks, and 2) zones or municipalities of the city. This second criterion is particularly relevant for water utilities (given their generally public nature) since the total investment amount has to be equitably distributed among the different districts of the city. For this purpose, the methodology allows to distribute the available budget proportionally according to the districts' population or existing network length. This also avoids the excessive concentration of renovation works in those districts where the network is older, which would represent a burden for the residents.

It has to be noted that the incorporation of these criteria, especially the convenience ones, impose restrictions on the problem that move the solution away from the exclusively technical investment one, i.e., the most efficient from the risk reduction point of view. However, these factors provide the problem with both realism and practicality, and should not be overlooked, since their non-consideration may lead to underestimated investment needs and long-term infrastructure sustainability problems. This issue will be further discussed in Section 5.

Step 3. Definition of KPIs and target values.

The third step consists of defining indicators and metrics to assess the infrastructure covering three fundamental areas: network condition, quality provided and economic performance. For every KPI and a given time horizon, target values are set. These objectives, that should be specific, measurable, achievable and realistic, are a quantitative reflection of the company's strategy and policy towards their customers and society in general.

The difference between the initial and desired final values of these KPIs will determine the investment effort required. In this sense, the following four indicators are proposed in this framework:

- The infrastructure value index (IVI), developed by Alegre et al., is the most frequently used indicator in the scientific literature at the European level [70].
- The average probability of failure (PF) is the most reliable indicator to evaluate the network condition.

- The average risk index (RI) is presented in this work as a novel metric that encompasses all relevant factors in the decision-making process.
- The average network age (Age), for its objectivity.

All of them provide an overall assessment of the network, being the last three of them computed as the length-weighted average of every street section's value. For example, the global network RI is calculated as the risk index of all street sections weighted by their length (see Eq (1)).

$$RI = \frac{\sum_{\forall \ street \ sections} risk \ index \times length}{\sum_{\forall \ street \ sections} length} \tag{1}$$

In addition, these KPIs, whose calculation and interpretation are straightforward and unambiguous, offer diverse and comprehensive information on the network's condition and performance.

The final intention of the developed methodology is to determine the most efficient and practical investment strategy that guarantees the long-term sustainability of the infrastructure. For this purpose, and for a given planning horizon, the following strategies for each indicator are proposed:

- According to Alegre et al., an appropriate IVI value is between 0.45–0.55 [1]. Therefore, for this indicator, a target value of 0.45 or higher should be ensured at the end of the horizon.
- Regarding the current and desired network condition, in terms of the current failure rate and incurred repair costs, the company can decide either to maintain or reduce the PF metric.
- The same applies for the RI. If the current infrastructure condition is sustainable in the long-term, this indicator should at least be maintained for the analysis horizon.
- For the last indicator (Age), and depending on the initial infrastructure condition, we propose the long-term maintenance of the relative average age of the network, i.e., the ratio between the network's average age and estimated service life. For this, the future service life, including the influence of the new materials installed, has to be estimated.

Furthermore, it might be of interest to discuss the effect of a replacement task on the behavior of the KPIs. First, when a pipe with a certain age is replaced by a new one, i.e., whose age is zero, the average network age is reduced. The same applies in economic terms for the IVI: the residual and replacement value of the new pipe coincide, which has a positive influence on this indicator. Also, the new pipe generally has a lower failure probability than the replaced one, which reduces the overall network likelihood of failure. This, together with the elimination of the leakage flow associated to the pipe replaced, leads to a reduction of the global risk index. Hence, a higher investment in replacement tasks results in an increase in IVI and reductions in PF, RI and Age.

Step 4. Determination of the investment needs and the concrete action plan.

Once the system's performance is known and the targets have been established, the fourth step requires the development of a long-term investment plan to achieve the set objectives.

It has to be noted that, since four different metrics are used and distinct sustainability targets have been assigned to each KPI separately, meeting each target individually might result in different required investment efforts. Thus, even though all four indicators are somehow linked to each other, there will always be one that is more restrictive. The final investment required will therefore be given by the minimum amount that satisfies all 4 objectives simultaneously.

In addition, since the economic resource is always limited, the investment strategy must be as efficient as possible. Hence, the minimum investment amount that simultaneously satisfies all the sustainability objectives defined in the previous step (section 0) has to be determined. For this purpose, the mathematical bisection method will be used. This is an iterative root-finding algorithm that consists in dividing a solutions interval in half and selecting the subinterval containing the sought solution. This algorithm is therefore also called as "the interval halving method". To adapt this method to the currently addressed problem:

a) Two lower and upper investment threshold values (A and B, respectively) are defined, so that A is an insufficient investment level to achieve the KPIs targets, while B ensures that these are met. This way, the sought investment amount is guaranteed to be contained within the interval [A, B].
b) The interval [A, B] is then divided in half, where $C = (A + B)/2$. The problem will be reduced to one of the two resulting subintervals. If the investment level corresponding to C is still insufficient to meet the KPIs objectives, then C will become the new investment lower bound, i.e., $A = C$. Instead, if C satisfies all objectives, it will become the new upper limit: $B = C$.

This algorithm iterates until the difference between B and A is smaller than a certain predefined accuracy level, ε. The followed steps to adapt the bisection method to the problem in this work are described in Flowchart 1. On the chart, parameters A, B, C and ε correspond to investment amounts.

Another less sophisticated possible approach would have been to determine the investment amount using an increasing linear search algorithm, i.e., starting from an insufficient investment quantity and increasing in steps (given by the accuracy level) until the KPI objectives are first met. Nonetheless, this approach is not applicable to our methodology, since the work programs algorithm, introduced in the second step (section 0), has to be executed in every iteration. This simulation, along with the complete analysis for a long-term time horizon, requires a significant computational effort. Therefore, the bisection method, while more sophisticated, saves a considerable number of unnecessary iterations and significant computational time.

Additionally, in this step, the concrete action plan, i.e., the street sections to be intervened and its execution date, has to be determined. For this purpose, the use of visualization tools like a geographic information system (GIS) is of great use.

Moreover, it is also convenient to perform sensitivity analyses on the parameters with higher uncertainty. This consists of simulating different future scenarios for influential variables like possible demand levels [77], discount rates [81] or the average assets' service life [84] to determine the robustness of the proposed solutions against possible inaccuracies of the input data. This is especially relevant when considerable long-term time horizons are considered.

Step 5. Monitoring and review of the investment strategy.

Finally, the last step of the framework is to carry out an appropriate control and monitoring of the infrastructure condition and performance through the KPIs. The consequences of investing less in maintenance tasks than necessary could result in:

- An increase of network failures, resulting in supply interruptions or collapses and the consequent social impact.
- An increase in the associated repair costs.
- An increasing cost of returning the system to a state of sustainability.

These consequences may be unnoticeable in the short term but can lead to irreversible situations in the long term. It is therefore essential to combine short- and mid-term decisions (1–5 years) with the thorough monitoring of the long-term evolution of the system (20- or 25-year indicators evolution trends).

In this sense, even though this methodology provides a long-term planning, it must be employed by the water company on an annual basis: year by year. In other words, if a company determines at the end of 2021 the investment strategy that ensures the sustainability of its infrastructure for 20 years (2022–2041), the company should implement the investment plan and carry out the replacement tasks corresponding only to the first year of analysis, this is 2022. Afterward, at the end of 2022, the company will have to perform again the same analysis for the subsequent 20 years, i.e., 2023–2042, and implement in 2023 the investment plan just for the first year of this second simulation. This is to say, the company should employ the methodology annually, and always undertake the investment plan corresponding to the first year of analysis. This procedure is known as rolling horizon and allows to keep the network state up-to-date, correct deviations or redefine strategic objectives.

This rolling horizon approach also allows for incorporating modifications in the structure of the network. The analysis is performed in the base year with a static picture of the network, but the network may change due to extensions of the urban limits, modification of pipe diameters, etc. This dynamic nature of the network cannot be taken into account with a 20-year planning horizon, but it can easily be addressed with a rolling horizon approach. It is nevertheless important to remember that this methodology is designed for the renovation of downgrading pipes (due to aging and deterioration), so new network extensions or modifications are not likely to be included in work plans for several decades.

