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A digital water strategy based on the digital water service concept to support asset management in a real system

Daniele Biagio Laucelli [a,*], Laura Vanessa Enriquez[a], Andres David Ariza[a], Francesco Gino Ciliberti[b], Luigi Berardi [b] and Orazio Giustolisi [a]

[a] Department of Civil, Environmental, Land, Building Engineering and Chemistry, Technical University of Bari, Bari 70126, Italy
[b] Department of Engineering and Geology, University 'G. D'Annunzio' of Chieti Pescara, Pescara 65127, Italy
*Corresponding author. E-mail: danielebiagio.laucelli@poliba.it

DBL, 0000-0003-0974-4578; LB, 0000-0002-6252-2467; OG, 0000-0002-5169-7798

ABSTRACT

Digital transformation currently represents a clear opportunity for innovation in better management and planning of water distribution networks. Coupled with the increased investments in assets and the growing need of safe and high-quality water for the public, new opportunities are opening for digital tools that can help operators, consultant companies and researchers to support asset management tasks. This work presents the applications of a comprehensive digital water strategy on two real case studies with information provided by the Italian water company Acquedotto Pugliese. The proposed digital water strategy is based on the paradigm named digital water services. The strategy starts by improving the value of GIS and existing models' data. Then, advanced hydraulic modelling and topological analyses, using the complex network theory, along with artificial intelligence methodologies are the basis for the development of digital water services, which are the engineering apps that use the network digital twin to support the different stages of asset management, i.e., digital water strategy.

Key words: advanced hydraulic modelling, digital twins, digital water services, leakage management, water distribution networks

HIGHLIGHTS

- Innovative digital water strategy to support asset management and leakage reduction exploiting digital transformation opportunities.
- Demonstration of robustness and flexibility of the digital water workflow on two real networks.
- Digital water services as a novel integration of advanced hydraulic modelling and digital twins.

1. INTRODUCTION

Water distribution networks (WDNs) must provide a reliable, continuous, and quality service to ensure human consumption and support the execution of economic activities. There are multiple factors that have increasingly impaired water supply, such as pipeline deterioration, population growth (Sinha 2014), and water scarcity (Giustolisi *et al.* 2016). Deteriorated pipes are associated with higher background leakages and head losses (Lambert 1994), which increases the probability of pressure-deficient scenarios. For this reason, asset management in terms of leakage reduction is fundamental to guaranteeing a constant water supply with a perspective that seeks a rational and efficient use of resources.

The classification of leakages, also known as real water losses, includes two categories: bursts and background leakages (Lambert 1994). Bursts are associated with large outflows and supply disruption, while background leakages are small outflows from joints, fittings, and small cracks along pipelines, that are too low to be detected by active leakage control actions (Germanopoulos 1985). Consequently, background leakages have a high impact on the long-term mass balance of WDNs, and thus they are usually referred to as volumetric leakages (Berardi *et al.* 2018). Moreover, pressure levels that are higher than required for a correct service increase volumetric leakages that can cause accelerated pipe deterioration, resulting in a higher rate of bursts and/or failures of larger dimensions.

In this sense, leakage reduction diminishes the waste of water resources and increases the service life of pipelines, which boosts the hydraulic capacity of WDNs. Furthermore, it decreases the carbon footprint and costs related to water treatment and energy consumption for pumping (Colombo & Karney 2005). The reduction of volumetric water losses in the short-term (i.e., operational) and medium-term (i.e., tactical) time horizons, may be achieved through pressure control strategies such as the installation of pressure control valves (PCVs) (e.g., Saldarriaga & Salcedo 2015; Berardi *et al.* 2018) and district metered areas (DMAs) definition (e.g., Ferrari & Savic 2015). In addition, medium-term and long-term (i.e., strategic time horizon) solutions include pipelines rehabilitation (Alvisi & Franchini 2009), enlargement of existing tanks or renewal of pumping stations (Giustolisi *et al.* 2016), which require higher investments in comparison with short-term actions.

In this context of decision-making complexity, water managers need to be assisted by reliable, robust, and flexible tools for asset management decisions; nowadays, these can be based on digital technologies, exploiting the potential of *Digital Transformation*. In fact, the growing power of computers, as well as data acquisition and storage, has accelerated the introduction of digital tools in the field of WDNs. Such decision-support tools require, among others, the integration of (i) the concept of Digital Twin; (ii) advanced hydraulic modelling with a pressure-driven approach, accounting for variable topologies due to different operational conditions of the WDN; (iii) a Geographic Information System (GIS) environment with a consistent data format for the interoperability with analysis tools; and (iv) multi-objective optimization algorithms aimed at returning sets of feasible solutions with a variable budget.

This integration is here presented within a digital water strategy based on the paradigm of digital water services (DWSs), that represent the last mile for digital transition in WDNs since they promote the interaction with water operators, who may modify optimal alternatives based on expert knowledge. DWSs are developed as plug-ins in the GIS environment, incorporating advanced hydraulic analysis and optimization capabilities.

Hence, this research presents a comprehensive digital water strategy framed within a structured and replicable workflow that implements DWSs as decision-support tools for each step of the asset management workflow. This scheme consists of analysis of the topological domain of the WDN, and hydraulic model calibration based on mass balance as a starting point, followed by design of hydraulic DMAs integrated with pressure control and pipeline rehabilitation. Hydraulic networks of the cities of Modugno and Bari (Italy) are used to demonstrate the methodology application.

2. ADVANCED HYDRAULIC MODELLING FOR ASSET MANAGEMENT

The presented digital water strategy is supported by advanced hydraulic modelling based on a pressure-driven approach embedded in the WDNetXL-WDNetGIS system (Berardi *et al.* 2018). It includes advanced hydraulic analysis capabilities, that fit crucial pre-requisites to support asset management and outperform the limitations of traditional modelling software, consistently with the digital transformation paradigm. The majority of traditional software (generally based on the traditional EPANET paradigm) only uses a demand-driven approach, which does not allow a consistent analysis of pressure-deficit scenarios and pressure-dependent leakages at a single-pipe level (Giustolisi & Walski 2012). In contrast, the advanced modelling technique used herein implements a pressure-driven analysis paradigm, allowing a more accurate evaluation of WDN functioning in several operational conditions, thus evaluating different features such as (a) the real volume of water provided to each consumer and (b) the volumetric water losses at the pipe level.

Regarding water demand representation, recently traditional models tried to embed a pressure-driven function (Wagner *et al.* 1988; Giustolisi & Walski 2012), although still maintaining water demands as aggregated at nodes. This condition does not consider the different connection configurations that each user may have and is ill-adapted to the scenario that digital transformation is outlining, for example, single user telemetry that water companies are using for billing consumption. Conversely, the advanced modelling approach here used accounts for each user connection with three possible configurations: direct connection, direct connection accounting for floors number of supplied building, and connection with private storage tank, thus having water storage capability and a dedicated pumping system. Hence, the used model incorporates the real elevation and the georeferenced location of each user meter, as well as the database of water consumption of each consumer, which is usually available at water providers. Such a database is kept apart from the model so that changes in the status and number of connections do not require changes in the model definition.

