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From digital twin paradigm to digital water services

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ABSTRACT

In the context of water distribution networks (WDNs), researchers and technicians are actively working on new ways to transition into the digital era. They are focusing on creating standardized methods that fit the unique characteristics of these systems, with a strong emphasis on developing customized digital twins. This involves combining advanced hydraulic modeling with advanced data-driven techniques like artificial intelligence, machine learning, and deep learning. This paper begins by giving a detailed overview of the important progress that has led to this digital transformation. It highlights the potential to create interconnected digital water services (DWSs) that can support all aspects of managing, planning, and designing WDNs. This approach introduces standardized procedures that allow a continuous improvement of the digital representation of these networks. Additionally, technicians benefit from DWSs developed as QGIS software plugins. These services strategically enhance their understanding of technical decisions, improving logical reasoning, consistency, scalability, integrability, efficiency, effectiveness, and adaptability for both short-term and long-term management tasks. Notably, the framework remains adaptable, ready to embrace upcoming technological advancements and data gathering capabilities, all while keeping end-users central in shaping these technical developments.

Key words: advanced hydraulic modeling, decision-making support, digital twin, digital water services, water distribution network management, water distribution networks

HIGHLIGHTS

- The paper explores the digital transformation in water distribution network management.
- It emphasizes the opportunities offered by ICT/IoT and GIS/BIM tools, hydraulic modeling advancements, and AI algorithms for planning and management tasks.
- The paradigm is implemented as digital water services, enhancing engineering awareness and supporting management activities.

INDEX OF NOTATIONS AND ABBREVIATIONS

5G	5th Generation of mobile network
AI	artificial intelligence
ANN	artificial neural network
BIM	building information modeling
CNT	complex network theory
COVID 19	COronaVIrus Disease '19
CPS	cyber-physical system
DL	deep learning
DMA	district metered area
DT	digital twin
DWS	digital water service
EPR	evolutionary polynomial regression
GIS	geographic information system
ICT	information and communication technologies

IoT	Internet of Things
IVS	isolation valve system
LPWAN	low-power wide-area network
ML	machine learning
MOGA	Multi-Objective Genetic Algorithm
WebGIS	Web Geographic Information System
WDN	water distribution network

1. INTRODUCTION

Digital transition involves reevaluating processes to enhance their efficiency by leveraging products grounded in digital technologies (Vial 2019). Streamlining the acquisition and assessment of process data in a user-friendly and comprehensive manner forms the bedrock for generating valuable insights to bolster their effectiveness.

Indeed, the digital transformation concept has gained much attention in recent years (Ebert & Duarte 2018; Zaoui & Souissi 2020). In the last years, deep changes have taken place in society and industries using new digital technologies.

The dissemination of digital technologies has revolutionized the integration and delivery of products and services across all levels, including functional and organizational aspects (Sebastian *et al.* 2017). Through the utilization of digital devices connected via the Internet of Things (IoT) for data collection, in conjunction with services and data analytics, real-time monitoring and decision-support systems are made possible (Soto Setzke *et al.* 2021). This transformative process introduces innovative solutions for decision-making in various industries, empowered by data-driven algorithms that enable the development of business models (Zaki 2019), operational processes (Zaoui & Souissi 2020), and enhanced customer experiences to drive value creation (Tao *et al.* 2019).

Furthermore, digital infrastructures, such as data analytics and cloud computing, offer novel tools for rapid scaling and extracting valuable information from data (Hwang & Chen 2017). As a result, digitalization brings together the realms of technology and management, introducing new tools and conceptual frameworks within the digital environment that reshape how organizations tackle management challenges, foster innovation, and formulate strategies. In such context, the terms 'digital transition' or 'digitalization' can be defined as the utilization of technology to significantly enhance enterprise/process performance and expand reach (Westerman *et al.* 2011), or as a process aimed at instigating substantial changes and innovations within a system through the integration of information, computing, communication, and connectivity technologies (Vial 2019).

Several researchers and organizations have drawn upon the concept of 'digital transformation' from various industrial sectors, leading to the development of cyber-physical systems (CPS) (Baheti & Gill 2011) and digital twins (DTs) (Shafto *et al.* 2012; Grieves & Vickers 2017). These innovations stand as digital ecosystems, aimed at expediting the sustainable, and streamlined handling of operational responsibilities, particularly in the context of water utility management (Wang *et al.* 2015).

Water distribution networks (WDNs) exhibit distinct characteristics that differentiate them from other industrial and commercial sectors. Unlike industrial cases, WDNs are influenced by their surrounding environment, socio-economic activities, and interactions with other infrastructures. Moreover, WDNs vary in scale, ranging from urban to territorial, with urban networks spanning kilometres of pipelines. The control of WDNs involves the manoeuvring of devices whose effects on the systems are felt a few seconds or minutes later in the system. This makes the concept of 'real-time control' significantly different from other infrastructures (e.g., electrical networks) where the information travels with the speed of light which is a few orders of magnitude higher than the celerity of transient propagation in water. Besides, frequent network manoeuvres can lead to hazardous transient oscillations in pressure and flow. Additionally, WDNs consist of tangible networked infrastructures, and concepts derived from network theory applicable to trading, commercial, or social networks are not readily applicable to WDNs. Therefore, a straightforward application of digital transformation concepts from industrial and manufacturing domains is inadequate to address the unique characteristics of WDNs.

The initial steps toward embracing the concept of digital transformation in WDN management have been made relatively recently. The utilization of digital representations of WDNs on platforms such as GIS (geographic information system), BIM (building information modeling), and WebGIS (web geographic information modeling) is rapidly becoming the industry standard for WDN operators (Klug *et al.* 2012; Mirshafiei *et al.* 2019; Zhao *et al.* 2019; Daniel *et al.* 2023). By incorporating these technologies into WDN management, several opportunities arise for enhancing understanding of WDN behaviors and addressing various operational challenges (Savić *et al.* 2014; Wang *et al.* 2015; Oberascher *et al.* 2022; Arnell *et al.* 2023).

Conejos Fuertes *et al.* (2020) have identified the key factors driving the 'digital transformation', including advancements in information and communication technology (ICT) and the internet of things (IoT). These advancements encompass fast communication networks such as narrowband-IoT, low-power wide-area network (LPWAN) protocols, and 5th Generation of mobile (5G) networks, as well as the implementation of sensors and the gathering and analysis of large-scale data, all of which have been introduced into WDNs within the past two decades. Recently, Ramos *et al.* (2023a) proposed a replicable DT framework for evaluating WDNs' efficiency and reliability, while Ramos *et al.* (2023b) developed a DT model by integrating GIS and water models for assessing the technical and economical performances of WDNs. Furthermore, Pesantez *et al.* (2022) introduced a DT model to evaluate the effects of changing customer demands on WDNs resilience during the COVID-19 pandemic through the combination of a hydraulic model and hourly consumers' data acquired by smart meters.