4. Application to a case study

This section illustrates the application of the proposed framework to EMASESA, the public water company of Seville (Spain), that provides service to more than 1 million inhabitants. The company services the city of Seville and 11 other municipalities in its metropolitan area. The infrastructure is made up of three different sub-network types: (1) water distribution mains, (2) collectors and (3) secondary water supply and sewer networks. Altogether, the entire network is over 7000 km long with more than 230,000 pipes and has a total replacement cost of 3200 M€.

The purpose of this study is to obtain the level of investments that guarantee the long-term sustainability of EMASESA's supply and sanitation networks. This investment strategy must be as efficient as possible, so that it satisfies all the defined objectives and restrictions at the lowest possible cost. From this study, the investment required for other assets such as facilities, dams or irrigation and water fire networks has been excluded.

Step 1. Establishment of the replacement priority for every network intervention unit.

As shown in Fig. 1, the first step of the methodology is to determine the replacement priority for every network asset. For this purpose, the model developed by Muñuzuri *et al.* [49] has been employed, with weights determined from a discrete choice questionnaire responded by the company's technical staff. Their risk index formulation can be indistinctly applied to all network types, establishing a comparable replacement priority for every pipe constituting the whole system.

As previously discussed in subsection 0, we consider street sections between the two nearest intersections as the operational replacement unit. Even though Muñuzuri et al. developed a model to calculate a risk index for individual pipe objects, we have applied its formulation directly on these urban elements. This way, all street sections of the network are assigned a risk index and can therefore be ranked for intervention. The result of this characterization for the EMASESA network can be seen in Fig. 2, where the darkest color represents a higher replacement priority.

Step 2. Incorporation of operational and convenience criteria.

Next, operational and convenience considerations are incorporated into the methodology. Firstly, criteria for network assets adjacency and convenience of simultaneous replacement, i.e., within the same intervention program, are included. To do this, we have put into practice the methodology developed by Ramos-Salgado et al. [86]. It consists of a two-stage algorithm. The first phase produces initial work programs spreading along one only street, while the second one targets street sections according to their replacement needs. i.e., their risk index, regardless of the streets they belong to.

Besides, the algorithm includes a set of five parameters that controls the resulting work programs configurations. This is if they are larger or

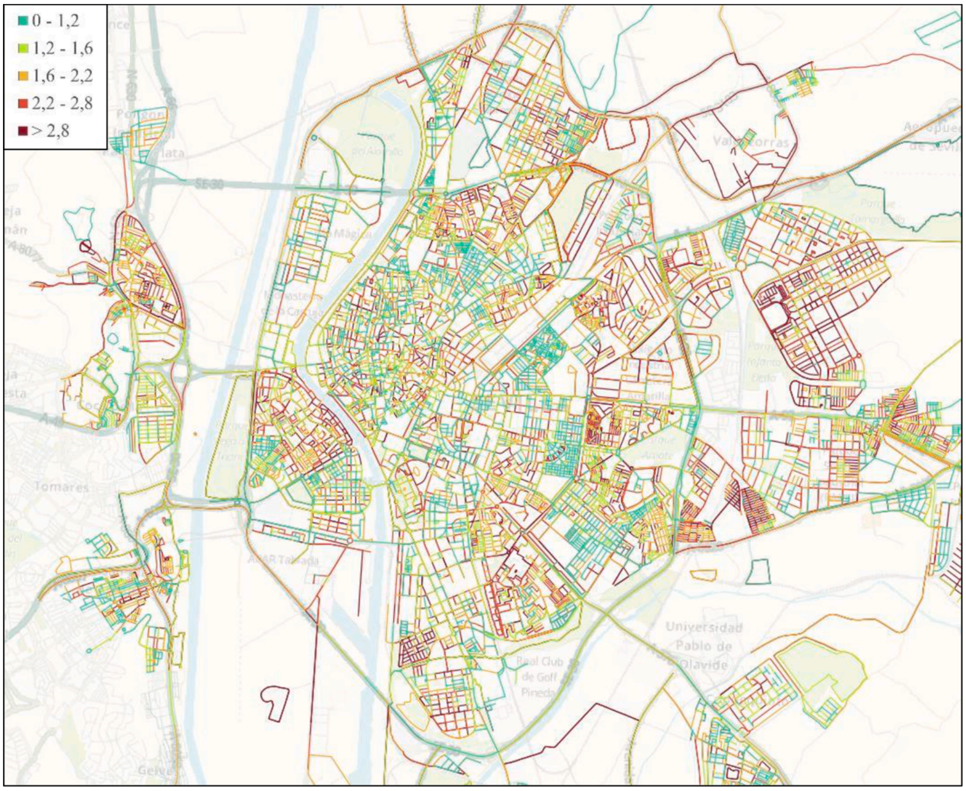


Fig. 2. EMASESA network characterization according to the risk index.

smaller, linear or branched, etc. The parameters' calibration, in which the risk indicator used plays an essential role, consists of computing the values of these parameters that best adapt the model to the company under study. In this work, to simulate the works configuration, the calibration solution obtained in [86] will be used.

Furthermore, criteria for the distribution of the available budget according to the type of network are introduced. As previously mentioned, the EMASESA network consists of 3 network types: (1) main water supply, (2) collectors and (3) secondary supply and sewer networks. According to the company, the distribution of the available annual budget is broken down into 10%, 20% and 70%, respectively. Likewise, the total investment amount has to be equitably distributed geographically. The network is divided in 12 sectors, and the allocation of the renovation budget is proportional to the population of each sector.

Step 3. Definition of KPIs and target values.

In the third step, a set of indicators and metrics to assess the infrastructure are established. As described in 0, the IVI, the average probability of failure (PF), the average risk index (RI) and the average network age (Age) will be utilized. The four indicators were proposed to the EMASESA technical staff and accepted by them. They could be calculated with the data already available at the company, and formed a combination that covered all their needs: the IVI is the most widespread indicator, and the only one used previously to evaluate their network; the average risk index (RI) was viewed as a good metric for decision-making; the average probability of failure (PF) is the main component of the RI and is therefore somewhat redundant with it, but is a good complement for it in case the RI correlation (estimated with a discrete choice questionnaire) is not entirely sound; and the average network age is an objective metric, unlike the three previous ones, that need to be estimated after a series of assumptions.

The current values of these KPIs for the EMASESA's overall system, i.e., considering the three network types as a whole, are shown in Table 2.

The final goal of this case study is to prove the utility of the developed methodology. In this sense, sustainability criteria for each KPI have to be first defined. Also, a planning horizon of 20 years (2022–2041) is considered. The proposed objectives for each indicator are:

- Following the indications provided by Alegre et al., a minimum target value of 0.45 is set for the IVI at the end of the time horizon.
- Regarding the PF, since the current failures rate and incurred repair costs are acceptable by the company, the same value of PF (1.35%) should be ensured by 2041.
- In contrast, the overall RI is to be cut down by 5%, which translates into reducing this KPI to, at least, 2.07.
- Regarding the last indicator, the strategy is aimed at maintaining the relative average age of the network. Considering the current average pipes' service life and its expected evolution as a function of the new materials installed this objective corresponds with guaranteeing a maximum Age value by 2041 of 33.50 years.

These target values are summarized in Table 3.

Step 4. Determination of the investment needs and the concrete action plan.

Once the target values have been set, the estimation of the annual investment needed to meet the target indicators at the end of the planning horizon is addressed. In addition, this calculation must be as economically efficient as possible, that corresponds to minimum investment amount that ensures that all sustainability goals are met.

Table 2
Current state of EMASESA's network (year 2021).

IVI (-)	PF (%)	RI (-)	Age (years)
0.46	**1.35%**	**2.18**	**27.39**

Table 3
Desired state of EMASESA's network at the end of the time horizon (year 2041).

