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Drinking water supply modelling for Advanced Metering Infrastructures

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ABSTRACT

L'evoluzione della società umana e dei processi produttivi sta accrescendo il fabbisogno idrico mondiale. La risorsa idrica è distribuita in maniera disomogenea e sta subendo una progressiva riduzione a causa dei cambiamenti climatici in atto. La necessità di gestire con maggiore attenzione e di ottimizzare il Sistema idrico integrato rende necessario l'utilizzo di strumenti messi a disposizione da nuove tecnologie che devono collaborare in una gestione multidisciplinare ed integrata. Le attuali normative italiane ed europee sanciscono tale necessità, prescrivendo l'utilizzo di strumenti elettronici specifici per la progettazione e la creazione di database territoriali standardizzati e di facile accesso. L'obbiettivo del progetto di dottorato è lo sviluppo di modellistica idraulica a supporto dei processi gestionali delle reti di distribuzione idropotabile. La modellistica va ad integrarsi nel framework gestionale origAMI, che supporta la gestione operativa, economica e della Workflow Management, attraverso l'integrazione di software idraulico, strumenti previsionali e di Anomaly Detection. In questo lavoro sono state approfondite le azioni ed i criteri necessari alla costruzione dei modelli digitali delle reti di distribuzione, presentando diversi casi applicativi che hanno raggiunto diversi livelli di dettaglio e maturità. Sono approfondite le procedure di stima delle prestazioni mediante indici sintetici e misure surrogate, approfondendo concetti come l'affidabilità e la resilienza delle reti. È inoltre presentato un approccio metodologico che si integra nei modelli di progettazione ed ottimizzazione delle infrastrutture di trasporto della risorsa idrica. Tale approccio permette una modellazione più realistica dell'orografia reale introducendo la possibilità di imporre vincoli territoriali ed idraulici nella ricerca degli schemi progettuali.

The human society and production processes evolution is increasing the world's water needs. The water resource is unevenly distributed and is undergoing a progressive reduction due to the ongoing climate changes. The need to more carefully manage and optimize the integrated water system makes it necessary to use tools made available by new technologies, which must collaborate in multidisciplinary and integrated management. Current Italian and European regulations underline this need, prescribing the use of specific electronic tools for the design and creation of standardized and easy-to-access territorial databases. The goal of the PhD project is the development of hydraulic modelling to support the management processes of drinking water distribution networks. The modelling is integrated into the origAMI management framework, which supports operational, economic and workflow management, through the integration of hydraulic software, forecasting and anomaly detection tools. In this work, the actions and criteria necessary for the construction of digital models of distribution networks have been studied in-depth, presenting various application cases that have reached different levels of detail and maturity. Performance estimation procedures are explored using synthetic indexes and surrogate measures, deepening concepts such as network reliability and resilience. The thesis presents a methodological approach integrated into the design and optimization models of water resource transport infrastructures. This approach allows more realistic modelling of the real orography by introducing the possibility of imposing territorial and hydraulic constraints in the search for design schemes.

INTRODUCTION

The PhD project focuses on the advanced management of drinking water distribution networks (WDN). "*Drinking water supply modelling for Advanced Metering Infrastructures*" (DWSMAMI) is a research project that pursuits the design and integration of innovative modelling in the WDNs management processes. The research activity aims at defining a layered architectural logic model of Advanced Metering Infrastructure (AMI) and designing a Decision Support System (DSS) framework.

The DWSMAMI research field of the project focuses on the study and development of WDN mathematical modelling and the optimization of complex systems. The project supports the integration of modelling in management systems, using the Information and Communications Technology (ICT) tools together with the Advanced Metering Infrastructures (AMI), in a perspective of the Internet of Things (IoT) and Big Data.

The research activities aim at the development of mathematical modelling to support the management phases of water systems, capable of quantifying the drinking water risk associated with the different management conditions and proposing the solution interventions. The DSS aims to guarantee the integration of hydraulic-mathematical models and the use of management tools, smart monitoring, and control interfaces, in the Building Information Modeling (BIM) visual and architectural environment. The framework uses simulation and optimization models; sensors data (over Cloud) management models; a monitoring/alarm dashboard and a remote management cockpit.

The research project for the industrial PhD deals with different thematic areas and trajectories defined by the "*Strategia Nazionale di Specializzazione Intelligente*" [1] (*National Strategy of Intelligent Specialization*) (SNSI). The project is consistent with three thematic areas and five development trajectories:

- Smart and sustainable industry, energy and the environment:
  - Systems and technologies for water and waste treatment;
- Health, nutrition, quality of life:
  - Smart urban mobility systems for logistics and people;
  - Systems for the safety of the urban environment, environmental monitoring and the prevention of critical or risk events;
- Digital Agenda, Smart Communities, Intelligent Mobility Systems:
  - "Embedded" electronic systems, intelligent sensor networks, internet of things;
  - Technologies for smart buildings, energy efficiency, environmental sustainability;
  - Technologies for the diffusion of the Ultra-Broadband connection and the web economy.

The development and sustenance of human settlements rely on various resources and energy transport infrastructures and services. These facilities, defined for their importance as critical infrastructures, include the integrated water service (IWS) that consists of all the infrastructures that abstract raw water, transport, produce drinking water, storage and distribution to the population. The IWS also includes the infrastructures necessary for the wastewater collection, purification and return to the environment. Chapter 1 describes the components of the integrated water service and provides an Italian and European regulatory framework, which describes the authorities and plans responsible for managing the IWS components including the

[1] https://www.agenziacoesione.gov.it/s3-smart-specialisation-strategy/strategia-nazionale-di-specializzazione-intelligente/

WDNs. The chapter provides an in-depth study of hydraulic modelling and the software used in the thesis.

The WDNs have the task of making the water resource available to end-users. The water distribution takes place through a complex network of pipes and devices. Most Italian WDNs are old infrastructures in a bad state of conservation. A large part of the water resource fails to reach end-users being lost along with the network.

The state of the infrastructures is part of a general scenario characterized by various criticalities. Climate change reduces the availability of water while the demographic development and the evolution of production processes change the water needs of the population.

Resource availability and quality degradation require sustainable and conservative management. European and Italian legislation and large international associations support the need for an evolution in management paradigms to reduce consumption and optimize existing systems.

The sustainable management of these infrastructures requires the use of advanced technological and modelling tools. Tools such as DSS allow supporting those involved in infrastructure management, providing advanced analysis tools, decision-making alternatives, sustainability aspects assessment, and environmental impacts.

The DWSMAMI research project integrates and supports the "origAMI" project in the development of an advanced management platform for WDNs managers. OrigAMI is a research and development project financed by the "*Fondo Europeo di Sviluppo Regionale"* (*European Regional Development Fund*) (POR FESR) on the issues identified in the "*Smart Specialization Strategy"* (S3)[2]. The project involves the collaboration of the research institution with business partners for the construction of the management framework. The development involves the construction of the tools (software, interfaces, communication and data collection systems) that make up the management DSS that provides tools for the technical and economic management of the infrastructure. The hydraulic modelling for the simulation of the networks operating regime is integrated with the data collected by the sensors, enabling near-real-time management of the infrastructure. The project is designed for networks equipped with AMI, so it is prepared to manage data from the end-users smart water meters. **Chapter 9** explores the characteristics of the DSS developed for the IWS management and provides a technical and architectural description of the management platform developed within the DWSMAMI and origAMI research project.

Advanced management tools, based on the use of Information Technologies (IT), rely on database management tools containing the AMIs' data and the infrastructures Building Information Model. The integration and use of hydraulic modelling within the developed management framework presupposes the availability of complete and reliable models of the infrastructures. Unlike other sub-services, the digitalization status of WDNs is commonly lacking and inhomogeneous. **Chapter 2** explores the procedures for the creation of a complete and reliable WDN model and defines the minimum amount of information to be achieved for the application of hydraulic modelling. The chapter provides a regulatory framework on the organization of territorial databases for utility networks and the use of Building Information Modelling (BIM) for the design. The data collection and organization procedures presented in **Chapter 2** are applied to build the digital model for four case studies. **Chapter 3** describes the construction of the digital model of the network serving the city of *Rende* (Italy). This network is the experimental site of the origAMI project. **Chapter 4** describes the construction of the digital model of the WDN serving the city of *Serra San Bruno* (Italy), **Chapter 5** describes the model of the network serving the city of *Santarém*

[2] https://www.agenziacoesione.gov.it/s3-smart-specialisation-strategy/

(Portugal) and finally, Chapter 6 describes the model of the network serving the city of *Castel San Giorgio* (Italy).

A framework such as origAMI cannot forbear the use of multidisciplinary management paradigms that integrate modelling and information systems. Other management and optimization models are associated with the hydraulic modelling integrated into the framework (Chapter 1). The legislation and the network managers aim to improve the operational performance of the WDN. The need to assess the performance of the infrastructure has prompted the research to focus on the study and definition of synthetic performance indicators. Chapter 7 describes the research activity relating to this topic. The chapter deepens the concept of "reliability", and how different authors present numerous definitions and methodologies for its assessment. Various applications relating to new performance indices and the application of some commonly used indices are presented. One of the applications involves the *Santarém* network. Upon reaching a sufficient degree of maturity, the study and development of the performance indices will involve the remaining networks models.

The developed modelling does not only support the management phases. Chapter 8 presents a model to support the design of the network. The progressive reduction of the available water resource and the need for optimization presupposes the implementation of targeted optimization interventions. The model presented provides a tool that integrates into resource allocation optimization problems. These engineering problems aim to provide design schemes that best distribute the resource while keeping the construction or modernization works costs low. The developed component allows integrating the real orography and the territorial constraints in the definition of the optimal paths for the construction of the distribution mains.

1 WATER DISTRIBUTION NETWORKS AND HYDRAULIC MODELS

1.0 SUMMARY

1.1 THE INTEGRATED WATER SERVICE

The urban area's development relies on a complex network of services and underground utilities that transfer different types of resources. A city that contains residential homes, commercial and industrial facilities, depends on a set of resources (electricity, gas, water) and services (transport, health services, security services, etc…). The infrastructures that support these services crucial to the society are defined as critical infrastructures (CI). CIs ensure the proper functioning of urban agglomerations and their organizational structure. Damage or malfunctions afflicting CIs have serious repercussions on the involved population. The managerial and organizational complexity is intrinsic in such infrastructures due to the degree of interconnection that exists between them.

The Integrated Water Service (IWS) is classified as a CI. IWS includes the set of regulation devices, elements, and infrastructures relating to the consumption of water resources (raw water abstraction, transport, production of drinking water, storage and distribution; collection of wastewater, transport, purification, possible reuse, or return to the environment of treated wastewater). The infrastructures composing IWS can be schematized into three main groups: collection and transport; distribution, wastewater collection; removal, and return to the environment.

The abstraction to storage infrastructures include the buildings and devices necessary from resource abstraction to the storage, and the latter delivers the drinking water to the distribution infrastructures. The water resource is unevenly available in the territories in different types of sources. The abstraction can take place in surface water bodies, deep aquifers, natural springs, and, in some cases, the sea. Depending on the source type, the water requires chemical and/or physical treatments to make it suitable for human consumption (water purification). A series of storage structures and a network of pipes make the resource available to the end-users of urban centres. Networks of water mains are commonly built to ensure the distribution of water over large areas.

Drinking water, available for consumption, requires an infrastructure that allows extensive distribution to domestic, public, commercial, and industrial users. The network of pipes, tanks, and valves that allows water distribution is defined as a Water Distribution Network (WDN). WDNs are very complex infrastructures as they contain a large number of regulation devices and kilometres of pipes located in the cities underground. Two groups of components are commonly distinguished in WDNs: a network of main pipes, necessary for the transport of water across the territory, and a set of secondary pipes necessary for extensive distribution to all users and services.

The water withdrawn for daily activities is not completely consumed or lost to the environment. Most of the water, no longer drinkable, must be disposed. It is necessary to collect wastewater and rainwater from urban areas and convey it to the collection systems and treatment plants. The purified water must be returned to the environment with characteristics that do not negatively affect the ecosystems. If the economic conditions apply, it is useful to set the purification process to make the treated water compatible with agricultural or industrial reuse, improving the overall water balance.

1.1.1 EUROPEAN REGULATORY FRAMEWORK

The Italian and European legislation regulates the integrated management of water abstraction, distribution, and recovery. The European Community, on the subject of sustainable management of water resources, has issued a framework policy through *Directive 2000/60/EC (Directive of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy)*. The directive acts as a framework and it is associated with specific IWS directives:

- *Council Directive 91/271 /EEC, concerning urban waste water treatment* (21/05/1991).
- *Council Directive 2006/7/EC concerning the management of bathing water quality* (15/02/2006).
- *Council Directive 2007/60/EC on the assessment and management of flood risks* (23/10/ 2007).
- *Council Directive IVE 2013/59/EURATOM laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation* (5/12/2013).
- *Council Directive 2020/2184/EC on the quality of water intended for human consumption* (16/12/2020).

2000/60/EC is known as the *Water Framework Directive* (WFD). The legislation introduces an organic approach to the IWS management and emphasizes the need to protect aquatic ecosystems and ensure quantitative and qualitative conservation of surface and deep-water bodies. The Directive establishes that the individual Member States must organize water protection management at river *basin district* level. A *basin district* is an area that includes one or more neighbouring drainage basins (or watersheds). The management of each district concerns the surface waters, the aquifers, and the coastal areas falling within it. The activities of the basin districts must be codified within a management plan. The management objectives include the state of ecosystem maintenance and improvement.

In 2012 the European community adopted *"A Blueprint to Safeguard Europe's Water Resources" (COM/2012/0673 final)*. The plan is developed from the collaboration of a large number of stakeholders (citizens, infrastructure managers, representatives of member states, and EU bodies). The directive deepens many aspects introduced with the *2000/60/EC*. It is necessary to quantify the available water resources and define their current status. The blueprint underlines the need to reduce resource consumption improving resource extraction and distribution management. The consumption reduction should also take place through awareness campaigns that disseminate good usage practices among citizens and through the use of appropriate pricing. The distribution of drinking water is a service and an adequate rate should cover the infrastructure maintenance costs and prevent waste.

The recent directive *2020/2184/EC* defines quality standards and general obligations regarding water for human consumption. The directive has the objective of safeguarding health from the negative effects resulting from contaminated water consumption. *2020/2184/EC* replaces the previous *Council Directive 98/83/EC on the quality of water intended for human consumption* (3/11/1998). It updates the quality standards of drinking water (chemical and microbiological), approaching the health risk assessment throughout the supply chain.

1.1.2 Italian regulatory framework

In Italy, the first legislation regarding water protection dates back to 1976 (Law No. 319, *Norme per la tutela delle acque dall'inquinamento*, *Rules for the water protection from pollution*). The law has undergone several changes and adjustments over time. In 1989, Law 183/1989 *Difesa del* *suolo e sulla tutela e sull'uso razionale delle risorse idriche* (*Soil defense in the protection and rational use of water resources*) was introduced.

Art. 1: "La presente legge ha per scopo di assicurare la difesa del suolo, il risanamento delle acque, la fruizione e la gestione del patrimonio idrico per gli usi di razionale sviluppo economico e sociale, la tutela degli aspetti ambientali ad essi connessi"

Art. 1: "The purpose of this law is to ensure the soil defence, water rehabilitation, the use and management of the water assets for rational economic and social development, the environmental aspects connected to their protection."

As defined by the first article, the law aims to ensure water reclamation, rational management of the resource that guarantees economic and social development. The law introduces an organic management view which links physical, quantitative, and qualitative aspects of water resources. The water resources management is organized in "*Bacini Idrografici" (drainage basins or watersheds).* The management of aspects relating to safeguarding and management is assigned to the "*Autorità Di Bacino" (Basin Authorities)*. The basin authorities plan the management and protection actions in the "*Piani di bacino"* (basin plans).

Law N.36 "*Disposizioni in materia di risorse idriche*" (Regulation on water resources)(5/01/1994) replaces and integrates the previous legislation on water management and protection. The law defines the protection objectives and the resource use scopes. Water protection must guarantee resource conservation and availability. Human consumption takes priority over other uses. The law defines the state competencies and outlines the management criteria for the "*Servizio Idrico Integrato*" (SII)(Integrated Water Service, IWS). SII management includes all aspects regarding water abstraction, transport, distribution, purification, eventual reuse, and return to the environment. It is envisaged the production of "*Piani d'Ambito*"(*Scope plans*). These plans define the investment planning over time and interventions necessary to support and adapt the service levels, the definition of an adequate rate that covers the infrastructure management costs. The scope plans production is entrusted to the "*Ambiti Territoriali Ottimali*"(*Optimal Territorial Areas*)(ATO). The Provinces and Municipalities keep the service ownership, while the operational management is entrusted through a tender. Management can be entrusted to municipal special companies, private concessionaires, or mixed public/private companies.

In 1999 it is issued the Legislative Decree No.*152, "Disposizioni sulla tutela delle acque dall'inquinamento e recepimento della direttiva 91/271/CEE concernente il trattamento delle acque reflue urbane e della direttiva 91/676/CEE relativa alla protezione delle acque dall'inquinamento provocato dai nitrati provenienti da fonti agricole.*" (*Regulation water protection from pollution and implementation of Directive 91/271 /EEC concerning the treatment of urban wastewater and of Directive 91/676 / EEC relating the water protection from pollution caused by nitrates from agricultural sources.*) (11/05/1999).

The decree integrates Law No. 36 regulating the surface, deep, and marine waters protection. It defines actions to prevent and reduce pollution and to implement rehabilitation actions for polluted water bodies. The decree pursues sustainable and conservative water resources use prioritizing human consumption. Management actions must guarantee the maintenance of the natural self-purification capacity of water bodies and support the maintenance of biodiversity. In the SII management, the objectives of sustainability and conservation must correspond to actions to improve the efficiency of water distribution, sewerage, and treatment.

In 2006 it is issued the Legislative Decree n. 152 "*Testo unico ambientale*"(Overall environmental document)(3/04/ 2006). The document reforms national legislation on environmental issues. The text consists of six parts, which then became eight in subsequent expansions. The IWS managing regulation are contained in the third part: "*Norme in materia di difesa del suolo e lotta alla desertificazione, di tutela delle acque dall'inquinamento e di gestione delle risorse idriche*"(*Rules on soil protection and fight against desertification, water pollution protection and water resources management*). Article 141 of the consolidated environmental text defines the SII as:

"Il servizio idrico integrato è costituito dall'insieme dei servizi pubblici di captazione, adduzione e distribuzione di acqua ad usi civili di fognatura e di depurazione delle acque reflue, e deve essere gestito secondo principi di efficienza, efficacia ed economicità […]"

"*The integrated water service consists of the set of public services for the abstraction, transport, and distribution and sewerage and wastewater depuration, and must be managed according to principles of efficiency, effectiveness and cost-effectiveness* [...]"

The coordination of planning and management previously entrusted to the *Basin Authority* (*Law No. 183/89*), passes to the "*Autorità di Distretto*" (*District Authorities*) as defined in *Directive 2000/60 / EC*. The *Basin Authorities* must draft the "*Piani di gestione dei distretti* "(*Water district plans*) to achieve the objectives of quality and efficiency indicated in the European framework legislation.

1.2 WATER DISTRIBUTION NETWORKS

Water distribution networks (WDNs) are one of the IWS components. WDNs refer to the system of pipes, tanks, and managing devices necessary to distribute the water resource to end-users. The design of the distribution networks involves meeting the water needs of an urban area while respecting criteria of minimum cost and good reliability.