In addition, traditional approaches model leakages as emitters, that correspond to nodes with a pressure-dependent outflow. However, background leakages are distributed among the network, and they are an indicator of pipe deterioration, thus they can be more realistically represented as outflows for each pipe (Giustolisi *et al.* 2008a). In this sense, the method used here represents leakages as uniformly distributed outflows at the pipe level considering the dependence on pressure and on deterioration through the structure of the Germanopoulos' model (Germanopoulos 1985) (β parameter), or through the FAVAD approach (May 1994; Van Zyl & Cassa 2014). This modelling technique improves the accuracy of the hydraulic analysis and provides information about the deterioration level of every pipe of the system, which is essential to support decisions related to asset management, such as pipe rehabilitation (Laucelli *et al.* 2023).

In the case of variable WDN topology (e.g., due to works and/or interruptions), traditional models consider a fixed topology while assigning a very small flow rate to pipes to close instead of removing them from the hydraulic analysis; this introduces accuracy problems and does not contemplate the possible disconnection of some sections of the WDN. The advanced hydraulic modelling here used accounts for WDN topology really connected to water sources before and during hydraulic simulations since it automatically detects network segments based on the status of devices, such as pressure reducing valves or flow meters (Giustolisi *et al.* 2008b). In this sense, the used tools exploit the complex network theory (CNT) metrics tailored for WDNs to perform the topological analysis of networks and drive DMA design in an optimal way (Laucelli *et al.* 2017). Moreover, the used advanced hydraulic modelling is fully interoperable with GIS given its consistent data format.

This work shows the application of a thorough digital water strategy that integrates DMA planning, pressure control, and system rehabilitation in a GIS environment to find robust and flexible alternatives to support asset management decisions for system operators. This application is performed through DWS using the Digital Twin of the WDNs (Ciliberti *et al.* 2021; Laucelli *et al.* 2023).

3. COMPREHENSIVE FRAMEWORK FOR WDN ASSET MANAGEMENT

Figure 1 presents the comprehensive methodological proposal with the scope of enhancing asset management in terms of leakage reduction. Each process of the workflow, represented by grey squares, is supported by a DWS.

In the first step, the consistency of the topological and demand data is integrated, verified, and corrected when necessary. Next, an analysis of the topological domain is performed to identify the most relevant elements (pipes and nodes) of the network graph before any hydraulic simulation, to improve the understanding of WDN behaviour. Subsequently, two parallel processes are executed: (a) a calibration based on mass balance using hydraulic measurements and topological data and (b) a topological segmentation into virtual districts to identify the candidate positions for flow meters and closed sectioning

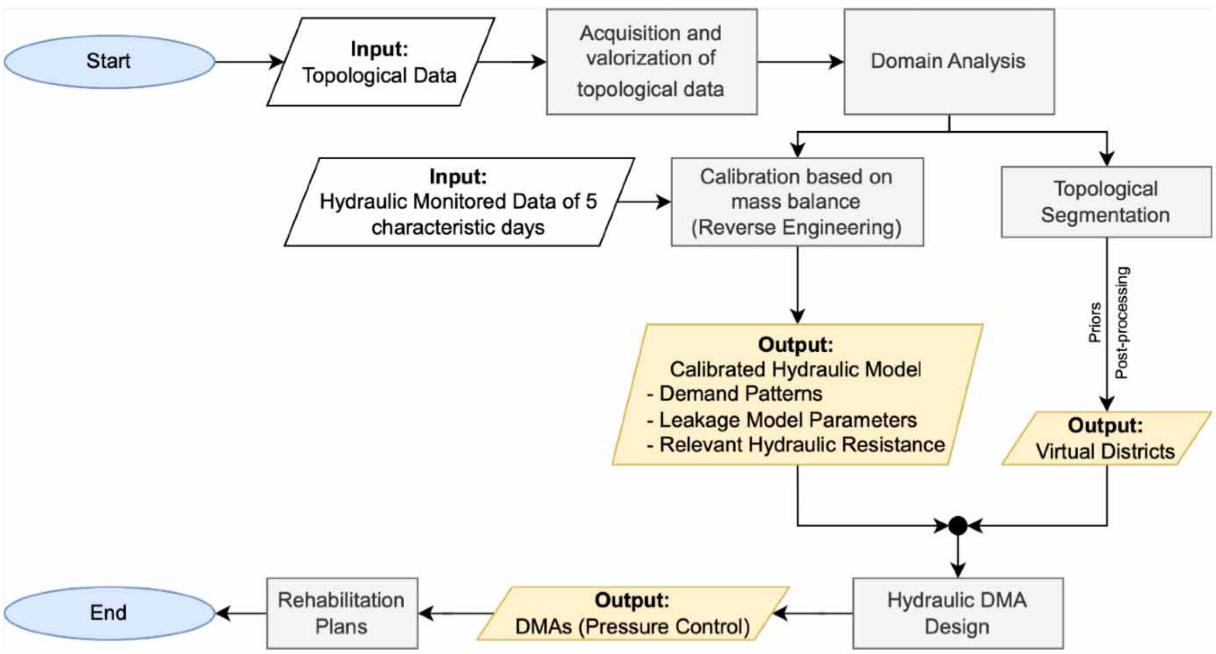

Figure 1 | Workflow of the asset management strategy.

valves. The latter provides alternatives for the next hydraulic DMA design integrated with pressure control. Finally, optimal rehabilitation plans are identified based on cost–benefit analysis.

The reduction of volumetric water losses is achieved in two complementary ways: the DMAs design integrated with pressure control and the pipeline rehabilitation. First, closing valves to delimit DMAs reconfigures the water paths to achieve little reduction of average pressure throughout the network while avoiding pressure deficit at consumers. Additionally, the implementation of PCVs in optimal locations puts under full control the pressure head on the WDN as well as the water losses. Second, pipe rehabilitation/replacement in a pressure controlled WDN can further reduce leakages, while preserving the necessary pressure levels for a correct service at users, avoiding unintended pressure surges due to new pipes in a network with uncontrolled pressure. Further details on each step will be provided in the next sections.

4. CASE STUDIES

This paper presents the above-mentioned integrated approach on the WDN of Modugno (36,000 inhabitants) and Bari (330,000 inhabitants), two cities in the Apulia region, Italy. The hydraulic model of Modugno WDN consists of 1,814 pipes and 1,585 nodes, with three reservoirs. One of these feeds both Modugno and an area of Bari, the largest city in the area. The hydraulic model of Bari WDN consists of 9,057 pipes and 7,762 nodes, with eight reservoirs. The network of Bari was modelled and analysed considering six hydraulically independent sub-networks: Torre a Mare, Japigia, Bari Downtown, Carbonara-Ceglie, Loseto, and Santo Spirito-Palese. The sub-networks correspond to neighbouring municipalities to the city of Bari.