IVI (-)	PF (%)	RI (-)	Age (years)
0.45	**1.35%**	**2.07**	**33.50**

To do this, the bisection method is now applied. As described in subsection 0, the procedure consists in dividing the solution interval, i.e., the investment amount domain, into smaller intervals in an iterative process. Fig. 3 shows the evolution of the lower and upper investment threshold values, A and B, respectively. For an accuracy level, i.e., difference between B and A, of ε=10 k€, an estimated investment requirement of 46.38 M€ is derived. Eleven iterations of the method were required.

The investment simulation obtained can be seen in Fig. 4. The columns indicate the annual budget allocation, while the dark green dashed line corresponds to the annual average investment of 46.38 M€. We have neglected inflation and worked with real monetary values, assuming that all costs and budgets will vary equally with inflation over the planning horizon [87].

Nonetheless, it is worth noting the difference between the two amounts shown in the graph. Even though the resulting annual investment is indeed 46.38 M€, it can be seen that the columns show slight deviations with respect to this average target value. This is because the columns in Fig. 4 represent the annual budget allocation, but not what actually is invested each year. When performing an intervention work, its estimated overall cost will be entirely allocated to the first year of its execution, even though it may take over a year to complete. However, in practice, the whole intervention amount is proportionally spent during each year of its execution. Thus, the amount that is effectively invested each year in replacement tasks is invariant and equal to 46.38 M€ (dark green dashed line in Fig. 4).

This also explains the decrease of the annual budget allocation in the last years of the planning horizon. During the last years of the time horizon, a significant part of the available budget will be employed to complete the works that already started in previous years, while only the remaining available budget of these years will be spent to start new interventions programs.

Additionally, the yellow line in the figure represents the evolution of the RI, that turned out to be the most restrictive indicator. It decreased from the original value in 2021 (2.18) to the target for 2041 (2.07). The fact that the RI has been the most restrictive KPI, means that the rest of targets are reached more easily, i.e., with greater margin. The annual evolution of the remaining KPIs can be seen in Fig. 5, while Table 4 presents estimated final value of the four metrics in 2041.

It should be noted that the methodology ensures that all the sustainability objectives are accomplished by the end of the planning horizon: in this case, 2041. However, it may occur that not all the KPI meet their target values over the entire planning horizon. For example, in Fig. 5(a), it can be seen that the IVI, while has a value of 0.46 both at the beginning and end of the time horizon, is lower than 0.45 between 2030

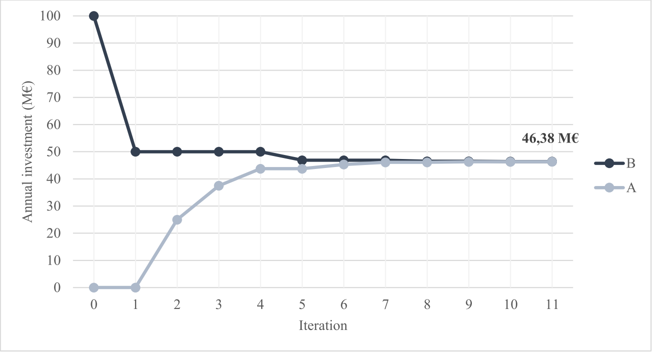


Fig. 3. Application of the bisection method to obtain the annual investment needs.

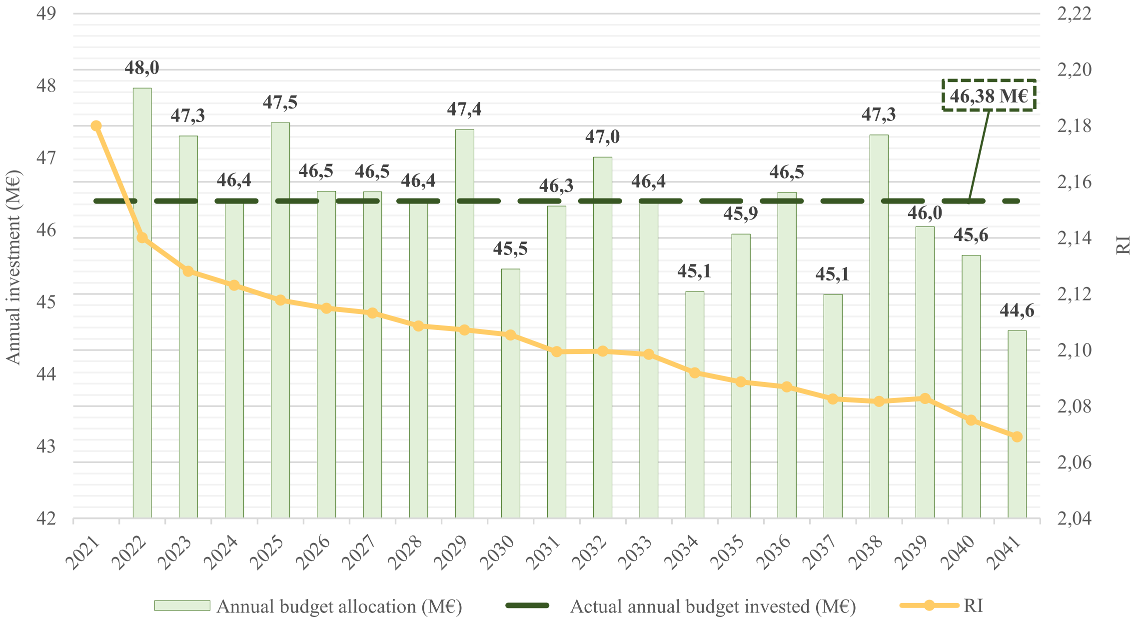


Fig. 4. Scenario 1. Annual investment simulation and evolution of the RI over the time horizon (2021–2041).

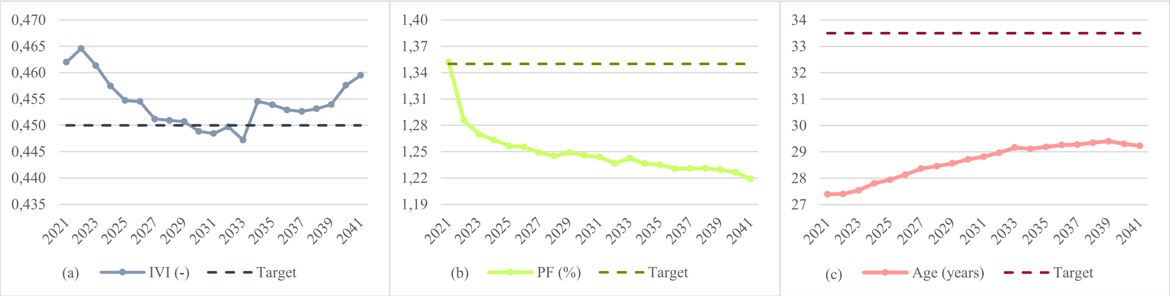


Fig. 5. Evolution of the (a) IVI, (b) PF and (c) Age over the planning horizon.

Table 4
Scenario 1. Annual investment needed and expected condition of the network at the end of the planning horizon (2041).

Annual investment (M€)	IVI (-)	PF (%)	RI (-)	Age (years)
46.38	**0.46**	**1.22%**	**2.07**	**29.22**

and 2033. This may be due to the accumulation in those years of the replacement of pipes whose unit cost per length is higher than compared to other time period. Thus, even though the investment allocated is invariant, less network length is replaced during that period of time, contributing less efficiently to the IVI.

If the company wished to avoid this situation and guarantee an IVI over 0.45 during the whole planning horizon, it would be necessary to simulate another more short-term planning, for example for the next 12 years, and ensure that the IVI target is met by 2033. This new objective and scenario would naturally require a higher investment effort. An annual investment of 47.11 M€, which is an increase of 0.72 M€ each year with respect to the original scenario, would be necessary.

Back to the original results (Table 4), it can be seen that, while the PF and Age amply comply with their objectives, the IVI reaches a value of 0.46 at the end of the planning horizon, i.e., slightly over the target value. Moreover, this indicator is highly dependent on the pipes service life, a parameter with significant uncertainty. This is especially true for long-term planning horizons because new materials, whose service life can only be estimated (since there exist no data on previous usage experience), are installed. It would therefore be convenient to perform a sensitivity analysis on the estimated pipes service life and simulate possible future behavior scenarios for this parameter.