The realization of a WDN foresees that the infrastructure will satisfy the needs of the users for a long period. The design takes into account the cities development and the possible demand rise due to population growth and socioeconomic changes. The network consumption assessment needs end-users characterization. A WDN serves public and private, commercial, industrial, and touristic buildings and facilities. The consumption characterization includes management and emergency services as well as a non-avoidable share of systematic losses.

The WDN manager must ensure that the network satisfies the water requirements of the users, also guaranteeing the quality of the resource. Maintaining a degree of efficiency involves scheduling ordinary predictive maintenance, improvement interventions as well as managing emergencies and extraordinary corrective maintenance.

Optimized management requires detailed knowledge of the individual components, and the operating regime. The *District Management Plans*, defined by Legislative Decree No. 152, include the organization of infrastructures surveying actions, and the production of detailed maps. The use of hydraulic modelling is part of good WDN management practices. The modelling allows deepening the knowledge of the operating regime of the networks and make available a large amount of system information.

1.2.1 WDN HYDRAULIC MODELLING

A drinking water distribution network is a complex infrastructure consisting of a set of elements and devices that distribute water from the storage sites to end-users. It is necessary to define a simple and effective criterion to represent WDN elements. The physical components composing a network can be organized into two groups: node elements (points) and link elements (lines). A graph formalization is suitable for WDNs, Figure 1.2.1. In scientific literature, networks are commonly represented by graphs (Capano et al 2019, Hajebi et al 2015, Di Nardo et al 2018, Herrera et al 2016, and many others). This schematization can be found in the current legislation (European *INSPIRE* and the Italian "*Obbligatorietà SINFI*") detailed in **Chapter 2**.

A network can therefore be represented by a graph:

$$G = (\boldsymbol{N}, \boldsymbol{L}) \qquad \text{Eq. 1.2.1}$$

In which:

- G Network graph.
- N List of graph vertices, node elements.
- L List of graph edges, link elements, connecting the network nodes.

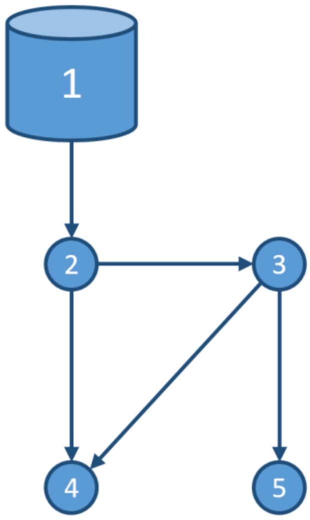

Figure 1.2.1 Graph schematization from a WDN containing a tank and 4 junction nodes.

A globally accepted schematization in WDN representation is proposed in Rossman (2000) and Rossman et al (2020) and implemented in EPANET. EPANET is a software developed by the USEPA (*United States Environmental Protection Agency*). It is one of the most popular software in WDN hydraulic simulation.

The software schematizes a network distinguishing between physical and non-physical components, Figure 1.2.2. The first category includes all the elements corresponding to physical network elements (pipes, valves, tanks, etc.). Non-physical elements consist of a set of curves and information that define the physical elements functioning regime or describe the temporal variability of attributes (characteristic curves of the pumps, volume curves of the tanks, variation patterns). For the physical components, EPANET uses a graph schematization that distinguishes between nodes and links, Figure 1.2.3.

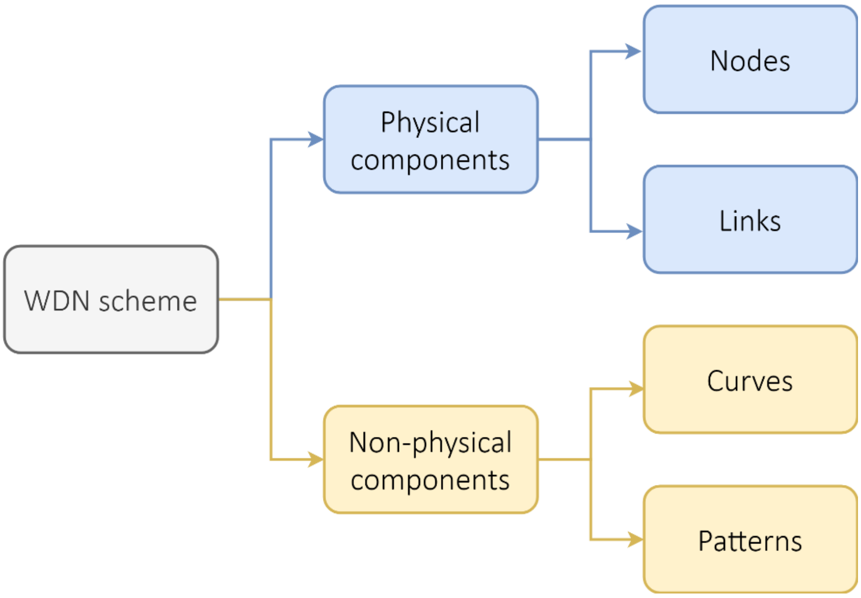

Figure 1.2.2 EPANET model components classification.

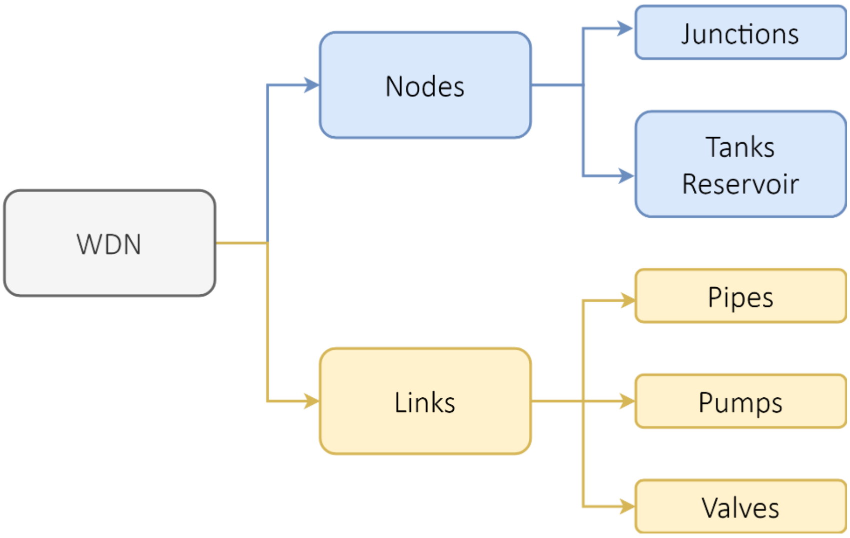

Figure 1.2.3 EPANET physical components classification.

The nodes represent the set of point elements. The category distinguishes the accumulation nodes and the junction nodes. The junctions are the connection nodes, without storage capacity. EPANET assigns the water demand to the junctions. Storage nodes are tanks and reservoirs. The first schematize a defined volume tank, the latter a tank with known head and infinite volume. The links represent the set of line elements, which connect the nodes. The links include pipes, pumps, and regulation devices (valves). The formalization expressed in Eq. 1.2.1 can be updated to differentiate the subcategories of nodes and links presented in Rossman (2000) and Rossman et al (2020).

$$G = (\boldsymbol{N}, \boldsymbol{L})$$
$$\boldsymbol{N} = \boldsymbol{J} \cup \boldsymbol{R} \qquad \text{Eq. 1.2.2}$$
$$\boldsymbol{L} = \boldsymbol{C} \cup \boldsymbol{P} \cup \boldsymbol{V}$$

- $\boldsymbol{N}$ List of graph vertices (WDN nodes), obtained as the union of the junctions set $\boldsymbol{J}$ and the reservoirs and tanks set $\boldsymbol{R}$.
- $\boldsymbol{L}$ List of graph edges (WDN links), obtained as the union of the pipes set $\boldsymbol{C}$, the pumps set $\boldsymbol{R}$ and the valves set $\boldsymbol{V}$.

The set of links and nodes formalized in Eq. 1.2.2 count respectively a fixed number of elements:

$$\boldsymbol{J} = \{j = 1, \dots, J\};$$
$$\boldsymbol{R} = \{j = 1, \dots, R\};$$
$$\boldsymbol{N} = \{j = 1, \dots, R + J\}; \qquad \text{Eq. 1.2.3}$$
$$\boldsymbol{L} = \{i = 1, \dots, L\};$$

The hydraulic models allow simulating the physical phenomena that govern the motion of the liquid flowing in the network. The model goal is to determine the network elements operating regime: flow, velocity, and head losses along the pipes; junctions pressure and piezometric head; water level and volume stored in the tanks. The water motion within a network is governed by a system of equations. At the links, the energy equations express the hydraulic head losses in the pipes. At the nodes, the continuity equations express the mass balance in the junctions.

Equations of motion

The passage of water in a pipe is governed by a pressure gradient. The water movement inside a pipe causes head loss. The energy equation for a pipe connecting nodes i and j is:

$$h_i - h_j = \Delta h_{ij} = K_{ij} \frac{{q_{ij}}^m}{{D_{ij}}^n} + k_{ij}^{loc} \left(\frac{{v_{ij}}^2}{2g} \right) \quad \text{Eq. 1.2.4}$$

- h_i upstream piezometric head, node i;
- h_j downstream piezometric head, node j;
- q_{ij} flow along the pipe;
- Δh_{ij} head loss along the pipe;
- K_{ij} resistance coefficient;
- D_{ij} pipe diameter;
- k_{ij}^{loc} minor head losses coefficient;
- v_{ij} flow average velocity;
- g gravity

Using a compact formulation, the pipe head loss can be expressed as a function of the flow using the hydraulic resistance:

$$\Delta h_{ij} = R_{ij} {q_{ij}}^m + R_{ij}^{loc} {q_{ij}}^2 \quad \text{Eq. 1.2.5}$$

- R_{ij} hydraulic resistance;
- R_{ij}^{loc} minor head losses resistance coefficient.

There are L energy equations associated with the entire network. It is possible to write Eq. 1.2.5 using a notation that uses the network incidence matrix. A graph incidence matrix counts L rows and N columns. The element construction comply with the criterion:

$$a_{ij} = \begin{cases} +1 & if\ the\ k^{st}\ link\ enters\ to\ the\ i^{th}\ node \\ -1 & if\ the\ k^{st}\ link\ exit\ from\ the\ i^{th}\ node \\ 0 & otherwise \end{cases} \quad \text{Eq. 1.2.6}$$

Each matrix row refers to a link. For a link i the elements a_{ij}, according to the definition in Eq. 1.2.6, is a coefficient that has a value of -1 at the link starting node, +1 at the link ending node, and zeroes otherwise. In a WDN, links represent pipes. Water moves by gravity from nodes with a greater hydraulic head to nodes with a lower hydraulic head.

Nodes Pipes	1	2	3	4	5
1-2	-1	1	0	0	0
2-3	0	-1	1	0	0
2-4	0	-1	0	1	0
3-4	0	0	-1	1	0
3-5	0	0	-1	0	1

Table 1.2.1 Incidence matrix of the Figure 1.2.1 network.

Figure 1.2.1 shows the graph associated with a network made up of 5 nodes and 5 links. Table 1.2.1 reports the network incidence matrix. The first matrix row represents the pipe connecting the tank node (1) with the first junction (2). The head difference between the tank and the junction can be expressed as:

$$\Delta h_{12} = -a_{11}h_1 - a_{12}h_2 \qquad \text{Eq. 1.2.7}$$

Eq. 1.2.5 can include the elements of the incidence matrix:

$$\sum_{j=1}^{N}(-a_{ij}\,)h_j = R_i {q_i}^m + R_i^{loc} {q_i}^2 \qquad \text{Eq. 1.2.8}$$

$$i = 1, \dots, L.$$

The set of L equations formulated as in Eq. 1.2.8 express the piezometric head loss associated with the L pipes. The term representing the hydraulic resistance depends on the chosen resistance law (head loss formula). The hydraulic resistance can be assessed by formulas that can be expressed as presented in Eq. 1.2.9. This formula expresses the head loss as a function of the hydraulic resistance coefficient, which depends on the pipes' geometric characteristics (diameter and length) and a roughness coefficient. The minor head losses, also known as local head losses, are caused by the turbulence following curves, joints, and special devices. The minor head losses hydraulic resistance depends on the type and number of bends and devices in the pipe. In modelling, the minor head losses are commonly considered negligible or can be expressed as a hydraulic resistance increase.

Hydraulic resistance coefficient

In the resistance formulas it is possible to express the head losses as the product of a term that depends on the pipe characteristics and a power function of the flow:

$$\Delta h = Rq^m \qquad \text{Eq. 1.2.9}$$

- Δh head loss along the pipe [m];
- R hydraulic resistance coefficient;
- q flow [m^3/s];
- m flow exponent.

The Hazen-Williams resistance coefficient:

$$R_{HW} = \left(\frac{C_f l}{C^m D^{4.87}}\right) \qquad \text{Eq. 1.2.10}$$
$$m = 1.852$$

- l Pipe length [m];
- D pipe diameter [m];
- C_f unit conversion factor (10.68 for SI);
- C Hazen-Williams roughness coefficient.

The Manning resistance coefficient:

$$R_M = \left(\frac{C_f \, l \, n^m}{D^{5.33}}\right) \qquad \text{Eq. 1.2.11}$$
$$m = 2$$

- C_f unit conversion factor (10.3 for SI);
- n Manning's roughness;

The Darcy-Weisbach resistance coefficient:

$$R_M = \left(\frac{8 \, f \, l}{g \, \pi^2 D^5}\right) \qquad \text{Eq. 1.2.12}$$
$$m = 2$$

- f Darcy-Weisbach friction factor.

Continuity equations

The continuity equation represents the water balance at the nodes. For each network node j:

$$\sum_{j=1}^{N} q_{ij} - \sum_{j=1}^{N} q_{ji} + \Delta W_j = d_j \qquad \text{Eq. 1.2.13}$$
$$j = 1, \dots, R + J$$

- d_j nodal water demand;
- ΔW_j node stored volume variation;

Eq. 1.2.13 sets the incoming flows positive and the outgoing flows negative . The first two terms represent respectively the pipes incoming and the outgoing flows. The node water demand has a positive value. The junction nodes cannot store water.

It is possible to write the continuity equations associated with the N (R+J) network nodes using the incidence matrix. For a node j (column), the corresponding row elements that refer to incoming pipes have $a_{ij} = +1$, those corresponding to outgoing pipes have $a_{ij} = -1$.

For a junction j:

$$\sum_{i=1}^{L} a_{ij} q_i - d_j = 0 \qquad \text{Eq. 1.2.14}$$
$$j = 1, \dots, J.$$

The network system of equations can therefore be written as:

$$\begin{cases} \sum_{j=1}^{N} (-a_{ij}) h_j = R_i {q_i}^m & i = 1, \dots, L. \\ \sum_{i=1}^{L} a_{ij} q_i - d_j = 0 & j = 1, \dots, J. \end{cases} \qquad \text{Eq. 1.2.15}$$

The system has $L + J$ equations. The system is linear for the hydraulic heads but non-linear for the pipe flows, whose exponent, depends on the resistance law chosen.

For pumps, the system must include the equations expressing the associated head loss (obviously negative). For a pump connecting nodes i and j:

$$\Delta\, h_{ij} = -\omega^2 \left(h_{so} - c \left(\frac{q_{ij}}{\omega} \right)^n \right) \qquad \text{Eq. 1.2.16}$$

- h_{so} shutoff head for the pump;
- c pump curve coefficient;
- n pump curve exponent;
- ω relative speed setting.

Using the formulation with the incidence matrix, the pump equations associated with the P network pumps become:

$$\sum_{j=1}^{N} -a_{ij} h_j = -{\omega_i}^2 \left(h_i^{so} - c_i \left(\frac{q_i}{\omega_i} \right)^{n_i} \right) \qquad i = 1, \dots, P \qquad \text{Eq. 1.2.17}$$

A WDN commonly contains a series of devices for flow and pressure management and control. There are various types of pressure control valves. A common type of valve is the Pressure Reduction Valve. This type of valve imposes a localized pressure drop. Valves commonly modify the motion equation of the corresponding link.

Demand-Driven Analysis and Pressure-Driven Analysis

The system of equations formalized in Eq. 1.2.15 is based on an implicit hypothesis that characterizes most of the classical solution models. The system solution provides the network operating regime that guarantees the assigned water demand satisfaction. In the literature, the modelling approaches in which the algorithm identifies an operating regime that fully satisfies the nodal water demand are classified as Demand-Driven Analysis (DDA). Pressure Driven Analysis (PDA) models foresee the possibility that, in the event of pressure deficit conditions, the supply can be lower than the actual demand. EPANET 2 (Rossman 2000) is based on a DDA approach. EPANET uses the nodal drinking water demand as a network model input. The most recent version of EPANET (Rossman *et al*. 2020) and other software such as WaterNetGEN use the PDA approach. WaterNetGEN is a stand-alone extension of EPANET, presented in Muranho *et al*. (2012,2014). The software integrates the modelling potential of EPANET and provides a series of advanced tools for the analysis and generation of synthetic WDNs.

The main weakness of the DDA is found in the modelling of networks characterized by a low-pressure operating regime, or in the modelling of networks in critical scenarios (pipe break, fire fighting, and peak demand). PDAs modify the system in Eq. 1.2.15 by adding an equation that describes the pressure-demand relationship and allow to estimate the flow rate supplied to users in the event of low pressure. For a junction i:

$$q_i^{avl} = q_i^{ser} \begin{cases} 1 & \hbar_i \geq \hbar_i^{ser} \\ \left(\dfrac{\hbar_i - \hbar_i^{min}}{\hbar_i^{ref} - \hbar_i^{min}} \right)^{\frac{1}{\alpha}} & \hbar_i^{min} < \hbar_i < \hbar_i^{ser} \\ 0 & \hbar_i \leq \hbar_i^{min} \end{cases} \quad \text{Eq. 1.2.18}$$

In which:

- q_i^{avl} nodal available flow;
- $\hbar_i$ nodal pressure;
- q_i^{ser} nodal water demand;
- $\hbar_i^{min}$ minimum pressure below which there is no supply in the i^{th} node;
- $\hbar_i^{serv}$ service pressure (necessary to fully satisfy the demand) in the i^{th} node;
- $1/\alpha$ exponent of the pressure-demand relationship.

WaterNetGEN solver (Muranho *et al*. 2012,2014) and the new version of EPANET (Rossman *et al*. 2020) use the equation presented by Wagner *et al*. (1988), Eq. 1.2.18. The equation introduces two pressure thresholds and provides three possible operating scenarios, Figure 1.2.4.