Results on Bari WDN will be reported to demonstrate the application on a large system, while the Modugno WDN will be used to illustrate the details of the procedure along with relevant considerations for each phase, focusing on how DWSs support the execution of every phase (Laucelli *et al.* 2023).

4.1. Acquisition and valorization of topological and consumption data

The topological and hydraulic data of the Modugno WDN was provided by the water company Acquedotto Pugliese in EPANET and ESRI® shapefile format. The information consisted of:

- a geodatabase that included the attributes of pipes, tanks, and devices;
- the georeferenced water meters and consumption database for each user;
- information about the replaced and recently built pipelines;
- data recorded at flow and pressure meters in 2019.

As a first approach, the data were analysed to detect possible inconsistencies and errors by comparing hydraulic measurements and topological data (e.g., inconsistent flow/pressure data). Initially, one missing PCV was identified in the Modugno WDN. Subsequently, the advanced topological functions based on CNT were used to perform two verifications. First, this tool simplified the topology of the pipes with isolation valves including them as a feature of the adjacent pipes instead of separated pipes with one valve each. Second, double nodes were identified and joined into one to restore hydraulic connectivity. The georeferenced water meters and the water consumption data were included in the hydraulic model. The software allows specifying the type of consumer (e.g., commercial, industrial, household), the status of the service (i.e., active or inactive) and the attributes of the connection (e.g., number of floors and height of the buildings, location of private tanks, directly connected taps) whenever available. Hence, the value of the data was increased by integrating and verifying topological, hydraulic and water demand information into the WDN digital twin.

The analysis tools allowed identifying the existing monitoring districts based on available flow meters and closed gate valves. These are here defined as pseudo-districts since there are no flow meters at the inlet/outlet of the districts, while pressure is attempted to be controlled by closing several valves and each one of them is fed by a single different reservoir.

4.2. Analysis of the topological domain of the WDN

WDN topology mostly determines its hydraulic regime. The analysis of the topological domain of WDNs involves the evaluation of centrality metrics derived from the CNT, that are reformulated for WDN infrastructures. The metric applied for the WDN topological analysis was the Tailored Edge Betweenness, which measures the importance of each pipe accounting for the intrinsic relevance without considering hydraulics (Giustolisi *et al.* 2019). The integration of CNT metrics allowed us to conceptualize WDNs as graphs and identify the prevailing elements of the network considering the shortest paths of the system (Giustolisi *et al.* 2020). In such a context, domain analysis is essential for the methodological proposal since it allows to define the main paths of the system, whose hydraulic resistance is likely to have a strong influence on the pressure status of the network, and thus deserves careful calibration. Moreover, such analysis supports the next virtual segmentation of the WDN since it identifies the most relevant pipes as candidate locations of flow meters during DMA design, hydraulically consistent with the connectivity of the system.

4.3. Model calibration based on the mass balance approach

The hydraulic model was calibrated with an innovative approach based on the concept of mass balance (Berardi & Giustolisi 2021), which leverages the capability of separating the consumers' water demands (stochastic demand component) and the volumetric water losses (deterministic demand component) from the monitored total input volume m thanks to the pressure-driven analysis implemented in the advanced hydraulic model. This procedure allows us to identify, for each monitored area, primarily: the β parameter of the leakage model for each pipe, and a unique consumers' demand pattern. In the case of Modugno WDN, the uncertainties about the pseudo-districts shown above makes it technically reasonable to consider the entire network as a unique area with monitored inflow close to the three reservoirs.

Therefore, a unique demand pattern is assumed to be observable and calibrated for the entire system. Furthermore, this strategy also allows us to simultaneously calibrate the hydraulic resistances of the most relevant pipes, which are identified based on the topological domain analysis, while the hydraulic resistances for the remaining pipes were assumed from previous models and verified considering the ranges in technical literature. The initial values of the β parameter were assessed for each pipe based on the propensity to fail as a function of diameter and number of connections (Berardi *et al.* 2008) since they have proved to influence the development of leakages.

The calibration was performed using the flow measurements at the inlet points from the three reservoirs. Five representative days (i.e., working/holiday, winter/summer conditions, and New Year's Day) were chosen to describe the different characteristic hydraulic status of the network. Based on this information and the information on annual demand for each consumer, the DWS named *DigitalWaterMass_Calibration* was used to identify a unique demand pattern together with the β parameters at a single-pipe level (Berardi & Giustolisi 2021), consistently with pressure the pressure regime based on available data.

Figure 2 shows the DWS interface of *DigitalWaterMass_Calibration* with results for the Modugno WDN showing the pattern of consumers' demand and the linear leakage indicator (i.e., M1a according to the Italian regulation (ARERA 2017) in (m^3/km/day)) calculated for 5 days. Additionally, this DWS computed the average and maximum errors at flow meters, as

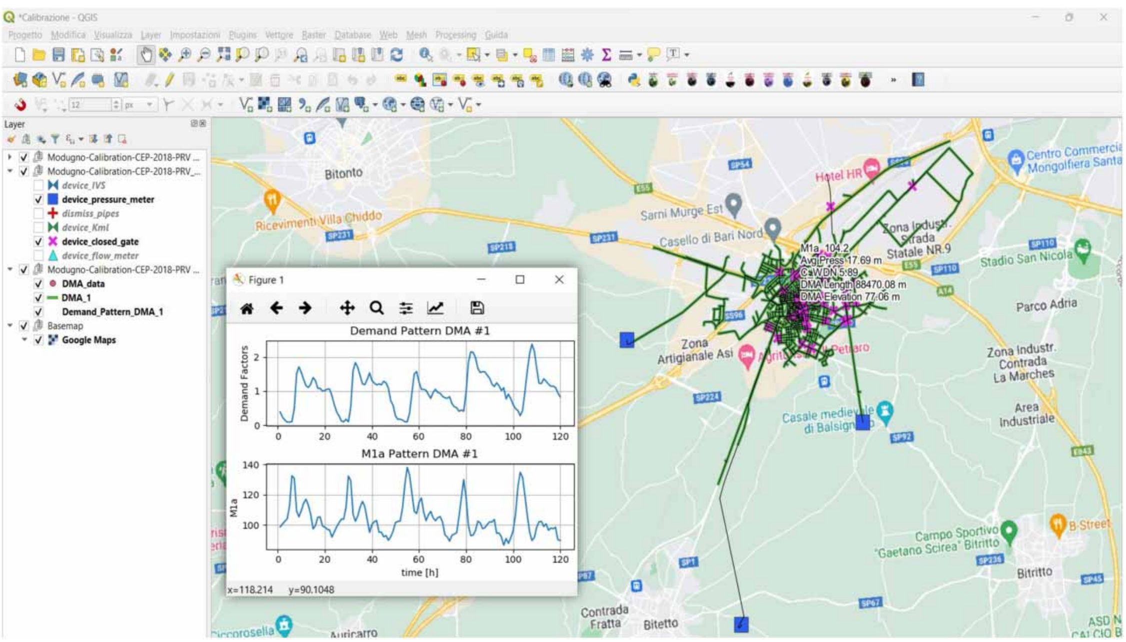

Figure 2 | *DigitalWaterMass_Calibration* interface: patterns of consumers' demand and linear leakage index M1a (m^3/km/day). Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

well as mass balance errors. The calibration solution showed a minimum difference between flow measurements and the values from the calibrated model, with an average mass balance error equal to 0.0569 L/s.