In this sense, the same analysis will now be proposed for a second scenario in which the service life of the pipes, both those already existing and those that will be installed over the study horizon, are, on average, 5% less than those initially estimated. The IVI, that directly relies on this parameter, is negatively affected by this modification, reducing its initial value in 2021 from 0.46 to 0.41.

Again, the investment needs that meet the long-term sustainability objectives are estimated through the bisection method and a long-term simulation is carried out. The target values for each KPI are maintained, being the same that in scenario 1 (see Table 3).

Fig. 6 shows the results for this second scenario. In this case, an average investment of 51.36 M€ would be required each year (orange dashed line), which is nearly 5 M€ more than in the first scenario. Moreover, on this occasion, the limiting KPI is no longer the RI, but the IVI. This result was to be expected, since the modification of the estimated service life directly affects the IVI, while it is invariant for IR, PF and Age. The gray line in the figure displays its evolution from its original value to the target of 0.45 in 2041.

Again, the annual investment needed and the estimated KPI values in 2041 for this second scenario are summarized in Table 5.

This is naturally a worse economic scenario, but which is worth considering and being alert in case, as time progresses and more precise information becomes available, that the performance of new materials

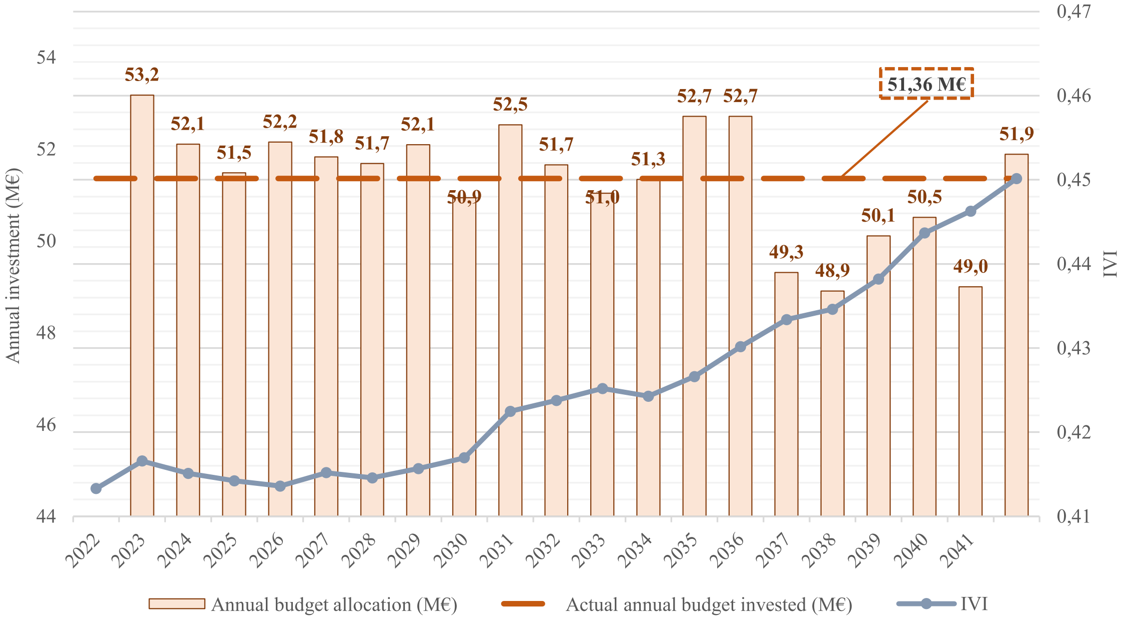


Fig. 6. Scenario 2. Annual investment simulation and evolution of the IVI over the time horizon (2021–2041).

Table 5
Scenario 2. Annual investment needed and expected condition of the network at the end of the planning horizon (2041).

Annual investment (M€)	IVI (-)	PF (%)	RI (-)	Age (years)
51.36	**0.45**	**1.21%**	**2.06**	**27.63**

actually turns out to be worse than originally estimated.

As indicated in Section 3, together with the investment planning, the concrete action plan should be clearly specified. This is to indicate which street sections will be replaced within each intervention work and when they are scheduled to be performed.

Over the 20-year horizon, and for the first of the two scenarios proposed, a total of 1227 intervention works are to be carried out throughout the city (12 municipalities). Fig. 7 displays an example of this action plan for the first four years of the planning horizon (2022–2025). In the figure, that focuses on the boroughs of Triana and Los Remedios (Seville), each color differentiates an individual work program from another. The free and open-source software QGIS has been used for its visualization.

Step 5. Monitoring and review of the investment strategy.

Finally, this investment strategy must be supported by a rolling horizon procedure. The methodology should thus be executed and the investment strategy should be updated annually, year by year. This is to say, even though EMASESA can produce and define an investment strategy for the next 20 years (2022–2041), they should implement the first year of the investment planning and carry out the intervention works corresponding only to 2022. The same analysis should be performed at the end of 2022, when the company will have to produce the same simulation for the subsequent 20 years (2023–2042) and implement the investment plan just for the first year of this second simulation, i.e., 2023. This procedure can help avoid insufficient or inappropriate maintenance of the network and prevent possible future irreversible situations. Therefore, it is crucial to collect data annually, analyze its evolution and modify the investment strategy if necessary.

5. Discussion and implications

This work has presented a methodology to efficiently develop and implement investment strategies for supply and sewer networks. In

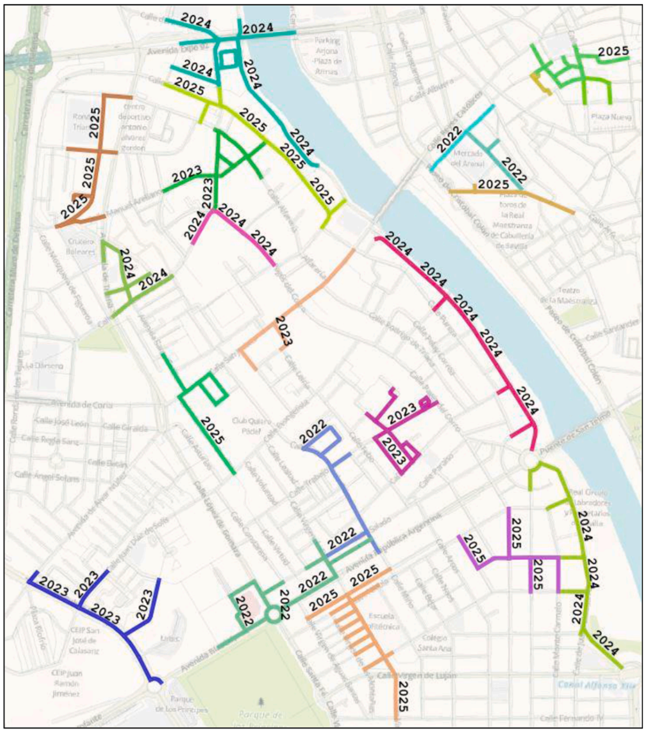


Fig. 7. Example of the resulting action plan (2022–2025). Scenario 1.

addition, the proposed framework integrates an innovative feature that had not been previously addressed. This is the incorporation of specific operational and convenience criteria that have not been generally considered in the decision-making process.

The first type of criteria includes adjacency and group replacement considerations. It proposes that pipe objects should not be replaced individually, but within the framework of a unified and more elaborated replacement work program. Its integration into the methodology will result in network elements with a lower risk index being replaced first, instead of others with a higher replacement priority. This is because the grouping process has included them in work programs to be carried out earlier in time.

Something similar occurs with the criterion of distribution of the available budget by type of network and sector. These types of restrictions inevitably lead to the replacement of assets that, according to exclusively technical criteria, are not yet necessary and could indeed be further delayed.

The inclusion of these factors goes against the theoretical or purely technical approach, that proposes the replacement of pipes according only to their risk index. In this case, where no adjacency criteria were considered, one only pipe or basic network unit would be intervened within every work program. Besides, the available budget would be distributed only on the basis of risk reduction, which could result in a concentration of replacement tasks on a single type of network or a single area of the city.