The enhanced computing capabilities and the abundance of high-quality data from distributed sensors and smart meters are boosting the use of machine learning (ML) and artificial intelligence (AI) techniques to extract knowledge on complex physical phenomena in the WDNs from data.

Nonetheless, replacing the phenomenological description of complex hydraulic processes in WDNs with tools that allow for the identification of operating patterns based on the functioning observed by the sensors is misleading. Indeed, it is well known from hydraulic engineering that the management actions might cause alterations to the normal functioning of WDNs (e.g., by pressure control, closing of gate valves, pipe replacement) which have not been observed in the past, making it impossible to encapsulate such complex physical systems using data-driven models.

On this side, over the past two decades, significant advancements have been made in hydraulic modeling to enhance the analysis of WDNs providing increasingly accurate and physically grounded representations of the complex phenomena within such infrastructures. Using phenomenological models also improves the interpretability of analyses as a key prerequisite to support technical decisions (Giustolisi *et al.* 2008; Giustolisi & Walski 2012).

Therefore, the main goal of increasing the efficiency of WDN management using digital transition should take the hydraulic model as the primary means of representing the functioning of WDNs, and support various technical tasks.

Moreover, the incorporation of metrics and algorithms derived from complex network theory (CNT) and AI has introduced new approaches for the hydraulic analysis of WDNs. These methods enable the detection of inherent topological characteristics within the networks and offer solutions for numerous challenges associated with the planning and design of WDNs.

The last mile of the digital transformation in WDNs asks for innovations on two sides: integrating the latest technological capabilities and scientific advancements as novel processes-products to support technical activities; and facilitating the training of the technical personnel which represents the irreplaceable component of the decision-making process on such infrastructures.

In order to be accepted in the technical community, novel tools have to satisfy three specific requisites: (i) they should be interoperable and run on widely used platforms for data management and visualization; (ii) they should preserve the central role of technical skills and knowledge of the users; and (iii) they should provide explicit support on technical challenges at tactical, strategic and operational levels, namely on short-, medium-, and long-term perspectives.

Based on such motivations, this work proposes a conceptual framework for the digital transformation in WDNs, which moves from technical-scientific achievements so far and technology advancements in the WDNs sector to provide innovation in the real technical world.

The proposed paradigm for the digital transition in WDN management involves the integration of the WDN DT (Ciliberti *et al.* 2021) with information from data, AI techniques, and methodologies for advanced network topological and hydraulic analyses within 'Digital Water Services' (DWSs). Such services have been developed as 'engineering apps' to support problem-solving on specific technical tasks making the digital transition suitable for technicians and providing a structured framework to translate digital transition into improved technical actions.

The proposed approach is conceived to account for the human component during all phases of the process accounting for the technical expertise on the peculiar infrastructure, the need for progressive improvement of the knowledge base even using digital transition, and the responsibility of taking technical decisions on public infrastructures.

Such a paradigm for the digital transformation in WDN management is demonstrated with the implementation of various DWSs as plugins in the QGIS environment, which share the same data structure of the DT pursuing the interoperability between the most adopted data management platform, i.e., Microsoft Excel and QGIS software.

2. KEY STEPS TOWARD DIGITAL TRANSFORMATION FOR WDN MANAGEMENT

In the 20th century, a significant breakthrough occurred in the field of computer science, marked by an escalating interest in automatic problem-solving that permeated various scientific and industrial domains, including applications in WDNs. CNT studies, advancements in AI, and the emergence of population-based optimization algorithms are the key foundations upon which the latest technological advancements can facilitate digital transformation within the WDN management sector. While it is important to note that these innovations alone do not suffice to encompass the entirety of the digital transition in WDNs, they represent an integral component of the proposed innovation paradigm. This section recalls in brief some key steps in the application of CNT, AI, and population-based optimization algorithms in the WDN sector since an extensive review is out of the scope of this work.

2.1. Complex Network Theory for WDNs

The field of CNT has gained prominence through its application to biological structures and large-scale systems such as the Internet, social networks, and wireless communication networks. In the 1950s, Erdos established the foundations of random graph theory (Erdos 1959), while Watts and Barabási contributed to the understanding of small-world and scale-free network dynamics (Watts 1999; Barabási 2009). Furthermore, advancements in computational complexity theory, the evolution of supercomputers, and the availability of extensive datasets capturing intricate real-world features have revolutionized conventional perspectives on network systems.

The fundamental principles of CNT have provided new insights into the analysis of WDNs viewed as interconnected graphs composed of edges and vertices (e.g., Yazdani & Jeffrey 2011). Such an approach allowed developing numerous methodologies to support various management activities with extensive application in the context of WDNs, including network segmentation analysis (e.g., Giustolisi & Ridolfi 2014), which is essential for optimal district metered area (DMA) design (e.g., Laucelli *et al.* 2017), reliability analysis of isolation valve systems (IVSs) (Giustolisi *et al.* 2022), simulation of hydraulic behavior using standard CNT metrics (e.g., Simone *et al.* 2020), and identification of intrinsic features of WDNs using intrinsic-relevance metrics (Giustolisi *et al.* 2020).

2.2. Population-based optimization strategies for WDNs

The first theorization of population-based strategies was defined by Rechenberg (1978)), while Golberg (1989) and then Holland (1992) established the theory for genetic algorithm (GA), which are search methods based on principles of natural selection and genetics. GA methodologies are inspired by the principles of natural evolution, such as selection, recombination, and diversification, to share properties between optimal solutions, and were widely used to solve complex problems from economics, engineering and management. In the WDN field, several authors applied GAs to minimize the design cost of WDNs (e.g., Savic & Walters 1997; Cunha & Sousa 1999; Vairavamoorthy & Ali 2005). Multi-Objective Genetic Algorithms (MOGAs) have been applied in many contexts including optimal pipe replacement (e.g., Giustolisi & Berardi 2009; Nafi & Kleiner 2010), pump scheduling (e.g., Barán *et al.* 2005), and DMA designs (e.g., Laucelli *et al.* 2017).

2.3. Artificial Intelligence for WDNs

The concept of machine intelligence, as introduced by Turing (Turing 1950), marked the inception of the field of AI and has since become a fundamental aspect of the ongoing digital transformation. Turing's work highlighted the potential to create computers capable of learning from past experiences or data to solve new problems. After that, McCulloch and Pitts introduced the first artificial neural networks (ANNs) (McCulloch & Pitts 1943), which allowed the development of complex information processing systems mirroring biological neural networks of the human brain: the applications of ANN, ML, and deep learning (DL) algorithms enable the heuristic analysis of systems and phenomena, particularly not fully understood or modeled, by extracting information and detecting patterns from data. Several AI algorithms have been implemented for many WDN management purposes, including pipe burst location and detection (e.g., Mounce & Machell 2006; Zhou *et al.* 2019), through the assimilation of past failure events to identify pipes that are more prone to fail, urban water demands forecasting (e.g., Ghiassi *et al.* 2008), leakage detection and localization (e.g., Mashhadi *et al.* 2021).