4.4. Topological segmentation

The DMAs design is carried out in a two-step process: (1) topological segmentation, that identifies the candidate locations for two types of devices: closed sectioning valves and flow meters and (2) the hydraulic DMAs design, in which a device is assigned at each candidate location. It is worth noting that the location of possible PCVs is left to the user based on engineering judgement and practical constraints; it is recommended that PCV are at the inlet points of the network since they enable more flexibility in WDN operation, also considering the time lag between the design of the DMA and its implementation.

Topological segmentation is formulated as an optimization process with two objectives: to maximize the modularity index tailored for WDN, that measures the efficiency of the topological division into segments, and to minimize the number of conceptual cuts that separate them (Laucelli *et al.* 2017). For this stage, two DWSs called *DigitalWaterVirtualDMA_Design* and *DigitalWaterSegment_Viewer* are allowed to optimize and visualize topological segmentation solutions with a different number of virtual districts. The GIS visualization of the solutions, which can account for the information from the analysis of the topological domain, makes it possible to modify the candidate positions considering constraints before performing the hydraulic DMA design, e.g., existing locations of flow observations. Hence, topological segmentation encompasses CNT and optimization algorithms to rationalize DMAs design considering advanced analysis techniques and practical constraints. Figure 3 presents the interface of *DigitalWaterVirtualDMA_Design* with the possible solutions for the Modugno network (i.e., groups of layers) and Figure 4 shows the interface of *DigitalWaterSegment_Viewer* and the segmentation selected as the basis for the hydraulic DMA design in the same network.

4.5. Hydraulic DMAs design and pressure control

Hydraulic DMAs design is based on a multi-objective optimization that finds the optimal positions for flow meters and closed sectioning valves, considering the conceptual cuts identified by the topological segmentation as candidate locations. The objectives are to maximize the reduction of volumetric losses, while simultaneously minimizing the number of flow meters between DMAs and unsupplied user's demand. If the WDN incorporates PCVs, their set-points are included as decision variables.

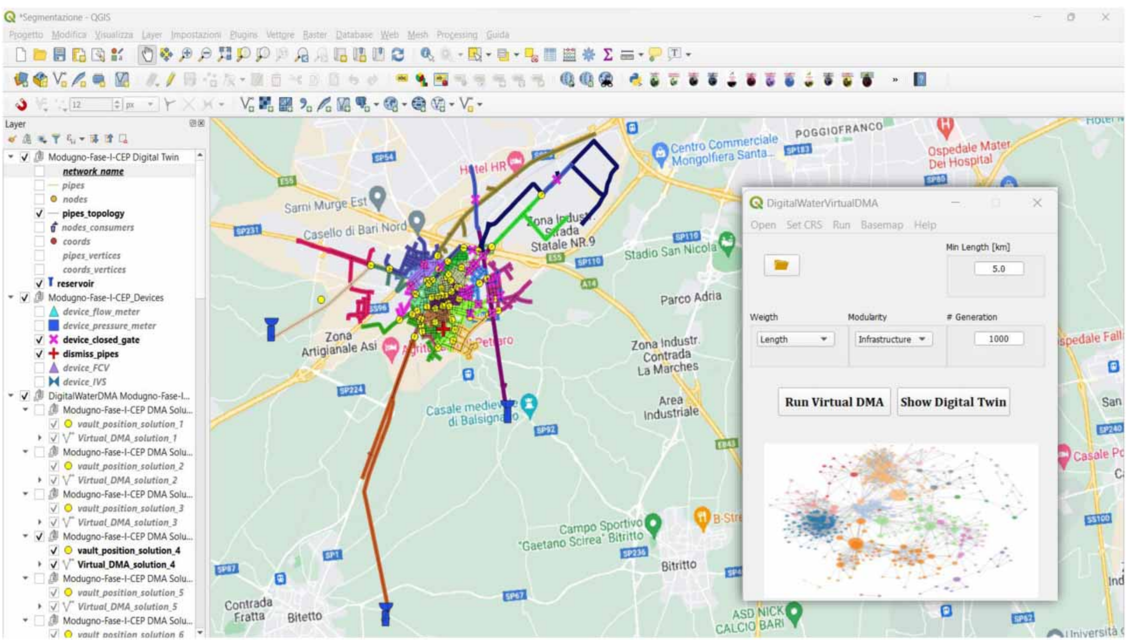

Figure 3 | *DigitalWaterVirtualDMA_Design* interface. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