The solution obtained through this approach, hereafter referred to as the “pure technical solution”, is the most efficient from the technical point of view, i.e., risk reduction. In other words, replacement tasks are prioritized based solely on the difference in the risk index of the pipe before and after the intervention.

The pure technical solution will always be economically preferable to the one that results from integrating the grouping and predefined budget allocation criteria, henceforth referred to as the “real solution”. Thus, any risk reduction objective can be more easily achieved, this is, with less economic effort, through the pure technical solution since no budget will be spent to replace network elements that do not reduce the risk the most.

This will be illustrated with an example. In Section 4, the evolution of EMASESA’s network over the next 20 years was simulated and required investment to achieve a set of sustainability objectives for that horizon was estimated. In this case, in order to replicate the most realistic and practical scenario possible, the real solution was obtained: the adjacency and budget distribution criteria were considered. It resulted in an average investment needed of 46.38 M€ each year (see Table 4).

Next, a different scenario is considered. Now, these criteria are not taken into account and the pure technical solution is therefore computed. In this case, an annual investment of 43.82 M€ is required (see the blue dashed line in Fig. 8). Hence, the non-consideration of the operational and convenience criteria would allow to achieve the same sustainability objectives than in the first scenario while sparing an average of 2.56 M€ compared to the real solution.

In addition, the limiting KPI is no longer de RI (yellow line in Fig. 4). This is because the pure technical solution is more efficient from the point of view of RI reduction. For instance, while according to the real solution, the average risk index of the intervened pipes during the first year of the planning horizon is 3.96, the average risk index of the elements replaced in 2022 through the pure technical solution is 4.48. Thus, the sustainability objective defined for the RI is more easily met and the IVI becomes the most restrictive one (red line in Fig. 8).

This solution, although preferable from a technical and economic point of view, is not aligned with the real replacement strategies carried out by water companies, as it does not include social, geographical or convenience considerations. The company acknowledged this solution as a lower bound to the renovation budget requirements, but contemplated only the implementation of the real solution for the practical reasons detailed above. Therefore, the criteria discussed should not be disregarded from the problem.

Nonetheless, most of the existing works and approaches so far dismiss the replacement of real and practical intervention programs, estimating the investment needs based on replacement tasks on individual pipes. This approach is not realistic though. Each replacement task is associated with fixed mobilization and setup costs that promotes the simultaneous replacement of several contiguous elements. Therefore, when a deteriorated pipe is to be replaced, other adjacent pipes, that may not need an immediate replacement yet but will in the near future, are replaced at the same time within the same maintenance activity.

Similarly, an appropriate predefined distribution of the available budget, especially according to social and geographic criteria, is essential. This is due to the fact that water utilities are generally public organizations, and the total investment spent should be equitably distributed between neighborhoods and municipalities.

In fact, if the available budget were allocated considering only the effectiveness of the RI reduction, and the pipes requiring more urgent replacement were located close to each other, a concentration intervention works in the same area could occur. This is possible, given that the pipelines physically closed to each other were installed on the same date, are of the same material, suffer the same external impact, etc.

For instance, Fig. 9 shows the action plan corresponding to the EMASESA’s pure technical solution during the first four years of the planning horizon (2022–2025). The effect of not considering the two criteria can be distinguished, since a large number of small and dispersed works are scheduled. Besides, they are concentrated in the city

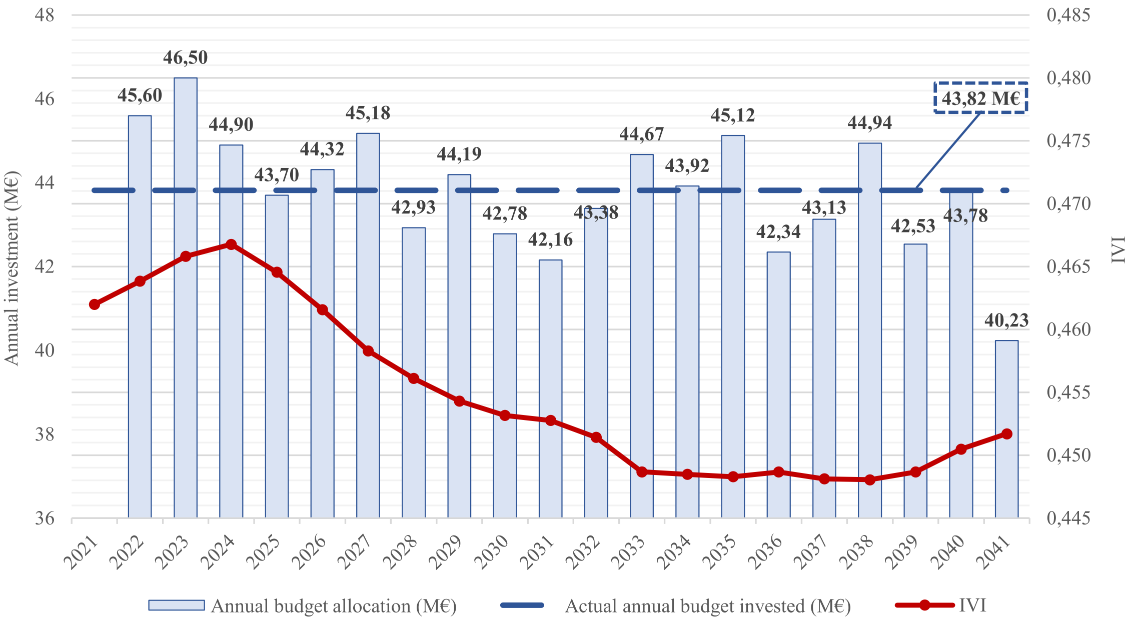


Fig. 8. Pure technical solution. Annual investment simulation and evolution of the IVI over the time horizon (2021–2041).

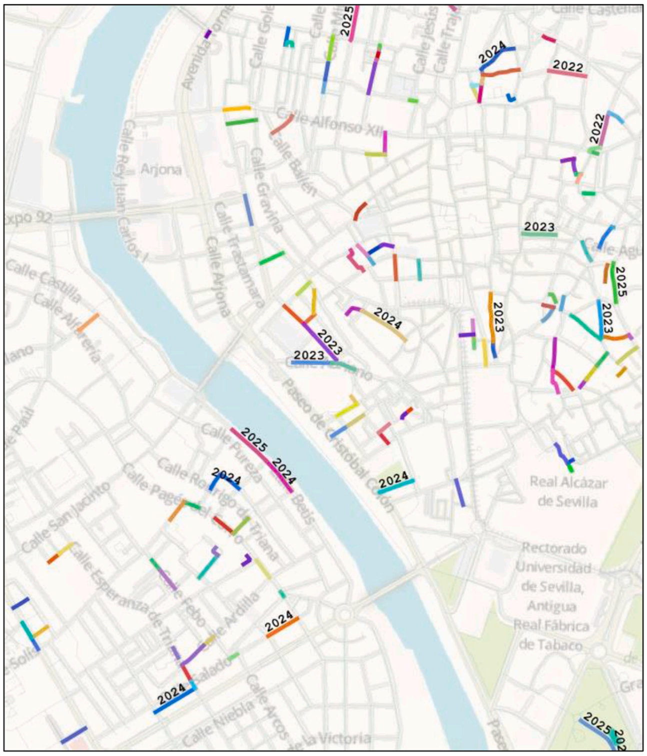
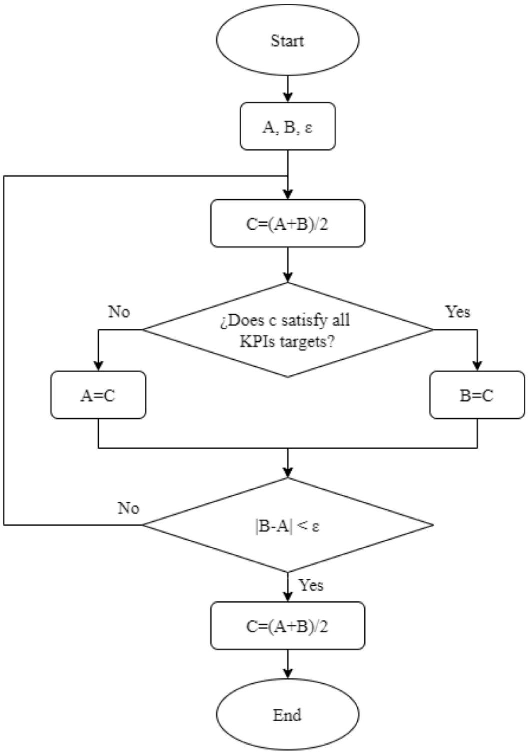


Fig. 9. Example of the resulting action plan (2022–2025). Pure technical solution.