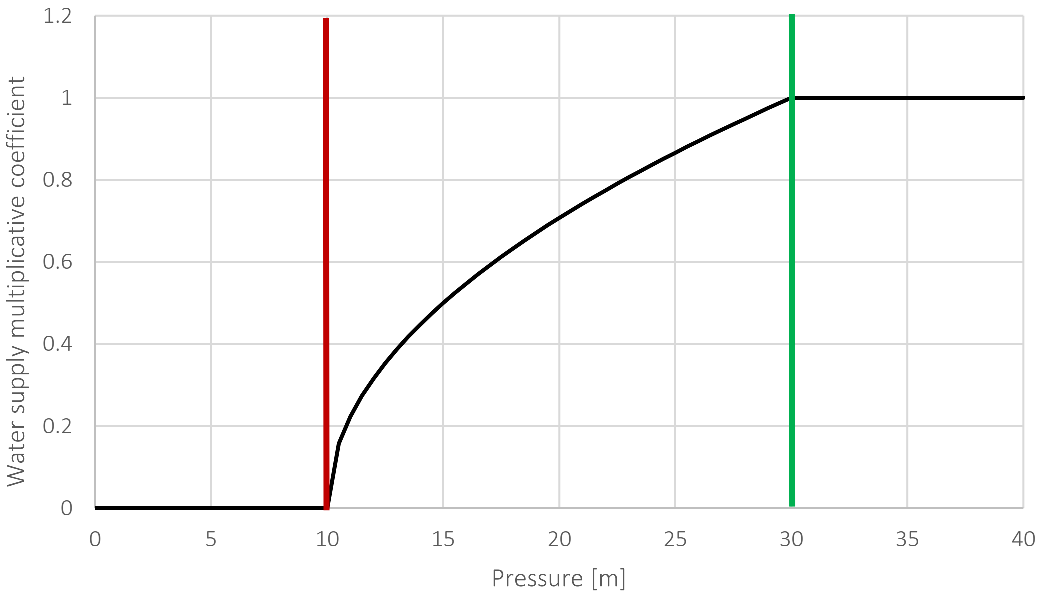

Figure 1.2.4 Pressur-demand relationship. $\boldsymbol{\hbar_i^{min} = 10m}$, $\boldsymbol{\hbar_i^{serv} = 30m}$, $\boldsymbol{\alpha = 2}$.

For a junction where the pressure (or hydraulic head) is below the minimum threshold, $\hbar_i^{min}$ there is no supply. If the pressure exceeds the service pressure threshold ($\hbar_i^{serv}$) the junction fully satisfy the demand. In intermediate conditions, the partialized supply follows the Wagner equation. The pressure-demand relationship exponent can assume values ranging from 1.5 to 2. Wagner *et al*. (1988) and Rossman (2000) suggest that $\alpha = 2$.

1.2.2 Hydraulic solution models

Given the motion equations' non-linearity in the system defined in Eq. 1.2.15, many solution algorithms use linear approximations of the original equations, determining the solution through iterative procedures. Todini and Rossman (2013) study the performance and the degree of convergence of the main solution models available in the scientific literature.

The authors classify the solution algorithms into two categories. Simplified approaches, in which the algorithm solves one equation at a time, and algorithms that simultaneously solve the entire system of equations. The Hardy-Cross method falls into the first category (Cross, 1936, Hoag and Weinberg, 1957). The method uses an approximate iterative solution. The solution method is noteworthy as it allows the resolution of systems associated with small networks without the use of automatic calculation methods, despite having poor applicability due to convergence problems.

The methods that simultaneously solve the entire system can be further categorized into methods based on linear theory or the Newton-Raphson linearization approach. The solution algorithms proposed by Wood and Charles (1972), Isaacs and Mills (1980) are based on the linear theory method. The solution algorithms presented in Wood and Rayes (1981), Martin and Peters (1963), and Todini and Pilati (1988) are based on the Newton-Raphson linearization approach.

The solver used in EPANET is the Global Gradient Algorithm - GGA (Todini and Pilati 1988). The GGA linearizes the equations with an iterative Newton-Raphson scheme. The solving procedure is structured in two steps for each iteration. The first step solves a sparse system of equations to derive the nodal heads. The second step updates the flow rates in the pipes. The GGA can be extended to PDA resolution by including Wagner's equation in the resolution algorithm (Giustolisi *et al*. 2008, Todini 2008, Muranho *et al*. 2014, Rossman *et al*. 2020).

1.3 BIBLIOGRAPHY

- Capano, G., Bonora, M. A., Carini, M., & Maiolo, M. (2019, June). Identification of Contamination Potential Source (ICPS): a topological approach for the optimal recognition of sensitive nodes in a water distribution network. In International Conference on Numerical Computations: Theory and Algorithms (pp. 525-536). Springer, Cham.
- Cross, H. (1936). Analysis of flow in networks of conduits or conductors. University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station.
- Di Nardo, A., Giudicianni, C., Greco, R., Herrera, M., & Santonastaso, G. F. (2018). Applications of graph spectral techniques to water distribution network management. Water, 10(1), 45.
- Giustolisi, O., Savic, D., & Kapelan, Z. (2008). Pressure-driven demand and leakage simulation for water distribution networks. Journal of Hydraulic Engineering, 134(5), 626-635.
- Hajebi, S., Roshani, E., Cardozo, N., Barrett, S., Clarke, A., & Clarke, S. (2015). Water distribution network sectorisation using graph theory and many-objective optimisation. Journal of Hydroinformatics, 18(1), 77-95.
- Herrera, M., Abraham, E., & Stoianov, I. (2016). A graph-theoretic framework for assessing the resilience of sectorised water distribution networks. Water Resources Management, 30(5), 1685-1699.
- Hoag, L. N., & Weinberg, G. (1957). Pipeline network analysis by electronic digital computer. Journal (American Water Works Association), 49(5), 517-524.
- Isaacs, L. T., & Mills, K. G. (1980). Linear theory methods for pipe network analysis. Journal of the hydraulics division, 106(7), 1191-1201.
- Martin, D. W., & Peters, G. (1963). The application of Newton’s method to network analysis by digital computer. Journal of the institute of Water Engineers, 17(2), 115-129.
- Muranho, J., Ferreira, A., Sousa, J., Gomes, A., & Marques, A. S. (2014). Pressure-dependent demand and leakage modelling with an EPANET extension–WaterNetGen. Procedia Engineering, 89, 632-639.
- Muranho, J., Ferreira, A., Sousa, J., Gomes, A., & Sá Marques, A. (2012). WaterNetGen: an EPANET extension for automatic water distribution network models generation and pipe sizing. Water science and technology: water supply, 12(1), 117-123.
- Rossman, L., H. Woo, M. Tryby, F. Shang, R. Janke, AND T. Haxton. (2020) EPANET 2.2 User Manual. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-20/133.
- Rossman, L.A. (2000) EPANET 2: Users Manualus Environmental Protection Agency; Water Supply and Water Resources Division, National Risk Management Research Laboratory: Cincinnati, OH, USA.
- Todini E. and Pilati S. (1988). “A gradient method for the solution of looped pipe networks.” in B. Coulbeck and C. H. Orr (Editors) Computer Applications in Water Supply. Volume 1 – System Analysis and Simulation, John Wiley & Sons, pp. 1-20.
- Todini, E. (2008). Towards realistic extended period simulations (EPS) in looped pipe network. In Water Distribution Systems Analysis Symposium 2006 (pp. 1-16).
- Todini, E., & Rossman, L. A. (2013). Unified framework for deriving simultaneous equation algorithms for water distribution networks. Journal of Hydraulic Engineering, 139(5), 511-526.
- Wagner, J. M., Shamir, U., & Marks, D. H. (1988). Water distribution reliability: analytical methods. Journal of Water Resources Planning and Management, 114(3), 253-275.
- Wood, D. J., & Charles, C. O. (1972). Hydraulic network analysis using linear theory. Journal of the Hydraulics division, 98(7), 1157-1170.
- Wood, D. J., & Rayes, A. G. (1981). Reliability of algorithms for pipe network analysis. Journal of the Hydraulics Division, 107(10), 1145-1161.

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2 DATA INTEROPERABILITY FOR WDNS DIGITIZATION AND MANAGEMENT

2.0 SUMMARY

2.1 INTRODUCTION

For innovative management of IWSs, it is necessary to pursue the management and cognitive supports digitization. The technological innovations available allow to significantly increase management systems efficiency and reliability. Advanced management of WDNs requires modelling and technological tools capable of effectively mimic the real behavior of the system, optimizing management processes, evaluating aspects of sustainability and environmental impacts (Maiolo and Pantusa 2014).

The utilities administration cannot ignore multidisciplinary management paradigms based on the use of an adequate information system. Smart management integrates monitoring systems (Supervisory Control And Data Acquisition - SCADA and Advanced Metering Infrastructures - AMI), hydraulic modelling systems, and information systems (Geographical Information System - GIS and Decision Support System - DSS) for data management.

Managers should rely on information systems capable of cataloguing and organizing both technical and administrative data. The correct knowledge framework to support management activities requires the availability and usability of a plurality of data, heterogeneous in terms of both type and format. Information interoperability (i.e., the ability to exchange data between different information systems) is of crucial importance.

The use of a GIS work environment is particularly suitable and convenient in managing the various aspects related to drinking water distribution infrastructures (Hauser and Roedler 2015, Armstrong *et al*. 2012, Kalinowski and Grzelak 2018). GIS is a class of software that allows managing, integrating, and relating different formats and types of data.

2.2 Data collection and homogenization

Before the advent of IT, cartographic database management was a strong limiting factor. The wide availability of these technologies allowed renewing the data management and organization approaches.

The water infrastructures' data quality and quantity are very varied and fragmented. The degree of fragmentation depends on local legislation and the water services organization. In Italy, most of the subjects involved in water systems management are not specialized.

According to ISTAT[1] estimates (2015), there are 2,857 water service operators in Italy. Of these, 17% are specialized managers, while the remaining 83% are non-specialized. As regards the specific management of drinking water distribution, in Italy, there are 2,306 managers and 14.4% of these are specialized.

In Italy[2] in 2020, the geo-referenced supply and distribution networks are about 77% of the total. The percentage rises to 94% in the northeast of the country but drops to 56% in the south and the islands.

Water network managers find themselves managing infrastructures with an average age of about 30 years. The infrastructure age causes disservices due to malfunctions and breakdowns, and in many cases implies data inhomogeneity and fragmentation. The current trend is witnessing progressive data digitization and organization. The legislation encourages the development of cartographic databases (INSPIRE - *INfrastructure for SPatial InfoRmation in Europe*) and the use of interoperable formats such as IFC, typical of BIM working environments.

2.2.1 Minimum informative content for hydraulic models

The hydraulic simulation of a WDN presupposes the solution of a system of equations, **Chapter 1**. The informative content and data structure necessary to be constituted for the modelling depends on the chosen hydraulic software. In the current work, the reference hydraulic modelling software is EPANET. The digitization procedure goal is the construction of an information database containing at least the amount of data necessary for the software input file construction. The knowledge of the EPANET input format (inp file) structure (Rossman 2000, Rossman *et al*. 2020) allows defining the data quantity and structure necessary for the simulation. As described in **Chapter 1**, EPANET classifies the WDN in its essential components:

Links:

- *Pipes*: allows moving water between the nodes;
- *Pumps*: pumps or pumping stations. Modelled as line elements, they supply energy to the fluid contained within them;
- *Control valves*: sectioning and management devices (pressure control valves, s, flow control valves, pressure breaking valves, pressure sustaining valves, etc…).

Nodes:

- *Junctions*: links connection points. The users' water demand is assigned to them.

[1] Istituto nazionale di statistica, National Institute of Statistics.

[2] ARERA (*Autorità di Regolazione per Energia Reti e Ambiente*),2020 Annual report: https://www.arera.it/it/relaz_ann/20/20.htm

- *Tanks*: schematization of storage tanks. *Tanks* are characterized by defined volume and shape;
- *Reservoir*: infinite infinite external source or sink of water. They model large tanks or sources with known head.

A network is modelled as a graph composed of vertices (nodes) and edges (links). The connections between the elements constitutes the topology of the network. For the WDN model elements is necessary to define a set of minimum information (nodes and links). Below is an indication of the characteristics necessary to model the elements:

- *Pipes*:
    - Geometric (diameter and length) and hydraulic (roughness) characteristics;
    - Topographic trace;
- *Junctions*:
    - Water demand;
    - Elevation;
    - Topographical position;
- *Valves*:
    - Diameter;
    - Valve type, operating mode, and setting;
- *Tanks and Reservoirs*:
    - Operating intervals and modes;
    - Geometric characteristics (volumes, level);
- *Pumps*:
    - Operating intervals and modes;
    - Power and characteristic curves.

Some of the network element characteristics, recovered in the data survey phases, are subjected to variations in the hydraulic model calibration phase. Calibration is mandatory and has the aim of making the behavior of the hydraulic model as similar as possible to the real network one. Calibration procedures are carried out by modifying some characteristics of pipes or nodes, affected by greater uncertainty.

2.2.2 GIS WORKSPACE

The digitization of different real scenarios allowed defining a repeatable and adaptable procedure. Maiolo *et al*. (2020) defined the series of software necessary for framing and defining the network topographic and topological characteristics.

The GIS work environment is chosen for the information database. The choice discriminating factors were effectiveness, ease of use, and the type of commercial license. Quantum GIS software is subjected to a general public (GNU) license. The QGIS software makes available numerous tools (Plug-ins), developed by third parties, which enable specific functions, such as the passage from/to different work environments. *QuantumGIS 2.18 Las Palmas* was used. Version 2.18 is the latest stable release of version 2 of the software (currently updated to version 3.18). An outdated version of the software was used due to the presence of some incompatible plug-ins in subsequent versions.

Data format

Despite the regulatory recommendations for the generation of standardized digital databases, to date, many administrations have not organized data according to EU regulations or using specialized software. Mainly for local, non-specialized managers, the available data is often organized in WEB-GIS, CAD (computer-aided design) drawings, paper, or digital maps. In most of the analysed applications, the topology and information are encoded in a CAD drawing. The CAD drawing final-purpose influences the data structure. For drawings or maps used in cartographic map production, such as thematic maps, the network plano-altimetric layout may not be to scale or provided with a geographical projection.

Transforming CAD drawings into shapefiles is a common procedure. QGIS allows importing files with .dxf [3] extension and converting them into shapefiles; also, AutoCAD-MAP [4] allows manipulating and export files in ESRI[5] shapefile format. A feature of GIS software is the use of a projection by assigning a Geodetic Datum and a coordinate projection system. The model construction in a GIS environment requires to georeference the network to define its scale, position and coordinate system. The Datums used in the modelling are consistent with those used by technical cartography and/or by software such as Google Earth.

2.2.3 MODEL VALIDATION AND EXTERNAL DATA INTEGRATION

The network topological model realization in the GIS environment involves the construction of vector files representing the network components (pipes, junctions, valves, etc…). In GIS software the connection between elements is represented by the planimetric position and the coincidence of vertices and nodes (position snap). For example, a pipe connected to a tank has one of its (final) vertices (snapped) in the same position as the point element that represents the tank.

[3] Autocad Drawing Exchange Format
[4] Developed by Autodesk
[5] Data format Developed by Environmental System Research Institute

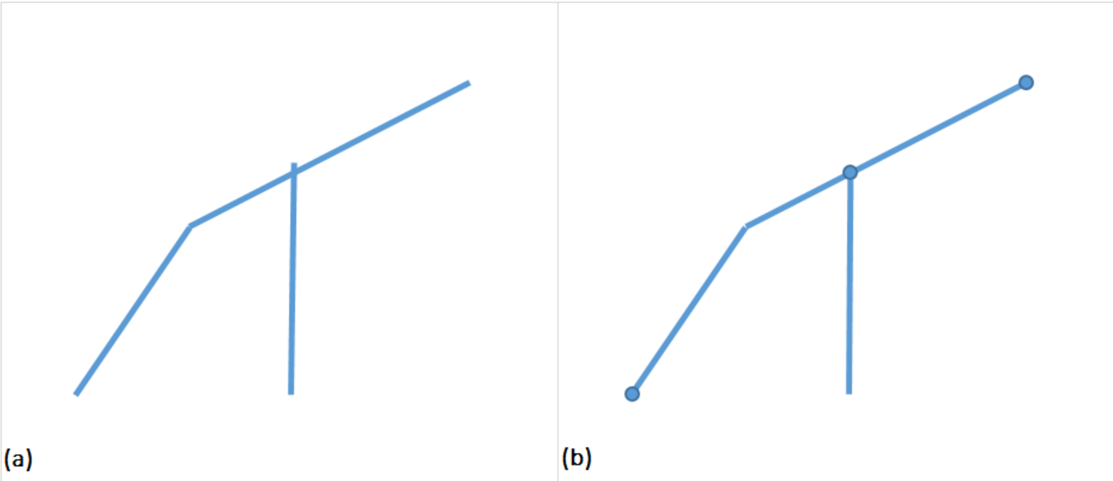

Figure 2.2.1 Two pipes intersection example. (a) sufficiently detailed intersection for a map (b) requested level of detail for hydraulic modelling.

Importing a CAD drawing or shapefile not drawn up according to these criteria can generate a series of imperfections, Figure 2.2.1. The hydraulic model generation requires a correction and validation phase of the element characteristics, relation and position. In some application cases, the network topology is derived from the use of un-scaled and not projected vector elements. The elements georeferencing can present project-related issues affecting the plano-altimetric positioning. The data validation can be carried out taking into account the WDN design practices that establish the relationship with other information layers, such as the relative position of the road graph or the buildings. Figure 2.2.2 example shows how the pipe planimetric positioning follows the road graph and does not commonly interact with the buildings.

Additional data such as road graphs, buildings or technical maps are available on regional or national map portals. It is possible to retrieve data from digital terrain models (DTM), made available by some providers such as Google or BingMaps[6]. QGIS allows importing these maps with a dedicated plug-in, QuickMapServices[7].

Data retrieved from external data sources allows achieving the minimum data amount necessary for the hydraulic model construction, indicated in Section 2.2.1. The nodal elevation can be sampled from a digital elevation model (DEM). The nodal characteristics assignment is enabled by query tools that allow sampling information contained in Raster layers, such as "Processing" available on QGIS[8].

[6] Servizio di mappe digitali del motore di ricerca BING, di Microsoft.
[7] Plug-in sviluppato da NexGIS, versione installate: 0.19.10.1.
[8] Plug-in Processing, Spatial data processing framework for QGIS, Svilupapto da Victor Olaya, Version: 2.12.99.

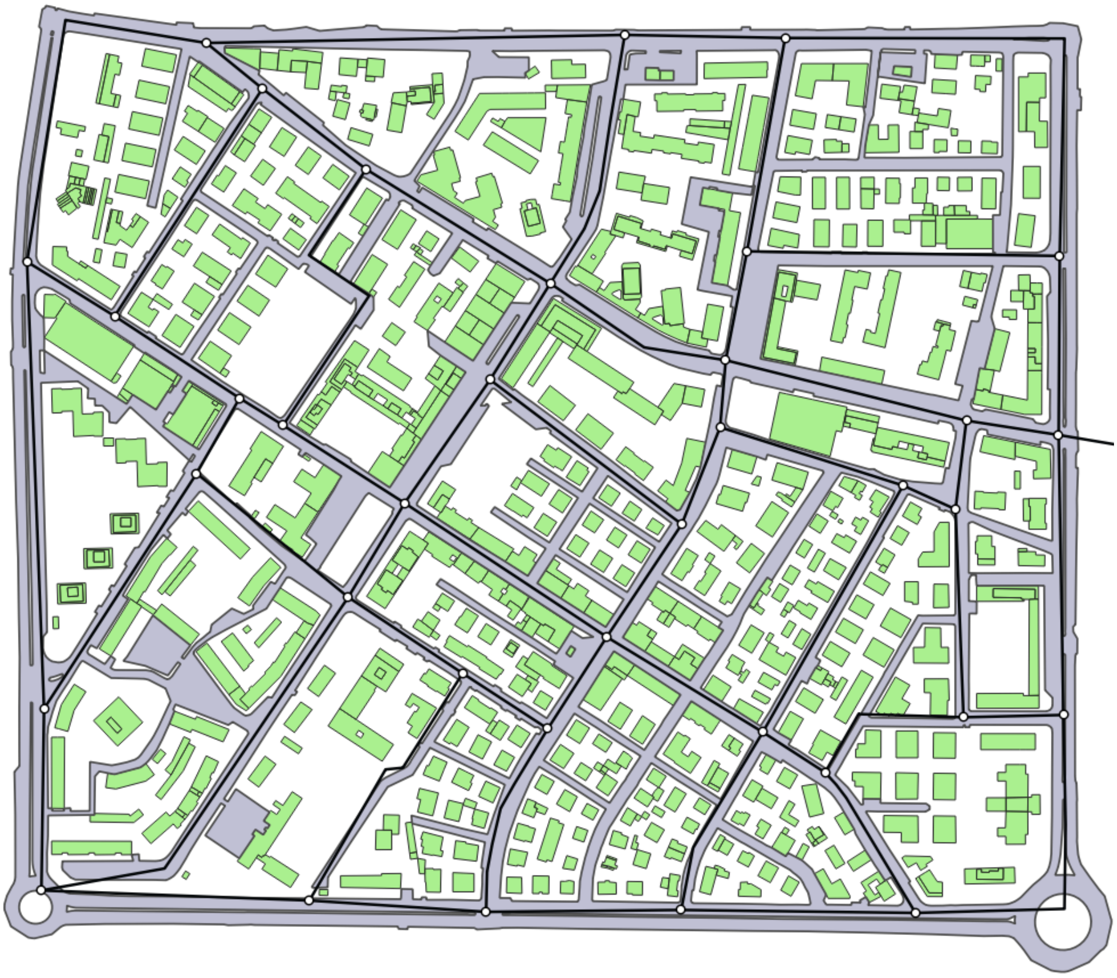

Figure 2.2.2 WDN planimetric layout positioning, placed with the building scheme and roads graph.