The concurrent development of ML and optimization strategies gave rise to hybrid techniques to extract knowledge on complex phenomena from data, fostering the integration between purely statistical analyses with symbolic models to be validated and used by engineers for WDN management purposes. This is the case of multi-objective Evolutionary Polynomial Regression (Giustolisi & Savic 2009) used to develop a failure model in WDN pipes (e.g., Berardi *et al.* 2008).

3. DIGITAL TWIN CONCEPT FOR WDNs MANAGEMENT

The DT is a virtual representation of a product, such as an object or a system that comprises its characteristics by means of models, information, and data across multiple life-cycle phases. DT technologies allow representing a 'virtual replica' of a real system, by collecting and analyzing data from the real system, to provide realistic analysis of different decisions within the system, as well as to perform unpredictable scenarios. In industry, DT technologies are applied to increase the efficiency, accuracy of the whole production system and consequently for gaining economic benefits in the production (Negri *et al.* 2017; Tao *et al.* 2019). From such perspectives, the DT is considered the candidate technology for sustaining the digital transformation in various industries (Kritzinger *et al.* 2018).

DT consists of three parts: the physical layer, representing reality, the digital layer, which contains all available information collected from the physical layer, and the connections between the two layers. The connections are represented by data, automatically gathered by sensors, and stored into the database of the water utilities, that flow from the physical layer to the digital layer, and by results and decisions, available from the digital layer to the physical environment.

In the WDN context, the physical layer is represented by the network, its real layout comprising pipes, sources, customer demands, devices (e.g., pumps, IVS, flow, and pressure control valves), and the hydraulic status of the real infrastructure, such as devices controls and technical constraints of the water company. All elements are translated into the digital layer, as a virtual representation of each geometric feature of the network representing the input for the hydraulic model. Therefore, two essential elements to define the DT in the WDN management sector are the digital representation of the WDN infrastructure on GIS and/or BIM, and the hydraulic model to describe the expected system behavior in various operating scenarios. The next sections highlight the essential elements of the GIS/BIM platform for WDN management, the key prerequisites for advanced hydraulic modeling WDN to be used in the WDN DT as well as the necessary feature to pursue interoperability among digital representation and hydraulic modeling.

3.1. GIS and BIM for Digital Twin of WDN

GIS, as well as BIM, stand as the main developing environment for the DT of WDNs: it enables the creation of relations between geographic features of the network, data and results from sensors and hydraulic modeling, the performance of spatial analysis as well as visualization and sharing information.

Indeed, GIS and BIM represent the essential key techniques for managing and analyzing spatial information, thus they represent the bedrock for the development of the rising digital transition of urban planning and the 'smart city' concept (Goyal *et al.* 2020). The advancements of such tools allow the integration of spatial information at different levels and make the full life-cycle operations of buildings and infrastructures, including planning, design, and management, more efficient, rational, and standardized.

In the WDNs sector, GIS software enables the collection, analysis, and visualization of each georeferenced feature of the networks, including the WDN layout, the geometric characteristics of pipes, tanks, and devices, as well as the position of consumers and the related information on tariff and water volume consumptions. GIS platforms can also be integrated within systems to immediately access hydraulic measurement data from distributed sensors over time.

3.2. Prerequisites of hydraulic model in Digital Twin of WDN

The objective of the digital transition is to harness the information inherent to the given system, thereby integrating data from digital technologies, which aims to enhance the efficiency of technical decision-making processes. In contrast to various other industrial sectors, the functioning of WDNs is underpinned by intricate physical processes primarily governed by hydraulic principles. The utilization of a phenomenological model for comprehending this system is imperative for supporting WDN management, driven by two principal rationales. Firstly, the intricate nature of WDN behavior eludes a concise description through a system identification approach founded solely on observed input–output data (Ljiung 1999). As a consequence, the outcomes of the model retain their interpretability and can be verified by users endowed with proficiency in hydraulic engineering. These users are entrusted with decision-making responsibilities and, as such, necessitate a comprehensible and credible model to guide their actions.

Figure 1 illustrates a range of modeling approaches, covering interpretability and associated construction and operation costs. ML models, relying mainly on monitored input–output data, stand out for their cost-effective development and execution. However, they fall into the 'black box' category, lacking user-friendly interpretability. On the other hand, models based on physical principles demand more data for calibration and computational resources. Despite this, they

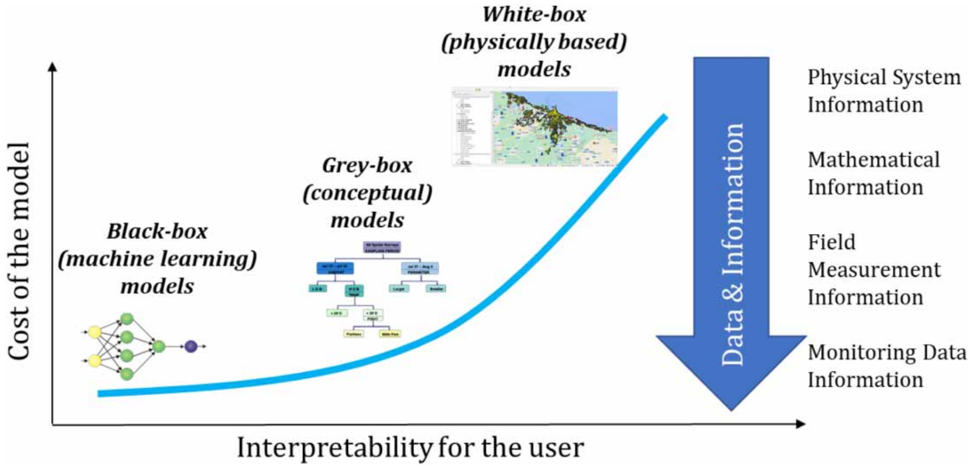

Figure 1 | Modeling of physical systems: interpretability vs. model cost.

offer interpretability and user verification. Between these two extremes lie 'grey models,' accommodating varying levels of conceptualizing physical phenomena while using collected data.

The digital transition provides the unprecedented opportunity to integrate the accurate physically based model of WDN with the data collected from sensors and smart meters.

To accomplish this task, the hydraulic modeling platforms should match some key requirements, reported as follows.

Each outflow from the network should be modeled using a pressure-driven approach (Giustolisi *et al.* 2008), either in terms of consumer demands or physical leakages, which can be comparable.