Flowchart 1. Bisection method to compute annual investment needs.

center of the city since they are older and made of obsolete materials.

This solution is unfeasible and unacceptable for social, geographical and convenience reasons. On the one hand, this replacement plan would imply a greater impact on society (traffic, pedestrians and shops nearby) since it would incur in duplicated road closures and the consequent undermining of the company image. On the other hand, water utilities are usually public institutions and consider investment allocation criteria on the basis of the municipalities' shareholding or population. Investing a considerably higher amount in one district or town may be unfair to others. The investment planning should always be equitable between districts and municipalities.

In conclusion, the incorporation of these criteria, especially the convenience ones, impose restrictions on the problem that move the solution away from the most efficient one in terms of risk reduction. However, these factors provide the problem with both realism and practicality. Moreover, their non-consideration may be misleading, as it may result in insufficient estimations of investment needs, incorrect future system conditions and long-term infrastructure sustainability problems.

6. Conclusion

Water supply and sanitation systems are critical infrastructures that provide a basic service to society. However, these systems constantly age and degrade over time. Besides, due to their large size, their maintenance requires a significant economic effort. Thus, water utilities face the challenge and responsibility of maintaining these infrastructures and ensuring their long-term operational, economic and social sustainability. Thereby, the need arises for companies to develop infrastructure asset management (IAM) methodologies that aid them in optimizing the systematic and methodological decision-making process and in specifying their network renewal needs.

In this sense, this work has presented a comprehensive and practical five-step IAM framework, whose effectiveness has been proven with its application to a large water company in Spain. The methodology combines the use of street sections as replacement units, the inclusion of adjacency and convenience criteria and the monitoring of four metrics to evaluate the evolution of the network. It results in a long-term investment plan with the minimum investment amount that ensures that all sustainability objectives are met by the end of the planning horizon.

The incorporation of adjacency and convenience factors provides both with realism and practicality to the problem, as it aligns with the actual replacement strategies implemented by water utilities. These criteria also imply moving away from the exclusively technical and economically most efficient solution. The discussion in Section 5 proved that, in order to meet the same sustainability objectives, the non-consideration of these factors in the EMASESA case study could result in a reduction in the investment needs of approximately 2.5 M€ each year. However, this does not mean that they should be avoided or dismiss. On the opposite, their non-consideration can lead to misleading results and future infrastructure sustainability problems.

Additionally, further enrichment of the methodology could be achieved if a dynamic, i.e., living network over time was taken into account. The performed analysis considers that the network length will be invariant for the next 20 years. However, the system will actually expand due to the incorporation of new network pipes. It may be of interest to incorporate this factor in the methodology, especially since the newly installed pipes will positively contribute to the network condition thanks to their young age. Nevertheless, the rolling horizon approach allows the methodology to address this issue from a practical point of view.

Apart from that, future research lines linked to this methodology could incorporate efficiency criteria to minimize the impact on society such as supply interruptions or traffic delays. For instance, if a measure of the impact on traffic were available, an optimization engine could avoid two different but nearby intervention works to be scheduled for the same year.

Furthermore, including the possibility of rescheduling work programs in time due to other convenience criteria, e.g., the coordination with other urban renewal projects or the incompatibility with social events taking place in that location, could be a promising direction to further enhance the practicality of the methodology.

CRediT authorship contribution statement

Cristóbal Ramos-Salgado: Methodology, Investigation, Writing – original draft. **Jesús Muñuzuri:** Formal analysis, Investigation, Conceptualization, Writing – review & editing, Supervision. **Pablo Aparicio-Ruiz:** Software, Validation, Investigation, Resources, Data curation. **Luis Onieva:** Investigation, Visualization, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work was supported by EMASESA (Empresa Metropolitana de Abastecimiento y Saneamiento de Aguas de Sevilla) [grant numbers 273/17, 286/17].