2.3 Digital model construction, working environment and software

The use of QGIS, or more generally a GIS software, for the database construction and management and the use of EPANET for hydraulic modelling, presupposes the possibility of integrating the software or being able to easily change the work environment

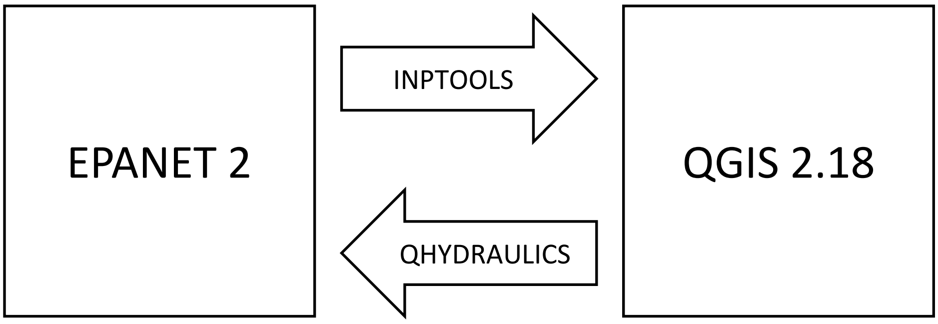

Figure 2.3.1 Working environment migration diagram.

In most of the practical applications, the conversion from the EPANET model to shapefile was carried out using a stand-alone command package: Inptools[9]. The executable allows manipulating the EPANET network and project files. It is possible to generate shapefiles containing information on each type of element encoded within the inp file (Junctions, Reservoirs, Tanks, Pipes Valves, Pumps, etc.). In the most recent versions of QGIS (3.+), it is possible to use plugs-in for the network import (QEPANET[10] and QGISRed[11]). The reverse process, the compilation of .inp files from shapefile, is entrusted to GHydraulics[12], a QGIS plug-in. The plug-in allows compiling the .inp file by defining the shapefiles for each type of network element. Both QEPANET and QGISRed allow using EPANET hydraulic simulation engine directly from the QGIS interface. QGISRed also allows compiling the .inp file.

[9] http://epanet.de/inptools/index.html.en
[10] Sviluppato da UNIBZ - UNITN versione 2.5
[11] Developed by REDHISP(Project Leader) Group (IIAMA-UPV).: WaterPi (Developer). https://plugins.qgis.org/plugins/QGISRed/
[12] Developed by Steffen Macke version 2.1.8.

2.4 Hydraulic model calibration

A calibration phase ensures that the simulation models, to be used in the WDNs management, reproduce the real behaviour of the network for different operating conditions. The application of a calibration procedure allows identifying and isolating errors affecting the topology, the characteristics of the elements (plano-altimetric layout, diameters, etc.), and the operating diagram (settings of special devices, status of the valves or bypass). A properly calibrated model is an effective management support tool available to the infrastructure manager.

The calibration phase aims to modify the model hydraulic operating regime acting on the parameters over which there is the least control and which are difficult or impossible to correctly assess or measure (Veltri *et al*. 1994, Walski 1983). These parameters modification aims to minimize the difference between the modelled regime (pressures and flow rates) and the field observations (obtained from remote metering or measurement campaigns).

Commonly the least controllable parameters are the pipe roughness, the nodal demand distribution, the presence of water losses and the positioning of minor losses. In addition to the values uncertainties, the simplifications in the representation of the infrastructure affect the difference in operation between a hydraulic model and the real network. An incomplete representation of the network due to any modelling simplification (omission of elements of little importance) (Ormsbee and Lingireddy, 1997) may produce unreliable results

The roughness depends on the pipe material and the internal surface finishing. Following the pipe installation, the roughness is influenced by countless factors that collaborate with the pipes ageing and degradation (formation of biofilm on the pipe walls, water hardness, formation of rust, etc.). The combination of these factors makes roughness the least controllable parameter. A further degree of uncertainty is due to the difficulty in making direct measurements of the phenomenon.

Another uncertainty element, very common in WDN modelling, is the distribution of the user demands. A WDN is rarely schematized up to the level of detail that takes into account all the users' connection points. Usually, the flow rates supplied by service connections along the pipes are divided between the pipe end junctions.

The indetermination affecting demand volume distribution is influenced by a series of factors depending on the infrastructure manager and the organization in consumption reading. WDNs are rarely equipped with extensive telemetry systems, such as user-scale smart meters. Managers commonly rely on manual readings, carried out by employees or users, which are very time-delayed and in some cases not very reliable.

The presence of water losses contributes to introducing another level of uncertainty in the water demand distribution. In Italy, 56% of the municipalities served have a water loss rate higher than 35%. Of the total, about 24% of the municipalities are characterized by significant water losses (55%) (ISTAT estimates). Such large water loss rates strongly affect the demand distribution, since they can involve areas of the network with apparently random distribution.

2.5 REGULATIONS FOR THE CONSTRUCTION OF DIGITAL DATABASES

The evolution in data management, with shared data structures and recent interoperable formats, is necessary for advanced infrastructure management. Both the Italian and European legislation support the use of these structures and formats.

Despite the legislation support for the digital information management evolution, at present, the quantity and quality of data relating to drinking water distribution infrastructures appear to be very uneven. Generally, the main sources of available data are:

- Paper or digital maps and project documentation;
- CAD drawings;
- Shapefiles.

Legislative Decree No. 50 *"Codice dei contratti pubblici"* (*Public contract code*)(18/04/2016) promotes the use of interoperable data to simplify the manipulation, modelling and access to the data. The reference standard at the European level is INSPIRE (*INfrastructure for SPatial InfoRmation in Europe*, 15/05/2007). The initiative establishes a community infrastructure for territorial information.

2.5.1 INSPIRE

INSPIRE aims to make the territorial databases developed by/for public authorities accessible and to define a single criterion for the territorial data organization. The use of a common and standardized format allows overcoming data availability and accessibility issues.

INSPIRE states:

"The infrastructures for spatial information in the Member States should be designed to ensure that spatial data are stored, made available and maintained at the most appropriate level; that it is possible to combine spatial data from different sources across the Community in a consistent way and share them between several users and applications;"

The ultimate goal of the legislation is to support the development of environmental policies:

"The Infrastructure for Spatial Information in the European Community (Inspire) should assist policy-making in relation to policies and activities that may have a direct or indirect impact on the environment."

INSPIRE is based on five fundamental principles[13]:

- Data must be collected once and managed efficiently;
- Data from different sources can be combined and shared between different users and applications;
- Information collected at various (administrative) scales must be shared at all levels;
- Geographic data must be available and accessible without impediments that limit its use;
- It must be easy to find the information and evaluate its usefulness and use conditions.

[13] https://inspire.ec.europa.eu/inspire-principles/9

Framework and data model

INSPIRE aims to define a single criterion for the organization of territorial data. The legislation consists of a data model and a data use framework. The two components do not only provide information on data type and format but also provide the data model and a roadmap to ensure the sharing, interoperability and organization of information.

The data framework is an infrastructure to create and keep up-to-date data. It includes metadata specifications and defines data collection and maintenance procedures. INSPIRE identifies the data structure for a large variety of environmental and administrative issues. The 34 themes[14] are organized into three groups:

- *reference systems (Annex I);*
- *topography (Annex II);*
- *social, natural or statistical datasets (Annex III).*

The Data Model uses the Geographic Markup Language (GML) data-encoding standard. The Open Geospatial Consortium (OGC) and the International Organization for Standardization (ISO) administer the GML. GML is an XML-based standard for modelling geographic features. The standard is simple to use and edit and allows representing geographic objects with varying levels of detail. For each of the 34 themes, the GML language provides all the attributes and characteristics to describe the type of geometry and elements involved.

Utility and governmental services

The subservices networks, and in detail the WDNs fall under the *Utility and governmental services*[15] *(Annex III)* theme. The theme covers a series of aspects such as resource distribution networks, public service networks, and environmental management facilities. The document: "*D2.8.III.6 Data Specification on Utility and Government Services – Technical Guidelines*", drawn up by *INSPIRE Thematic Working Group Utility and Government Services* (10/12/2013) report the data-model specifications. The approach consists of defining basic information on the services that fall under the topic:

- Feature location;
- Party involved in the service;
- Basic technical characteristics.

Utility and governmental services is a very broad topic. It has been further divided into three sub-domains:

- *Utility networks;*
- *Administrative and social governmental services;*
- *Environmental management facilities.*

Utility networks include service and resource transport networks:

- *Electricity network;*
- *Oil, Gas & Chemicals network;*

[14] https://inspire-geoportal.ec.europa.eu/theme_selection.html?view=qsTheme
[15] https://inspire-geoportal.ec.europa.eu/overview.html?view=themeOverview&theme=us

- *Sewer network;*
- *Telecommunications network;*
- *Thermal network;*
- *Water network.*

The sub-domain is divided into two further services: *Utility Networks Profile* and *Extended Utility Networks Profile*. The first contains simplified modelling based on an arch-node structure. *Utility Networks Profile* is structured for the representation of service networks for business purposes. The networks elements are described by very simple basic information (position, material, dimensions, etc.). The *Extended Utility Networks Profile* features modelling is similar to the previous one, providing more detailed and information-rich models.

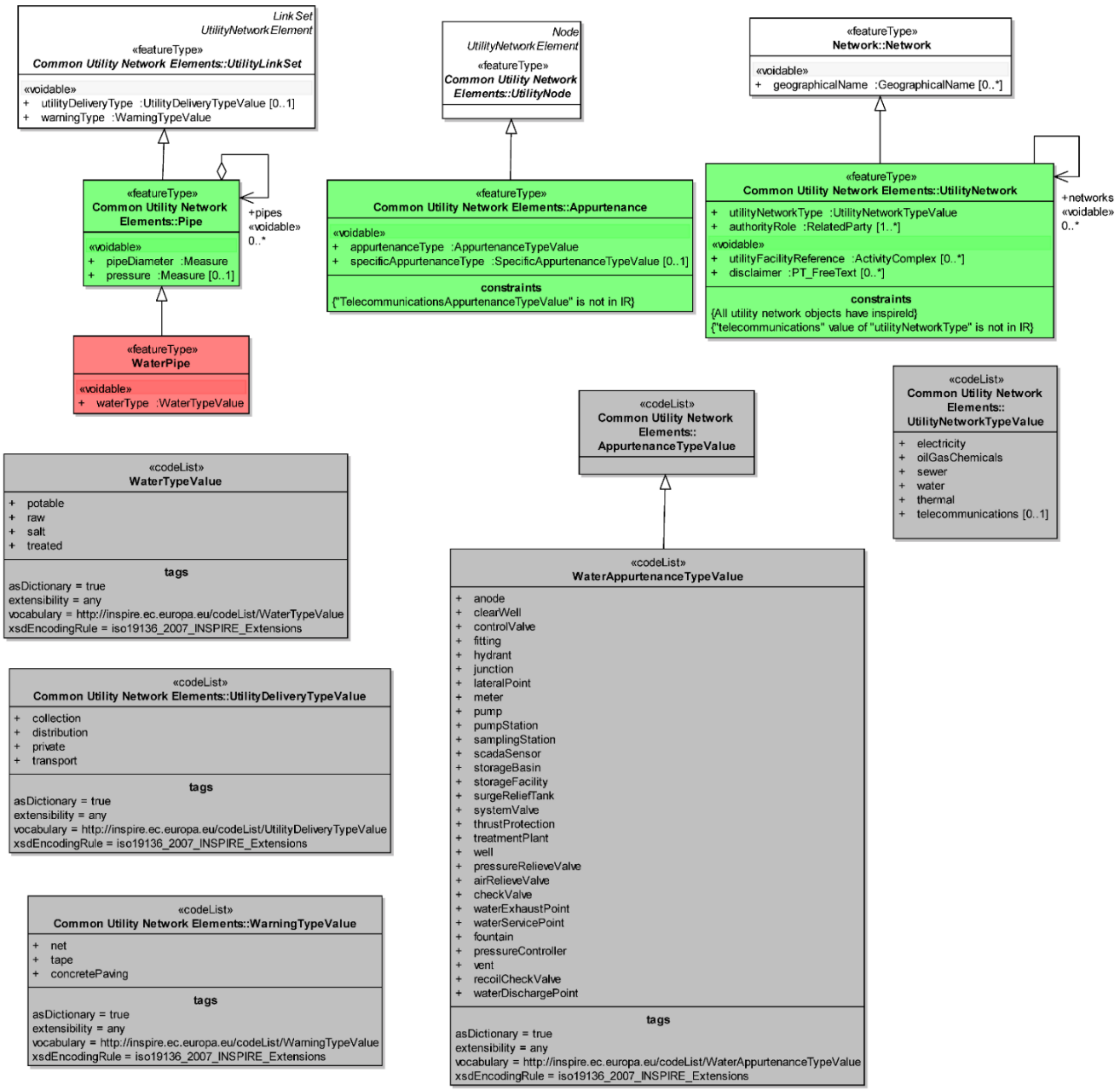

Figure 2.5.1 **UML class diagram: Overview of the "Water Networks".**

Water Network scheme

Figure 2.5.1 shows the UML diagram for the Water Network elements. The scheme organizes the WDN elements into three types:

- *Pipes*: contains line elements such as pipes.
- *Appurtenance node*: it contains a vast collection of specific network elements: control valves, fittings, hydrants, junctions, meters, pumps, SCADA sensors, water storages, wells, fountains, etc...
- *UtilityNetwork*: defines the type of utility described: electricity, oil gas and chemicals, sewer, water, thermal or telecommunications.

In addition to the Water Network components information, the scheme encodes information on the type of water conveyed (potable, raw, salted, treated) and other additional information.

2.5.2 Italian regulation transposition

On a national level, the "*Codice dell'Amministrazione Digitale"* [16] (CAD) (*Code of Digital Administration*) was established with the Legislative Decree No. 82, 7/03/2005. The CAD organizes the rules concerning the computerization of the Public Administration in citizens and businesses relations. Simultaneously with the development of European legislation, the CAD establishes the national repertory of territorial data and defines the technical rules for the survey documentation, exchange and use of territorial data. Article 59 establishes the "*Comitato per le regole tecniche sui dati territoriali*" (*Committee for technical rules on territorial data*). The committee has the task of defining the technical rules for the creation of the territorial databases, the documentation, the data usability and exchange.

The "*Agenzia per l'italia Digitale*" (AgDI) (*Agency for Digital Italy*) renews the Committee and supports the INSPIRE legislation transposition. The transposition takes place with Legislative Decree 32/10 (27/01/2010) "*Attuazione della direttiva 2007/2/CE che istituisce un'infrastruttura per l'informazione territoriale nella Comunità europea (INSPIRE)*" (*Implementation of Directive 2007/2/EC, which establishes an infrastructure for territorial information in the European Community - INSPIRE*). Article 11 establishes the "*Consulta Nazionale per l'Informazione Territoriale e Ambientale*" (*National Council for Territorial and Environmental Information*) to which the AgDI is a member.

To date, the rules for the construction and management of information databases refer to the activities carried out by the Committee. The "*Sistema Informativo Nazionale Federato delle Infrastrutture*" (SINFI) (*Federated National Information System of Infrastructures*) has produced further specifications on subservice networks.

For utility networks, and in particular for WDNs, the data model construction refers to the document "*Regole tecniche per la definizione delle specifiche di contenuto per i database delle Reti di sottoservizi*" [17] (*Technical rules for the definition of content specifications for databases of subservice networks*). The document derives from the activity carried out by the "*Gruppo di lavoro 8. Reti di sottoservizi istituito nell'ambito Comitato per le regole tecniche sui dati territoriali*" (*Working group 8. Subservices networks established within the Committee for technical rules on spatial data*).

The "*Specifiche di contenuto per i Database delle Reti di Sottoservizi*" (*Content Specifications for Sub-Service Networks Databases*) use the GeoUML[18] (Geographic Unified Modelling Language)

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[16] https://www.agid.gov.it/it/agenzia/strategia-quadro-normativo/codice-amministrazione-digitale
[17] Version 5.0, 19/06/2015
[18] http://umbriageo.regione.umbria.it/resources/Progetti/a%29%20Modello%20GeoUML%20regole%20di%20interpretazione%20delle%20specifiche%20di%20contenuto%20per%20i%20Data%20Base%20Geotopo.pdf

model. The GeoUML is a set of constructs divided into information elements and integrity constraints. The former is used to define the structure of the data content (Class, attribute, cardinality, enumerated domain, association, inheritance, spatial component, geometric attribute, etc.). The integrity constraints define the properties that the data elements must respect.

The territorial database for utility networks development referrers the *National Core* (NC). The NC is the minimum information content that the competent institutions must ensure for the implementation of a homogeneous and nationally covered subservice network database. The set of all elements and content specifications constitutes the "*Catalogo dei Dati Territoriali*" [19] (*Territorial Data Catalog*), the NC establishes the content of the attributes of the elements and specifies the mandatory and optional fields. The classification of the elements of the *Territorial Data Catalog* is structured to respect the information level required by the INSPIRE regulation.

The Legislative Decree n. 133 Art. 6 bis (12/09/2014) defines "L*'obbligatorietà SINFI delle Reti di Sottoservizi*" (*The SINFI mandatory of Sub-services Networks*) that is the minimum information content functional to the SINFI implementation.

Data-model organization

The Territorial Data Catalog organizes the elements composing subservice networks into 11 layers, 34 themes and 130 classes. The classes define the representation of a specific typology of spatial objects. Each class is characterized by a list of attributes. A class can have one, multiple, or no spatial components. Layers and Themes do not represent a classification but are homogeneous groups of classes.