In particular:

- demand outflow for each consumer should be computed based on pressure and accounting for the specific type of connection (i.e., direct from the network, free orifices, connection through private local tanks, multi-story buildings);
- background and unreported leakages, which amount to the major volumetric effects at an annual scale, should be modeled at a single pipe level as a function of pipe pressure and deterioration.

The hydraulic model within the digital layer of the WDN needs to accurately represent outflow demands at the individual consumer level. This can be achieved by separating the geometric representation of the hydraulic model from the consumer database. Indeed, such separation does not require updating demand data aggregated at model nodes at each change of individual or multiple consumers, and hydraulic results can be accessed at the level of individual connections in addition to classical model nodes.

All kinds of hydraulic devices (i.e., isolation valves, minor head-losses, pressure control valves and pumps) should be modeled consistently with any type of control based on either time scheduling or hydraulic status variables.

The model should be able to dynamically manage the topological variations over time, even due to closing devices during the simulation, without using heuristic rules which can make results far from real system hydraulics.

The advanced hydraulic model should avoid numerical instabilities in the simulation of tank filling (e.g., Giustolisi *et al.* 2014), as they represent a mandatory element for assessing the hydraulic behavior of the systems, as well as reliability in standard and anomalous functioning scenarios. In addition, tanks should be modeled accounting for actual feeding conditions from the top or bottom, without heuristic rules, since they definitively affect the setting of controls and WDN hydraulic behavior.

The advanced hydraulic model embodied in all DWSs is represented by the WDNetGIS-XL platform core (WDNetGIS-XL 2020), which overcomes some limitations of classical modeling package, like those based on EPANET (Rossman 2000).

3.3. Pursuing interoperability in Digital Twin of WDN

One key aspect of DT in WDN management is pursuing complete interoperability across the platforms used for the digital representation of the infrastructure, the hydraulic model and operational databases.

Indeed, digital representation of such systems, e.g., in GIS, was originally conceived to store the asset information on the infrastructure elements on georeferenced platforms mainly to support works and warehouse management. This makes most of the existing representation of WDNs on GIS unsuitable for use in hydraulic modeling, as demonstrated by two main drawbacks: (i) the graphic elements representing pipes are not always connected to each other, leading to the detachment of the network graph at various points and (ii) essential elements for hydraulic modeling, such as isolation valves, control valves, or pumps, are sometimes represented as either isolated points or short pipe elements.

These issues frequently pose challenges in accurately modeling and simulating the hydraulic behavior of the network, as the connectivity and proper representation of these elements are crucial for an accurate analysis.

Therefore, essential prerequisites to foster the development of the DT concept in WDNs are as follows.

The digital representation of the physical elements, using GIS and BIM, should accurately preserve the connectivity of the real system. This means that the graph representation of the digital model should mirror the actual hydraulic connectivity between the elements in the network.

Specifically, these devices should be represented as features of the pipe elements to account for them in the physical equations underlying the hydraulic model. Such an approach prevents the need for introducing ‘small pipes’ or fictitious pipes with ‘null’ lengths close to the nodes of the model. Indeed, such representation has negative impacts on the efficiency of the numerical routines used for simulation.

There should be a one-to-one correspondence between the elements represented in GIS/BIM and those used in the hydraulic model. This means that each physical element, such as pipes, valves, and pumps, should have a corresponding representation in both GIS/BIM and the hydraulic model. This ensures consistency and accuracy in capturing the network’s topology and attributes across both platforms.

Georeferenced customers’ meter information from GIS systems used by water utilities should be explicitly integrated into the hydraulic model. The model should overcome the limitation of aggregating customer demands at model nodes and the information on individual customers should be retrieved from the database of water consumption which can change on an annual or seasonal basis. Such representation enables the hydraulic model to accurately account for the specific demands and connections of each customer (i.e., direct connection, through private tanks, free orifices, multistorey building), which is of direct relevance during WDN operation. Furthermore, such data structure prompts the model to incorporate detailed information on connection type at single customer level, as a future capability of WDN databases.

To enhance the hydraulic model’s accuracy and effectiveness, it is essential to integrate georeferenced meter information on customers from GIS systems collected by water utilities. This integration addresses the limitation of aggregating customer demands at model nodes. By retrieving individual customer information from the water consumption database, which may vary annually or seasonally, the model can account for specific demands and connections of each customer, such as direct connections, private tanks, free orifices, and multistorey buildings. This level of detail is crucial for efficient WDN operations. Moreover, this data structure encourages future capabilities of WDN databases to incorporate detailed information on connection types at the individual customer level.

4. EXPLOITING DIGITAL TWIN FRAMEWORK INTO DIGITAL WATER SERVICES

The digital transition in the WDNs sector presents a unique opportunity to enhance management and planning activities using technological advances for integrating various sources of information.

The paradigm proposed in this work strives to offer tangible products to support technicians who may not be expected to be experts in the technological and methodological advancements discussed earlier. Instead, they have engineering insights and deep knowledge of the specific systems they are working with. The idea is to replicate the user experience commonly found in mobile phone applications where users are not required to have expertise in each process involved but are familiar with its ultimate purpose.

Operators can utilize intuitive tools and interfaces that streamline their tasks, without requiring in-depth knowledge of the underlying processes and algorithms. This empowers a broader range of individuals to effectively engage in WDN management activities, focusing on the knowledge of the peculiar system and exploiting technical skills.

Such a framework has been exploited by a set of dedicated DWSs, which are developed as plugins for the QGIS software platform. These DWSs are completely upgradable and customizable, depending on the technicians and water utilities’ needs, facilitating a seamless exchange of knowledge between researchers/innovators and technicians in the WDN sector.

Each DWS within this framework allows users to import the digital layer of the network, including the hydraulic model and the hydraulic data collected from sensors. With this information, users can conduct specific analyses that merge hydraulic analysis with AI and CNT algorithms. The results are generated and visualized as layers on the QGIS map canvas, while also being stored as ESRI® shapefiles and Excel files.

Such DWSs are designed to support and validate every phase of the WDNs management workflow, encompassing both the strategic and tactical planning horizons.

5. DISCUSSION ON THE PROPOSED APPROACH

The proposed approach provides a structured framework to integrate all the available sources of information keeping the central role of the decision maker. The DT represents the key component to integrate all available information. Therefore, to provide a reliable assessment of alternative actions, the DT should be as accurate as possible.

For this reason, the hydraulic models of WDN within the DT are improved to integrate data from smart meters and distributed pressure and flow sensors, exploiting the novel computing capabilities and the flow of high-quality data coming from digital devices.

From such a perspective this approach clarifies the conceptual distance between accurate models and standard hydraulic models (e.g., based on EPANET) that required oversimplification of the real system, e.g., by lumping consumers' demands and leakages at nodes or not allowing for variable topology during the simulation, to mention just a few.