References

[1] Alegre H, Coelho S, Covas D, Almeida M do C, Cardoso MA. A utility-tailored methodology for integrated asset management of urban water infrastructure. Water Sci Technol Water Supply 2013;13:8. https://doi.org/10.2166/ws.2013.108.
[2] Alegre H., Coelho S. Infrastructure Asset Management of Urban Water Systems 2013:2–26. https://doi.org/10.5772/51895.
[3] Herz RK. Exploring rehabilitation needs and strategies for water distribution networks. J Water Supply Res Technol - AQUA 1998;47:275–83.
[4] AQUA-Ingenieure. Programmdokumentation zu AQUA-WertMin 4.0 für Windows 1998.
[5] Hadzilacos T, Kalles D, Preston N, Melbourne P, Camarinopoulos L, Eimermacher M. UtilNets: a water mains rehabilitation decision-support system. Comput Environ Urban Syst 2000;24:215–32. https://doi.org/10.1016/S0198-9715(99)00058-7.
[6] Ariaratnam ST, MacLeod CW. Financial Outlay Modeling for a Local Sewer Rehabilitation Strategy. J Constr Eng Manag 2002;128:486–95. https://doi.org/10.1061/(asce)0733-9364(2002)128:6(486).
[7] Burn S, Tucker S, Rahilly M, Davis P, Jarrett R, Po M. Asset planning for water reticulation systems - The PARMS model. Water Sci Technol Water Supply 2003;3:55–62. https://doi.org/10.2166/ws.2003.0086.
[8] Sægrov S. CARE-W: computer-aided rehabilitation of water networks. 2004.
[9] Sægrov S. CARE-S: computer Aided Rehabilitation of Sewer and storm water networks. 2005.
[10] Moglia M, Burn S, Meddings S. Decision support system for water pipeline renewal prioritisation. Electron J Inf Technol Constr 2006;11:237–56.
[11] De Gueldre G, Herzeele FV, Boonen I, Thoeye C, Steene B Van D. Hydroplan-EU : an integrated approach for sewer asset management Hydroplan-EU : un outil intégré pour la gestion des égouts. Novatech 2007:1–8.
[12] Coelho S.T., Vitorino D., Alegre H. AWARE-P: a system-based software for urban water IAM planning. LESAM 2013, Sydney, Aust., 2013, p. 1700.
[13] Engelhardt M, Skipworth P, Savic D, Saul a, Walters G. Rehabilitation strategies for water distribution networks: a literature review with a UK perspective. Urban Water 2000;2:153–70. https://doi.org/10.1016/S1462-0758(00)00053-4.
[14] Kleiner Y, Adams BJ, Rogers JS. Long-term planning methodology for water distribution system rehabilitation. Water Resour Res 1998;34:2039–51. https://doi.org/10.1029/98WR00377.
[15] Kleiner Y;, Adams BJ;, Rogers JS, Kleiner Y, Adams BJ. Water distribution network renewal planning. J Comput Civ Eng 2001;15:15–26. https://doi.org/10.1061/(ASCE)0887-3801(2001)15:1(15).
[16] Park SW, Loganathan GV. Methodology for economically optimal replacement of pipes in water distribution systems: 1. Theory. KSCE. J Civ Eng 2002;6:545–50. https://doi.org/10.1007/bf02842007.
[17] Mailhot A, Poulin A, Villeneuve JP. Optimal replacement of water pipes. Water Resour Res 2003;39:1–14. https://doi.org/10.1029/2002WR001904.
[18] Hong HP, Allouche EN, Trivedi M. Optimal Scheduling of Replacement and Rehabilitation of Water Distribution Systems. J Infrastruct Syst 2006;12:184–91. https://doi.org/10.1287/opre.11.5.732.
[19] Kleiner Y, Adams BJ, Rogers JS. Selection and Scheduling of Rehabilitation for Water Distribution Systems. Water Resour Res 1998;34:2053–61. https://doi.org/10.1029/98WR01281.
[20] Dandy GC, Engelhardt M. Optimal scheduling of water pipe replacement using genetic algorithms. Water Resour Plan Manag 2001;127:214–23.
[21] Giustolisi O, Laucelli D, Savic DA. Development of rehabilitation plans for water mains replacement considering risk and cost-benefit assessment. Civ Eng Environ Syst 2006;23:175–90. https://doi.org/10.1080/10286600600789375.
[22] Dandy GC, Engelhardt MO. Multi-Objective Trade-Offs between Cost and Reliability in the Replacement of Water Mains. J Water Resour Plan Manag 2006;132:79–88.
[23] Alvisi S, Franchini M. Near-optimal rehabilitation scheduling of water distribution systems based on a multi-objective genetic algorithm. Civ Eng Environ Syst 2006;23:143–60. https://doi.org/10.1080/10286600600789300.
[24] Dridi L, Parizeau M, Mailhot A, Villeneuve JP. Using evolutionary optimization techniques for scheduling water pipe renewal considering a short planning horizon. Comput Civ Infrastruct Eng 2008;23:625–35. https://doi.org/10.1111/j.1467-8667.2008.00564.x.
[25] Nafi A, Werey C, Llerena P. Water pipe renewal using a multiobjective optimization approach. Can J Civ Eng 2008;35:87–94. https://doi.org/10.1139/L07-075.
[26] Jayaram N, Srinivasan K. Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing. Water Resour Res 2008;44:1–15. https://doi.org/10.1029/2006WR005316.
[27] Sheu SH, Liu TH, Sheu WT, Zhang ZG, Ke JC. Optimal replacement policy with replacement last under cumulative damage models. Reliab Eng Syst Saf 2021;209:107445. https://doi.org/10.1016/j.ress.2021.107445.
[28] Nafi A, Kleiner Y. Scheduling Renewal of Water Pipes While Considering Adjacency of Infrastructure Works and Economies of Scale. J Water Resour Plan Manag 2010;136:519–30. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000062.
[29] Kleiner Y, Nafi A, Rajani B. Planning renewal of water mains while considering deterioration, economies of scale and adjacent infrastructure. Water Sci Technol Water Supply 2010;10:897–906. https://doi.org/10.2166/ws.2010.571.
[30] Rokstad MM, Ugarelli RM. Minimising the total cost of renewal and risk of water infrastructure assets by grouping renewal interventions. Reliab Eng Syst Saf 2015;142:148–60. https://doi.org/10.1016/j.ress.2015.05.014.
[31] Li F, Ma L, Sun Y, Mathew J. Optimized Group Replacement Scheduling for Water Pipeline Network. J Water Resour Plan Manag 2016;142:1–10. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000559.
[32] Roshani E, Filion YR. Event-based approach to optimize the timing of water main rehabilitation with asset management strategies. J Water Resour Plan Manag 2014;140:1–11. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000392.
[33] Kerwin S, Adey BT. Optimal Intervention Planning: a Bottom-Up Approach to Renewing Aging Water Infrastructure. J Water Resour Plan Manag 2020;146. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001217.
[34] Kielhauser C, Adey BT, Lethanh N. Investigation of a static and a dynamic neighbourhood methodology to develop work programs for multiple close municipal infrastructure networks. Struct Infrastruct Eng 2016;13:361–89. https://doi.org/10.1080/15732479.2016.1162818.
[35] Robles-Velasco A, Cortés P, Muñuzuri J, Onieva L. Prediction of pipe failures in water supply networks using logistic regression and support vector classification. Reliab Eng Syst Saf 2020;196:106754. https://doi.org/10.1016/j.ress.2019.106754.
[36] Yin X, Chen Y, Bouferguene A, Al-Hussein M. Data-driven bi-level sewer pipe deterioration model: design and analysis. Autom Constr 2020;116:103181. https://doi.org/10.1016/j.autcon.2020.103181.
[37] Jara-Arriagada C, Stoianov I. Pipe breaks and estimating the impact of pressure control in water supply networks. Reliab Eng Syst Saf 2021;210:107525. https://doi.org/10.1016/j.ress.2021.107525.
[38] Chen TYJ, Guikema SD. Prediction of water main failures with the spatial clustering of breaks. Reliab Eng Syst Saf 2020;203:107108. https://doi.org/10.1016/j.ress.2020.107108.
[39] Marques J, Saramago A, Silva M, Paiva C, Coelho S, Pina A. Rehabilitation in Oeiras & Amadora: a practical approach. Water Asset Manag Int 2012;8:19–24.
[40] Antunes D, Freitas R, Antunes D, Cunha M da C. Multiple-criteria decision analysis for proactive management of risk of water distribution systems. 14th Water Distrib Syst Anal Conf; 2012. 1055-71.
[41] Kane G, Zhang D, Lynch D, Bendeli M. SydneyWater's critical water main strategy and implementation - a quantitative, triple-bottom line approach to risk based asset management. Water Asset Manag Int 2014;10:19–24.
[42] Baah K, Dubey B, Harvey R, McBean E. A risk-based approach to sanitary sewer pipe asset management. Sci Total Environ 2015;505:1011–7. https://doi.org/10.1016/j.scitotenv.2014.10.040.
[43] Elsawah H, Bakry I, Moselhi O. Decision support model for integrated risk assessment and prioritization of intervention plans of municipal infrastructure. J Pipeline Syst Eng Pract 2016;7. https://doi.org/10.1061/(ASCE)PS.1949-1204.0000245.
[44] D'Ercole M, Righetti M, Raspati GS, Bertola P, Ugarelli RM. Rehabilitation planning ofwater distribution network through a reliability-based risk assessment. Water (Switzerland) 2018;10. https://doi.org/10.3390/w10030277.
[45] Monteiro AJ, Silva AT, Sereno J, Marçal L, Franco AB. Scheduling the renewal of a water supply distribution system - a case study in Portugal. Water Asset Manag Int 2008;4:8–13.
[46] Zayed T, Mohamed E. Budget allocation and rehabilitation plans for water systems using simulation approach. Tunn Undergr Sp Technol 2013;36:34–45. https://doi.org/10.1016/j.tust.2013.02.004.
[47] Marzouk M, Hamid SA. El-Said M. A methodology for prioritizing water mains rehabilitation in Egypt. HBRC J 2015;11:114–28. https://doi.org/10.1016/j.hbrcj.2014.03.002.
[48] Kilinç Y, Özdemir Ö, Orhan C, Firat M. Evaluation of technical performance of pipes in water distribution systems by analytic hierarchy process. Sustain Cities Soc 2018;42:13–21. https://doi.org/10.1016/j.scs.2018.06.035.

[49] Muñuzuri J, Ramos C, Vázquez A, Onieva L. Use of discrete choice to calibrate a combined distribution and sewer pipe replacement model. Urban Water J 2020;17:100–8. https://doi.org/10.1080/1573062X.2020.1748205.

[50] Chavarriaga Hernández LÁ, Montoya CMÁ. Decision making model for the replacement and upgrading of sewer pipes in Colombia ' s Aburrá Valley. Water Asset Manag Int 2013;9:3–6.

[51] Mamo TG. Risk-based approach to manage aging urban water main infrastructure. J Water Supply Res Technol - AQUA 2015;64:260–9. https://doi.org/10.2166/aqua.2014.052.

[52] Tscheikner-Gratl F, Sitzenfrei R, Rauch W, Kleidorfer M. Integrated rehabilitation planning of urban infrastructure systems using a street section priority model. Urban Water J 2016;13:28–40. https://doi.org/10.1080/1573062X.2015.1057174.

[53] Shahata K, Zayed T. Integrated risk-assessment framework for municipal infrastructure. J Constr Eng Manag 2016;142:04015052. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001028.