Layer 7: *Reti di sottoservizi* (*Utility Networks*) contains seven Themes:

- *TEMA: Rete idrica di approvvigionamento 0701 (Water supply network);*
- *TEMA: Rete di smaltimento delle acque 0702 (Water disposal network);*
- *TEMA: Rete elettrica 0703 (Electricity network);*
- *TEMA: Rete di distribuzione del gas 0704 (Gas distribution network);*
- *TEMA: Rete di teleriscaldamento 0705 (District heating network);*
- *TEMA: Oleodotti 0706 (Oil Pipelines);*
- *TEMA: Reti di telecomunicazioni e cablaggi 0707 (Telecommunications networks and cabling).*

WDNs fall under the first Theme of the seventh layer. Different *classes* characterize them:

- Water supply network node (Springs, wells, tanks, junctions, hydrants, fountains, meters etc);
- Water supply network line (main and secondary pipes, service connections, etc.);
- Water supply network (represents the distribution network as a graph).

[19] http://geodati.gov.it/geoportale/images/Specifica_GdL2_09-05-2016.pdf

2.6 Building Information Modeling

Limited availability or quality of data imposes limitations on building complete and reliable infrastructure models. A complete digital model is part of the operational tools necessary for advanced management that can be defined as smart management. A complete model must contain precise information about the elements constituting the infrastructure to be able to represent all the possible states and operating scenarios. The presence of advanced modelling also contributes to intelligent and automated management mechanisms.

To globally improve the state of modelling and standardization of procedures, institutions and legislation support the use of the BIM (Building information modelling) approach in the design and management processes. BIM is a design methodology that allows generating and managing structures digital models.

"BIM is a digital form of construction and asset operations. It brings together technology, process improvements and digital information to radically improve client and project outcomes and asset operations"[20]

"Building Information Modelling (BIM) is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure"[21]

The new BIM modelling paradigm aims to increase efficiency, productivity, quality and sustainability of the structures and infrastructures designed. The BIM approach supports all design, construction and maintenance phases. This methodology simplifies the collaboration between the parties involved in the design, reducing project construction costs and times.

2.6.1 Regulatory framework

Italian and European legislation underlines the need for improvement in the design process and the standardized digital technical documentation production. In Italy, the *Public contract code* (*Legislative Decree No. 50/2016*) renews the previous legislation on the assignment and management of public contracts (*Legislative Decree 12/04/2006, No.163*). The new legislation inserts changes in the design phases and public contracts regulations. The *Article 23 "Livelli della progettazione per gli appalti, per le concessioni di lavori nonché per i servizi"* (*Levels of planning for contracts, for work concessions and services*) underline the need to use electronics modelling tools:

Art. 23: *"La progettazione* è intesa ad assicurare […] *la razionalizzazione delle attività di progettazione e delle connesse verifiche attraverso il progressivo uso di metodi e strumenti elettronici specifici quali quelli di modellazione per l'edilizia e le infrastrutture".*

Art. 23: "The design is meant to ensure […] the rationalization of design activities and related checks through the progressive use of specific electronic methods and tools such as the ones for infrastructures modelling for buildings".

[20] Handbook for the introduction of building information modelling by the european public sector. Strategic action for construction sector performance: driving value, innovation and growth , 2017, EU BIM Taskgroup.
[21] https://www.autodesk.com/solutions/bim/benefits-of-bim.

In the same article, the legislation specifies that these electronic tools must use:

"piattaforme interoperabili a mezzo di formati aperti non proprietari, al fine di non limitare la concorrenza tra i fornitori di tecnologie e il coinvolgimento di specifiche progettuali tra i progettisti".

"Interoperable platforms using non-proprietary open formats, in order not to limit competition between technology suppliers and the involvement of project specifications among designers".

The Legislative Decree n ° 50 is also implemented through the Ministerial Decree n. 560 (1/12/2017). The decree derives from the transposition of the:

- *Council Directive 2014/23/EU on the award of concession contracts;*
- *Council Directive 2014/24/EU on procurement by entities operating in the water, energy, transport and postal services sectors;*
- *Council Directive 2014/25/EU on procurement by entities operating in the water, energy, transport and postal services sectors and repealing Directive 2004/17/EC.*

The *2014/24/EU* specifies:

Art.22, Paragraph 4: "For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar. [...] "

In 2017 the European community made available the "*Handbook for the introduction of Building Information Modelling by the European Public Sector. Strategic action for construction sector performance: driving value, innovation and growth*"[22]. This document aims to provide a set of knowledge and a reference point for legislators who will have to develop policies regarding the BIM introduction.

2.6.2 BIM FEATURES AND ADVANTAGES

Regulations promoting BIM usage aims to counteract data fragmentation and optimizing the design procedures. BIM is designed to provide a work environment that guarantees collaboration between different designers. The collaboration is supported through data coding that reduces the issues afflicting file exchange, updating and transfer between different stakeholders.

BIM involves the construction of a three-dimensional digital model (Building Information Model), containing all the information on the designed structure and its elements. The information stored in BIM models does not only concern the construction phases of the work but include data on the entire life cycle:

- Design;
- Realization;
- Management and maintenance;
- Demolition, decommissioning and disposal.

BIM models are more accurate than the ones built with traditional processes. The greater modelling efficiency depends on the quantity of integrable data into the model and on the collaborative logic. BIM is strongly linked to the concept of interoperability. A collaborative design paradigm requires common interchange file formats to guarantee the ability to easily change

[22] http://www.eubim.eu/downloads/EU_BIM_Task_Group_Handbook_FINAL.PDF

work environments and transfer models without information loss or compatibility issues. The construction of a BIM three-dimensional model, in which each element is characterized, enables compatible software to carry out metric and economic calculations, reducing the uncertainty in the cost and volumetric assessment.

In the past, design and planning systems encoded information on documents and technical paper drawings. With the advent and greater availability of IT, design has evolved, using digital media, and taking advantage of CAD technologies and software. Often digital files generated with traditional CAD have display purposes and are composed of points, vectors or shapes, encoded by backgrounds, colours.

The BIM model retains the ability to generate more "classic" graphic designs while maintaining the connection with the main three-dimensional model. The presence of an overall model frees the design from a series of errors. The representation and the generation of tables (sections, plans) errors are reduced as they derive directly from the general 3D model. The presence of the overall model allows having more control over the components overlap and interactions (i.e., hydraulic network and electrical network, etc.).

The three-dimensional modelling has allowed increasing the level of detail and the characteristics of the elements represented. Unlike classic design, BIM software does not foresee the creation/modelling of all the structure basic components composing but rely on object libraries. These libraries, divided by families, contain a multitude of basic elements (simple pieces). The objects are an exact representation (with varying levels of detail) of the modelled elements. The objects encoded in the libraries are parametric and contain data and rules about their properties, attributes and relationships.

BIM parametric objects

The concept of a parametric object is essential for understanding the modelling approach. BIM objects differ from a classical representation (CAD) being characterized by having scalable properties and defined relation to other objects.

BIM objects are structured as containers holding data about the object and its geometry. BIM objects are parametric since their geometric characteristics may not be defined a priori but are defined through rules. The rules do not only influence appearance or dimensions, but the relationships between the various elements, Figure 2.6.1. A parametric "pipe" object can be characterized by its diameter and length, but it has also coded the connection rules with adjacent pipe segments or devices, defining for example the connection type (threaded, flanged, welded).

Commonly, BIM software uses parametric objects catalogues. Generic object catalogues are available directly in the BIM software or online repositories. The devices and components manufacturers build some of these catalogues. It is in the interest of the manufacturers of devices and components to produce libraries of their products, to make BIM design more accessible.

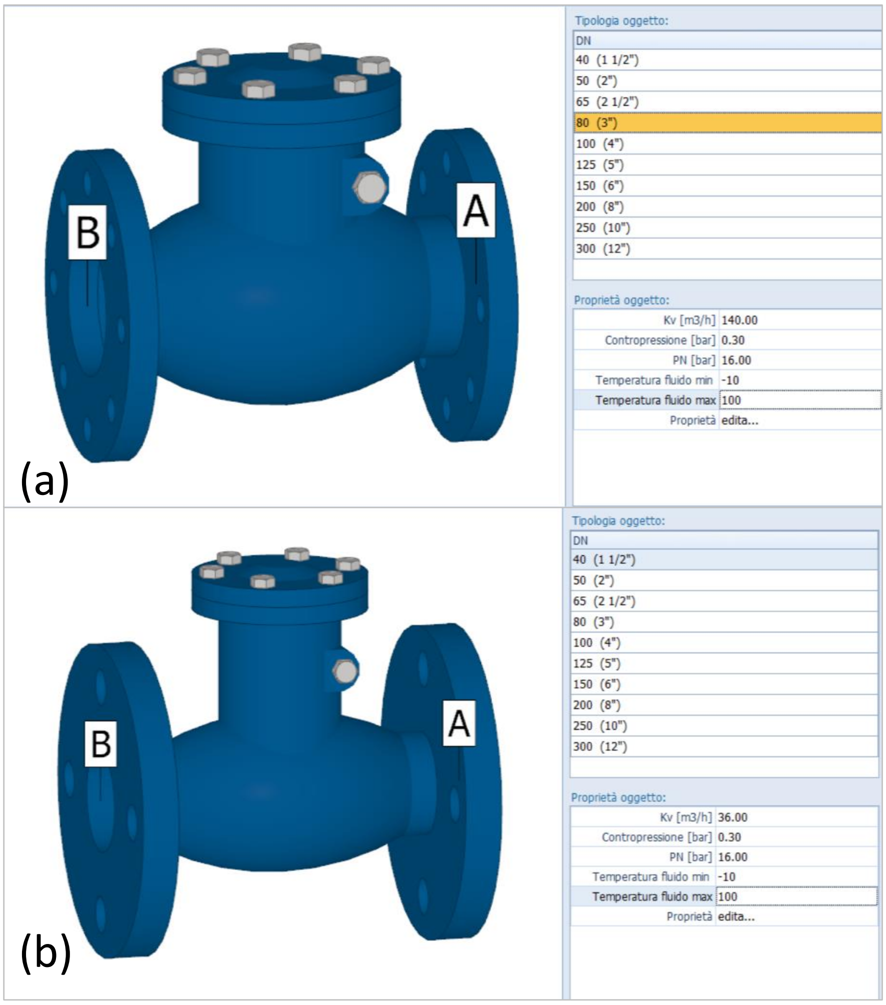

Figure 2.6.1 “Flanged valve” object. The figure shows the same BIM object with different diameters (a) 80mm (b) 40mm. The object rules define the dimension and the flange bolt number depending on the assigned diameter.

Level Of Development

The BIM design regulation foresees different levels of detail. The regulation defines the information content of each design level. Commonly, BIM design refers to LoDs (Level of Development). The LoDs quantify the quantity and quality of information that the digital model must contain and to what extent it is reliable (Cumo *et al*. 2016).

LoDs were defined by the "Institute of Architects (AIA)" which released the "Project Information Modelling Protocol Form"[23] (E202 of 2008). The AIA BIM standard protocol LoDs define six LoDs:

- *LOD 100 The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e., cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.*

[23] AIA® Document G202TM – 2013

- ***LOD 200*** *The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.*
- ***LOD 300*** *The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.*
- ***LOD 350*** *The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element.*
- ***LOD 400*** *The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element.*
- ***LOD 500*** *The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements.*

In the Italian legislation (*UNI 11337-4:2017 Building and civil engineering works - Digital management of the informative processes - Part 4: Evolution and development of information within models, documents and objects*) the term LOD is interpreted as the acronym for "*Livello di sviluppo degli Oggetti Digitali*" (*Development Level of Digital Objects*). The LoDs is indicated by a letter as follows:

- *LOD A oggetto simbolico (symbolic object);*
- *LOD B oggetto generico(generic object);*
- *LOD C oggetto definito (defined object);*
- *LOD D oggetto dettagliato (detailed object);*
- *LOD E oggetto specifico (specific object);*
- *LOD F oggetto eseguito (realized object);*
- *LOD G oggetto aggiornato (object updated).*

Industry Foundation Classes

One of the fundamental goals of the BIM methodology is to guarantee and simplify designer's collaboration and information exchange. To ensure this functionality it is necessary to use an open file format, exchangeable between different subjects and software without causing information losses.

In 1994 Autodesk founded a consortium called "*Industry Alliance for Interoperability*" to create a set of C+ classes that could support integrated application development. The Consortium's task was to create a product data model for the construction field, to support designers and field experts. The Consortium published the first version of the Industry Foundation Classes (IFC) in 1996. After some name changes, in 2005 the development and administration of IFC files moved to *BuildingSMART*.

The IFC data protocol was implemented by ISO, becoming a technical standard "*Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*" (*ISO/PAS 16739*). The most updated version of the standard is the *UNI EN ISO 16739:2016*

"Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries ".

Industry Foundation Classes is an open-source standard that ensures the data exchange for BIM modelling. Despite the regulation recommendation to use a single interoperable format, the various BIM software has their native project format, for example, Revit (.rvt), ArchiCAD (.pln), Edificius (.rfa, .edf), Allplan (.smt), etc.

2.7 State of the art and considerations

The WDN digitization process is strongly affected by the quantity and quality of the available data. Unlike other infrastructures, WDNs are in a particularly critical situation. Criticalities in data collection and validation derive from two main factors:

- Most of the infrastructures were built when the availability of design IT tools was limited and not widespread;
- WDN data retrieval campaigns are complex and expensive, due to the inherent complexity of the infrastructures. These are difficult to reach (mainly underground) and difficult to characterize.

The availability and diffusion of IT tools are leading many WDN managers to use digital database and management support systems. The legislation accelerated the digitalization process requiring advanced design criteria and the need to build common and open territorial databases. The adjustment process is characterized by several critical issues also linked to the presence of a large number of specialized managers.

2.8 BIBLIOGRAPHY

- Censimento delle acque per uso civile 2018 (2020) Istat
- Cumo F., Sferra A., Piras G., Mancini F., Barbanera F., Tiberi M., Sforzini V., De Lieto Vollaro B., Pennacchia E., Spiridigliozzi G. (2016) REPORT RDS/PAR2015/149, La metodologia BIM come strumento per una efficiente progettazione e gestione degli impianti degli edifici
- Hauser A., Roedler F. (2015). Interoperability: the key for smartwater management. Water Science & Technology: Water Supply, Volume 15, Issue 1
- Kalinowski, M., & Grzelak, D. (2018). Technological aspects of GEOSECMA for ArcGIS and EPANET integration-case study. In E3S Web of Conferences (Vol. 45, p. 00029). EDP Sciences.
- Maiolo M., Carini M., Pantusa D. Bonora M. A., Capano G., Mel R., Sinopoli S. (2020) INGEGNERIZZAZIONE E INTEROPERABILITA' DEI DATI PER LA GESTIONE INTEGRATA DELLE RETI IDRICHE URBANE XXXVII Convegno Nazionale di Idraulica e Costruzioni Idrauliche Reggio Calabria, 7-9 Settembre 2020
- Maiolo M., Pantusa D. (2014). Tecniche per la gestione evoluta del sistema idrico integrato. XXXVI Corso di aggiornamento in "Tecniche per la difesa dall'inquinamento", Edibios, ISBN 978-88-97181-39-2
- Ormsbee, L. E., & Lingireddy, S. (1997). Calibrating hydraulic network models. Journal-American Water Works Association, 89(2), 42-50.
- Project Building Information Modelling Protocol Form AIA® Document G202TM – 2013
- Rossman, L., H. Woo, M. Tryby, F. Shang, R. Janke, AND T. Haxton. (2020) EPANET 2.2 User Manual. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-20/133.
- Rossman, L.A. (2000) EPANET 2: Users Manualus Environmental Protection Agency; Water Supply and Water Resources Division, National Risk Management Research Laboratory: Cincinnati, OH, USA.
- Veltri P., Maiolo M., Fiorini Morosini A. (1994). Una procedura per la calibrazione dei modelli di reti di distribuzione idrica. XXIV Convegno di Idraulica e Costruzioni idrauliche, Naples (Italy), 20-22 settembre.
- Walski T. M. (1983) Technique for Calibrating Network Models. Journal of the Water Resources Planning and Management, 109, 4, 360-372.

3 Rende Water Distribution Network digital model

3.0 Summary

3.1 GEOGRAPHICAL FRAMEWORK

The municipality of *Rende*, located in *Calabria*, falls within the province of *Cosenza*. According to ISTAT data (updated to January 2018), the municipality has a population of 35,555 inhabitants, spread over an area of 55.28 km^2, with a density of 646 inh/km^2. The territory extends from the *Crati* river (west) to the *Serre Cosentine* (east). It has an altitude ranging from 130m a.s.l. up to an altitude of 1135m a.s.l. in proximity to the mountainous area to the southwest.

The WDN that serves the municipality is managed by a private company: *Acque Potabili Servizi Idrici Integrati S.R.L*. This company manages various aspects of the integrated water service (distribution of drinking water, collection and treatment of wastewater) in various Italian areas. The company serves about 80,000 people distributed in two provinces and seven municipalities. The company refers to the Acque Potabili S.p.A. serving 200,000 inhabitants and 33 municipalities.

Rende water network is part of a larger network that serves the urban territory of the municipalities of *Rende* and *Cosenza* that constitutes a single urban area. This chapter refers to the modelling of the the network portion serving the *Rende* municipal area, Figure 3.1.1. The served area is located in a complex and varied morphology. The network serves the *Rende* urban centre, the neighbouring industrial area, the old town of *Rende*, located in an elevated area, the university campus and the peripheral areas.

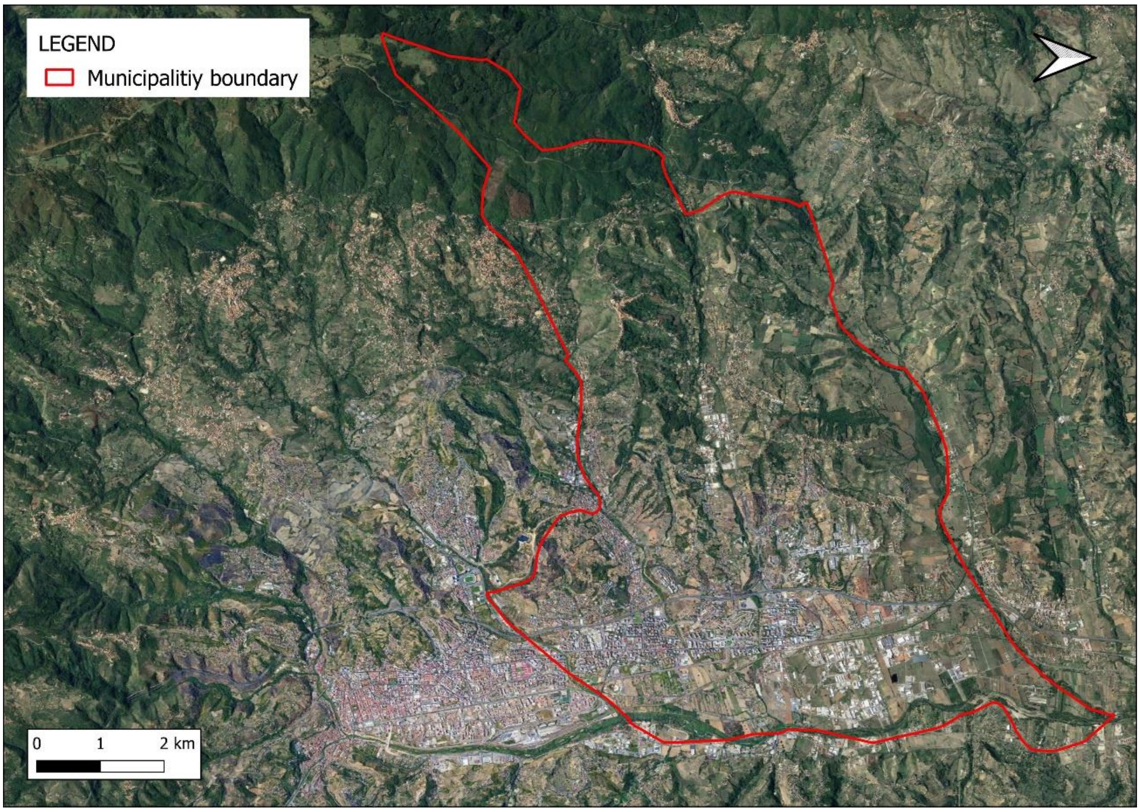

Figure 3.1.1 *Rende* municipality map. Google Satellite background.