The proposed approach also meets the limitations of implementing digital transition in real contexts. Indeed, improving the knowledge of real infrastructure systems is a process requiring time for installing devices, collecting, and validating data. Keeping separate DWSs to support different technical decisions is of strategic relevance to assist the progressive improvements of the knowledge base and allow dynamic decision-making processes.

The idea of integrating methodologies from AI, CNT, and optimization to provide task-specific decision support is conceived to valorize the technical skills of the users who are not experts in such algorithms. Indeed, powerful and efficient tools expose technically optimal alternatives that can be easily manipulated and verified by the end-users before decisions.

All previous points pursue the concept of 'sustainable digital transition', which is a process that lets technological improvements walk together with the technical skills of final users, accounting for practical obstacles in implementing the transition on real infrastructures. In such a perspective, the DWSs provide invaluable tools to train technical personnel toward using novel data and computing capabilities while valorizing their expertise. Consequently, DWSs represent a framework to transfer technical know-how among different generations of personnel at water companies.

Unlike the current trend to surrogate the knowledge of the system with massive data collection, the structured information in each DWS supports understanding which data are needed for peculiar technical tasks, also accounting for the technical consistency of the analysis. For instance, collecting consumers' data from smart meters every second or minute might capture the stochasticity or demands as pulses but does not provide useful information for hydraulic modeling, which is based on steady-state modeling assumption (Giustolisi & Walski 2012). This is of preeminent importance to implement effective technology that is to be maintained sustainably.

In a future perspective, the proposed paradigm is expected to further improve the integration of information from different sources (monitored data from sensors; data on water consumption from smart meters, expert knowledge on peculiar WDNs, and advanced hydraulic modeling) aiming at increasing the awareness of decision.

In addition, leaving separate DWSs will motivate further research on task-specific processes as well as on increasingly efficient components of AI, network theory, optimization or advanced hydraulic modeling routines, behind each DWS.

6. DIGITAL WATER SERVICES TO SUPPORT ASSET MANAGEMENT

As a demonstration of the concepts introduced above, this section describes the DWS implemented to support the key management areas in WDNs, as reported in Figure 1. These areas include services for analysing the WDN topological domain by applying some peculiar CNT metrics, performing the hydraulic model calibration and simulating the hydraulic analysis under pressure-dependent conditions (up-left), as functional to build and validate the WDN DT. The DWSs grouped under the IVS analysis and design section focus on assessing the mechanical reliability of WDN by detecting the isolated pipe segments for planned or unexpected pipe interruptions. The analysis of abnormal scenarios due to pipe bursts and subsequent interruptions, as of direct relevance to support operational activities, is supported by DWSs in the bottom left. Finally, various

DWSs have been developed to support asset management in terms of leakage reduction planning by pressure control and District Metering Areas (DMAs) design (tactical horizon), and pipes replacement (strategic horizon). It is worth remembering that such a list can be updated and expanded based on peculiar needs from technical end-users.

All DWSs described herein have been used to support asset management procedures in real operating contexts (Laucelli *et al.* 2023).

6.1. WDN analysis and Model Building

The DWSs grouped into the upper-left box of Figure 2 provide functionalities aimed at calibrating the hydraulic model of the network and evaluating the WDN behavior, both performing the analysis of its topological characteristics and the hydraulic simulation under pressure-dependent conditions.

The *DigitalWaterDomain_Analyzer* service identifies the most relevant pipes/nodes of the WDN from the topological point of view based on WDN-tailored metrics taken from CNT (Giustolisi *et al.* 2020). Such an analysis enables the detection of the hydraulic behavior of WDN without performing the hydraulic simulation, providing insights into the hierarchy of water transmission in the network (Figure 3).

The *DigitalWaterMass_Calibration* service facilitates the calibration of the hydraulic model embedded in the digital layer of WDN. It employs a mass-balance strategy (Berardi *et al.* 2017) based on separating the deterministic component (i.e., volumetric leakages), from the stochastic components of water outflow (i.e., water requests of consumers). It utilizes time series of water inflow, pressure and tank-level data collected over multiple days with different hydraulic functioning, even at a single DMA level. The outcome of the service includes the representation of the hydraulic model of the network and visualizes the calibrated demand patterns. Further analysis involving the estimation of the calibrated DMAs demand patterns can be carried out with the *DigitalWaterDMA_Balance*, which also enables early detection of anomalies based on the comparison between the calibrated model and data collected from sensors.

The *DigitalWater_Analyzer* service performs the hydraulic analysis of the WDN and returns the key data on demand patterns and pressure-dependent leakages at the DMA level; it also provides information on expected flow/velocity patterns at

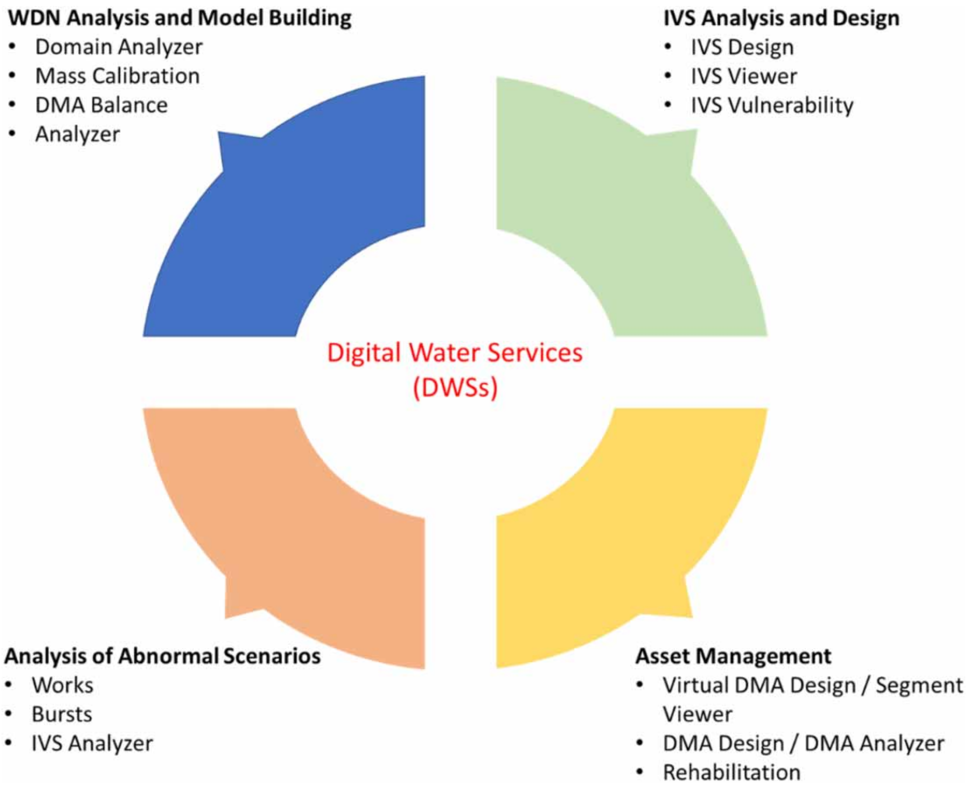

Figure 2 | DWS schematization.