[54] El-Abbasy MS, El Chanati H, Mosleh F, Senouci A, Zayed T, Al-Derham H. Integrated performance assessment model for water distribution networks. Struct Infrastruct Eng 2016;12:1505–24. https://doi.org/10.1080/15732479.2016.1144620.

[55] Carriço N, Covas D, Almeida MC, Leitão JP, Alegre H. Prioritization of rehabilitation interventions for urban water assets using multiple criteria decision-aid methods. Water Sci Technol 2012;66:1007–14. https://doi.org/10.2166/wst.2012.274.

[56] Trojan F, Morais DC. Prioritising alternatives for maintenance of water distribution networks: a group decision approach. Water SA 2012;38:555–64. https://doi.org/10.4314/wsa.v38i4.11.

[57] Fontana ME, Morais DC. Using Promethee V to Select Alternatives so as to Rehabilitate Water Supply Network with Detected Leaks. Water Resour Manag 2013;27:4021–37. https://doi.org/10.1007/s11269-013-0393-1.

[58] Wang Z, Li S. Data-driven risk assessment on urban pipeline network based on a cluster model. Reliab Eng Syst Saf 2020;196. https://doi.org/10.1016/j.ress.2019.106781.

[59] Christodoulou S, Deligianni A, Aslani P, Agathokleous A. Risk-based asset management of water piping networks using neurofuzzy systems. Comput Environ Urban Syst 2009;33:138–49. https://doi.org/10.1016/j.compenvurbsys.2008.12.001.

[60] Al-Zahrani M, Abo-Monasar A, Sadiq R. Risk-based prioritization of water main failure using fuzzy synthetic evaluation technique. J Water Supply Res Technol - Aqua 2015. https://doi.org/10.2166/aqua.2015.051. jws2015051.

[61] Anbari MJ, Tabesh M, Roozbahani A. Risk assessment model to prioritize sewer pipes inspection in wastewater collection networks. J Environ Manage 2017;190:91–101. https://doi.org/10.1016/j.jenvman.2016.12.052.

[62] Salehi S, Jalili Ghazizadeh M, Tabesh M, Valadi S, Salamati Nia SP. A risk component-based model to determine pipes renewal strategies in water distribution networks. Struct Infrastruct Eng 2020:1–22. https://doi.org/10.1080/15732479.2020.1842466.

[63] Phan HC, Dhar AS, Hu G, Sadiq R, Chi H, Sutra A. Managing water main breaks in distribution networks–A risk-based decision making. Reliab Eng Syst Saf 2019;191:106581. https://doi.org/10.1016/j.ress.2019.106581.

[64] Kabir G, Tesfamariam S, Francisque A, Sadiq R. Evaluating risk of water mains failure using a Bayesian belief network model. Eur J Oper Res 2015;240:220–34. https://doi.org/10.1016/j.ejor.2014.06.033.

[65] Matos R, Cardoso A, Duarte P, Ashley R, Molinari A, Schulz A. Performance indicators for wastewater services - Towards a manual of best practice. Water Sci. Technol. Water Supply 2003;3:365–71. https://doi.org/10.2166/ws.2003.0126.

[66] Haider H, Sadiq R, Tesfamariam S. Performance indicators for small-and medium-sized water supply systems: a review. Environ Rev 2014;22:1–40. https://doi.org/10.1139/er-2013-0013.

[67] Santos LF, Galvão AF, Cardoso MA. Performance indicators for urban storm water systems: a review. Water Policy 2019;21:221–44. https://doi.org/10.2166/wp.2018.042.

[68] Han S, Hwang H, Kim S, Baek GS, Park J. Sustainable Water Infrastructure Asset Management: a Gap Analysis of Customer and Service Provider Perspectives. Sustainability 2015;7:13334–50. https://doi.org/10.3390/su71013334.

[69] Cardoso MA, Coelho ST, Matos R, Alegre H. Performance assessment of water supply and wastewater systems. Urban Water J 2004;1:55–67. https://doi.org/10.1080/15730620410001732053.

[70] Alegre H, Vitorino D, Coelho ST. Infrastructure value index: a powerful modelling tool for combined long-term planning of linear and vertical assets. Procedia Eng 2014;89:1428–36. https://doi.org/10.1016/j.proeng.2014.11.469.

[71] Cabrera Rochera E, Estruch-Juan E, Gómez E, del Teso R. Defining complementary tools to the IVI. The Infrastructure Degradation Index (IDI) and the Infrastructure Histogram (HI). Urban Water J 2019;16:343–52. https://doi.org/10.1080/1573062X.2019.1669195.

[72] Francisque A, Tesfamariam S, Kabir G, Haider H, Reeder A, Sadiq R. Water mains renewal planning framework for small to medium sized water utilities: a life cycle cost analysis approach. Urban Water J 2017;14:493–501. https://doi.org/10.1080/1573062X.2016.1223321.

[73] Liu W, Song Z, Ouyang M. Lifecycle operational resilience assessment of urban water distribution networks. Reliab Eng Syst Saf 2020;198:106859. https://doi.org/10.1016/j.ress.2020.106859.

[74] Lee S, Burian S. Triple Top Line-Based Sustainability Measure for Water Distribution Systems. J Infrastruct Syst 2020;26:04020027. https://doi.org/10.1061/(asce)is.1943-555x.0000561.

[75] Lee S, Burian S. Triple top line-based identification of sustainable water distribution system conservation targets and pipe replacement timing. Urban Water J 2019;16:642–52. https://doi.org/10.1080/1573062X.2020.1713383.

[76] Cavazzini G, Pavesi G, Ardizzon G. Optimal assets management of a water distribution network for leakage minimization based on an innovative index. Sustain Cities Soc 2020;54:101890. https://doi.org/10.1016/j.scs.2019.101890.

[77] Carriço N, Covas D, Almeida M do C, Alegre H. Selection of the best rehabilitation solution using multicriteria decision analysis. Water Asset Manag Int 2013;9:7–11.

[78] Cardoso MA, Almeida M do C, Santos Silva M. Sewer asset management planning - implementation of a structured approach in wastewater utilities. Urban Water J 2016;13:15–27. https://doi.org/10.1080/1573062X.2015.1076859.

[79] Beheshti M, Sægrov S. Sustainability assessment in strategic management of wastewater transport system: a case study in Trondheim. Norway. Urban Water J 2018;15:1–8. https://doi.org/10.1080/1573062X.2017.1363253.

[80] Ferreira B, Carriço NJG. Urban Water Infrastructure Asset Management Plan: case Study. Open Eng 2019;9:459–67. https://doi.org/10.1515/eng-2019-0058.

[81] Large A, Le Gat Y, Elachachi SM, Renaud E, Breysse D, Tomasian M. Improved modelling of "long-term" future performance of drinking water pipes. J Water Supply Res Technol - AQUA 2015;64:404–14. https://doi.org/10.2166/aqua.2015.115.

[82] Urrea-Mallebrera M, Altarejos-García L, García-Bermejo J, Collado-López B. Condition assessment of water infrastructures: application to Segura River Basin (Spain). Water (Basel) 2019;11:1–21. https://doi.org/10.3390/w11061169.

[83] Brito RS, Alegre H, Machado P. Strategic asset management approach for planning investment in a large-scale irrigation system. Water Supply 2020;20:2165–74. https://doi.org/10.2166/ws.2020.115.

[84] Cabral M, Loureiro D, Covas D. Using economic asset valuation to meet rehabilitation priority needs in the water sector. Urban Water J 2019;16:205–14. https://doi.org/10.1080/1573062X.2019.1648528.

[85] Vieira J, Cabral M, Almeida N, Silva JG, Covas D. Novel methodology for efficiency-based long-term investment planning in water infrastructures. Struct Infrastruct Eng 2020;16:1654–68. https://doi.org/10.1080/15732479.2020.1722715.

[86] Ramos-Salgado C, Muñuzuri J, Aparicio-Ruiz P, Onieva L. A decision support system to design water supply and sewer pipes replacement intervention programs. Reliab Eng Syst Saf 2021;216:107967. https://doi.org/10.1016/j.ress.2021.107967.

[87] Hastings N.A.J. Physical asset management. 2010. https://doi.org/10.1007/978-1-84882-751-6.