1

Figure 3.1.2 *Rende* municipality geographical setting.

3.1.1 Aqueducts and tanks supplying the network

13 tanks supply water to the WDN modelled portion, Figure 3.1.3. The water comes from the *Abatemarco, Capo D'Acqua* and *Crocetta* aqueducts, all under the management and control of the regional company. *So.Ri.Cal.* (Società Risorse Idriche Calabresi, Calabrian Water Resources Company). *So.Ri.Cal*. manages the supply water schemes of Calabria. The company is responsible for completing and modernizing the storage, treatment and distribution works throughout the territory.

Due to the complex morphology and the elevation difference (from 130m a.s.l. up to over 660m a.s.l.) that constitutes the area served, the network requires a large number of tanks. Each tank serves an altimetric portion of the city, not necessarily planimetrically continuous, ensuring a suitable water pressure in each network section.

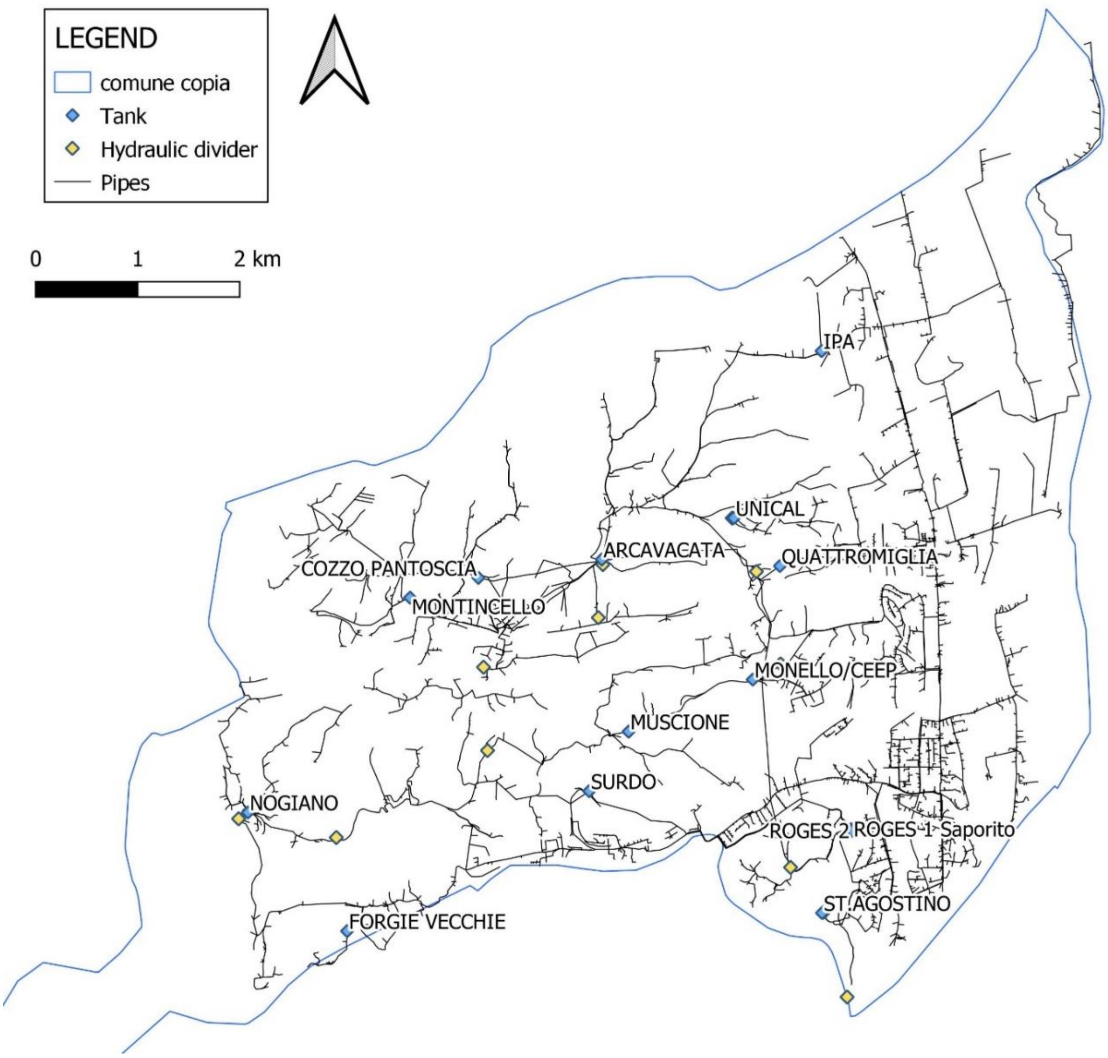

Figure 3.1.3 *Rende* WDN. Tanks names and locations.

The network tanks store the water supplied by regional aqueducts. Table 3.1.1 summarizes the average flow served by the aqueducts. Table 3.1.2 reports information regarding the tanks storage volume, outlet flow and elevation.

Cozzo Pantoscia is the main WDN tank. Thanks to the considerable storage capacity it also supplies other network tanks. The flow rate delivered by *Cozzo Pantoscia* (105 l/s) includes the values entering the *Roges* pair and *Ceep/Monello* tanks.

Aqueduct	Manager	Flow (l/s)
Abatemarco	So.Ri.Cal.	157
Capo D'Acqua	So.Ri.Cal.	38
Crocetta	So.Ri.Cal.	37

Table 3.1.1 Aqueducts list and flows supplied to the city tanks.

Tank name	Volume [m^3]	Average** outgoing flow (l/s)		
		Abatemarco	*Capo D'Acqua*	*Crocetta*
*Cozzo Pantoscia**	18.000	105.0		
*Roges (per zona Roges)**	400	45.0		
*Roges (per zona Saporito)**	400	22.5		
Ceep/Monello	700	30.0		
Arcavacata	250	40.0		
Quattromiglia	350		38.0	
Sant'Agostino	150	12.0		
Nogiano	500			13.0
Malvitani/Forge Vecchie	150			6.0
Surdo	250			9.0
Muscione	50			4.0
Montincello	50			5.0
IPA	50			
* Tanks supplied by *Cozzo Pantoscia* ** Annual average values				

Table 3.1.2 Tanks outgoing flow and volume summary.

3.1.2 WDN PIPES

The pipe network schematized in Figure 3.1.3 extends for about 250 kilometres. The pipes used are mainly made of steel, Figure 3.1.4. The nominal pipe size distribution is described in Table 3.1.3.

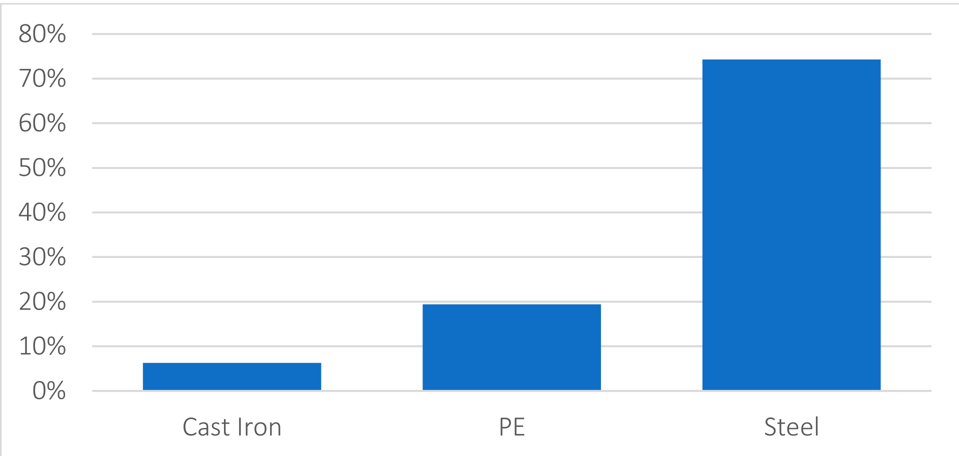

Figure 3.1.4 Length percentage of pipes divided for constituting materials.

DN	Length	%
3/8"	5367.01	2.17%
1/2"	10080	4.08%
3/4"	42522.46	17.20%
1"	32517.64	13.16%
1 1/4"	10274.29	4.16%
40mm	34517.94	13.96%
50mm	23426	9.48%
60mm	4644.47	1.88%
80mm	16643.09	6.73%
90mm	2667.7	1.08%
100mm	31135	12.60%
125mm	6354.88	2.57%
150mm	4712.23	1.91%
200mm	15371.52	6.22%
350mm	6952.59	2.81%

Table 3.1.3 Length [meter] and percentage of pipes divided for nominal pipe diameter.

3.2 Water distribution network digitization

The water company does not have an updated and complete network digital model available. This section deepens the main operations of data collection and homogenization. *Rende*'s WDN is digitized in a GIS environment. As described in **Chapter 2**, it is necessary to collect data and characterize all the water system physical components.

3.2.1 Data collection and inventory

The water company made available the network plans in a CAD drawing. The tables containing the network planimetric layout were draft for graphical display purposes (thematic and project map). The entire network plan is divided into seven tables, representative of the municipal different areas:

- *Settimo di Rende;*
- *Cozzo Pantoscia;*
- *Università della Calabria;*
- *Quattromiglia;*
- *Centro storico;*
- *Saporito;*
- *Metropolis.*

Each table contains the planimetric information on a portion of the network, suitably overlaying the *Calabria* technical map at 1:5000 scale (*Carta tecnica regionale 5000*). Information on the material and nominal diameter of the pipes are shown in graphical form. A colour legend assigned to pipes represents the material, each pipe has labelled the nominal pipe diameter.

The maps and plans cartographic purpose constitutes a criticality in the GIS database creation. The CAD drawing contains data about elevation, network topology and information on buildings but does not organize the data in layers. It was necessary to extract the information to isolate the network topology from other data.

3.2.2 GIS digital network model construction

The digital model of the CAD format is imported into the GIS environment and converted in ESRI shapefile format. The seven tables, appropriately merged, did not have a cartographic DATUM. The WDN is reprojected using an adequate transformation. The projection correctness verification is carried out by comparing the pipe planimetric layout with the thematic cartography. The cartography used consists of a set of orthophotos, 1:10000 scale, made available by the *Geoportale Regionale*[1] (*Regional Geoportal*), the Google Earth digital cartography and some thematic shapefiles (e.g. building scheme, road graph, administrative limits) of the *Regional Database* at 1:5000[2].

[1] http://geoportale.regione.calabria.it/opendata

[2] DB Geotopografico scale 1:5.000, 2008 updated to the technical rules D.M. 10/11/2011

In the tables boundary merging areas it was necessary to correct the phase shift errors due to the re-projection and it was also necessary to eliminate some redundant network areas due to the overlapping.

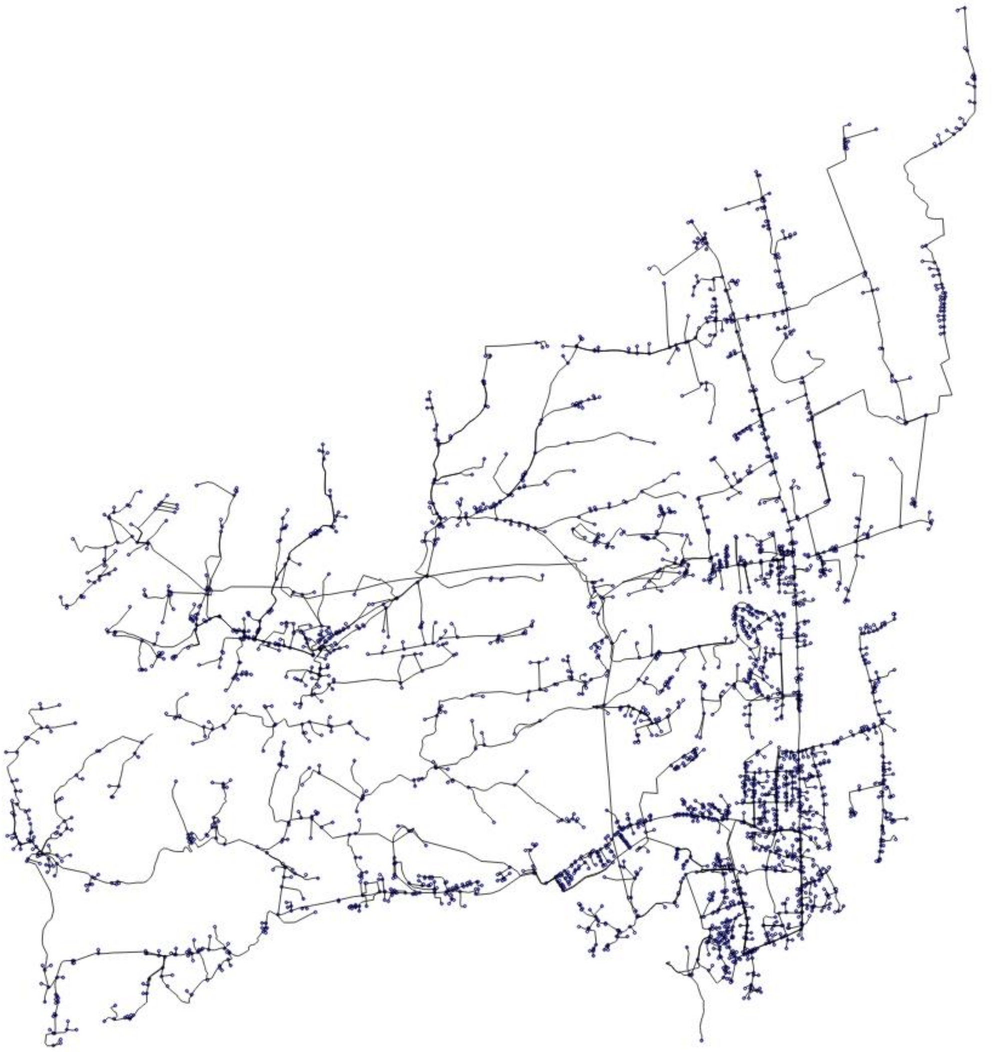

Figure 3.2.1 Complete digital model for *Rende* WDN.

3.2.3 NETWORK PLANIMETRIC AND TOPOLOGIC SCHEME

After the correction of macro errors due to scaling and projection, it is necessary to validate the network planimetry and update the topology of the elements. The validation process corrects projection errors (mismatches) and verifies planimetric layout and consistency with the road graph and the building scheme.

In the topology correction and refinement phase, it is necessary to verify the pipe connections correctness. In a hydraulic model, the pipes overlap may or not imply their connection. In the cartographic drawings, line-jumps represent crossing but not connected pipes, Figure 3.2.2

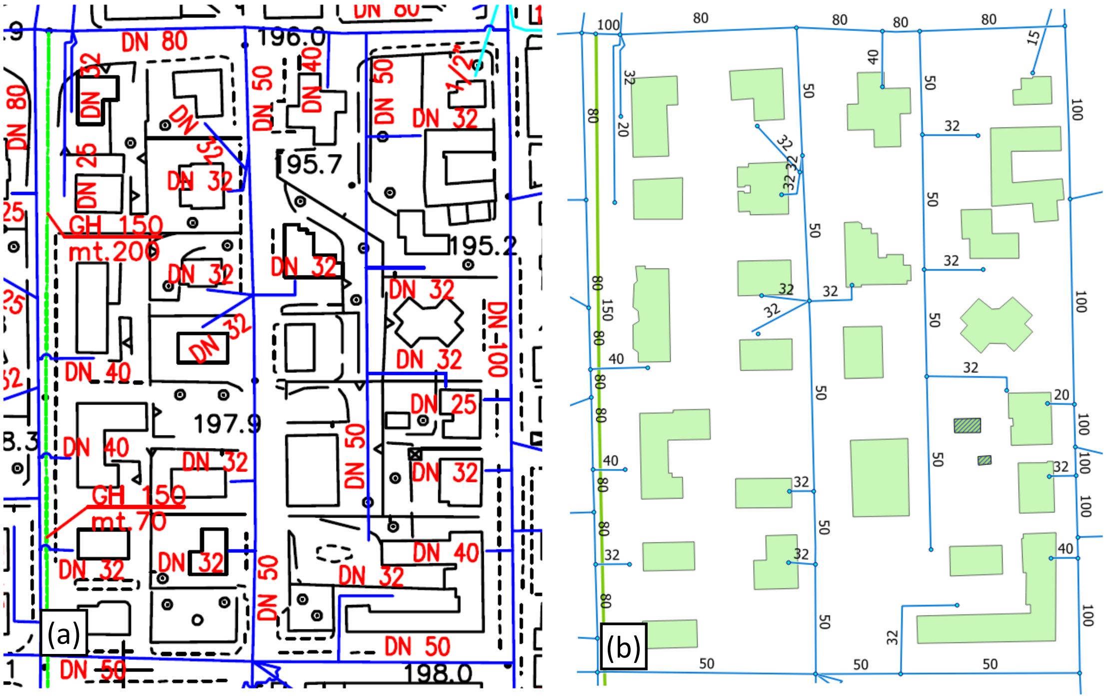

Figure 3.2.2 (a) Planimetric map extract containing graphic information on pipe material and diameter (b) GIS map of the area corresponding to the extract shown in (a).

In the model construction, the symbolisms and representative conventions were eliminated. The validated network model contains only the relational information of the various elements (topology) but lacks information on individual elements characteristics data. The network topology model enables the generation of the "junctions" elements. The junctions are generated where more than one pipe converges, or where one single pipe ends, or where there are pipe characteristic changes. The junction generation is an automatic and incremental process. The automatic generation allows identifying any topology residual errors, such as the connection of independent pipe connections or the lack of pipe subdivision in the event of a change in the pipe hydraulic-geometric characteristics.

3.2.4 Pipe characteristics

All the line type network elements must be characterized by a planimetric and topological trace. The element length can be obtained, with a good approximation, using the flat projection length. The projection and Datum assignment allows automating the length assessment.

The material and nominal diameter are not uniquely assigned to pipes in the available cartography. The material is encoded in a colour legend scale. The material assignment was carried out automatically because each pipe material was organized in different layers. This assignment required validation to verify the consistency of the materials with the pipes nominal diameters and the network topology. According to the technicians' indications, the network is mainly composed of steel and cast iron pipes. Recent extensions and replacements use polyethene pipes.

The pipe material knowledge allowed assigning indicative roughness values (Williams and Hazen 1908, Williams and Hazen 1914). The roughness value depends on the pipe material, age and condition.

Material	Material (tag)	C (Hazen-Williams)
Steel	S	140
Cast Iron	CI	80
Polyethylene	PE	140

Table 3.2.1 Hydraulic roughness values assigned depending on the pipe material.

The cartography indicates the pipe diameter using a textual label associated with the nearest pipeline (Figure 3.2.2a). This information coding criterion makes impractical an automatic assignment. This criterion causes ambiguities in the case of pipe sections of limited extension, areas containing many adjacent pipes, and changes in diameter along a pipe. Assigning diameter required a manual procedure. This phase needs further validation and correction, to ensure consistency with the topology. The validation took place in collaboration with the company technical staff that integrated the data with some detailed maps and personal knowledge.