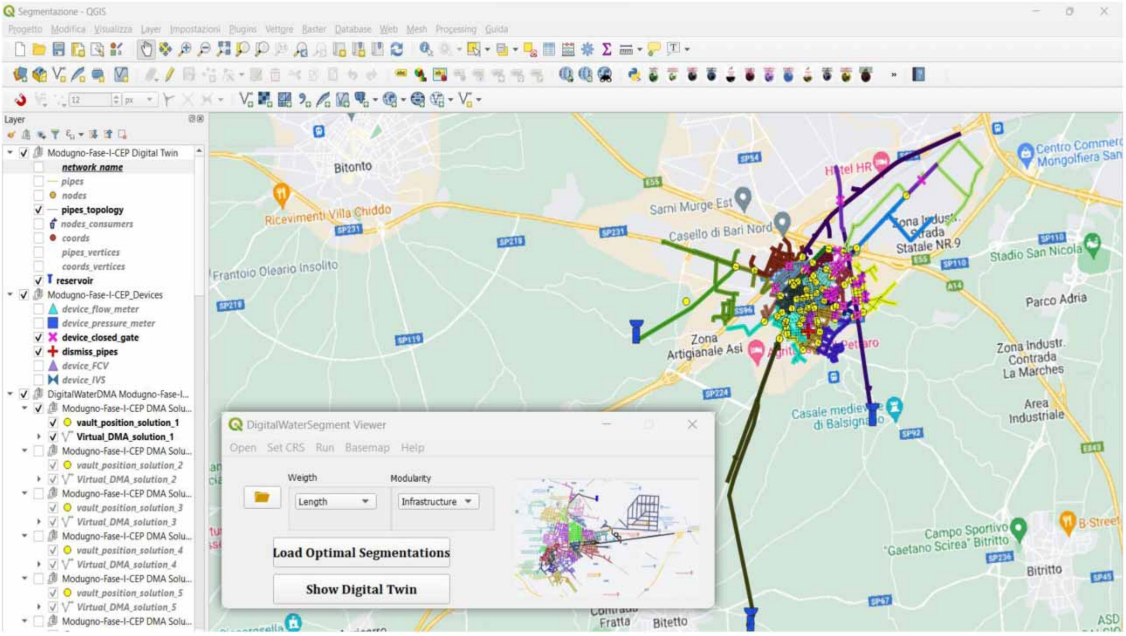

Figure 4 | *DigitalWaterSegment_Viewer* interface and solution used for hydraulic DMA design. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

The above is accomplished by *DigitalWaterDMA_Design* and *DigitalWaterDMA_Analyzer*, that are services used to optimize the design of hydraulic DMAs and visualize the corresponding solutions, respectively. The DWS *DigitalWaterDMA_Analyzer* allows to select the configuration of actual DMAs in a GIS environment, which is useful to support the final design, allowing the user *ad hoc* modifications of some positions of gate valves/meters. It is worth noting that removing flow meters means to join contiguous DMA, while preserving the information of the best locations of future meters to create nested DMAs into the existing ones.

Moreover, this DWS allows checking the expected values in flow observation points to evaluate the metrological effectiveness of these devices considering their accuracy and precision to reduce the uncertainty of mass balances in each DMA. For example, placing flow meters where flow inversions or small water velocities are expected should be avoided.

Figure 5 shows the interface of *DigitalWaterDMA_Design*, that generates different groups of layers for each DMA solution in the Pareto front, along with all the relevant parameters of the optimization. At the same time, Figure 6 displays the interface of the *DigitalWaterDMA_Analyzer* service with metrological information of tree flow meters for the network to support the selection of these devices.

4.6. Pipes rehabilitation

The pipeline replacement plans were designed considering the WDNs that incorporate pressure control through DMAs and PCVs. The design process is defined as an optimization between the costs and benefits of the interventions, i.e., to minimize the cost of intervention while maximizing the expected reduction of volumetric water losses due to replaced pipes (see the Pareto front on the right of Figure 7). It should be emphasized that the proposed solutions are contiguous, i.e., the cheapest solution contains the most critical pipe for losses (which is not simply the most deteriorated, but the one with the highest leakages assessed in the model by pressures and deterioration); such pipe is contained in the second solution which will be more expensive, and so on. The water company can choose the most suitable solution according to its current budget for rehabilitation, thus the strategy is suitable to take flexible decisions about rehabilitation plans. In the following years, when a new budget is available, the water company may be able to choose one of the higher-cost solutions knowing that the most critical pipes have been already replaced.

The DWS *DigitalWaterRehabilitation* supports the choice of rehabilitation plans. This service allows for an assessment of pipe replacement interventions in terms of the expected reduction of volumetric losses, the required investment and other

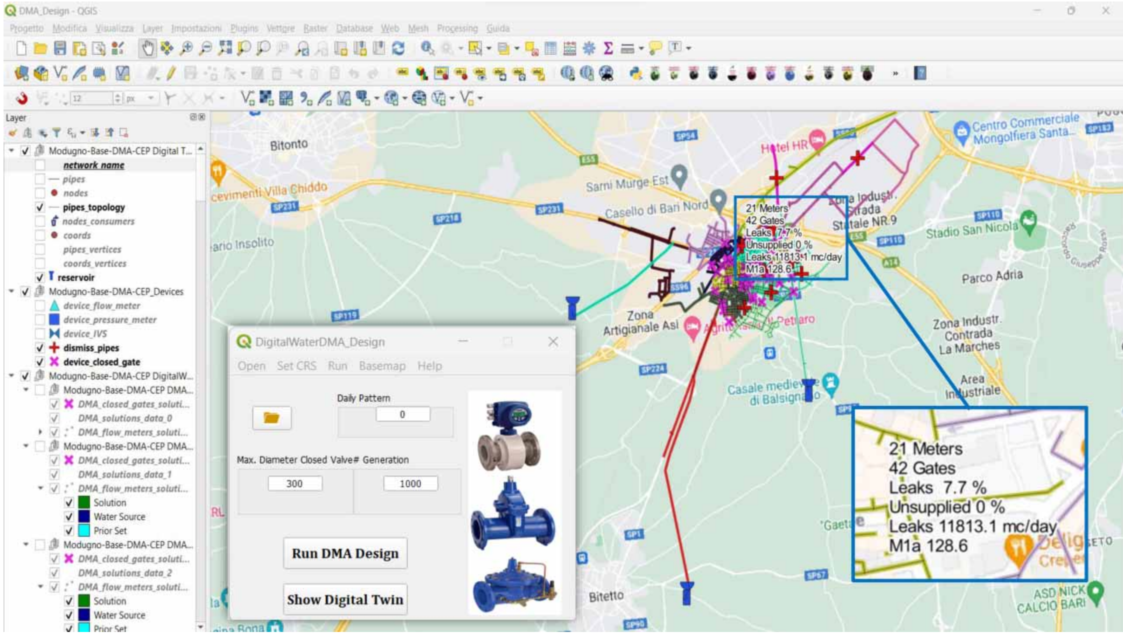

Figure 5 | *DigitalWaterDMA_Design* interface with the DMAs solution for the Modugno WDN. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