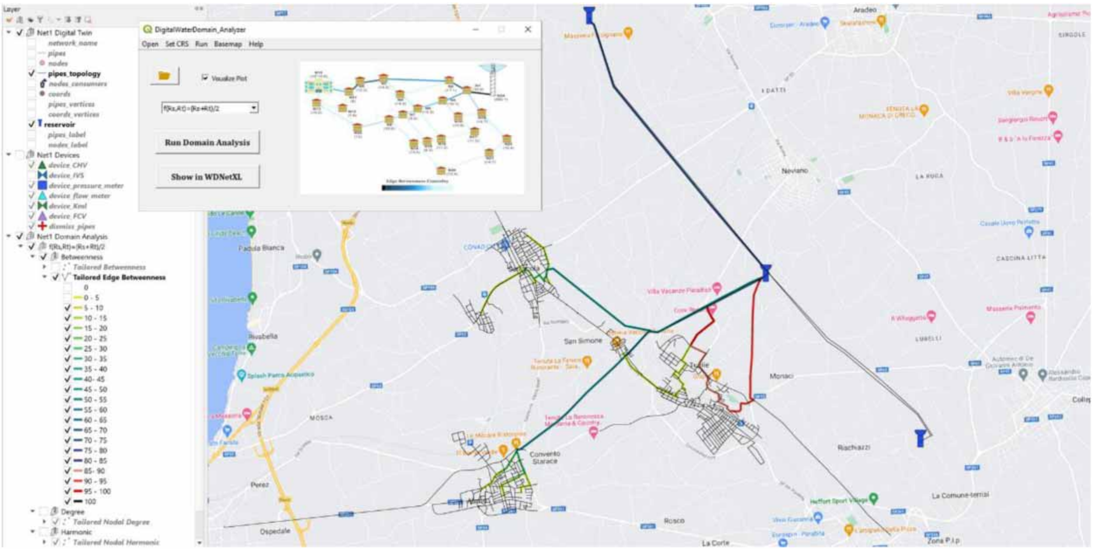

Figure 3 | Visualization of the results of the *DigitalWaterDomain_Analyzer* service.

assumed flow meters, thus enabling decisions based on metrological evaluations (e.g., suggesting removing flow meters where flow inversion is expected) (Figure 4).

6.2. IVS analysis and design

The *DigitalWaterIVS_Design* service allows for performing the optimal IVS design of the network by minimizing the risk of pipe disconnections and unintended isolations (Giustolisi 2020), based on multi-objective evolutionary optimization strategies. It returns a set of IVS solutions, which are visualized on map canvas and stored in the digital layer of WDN (Figure 5). The *DigitalWaterIVS_Viewer* service allows importing and visualizing solutions from previous optimal IVS design runs.

Lastly, the *DigitalWaterIVS_Vulnerability* service applies the IVS reliability strategy proposed by (Giustolisi *et al.* 2022) for mapping the spatial distribution of valves relevance in terms of WDN reliability, based on WDN-tailored CNT metrics, and it

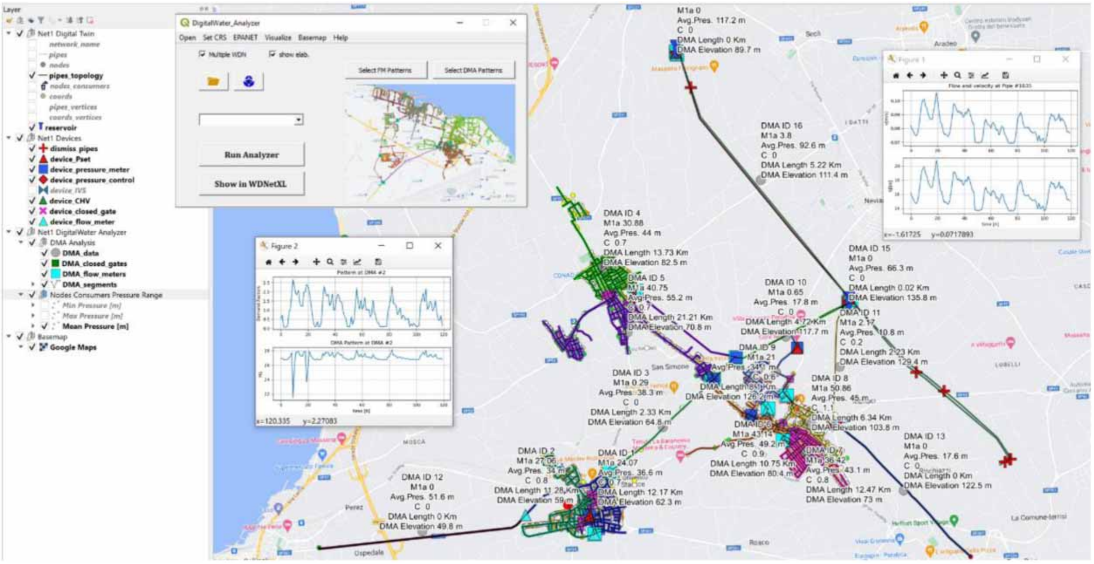

Figure 4 | Visualization of the results of the *DigitalWater_Analyzer* service.

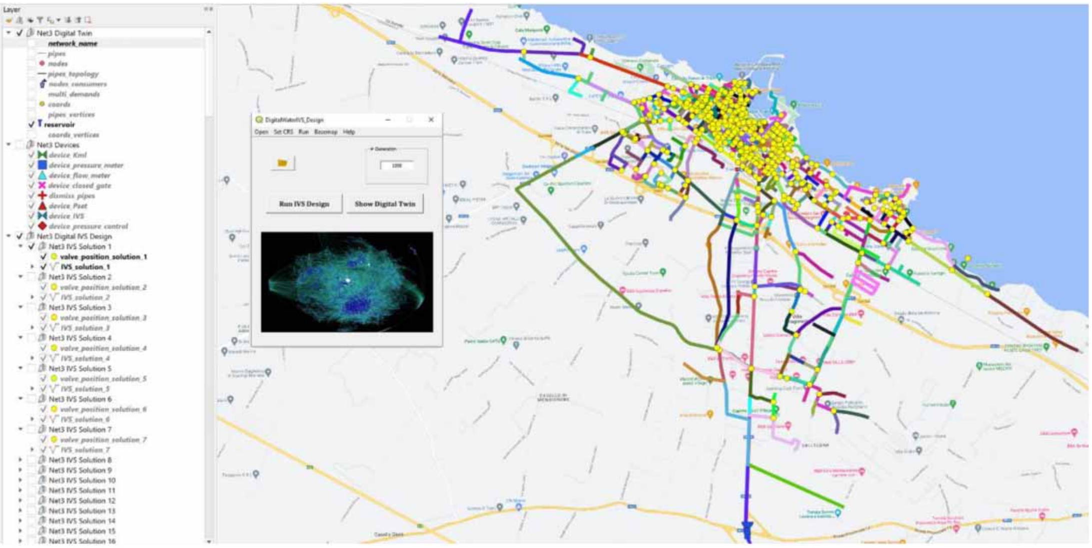

Figure 5 | Visualization of the results of the *DigitalWaterIVS_Design* service.