The cartography presents the pipes using the nominal diameter. The hydraulic model requires the use of the actual internal diameter. The pipes external diameter and wall thickness is obtained by crossing material and nominal diameter data with the pipe types commonly used in network construction. Since the characteristics of the pipes originally used in the construction are not available, the model use standard-pipe catalogue diameters:

- ***UNI EN 10255:2007*** *Non-Alloy steel tubes suitable for welding and threading - Technical delivery conditions;*
- ***UNI EN 545:2010*** *Ductile iron pipes, fittings, accessories and their joints for water pipelines - Requirements and test methods;*
- ***ISO/TC 5*** *Ferrous metal pipes and metallic fittings;*
- ***UNI EN 12201-1:2012*** *Plastics piping systems for water supply, and for drainage and sewerage under pressure - Polyethylene (PE) - Part 1: General.*

3.2.5 Network altimetry

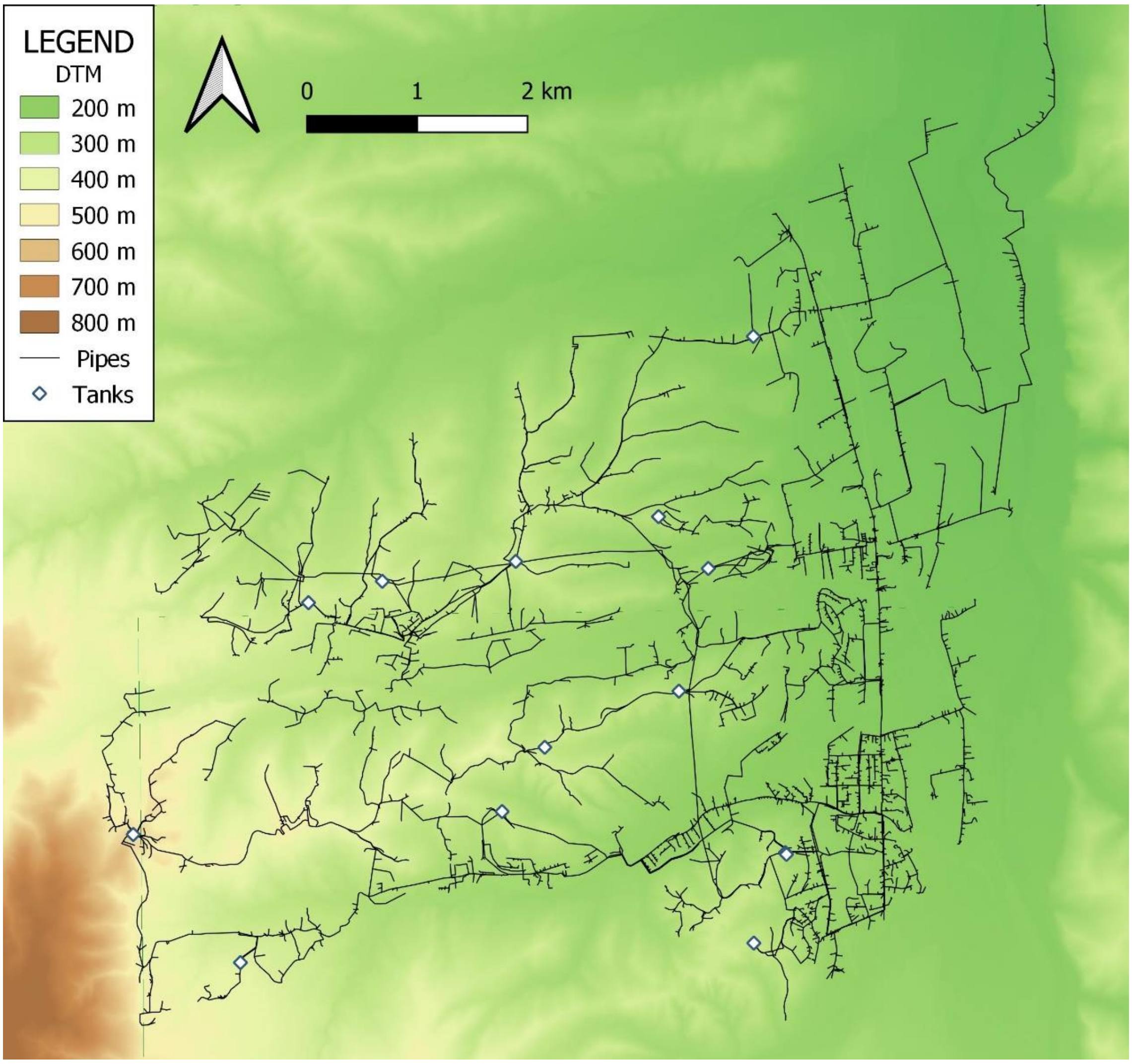

Figure 3.2.3 Digital Elevation Model of the network area.

All the "nodes" which constitute the network model must contain topographic information to uniquely define the spatial position of the element. The junctions elevation is obtained by sampling a DEM. The DEM (5-meter square cells) is available on the *Geoportale Regionale,* Figure 3.2.3.

3.2.6 Water storage tank characteristics

The tanks data, provided by the water company, is incomplete. The elevation of the individual tanks is assessed case-by-case basis because part of the tanks is buried or partially buried.

The tanks available data is shown in Table 3.1.2. For each tank, the data known are the average annual outgoing flow, the volume and the location. To model the tanks it is necessary to define the tank geometry and the operating levels (minimum and maximum). The software requires the definition of maximum, minimum and initial water levels for each tank. These data are obtained from the Digital Surface Model[3] (DSM) provided in Google maps, Figure 3.2.4.

Figure 3.2.4 Ceep/Monello tank characteristic surveying. The tank has two circular storage compartments partially buried. The figure shows a tank plan view (Google Earth).

The DMS allow characterizing the shape and number of tanks and obtain the base elevation and the operating levels for each tank, Table 3.1.2. The tanks were considered as only cylindrical storage with the base area and level identical to those surveyed. The tanks equivalent diameter of a cylindrical tank are calculated as:

$$d_{eq} = \sqrt{\frac{4\,A}{\pi}} \qquad \text{Eq. 3.2.1}$$

[3] DSMs differ from DEM or DTM because they contains both natural and built/artificial features.

In which A is the total base area. Therefore, once the diameter and tank capacity are known, the maximum level is:

$$H_{max} = \frac{W_{max}}{\pi\left(\frac{{d_{eq}}^2}{4}\right)}$$ **Eq. 3.2.2**

- W_{max} Total tank capacity;
- H_{max} The maximum level of the equivalent cylindrical tank.

In the case of (partially) buried tanks, the height of the structure beyond the ground level ($H_{sampled}$) is compared with the maximum water level inside the tank. The burial depth is estimated as:

$$z_{burial\ depth} = H_{max} - H_{sampled}$$ **Eq. 3.2.3**

Table 3.2.2 summarize the network tanks surveyed characteristics:

Tank Name	**Height from ground [m]**	**Equivalent diameter [m]**	**Maximum water level [m]**	**Burial depth [m]**	**Base elevation [a.s.l.]**
Cozzo Pantoscia	6	59.1	6.5	0.5	364.1
Roges (per zona Roges)	6.0	6.7	11.4	5.4	266.5
Roges (per zona Saporito)	6.0	6.7	11.4	5.4	262.5
Ceep/Monello	5.0	14.1	4.5	0	275.1
Arcavacata	1.0	18.0	1.0	0	355.0
Quattromiglia	4.0	10	8.9	4.9	233.7
Sant'Agostino	5.0	5.9	5.5	0.5	325.3
Nogiano	3	18.3	1.9	0	530.6
Malvitani/Forge Vecchie	3.0	10.0	1.9	0	395.0
Surdo	3.0	11.0	2.6	0	325.0
Muscione	3.0	5.0	2.5	0	346.5
Montincello	2.0	6.7	1.4	0	367.5
IPA	2.0	5.6	2.0	0	204.0

Table 3.2.2 Summary of tanks' topological, geometric and hydraulic data.

3.2.7 End-users water demand assessment

The hydraulic model requires the definition of the overall network water demand and its temporal variability. The overall demand contains the end-user demand and the water losses to be assigned to the network junctions. Table 3.1.2 provides the annual average consumption of the network. The available information is scarce and incomplete. The dataset contains the anonymized end-users consumption data, deriving from the meter readings carried out by Operators in the period between 07/02/2018 and 24/09/2018. The meter readings cover two different time scans:

- The first reading, from 07/02/2018 to 10/04/2018;
- The second reading, from 09/07/2018 to 24/09/2018.

As can be seen from Figure 3.2.5, the listed meters do not cover all the user connections.

Figure 3.2.5 End-users' private water meter location map.

The meter data consist of the cumulative water volume reading. Having at least a pair of readings for each meter allows defining an average consumption in the sampled period. The network counts 7829 meters but not all the readings are usable. All the incomplete or negative data have been excluded reducing the meter number to 5383, 68.7% of the total.

Zone	Inhabitants
Arcavacata	1831
Cucchiaio II	74
Dattoli	191
Dattoli Sud	4
Difesa	175
Forge Vecchie	33
Isoletta	94
Longeni	109
Malvitani	389
Monticello	137
Nogiano	323
Quattromiglia-Roges-Commenda	22884
Rende	1404
Rocchi	10
Rocchi Est	271
San Biagio	115
San Biase	6
Santo Ianni	110
Santo Stefano	1795
Settimo Inferiore	126
Settimo Superiore	12
Surdo	1659
Tufo	60
Villana	12
Sparse houses	1731
Total	33555

Table 3.2.3 *Rende* municipality resident population data organized in zones.

The total water consumption obtained from the valid meter readings is estimated at 6431.5 m^3/day (74.43 l/s), corresponding to 2347500 m^3/year. Since part of the users is excluded due to invalid readings, the assessed consumption is increased. The total demand is up-scaled proportionally with the total number of meters. The total demand corresponds to 9361.6 m^3/d (108.35 l/s). The total assessed demand must be assigned to the network junctions. The assignment follows the population distribution. The municipality inhabitants are 33555 (latest ISTAT survey 01/01/2011) distributed by zones according to Table 3.2.3.

The city of *Rende* hosts the *University of Calabria* campus and many companies. In the population assessment, it is necessary to take into account the non-resident population. The campus hosts around 28,000 students, mostly from neighbouring municipalities and provinces. The population is set to an indicative value of 60,000 inhabitants to take into account the student population and the presence of other types of commuter inhabitants.

Using the daily water consumption obtained from the meter readings, the per-capita water demand of the municipality was estimated as:

$$d = \frac{W_{daily}^{tot}}{Pop} = \frac{9361.6\ {m^3}/{day}}{60000\ \text{inh}} = 156\ \frac{l}{inh\ day} \qquad \textbf{Eq. 3.2.4}$$

- W_{daily}^{tot} Total daily water consumption;
- Pop Total population;
- d Per-capita water demand.

The tanks supply to the network an average volume of 20044.8 m^3/day equivalent to 232 l/s, Table 3.1.2. The total per-capita water demand, which includes the water losses, estimated used the tank outlet, is:

$$c = \frac{20044.8\,{m^3}/{day}}{60000\ inh} = 344\,\frac{l}{inh\ day} \qquad \textbf{Eq. 3.2.5}$$

The comparison between the supply and the overall user consumption allows assessing the non-revenue water. Around 53% of the supplied water does not reach the end-users. A rate of water losses (real losses and apparent losses) greater than 50% indicates the presence of several critical issues. This value is in accordance with ISTAT 2015 which estimates that 50.89% of the drinking water is lost in the distribution networks.

End-user average water consumption	9361.6 m^3/day
Average supplied water	20044.8 m^3/day
Non-revenue water volume	10683.2 m^3/day
Non-revenue water volume percentage	53.3 %

Table 3.2.4 Estimate of water losses.

Demand distribution criterion

The water demand assignment on the network junctions requires the definition of a distribution criterion. Since the data characterizing the meters were incomplete and fragmented, the assignment took into account the population distribution.

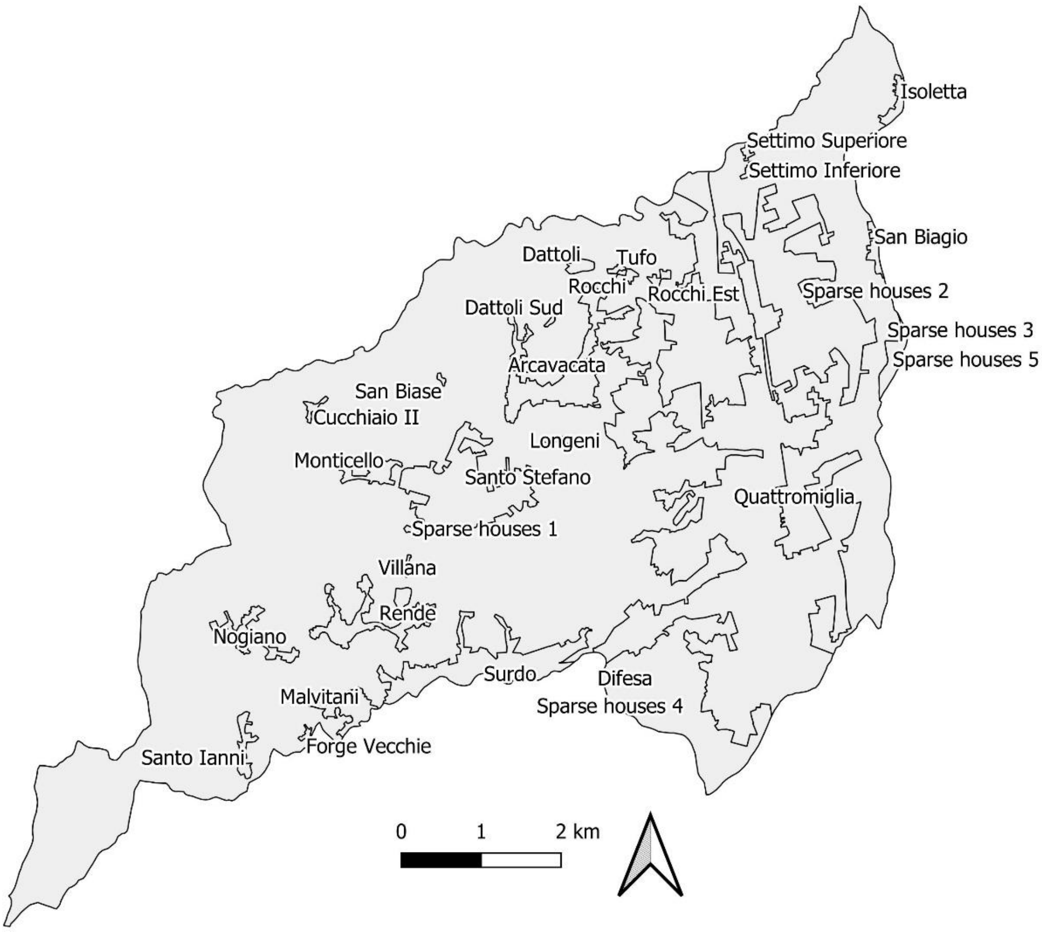

Figure 3.2.6 *Rende* municipality zoning map (ISTAT).

The assignment followed a zone criterion that took into account the inhabitants of each zone. By associating the inhabitants of each zone, Table 3.2.3, it is possible to assess the consumption of each zone proportionally:

$$Q_i^{loc} = Pop_i \, d \quad \text{Eq. 3.2.6}$$

$$c_i^m = \frac{Q_i^{loc}}{L_i^{tot}} \quad \text{Eq. 3.2.7}$$

in which for the i-th zone

- Q_i^{loc} Total water consumption;
- Pop_i Equivalent inhabitants;
- L_i^{tot} Total pipe length;
- c_i^m Water consumption per meter of pipe.

The total consumption is distributed over the pipes of the network proportionally to their length, allows calculating the demand for each network pipe (The service pipes connecting tanks are exluded). The pipe demand is plit between the pipe starting and ending junction.

The water consumption distribution criterion does not take into account the non-resident population. The hypothesized non-resident population residing in the municipality of *Rende* is 26445 (obtained from the difference between the total hypothesized total population and the resident one). The student population is located in the areas adjacent to the university campus: *Dattoli, Dattoli Sud, Rocchi, Rocchi Est, Arcavacata, Roges-Quattromiglia-Commenda*. The students are distributed proportionally to the zone areal extension. More than 90% of the student population falls within the *Roges-Quattromiglia-Commenda* area, Table 3.2.5.

Zone	Area [ha]	Non-resident population
Dattoli Sud	1.109733	32
Rocchi	3.1583	90
Rocchi Est	3.982224	114
Arcavacata	70.36752	2007
Dattoli	4.734247	135
Quattromiglia	843.6082	24067
Total	926.9602	26445

Table 3.2.5 Non-resident population for each zone.

3.3 WDN HYDRAULIC MODEL CONSTRUCTION

The collection and organization of the geometric and hydraulic data of the constituent network elements allowed the digital model construction in a GIS environment. Overall, the model, shown in Figure 3.2.1, consists of 3058 junctions, 3124 pipes and 13 tanks.

Digital model refinement

The work environment change to the simulation software enables an in-depth check of the topology and element characteristics. The network hydraulic model is simulated in average consumption conditions using a steady-state simulation. The validation made it possible to identify more precisely:

- Network isolated areas, unreachable by flows supplied by tanks;
- Topology errors;
- Errors in the Pipe diameters;
- Errors in the Junction elevations;
- Identification of of out of service pipes, through discussion with the technicians.

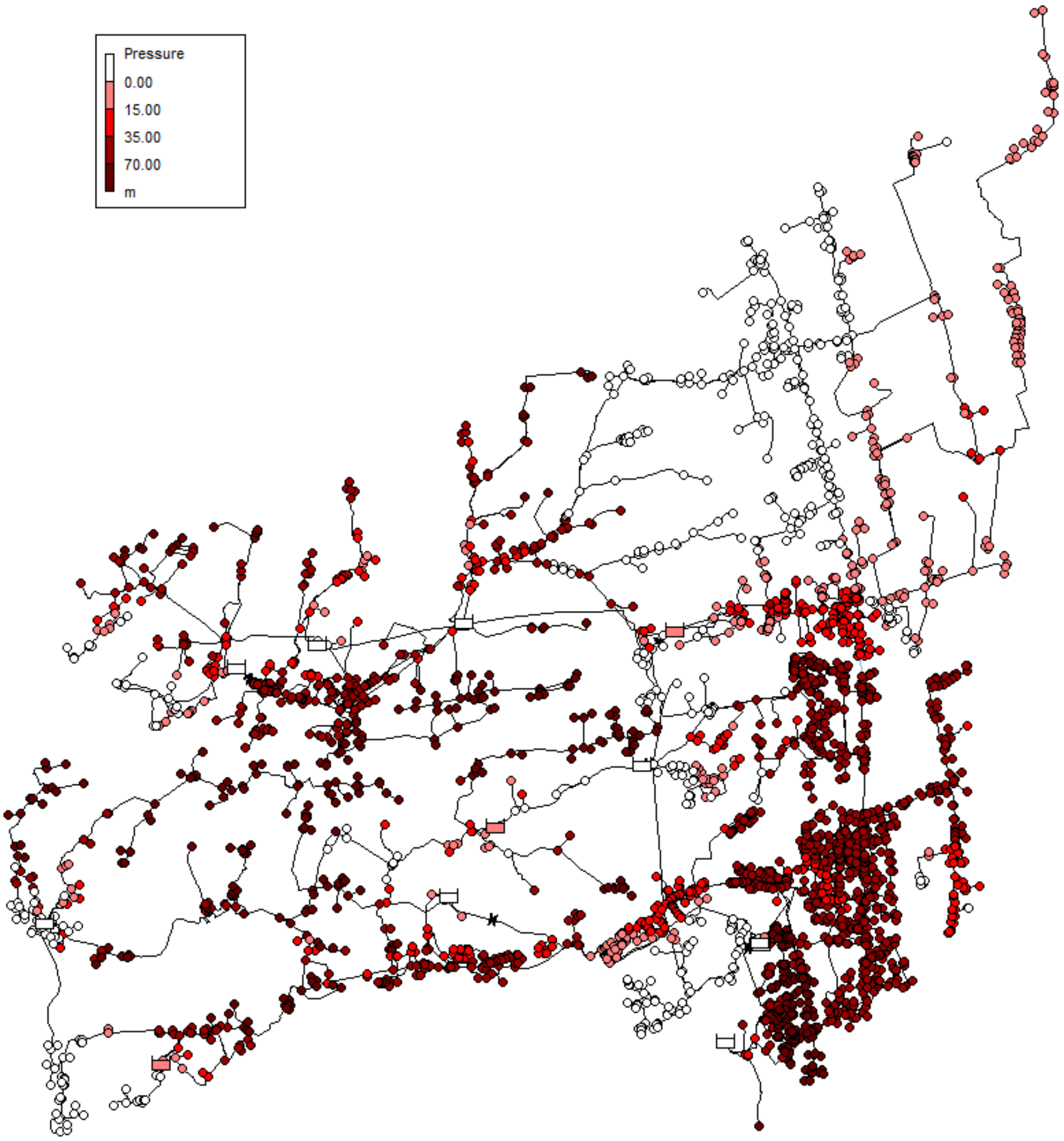

Figure 3.3.1 WDN node pressure map for the first hydraulic simulation.