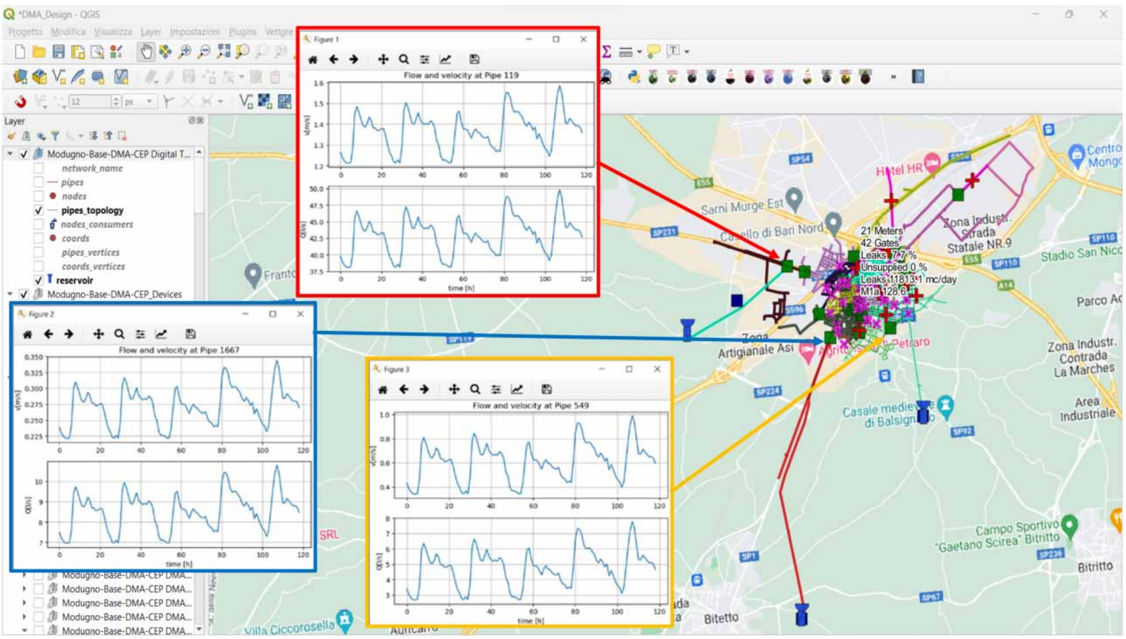

Figure 6 | *DigitalWaterDMA_Analyzer* interface for visualization and analysis of DMAs design solutions. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

efficiency indicators. This DWS sets the colour of each pipe based on the value of its linear leakage indicator (M1a) as in Figure 7, which enables the user to manually select the pipes to be replaced. Alternatively, external rehabilitation plans may be loaded, if any. Figure 7 displays the interface of this DWS and the expected results for a certain budget for the Modugno WDN, in which the replaced pipes are highlighted in yellow.

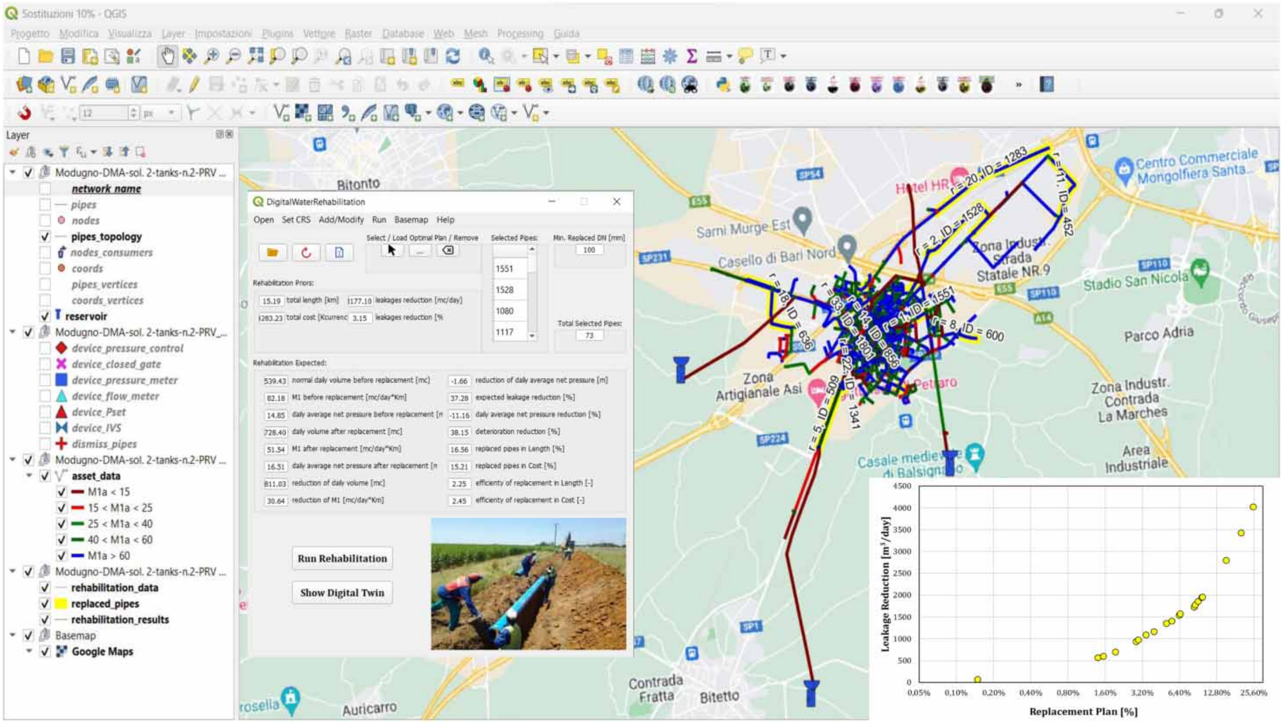

Figure 7 | *DigitalWaterRehabilitation* interface and expected results for a replacement cost of about 15% of the total network cost for the Modugno WDN. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

Therefore, this DWS allows evaluation of the reduction of leakages for different investment levels, which is aligned with the scope of digital transformation since it enhances and supports decision-making through digital tools that make part of a comprehensive workflow.

5. RESULTS AND DISCUSSION

This section presents the results obtained after applying the strategy to the Modugno WDN and shows how it can be applied to the larger and more complex WDN of Bari.

5.1. Topological segmentation and hydraulic DMA design

5.1.1. Modugno

The DMAs for the Modugno WDN are shown in Figure 8, and displays the comparison between the original state of the Modugno WDN vs. this network with DMAs and PCVs. Figure 8(b) shows that DMAs and pressure control generate more uniform and lower background leaks in comparison with Figure 8(a), in which the background volumes are generally higher, and they have an inverse behaviour when compared to the demand pattern. In addition, Figures 8(c) and 8(d) demonstrate the change in the distribution of the M1a indicator throughout the network, as well as the reduction in the average pressure in the Modugno WDN with DMAs and PCVs in contrast to the original network.

The results of the DMAs design in the Modugno WDN are shown in Table 1. The C_{WDN} coefficient is computed for Modugno WDN before the intervention, while all the other values are evaluated after the DMAs and pressure control. The C_{WDN} coefficient is the ratio between the M1a indicator and the average pressure in the network. In the case of Modugno WDN, the C_{WDN} parameter is much greater than 1, which implies that the water losses are mainly due to the deterioration of the infrastructure rather than high-pressure levels (Berardi & Giustolisi 2021). Therefore, in this case, a greater reduction of volumetric water losses is expected with rehabilitation in contrast with DMAs design and pressure control. In this sense, although the DMA design generated a significant reduction of water losses (i.e., around 18%), the M1a indicator is still high.