allows supporting the identification of the most impacting failure scenarios and enabling the WDN management planning for IVS inspections and retraining (Figure 6).

6.3. Analyses of abnormal scenarios

The *DigitalWater_Works* and *DigitalWater_Bursts* services allow simulating the hydraulic behavior of the WDNs when a failure pipe occurs and while isolation valves are closed for maintenance works. *DigitalWater_Works* results report the set of pipes and the customers involved in the failure events, the unsupplied water along the network as an attribute of the water meters of the digital layer.

The *DigitalWater_Bursts* service enables a burst scenario for a pipe to be simulated by defining the geometric parameters of the burst and the type of pipe which is manually selected on the map canvas. It returns the unsupplied demands to each customer (Figure 7). The *DigitalWaterIVS_Analyzer* service allows detection of the portion of the IVS shutdown to allow work on a failed pipe and the valves to be closed (Figure 8).

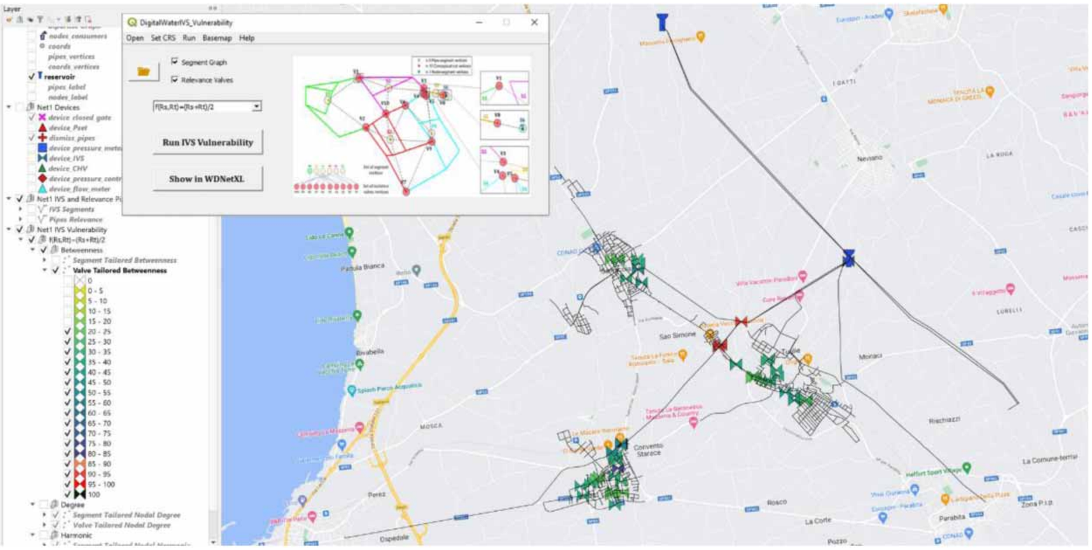

Figure 6 | Visualization of the results of the *DigitalWaterIVS_Vulnerability* service.

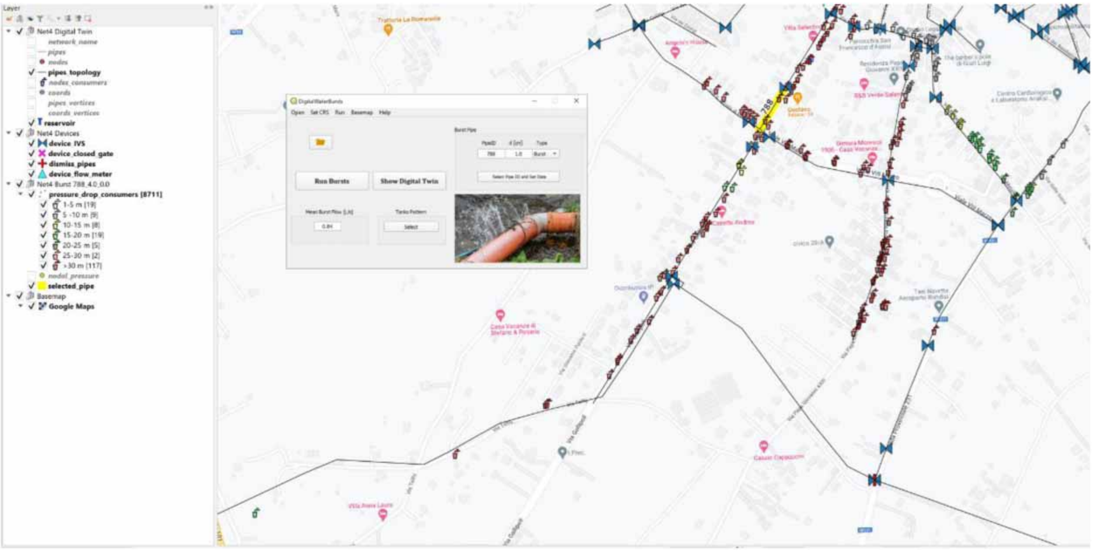

Figure 7 | Visualization of the results of the *DigitalWater_Bursts* service.