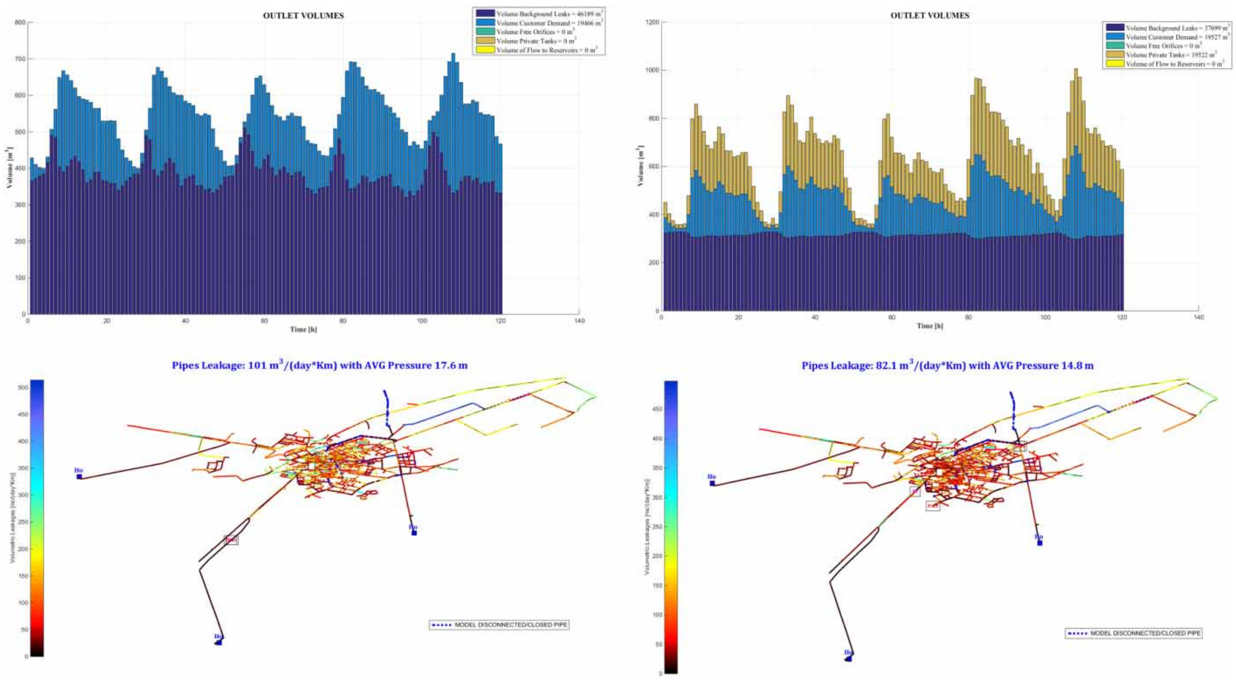

Figure 8 | Comparison of results for Modugno WDN: (a) Outlet volumes in the original hydraulic model, (b) Outlet volumes in the model with DMAs and PCVs, (c) M1a in the original hydraulic model, and (d) M1a in the model with DMAs. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

Table 1 | Indicators for DMA design in Modugno WDN

Indicator	Value
C_{WDN} (original)	5.74
No. of DMAs	17
No. of closed sectioning valves	45
No. of flow meters	18
No. of PRVs	2
M1a (m^3/day/km)	82.1
Reduction of volumetric water losses (%)	18.71%
Reduction of volumetric water losses (m^3/year)	620,000

5.1.2. Bari

The results of the DMA design of Bari WDN for each sub-network are shown in Table 2. The total amount of closed sectioning valves is 124, which corresponds to 101 valves inside each sub-network plus 23 additional valves that separate the sub-networks. The only sub-network that was not divided into DMAs was Loseto since the M1a of the calibrated model is 25.3 m^3/day/km, which indicated that no interventions were necessary to further reduce leakages. The sub-network with the highest reduction of volumetric water losses is Torre a Mare, that had the lowest C_{WDN} in its original state. Similarly, the sub-network with the lowest reduction is Japigia, that had the greatest original C_{WDN}, which implies a significant deterioration level.

The reduction of the volumetric water losses for the whole network does not exactly correspond to the sum of the values for each sub-network because the feeding of a zone between the sub-networks of Torre a Mare and Japigia was modified. The M1a indicator for the whole network of Bari is 77.2 m^3/day/km, with a total reduction of volumetric water losses equal to 13,097 m^3/day, that corresponds to a decrease of 19.95%.

Table 2 | Indicators for the DMA design in Bari WDN

Indicator	Torre a Mare	Japigia	City of Bari	Carbonara-Ceglie	Loseto	Santo Spirito-Palese	Total
C_{WDN} (original)	1.56	5.23	4.43	2.12	0.84	1.94	–
No. of DMAs	5	5	34	12	1	11	68
No. of closed sectioning valves	4	4	65	18	–	10	101
No. of flow meters	5	5	44	12	1	11	78
No. of PRVs	2	2	8	2	–	2	16
M1a (m^3/day/km)	42.30	123	92.90	40.70	–	45.10	–
Reduction of volumetric water losses (%)	44.12	11.51	13.98	17.28	–	25.45	–
Reduction of volumetric water losses ($\times 10^3$ m^3/day)	1.103	0.678	8.364	0.645	–	1.327	–

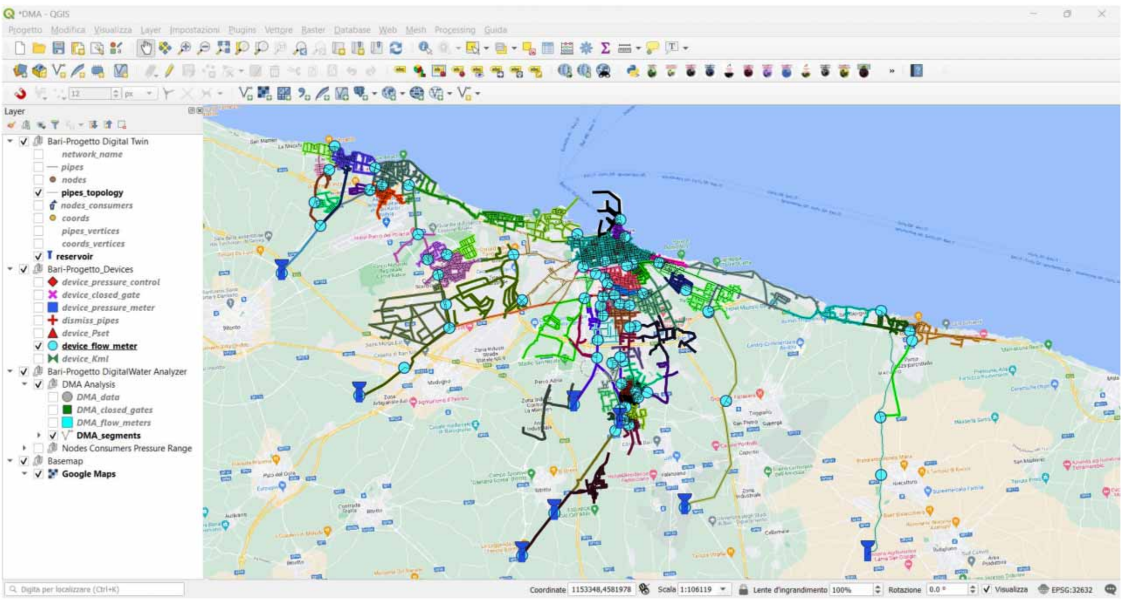

Figure 9 | DMAs for the Bari WDN. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

Figure 9 displays the DMAs for Bari WDN, that includes all the sub-networks. Additionally, Figure 10 shows the contrast between the original state of Bari WDN vs. this network with DMAs and PCVs. Similar to Modugno WDN, the background leakages are more uniform over time and the volume is lower for Bari WDN with DMAs and PCVs. In the same way, the average pressure is lower for this network.

5.1.3. Pipeline rehabilitation

5.1.3.1. Modugno. The rehabilitation plans for Modugno WDN considered a replacement cost of up to 25% of the cost of replacing the system, given the significant magnitude of the C_{WDN} coefficient. The plans included the pipes with the maximum cost–benefit ratio. In this way, the reduction of the volumetric water losses that can be achieved with an optimized replacement plan of 25% is 4,021 m^3/day, with a cost of € 7.05 million for 183 pipes. Note that the reduction of leakages reached with DMAs design and pressure control (see Table 1) may be obtained with an investment of only 8.32% for 20 pipes. Hence, rehabilitation is a necessary task in the Modugno WDN to generate a substantial reduction of volumetric losses, together with DMAs design integrated with pressure control.

5.1.3.2. Bari. The rehabilitation plans for the Bari WDN considered a pipeline replacement cost of up to 20%. Table 3 displays the reduction of volumetric water losses that can be achieved with an optimized solution of around 20% for each sub-network.

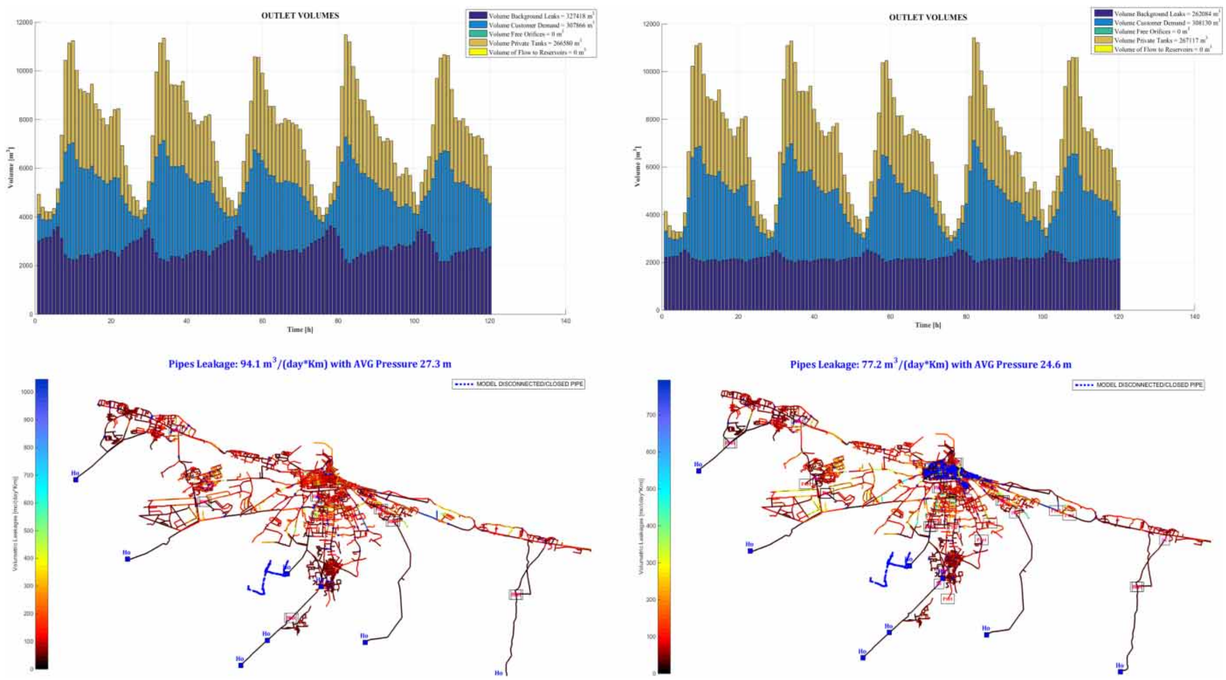

Figure 10 | Comparison of results for Bari WDN: (a) Outlet volumes in the original hydraulic model, (b) Outlet volumes in the model with DMAs, (c) M1a in the original hydraulic model, and (d) M1a in the model with DMAs. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/hydro.2023.313.

Table 3 | Reduction of leakages for the Bari WDN with a 20% cost

Indicator	Torre a Mare	Japigia	City of Bari	Carbonara-Ceglie	Loseto	Santo Spirito-Palese	Total
Cost (millions of €)	2.735	3.598	26.038	4.529	–	5.156	42.056
Reduction of volumetric water losses ($\times 10^3$ m^3/day)	1.19	3.48	17.66	1.20	–	1.74	25.27
No. of pipes	53	42	360	71	–	123	649

The greatest predominance of leakage decrease with rehabilitation plans over the DMAs design integrated with pressure control strategy is obtained in the sub-networks with the highest C_{WDN} coefficient (i.e., Japigia and the City of Bari).

This reduction should be added to that already achieved with the hydraulic DMA design and pressure control. Like the Modugno WDN, rehabilitation is also an essential task in the Bari WDN to obtain a significant leakage decrease and a strategic action for asset management.

6. CONCLUSIONS

This work shows a possible application of the digital transition potential to WDNs asset management. The advantages of using DWSs as a consistent decision-maker support tool for operators have been demonstrated, integrating the use of artificial intelligence, Digital Twins, GIS, and advanced hydraulic analysis at the service of technical skills of water managers, engineers and researchers.

The example WDNs that were presented in this paper illustrate the high coverage potential that digital transformation has and how it can be applied to diverse case studies without excluding factors of size or complexity. At each step of the asset management workflow, the DWSs do not provide a unique solution but expose a set of technically optimal alternatives that the user can easily evaluate, manipulate, and verify to reach the final design configuration. The application on two real networks, as part of a larger planning activity for asset management, proves that the digital water strategy enables rationality, repeatability and flexibility to solve complex and specific technical problems.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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