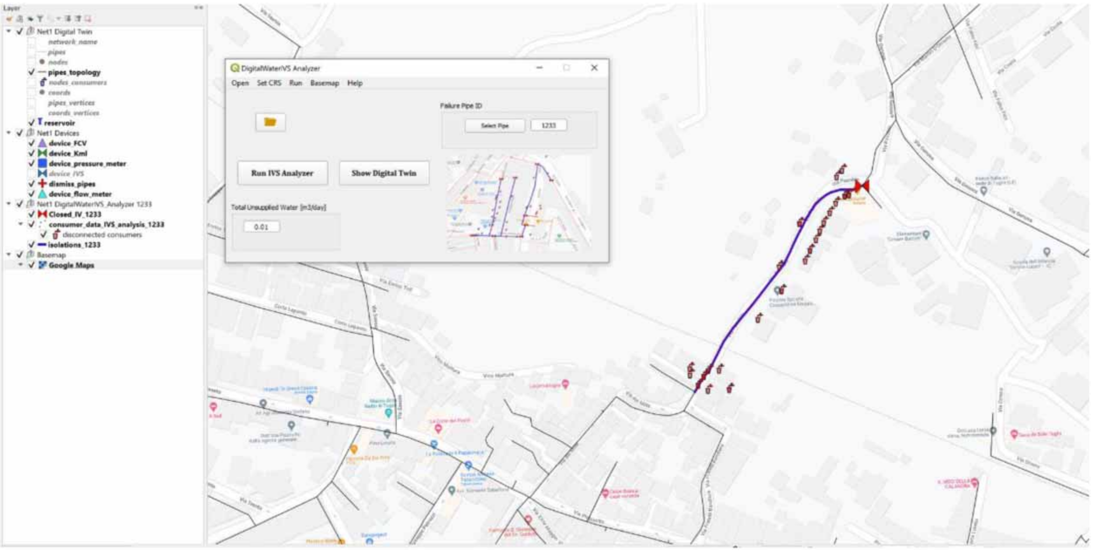

Figure 8 | Visualization of the results of the *DigitalWaterIVS_Analyzer* service.

6.4. Asset management

Asset management is conceived as tactical activities (i.e., DMA design and pressure control) and strategic planning (i.e., pipeline replacement). The DWSs support the two-stage strategy for DMAs design proposed by Laucelli *et al.* (2017). The *DigitalWaterVirtualDMA_Design* service (Figure 9) performs the topological segmentation of the network, formulated as a bi-objective optimization that maximizes the WDNs-tailored infrastructure modularity index (Giustolisi & Ridolfi 2014) and minimizes the number of 'conceptual cuts'. The user can assign the minimum length of each segment and the weight of the modularity index; Pareto fronts of optimal nested solutions of the segmentation are visualized as layers. The *DigitalWaterSegment_Viewer* service allows visualizing previously generated optimal segmentation solutions.

The *DigitalWaterDMA_Design* service performs the hydraulic districtualization, solving a multi-objective optimization to minimize the number of flow meters at the edge of DMAs and optimizing the closed sectioning valves for flow paths

Figure 9 | Visualization of the results of the *DigitalWaterDMA_Design* service.

reconfiguration and leakages reduction, while ensuring sufficient water to consumers. The optimization also includes the optimal setting of pressure control valves for each DMA configuration. Each DMA's configuration is represented by the DMA's layer, which shows the different districts along the network, the closed gates and the flow meter layers.

Moreover, users can customize the solutions provided by the *DigitalWaterDMA_Design* service through *DigitalWaterDMA_Analyzer*, which allows disabling some specific water meters of the solution based on technical-economical constraints.

The *DigitalWaterRehabilitation* service supports the evaluation of pipe replacement plans. Users have the option to manually select pipes to rehabilitate or load an external optimal plan, and then perform the hydraulic simulation which turns out the evaluation of the expected rehabilitation performances in terms of technical requirements and economic constraints, based on the advanced hydraulic solver embedded in the WDNetGIS-XL platform (Figure 10).

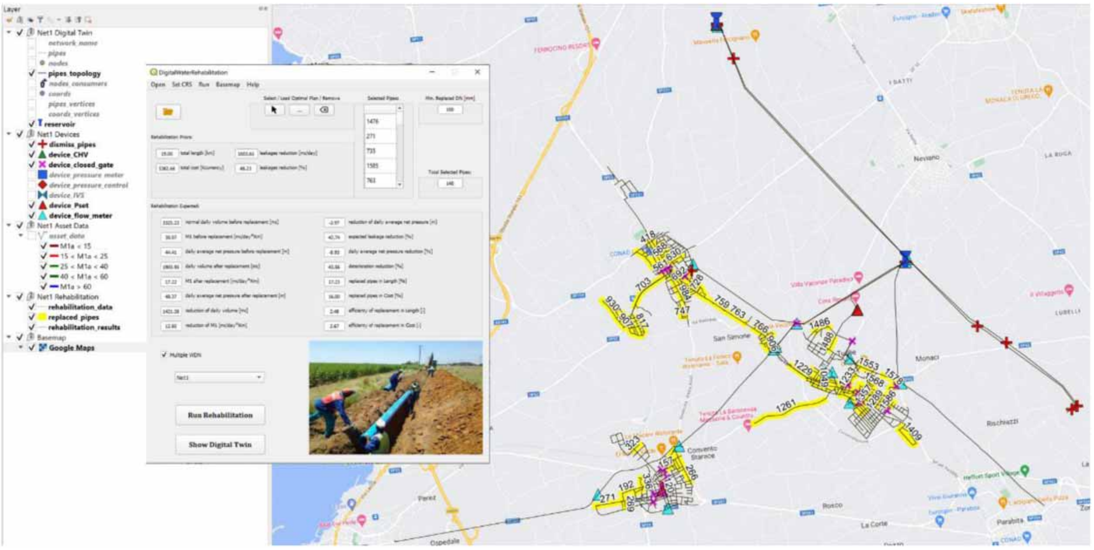

Figure 10 | Visualization of the results of the *DigitalWaterRehabiliation* service.

5. CONCLUSIONS

Technicians and researchers are currently engaged in the development of paradigms and strategies for the digital transition in WDNs. The primary objective is to establish standardized and robust methodologies for the development of DTs tailored to the unique characteristics of these infrastructures. Additionally, there is a focus on creating a framework that integrates physically based hydraulic modeling with the capabilities offered by advanced data-driven analysis techniques, such as AI, ML, and DL (Ramos *et al.* 2023a, 2023b).

This paper, starting from an overview of the significant advancements which led to the digital transition, highlights the potentiality to provide interoperable DWSs for supporting each single task of the WDN management, planning and design workflow. By adopting this paradigm, standardized procedures can be exploited for the continuous updating of the WDN digital layer and for supporting technicians through the development of DWSs, implemented herein as plugins in QGIS software. Such services are aimed at pursuing awareness of technical decisions for enhancing the rationality, replicability, scalability, efficiency, effectiveness, and flexibility from short- to long-term WDN management tasks. The framework is also open to the next technological potentialities and data collection capabilities, preserving the central role of end-user in the technical decisions.

Furthermore, the progressive 'digitalization' of WDNs will offer new perspectives to the water utilities: at the first stage, a unique and complete environment for strategic decision-making between companies, technicians, and customers. Indeed, from the operational point of view, it will represent a framework where different paradigms from AI algorithms and advanced physically based models are merged in order to improve technical solutions and define enhanced decision-support planning, and finally, an education tool for achieving advanced problem-solving skills for the next generation of technicians and engineers.

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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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