3.3.1 First simulation scenario

The network model, devoid of obvious errors, allowed performing a steady-state simulation. The simulation showed critical pressure operating regime. The worst critical issues affect the areas of *Nogiano, Forge Vecchie/Malvitani* (southwest) and the northern area of *Quattromiglia-Commenda-Rende*. The simulation output, shown in Figure 3.3.1, does not represent the actual network operating regime.

Through dialogue with the technical staff about the simulation results, it was clear that the flow supplied by the tanks is inconsistent with the values of Table 3.1.2. A check of the So.Ri.Cal regional distribution infrastructure allowed identifying some supply pipes serving tanks and the presence of some hydraulic dividers connected directly to the network supplying a greater hydraulic head to the network, Figure 3.3.2.

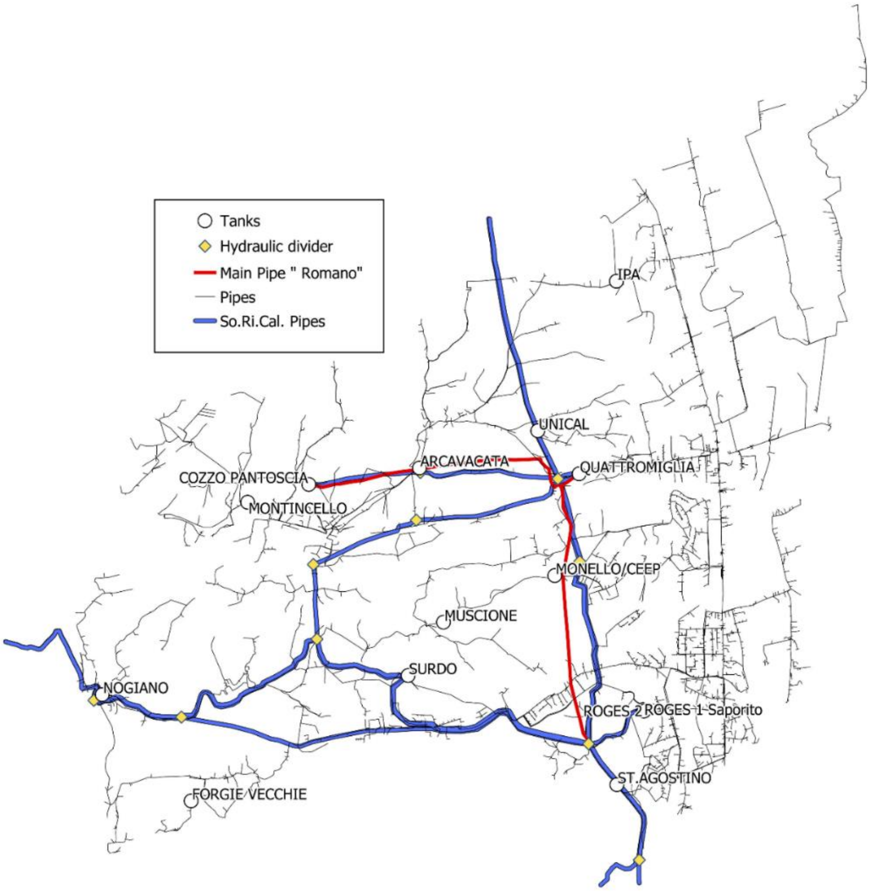

Figure 3.3.2 *Rende* WDN scheme overlapped on the regional aqueduct scheme.

3.3.2 Updated simulation scenario

The integration of the information about the dependencies of the *Rende* WDN with the *So.Ri.Cal.* water mains network allowed correcting some of the topological inconsistencies, Figure 3.3.2.

The *Cozzo Pantoscia, Arcavacata, Sant'Agostino, Ceep/Monello* and the two *Roges* tanks are supplied by the *Abatemarco* aqueduct. In Table 3.1.2, *Cozzo Pantoscia* supplies *Ceep/Monello* and the two *Roges* tanks through the *Romano* pipeline. The part of the *Romano* pipeline that supplies the *Arcavacata* reservoir and the *Quattromiglia* pair is therefore closed.

The *UNICAL* tank, supplied by the *Abatemarco* aqueduct, is not shown in the diagrams since it belongs to the Campus independent network. The *Quattromiglia* tank is supplied by *Capo D'Acqua* aqueduct, while the *Nogiano, Forge Vecchie/Malvitani, Monticello, Muscione, and Surdo* tanks are fed by the *Crocetta* aqueduct. The updated *Rende* WND scheme takes into account the dependencies on the regional aqueduct. Considering the layout of the *So.Ri.Cal* aqueducts, the hydraulic divider supply water through *Crocetta* aqueduct to *Muscione, Nogiano, Forge Vecchie/Malvitani and Monticello* tanks. The *Romano* acqueduct, and the other pipes connecting the hydraulic divider to the tanks are exluded from the model. The few zones connected directly to the water main are connected to reserviours (i.e. Figure 3.3.3). Non-return valves, CV (Check Valve) are added at the inlet and outlet of the tanks to ensure that the supply of the tanks was consistent with the indications in Table 3.1.2.

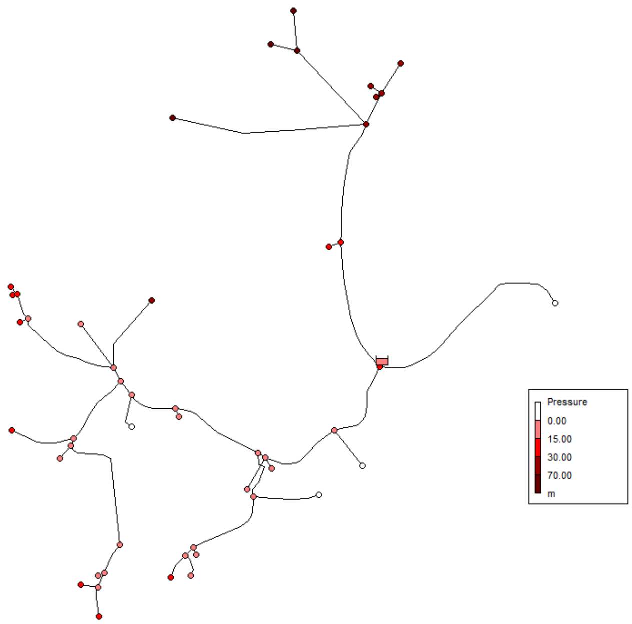

Figure 3.3.3 Network zoom-in. The connection of the sub-network that supply *Difesa* to the *Romano* aqueduct is modelled as a reservoir.

The modelling of the hydraulic dividers changes the network-operating regime allowed slightly improving the pressure regime. The lack of information for the *Quattromiglia-Commenda-Rende,* and *Arcavacata* area prevented the completion of the network modelling.

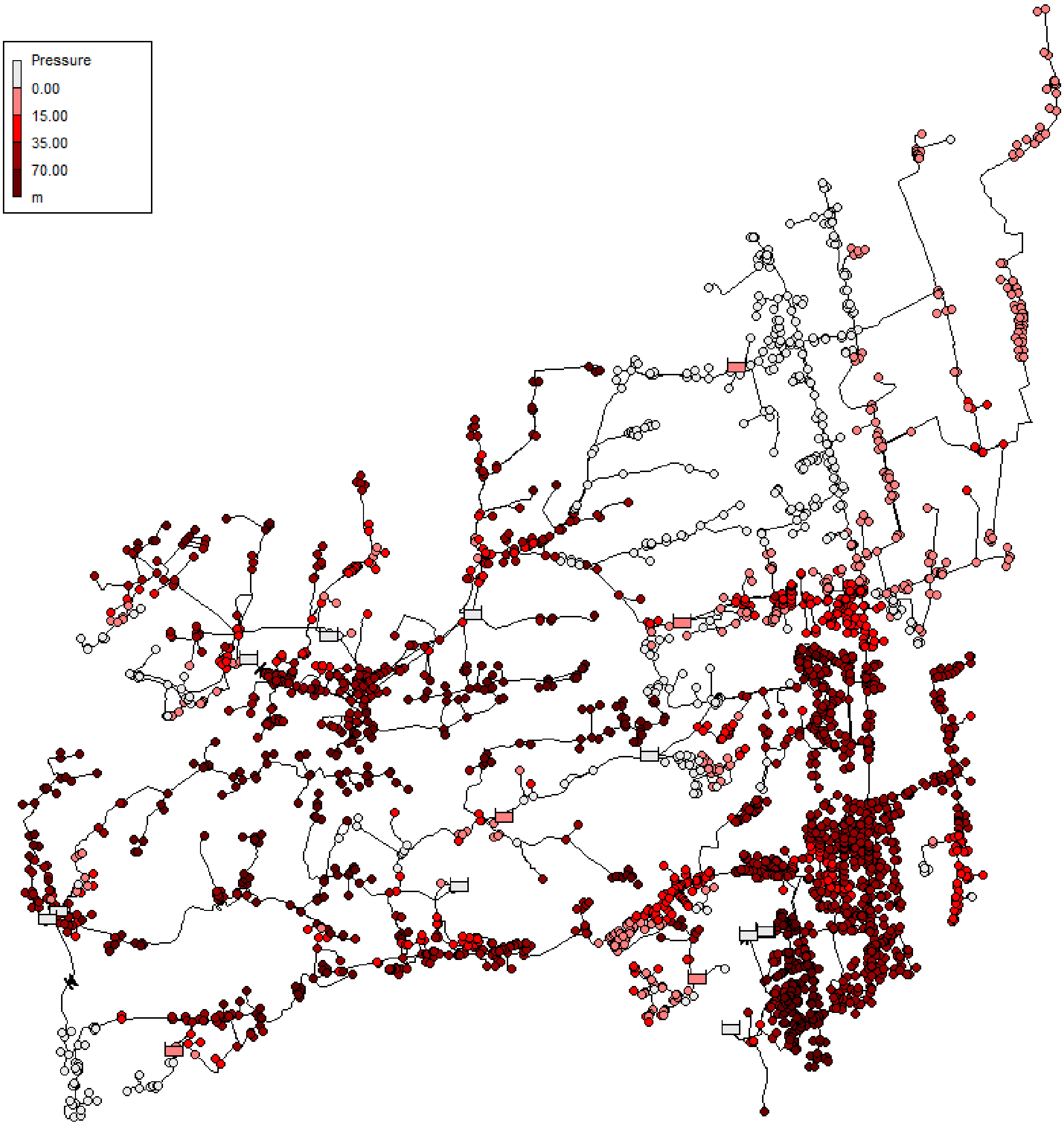

Figure 3.3.4 WDN nodes water pressure map for the second hydraulic simulation.

3.4 State of the art and future developments

Despite the efforts made for the construction of a digital model of the WDN supplying the Rende municipality, the incomplete and uneven data prevented the achievement of a maturity of the model such as to guarantee its hydraulic simulation. For correct modelling, it is mandatory integrating the missing or fragmented information. The network has a complex scheme, all the tanks are connected to a looped and non-partitioned network. There are few data on the relationship of the network with the adjacent ones and the water exchange. The water demand assignment is currently the most approximate procedure. The absence of telemetry meters or an extensive user consumption reading campaign, associated with the very high rate of non-revenue water, involves large approximations. Better consumption data, characterizing the water supply time variation, should reduce the model inaccuracy.

The use of telemetry meters to quantify the tanks and dividers inlet and outlet can enable a water balance, making it possible to characterize the water consumption on an hourly or sub-hourly scale. The water exchange accounting with neighbouring networks and with the regional aqueduct network should clarify the network overall water consumption. The use of an advanced meter infrastructure, using smart user-meters would simplify and rectify the demand assignment, allowing obtaining better simulations.

3.5 BIBLIOGRAPHY

- Williams, G. S., & Hazen, A. (1908). Hydraulic Tables: The Elements of Gagings and the Friction of Water Flowing in Pipes, Aqueducts, Sewers, Etc. as Determined by the Hazen and Williams Formula and the Flow of Water Over Sharp-edged and Irregular Weirs, and the Quantity Discharged, as Determined by Bazin's Formula and Experimental Investigations Upon Large Models. J. Wiley & sons.
- Williams, G.S.; Hazen, A. (1914), Hydraulic tables: the elements of gagings and the friction of water flowing in pipes, aqueducts, sewers, etc., as determined by the Hazen and Williams formula and the flow of water over sharp-edged and irregular weirs, and the quantity discharged as determined by Bazin's formula and experimental investigations upon large models. (2nd revised and enlarged ed.), New York: John Wiley and Sons

4 Serra San Bruno Water Distribution Network digital model

4.0 Summary

4.1 GEOGRAPHICAL FRAMEWORK

Serra San Bruno is a *Calabrian* municipality located in the *Vibo Valentia* Province. The entire municipal area extends for 39.6 km^2 and hosts a population of 6282 inhabitants. The area is located in a valley between mountains and has an average altitude of 790m.a.s.l. The infrastructure management is entrusted to the local administration.

Figure 4.1.1 Serra San Bruno municipality geographical .

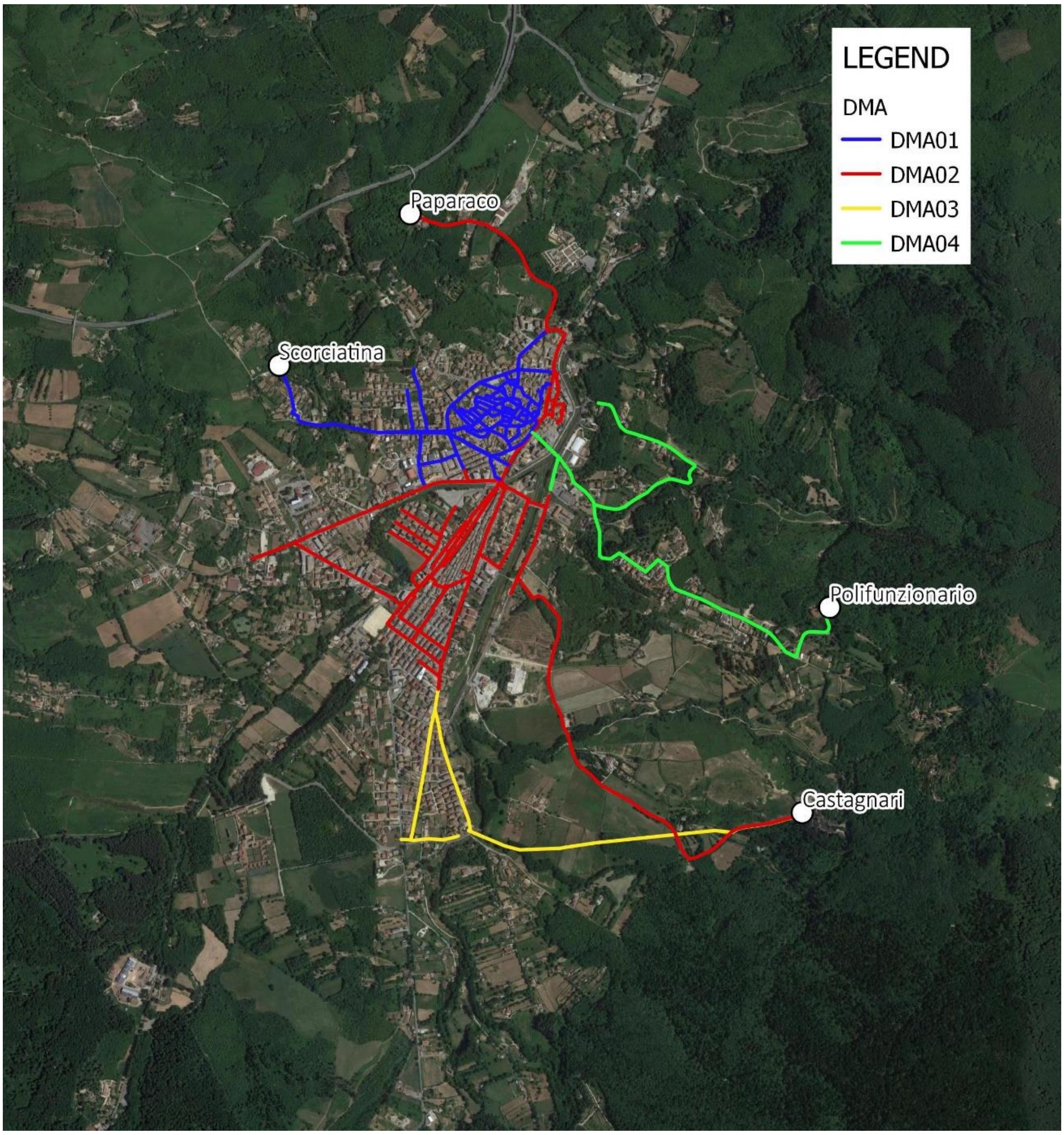

Figure 4.1.2 *Serra San Bruno* municipality map. Google Satellite background.

4.1.1 District Metered Areas

The WDN that serves the municipality is organized into four DMAs of variable extension Figure 4.1.2. Each district is served by the only reservoir, which supplies the network continuously, Table 4.1.3. The WDN counts two main and two secondary districts:

- DMA01, supplied by the *Scorciatina* tank, serves the historic part of the city Figure 4.1.3;
- DMA02, supplied by the *Paparaco* tank, goes through the old city area, serving part of the users. The district covers the most recently urbanized areas, Figure 4.1.4. In the hydraulic diagram, the DMA02 can reinforce the supply to the *Castagnari* tank in an emergency;
- DMA03 serves a very limited area of a new urbanization located south of the city Figure 4.1.5. The district is served by the Castagnari tank;
- DMA04 has a limited extension and serves a peripheral area of the city (east) characterized by sparse houses in small agglomerations, Figure 4.1.6. The area is served by the *Polifunzionario* tank.

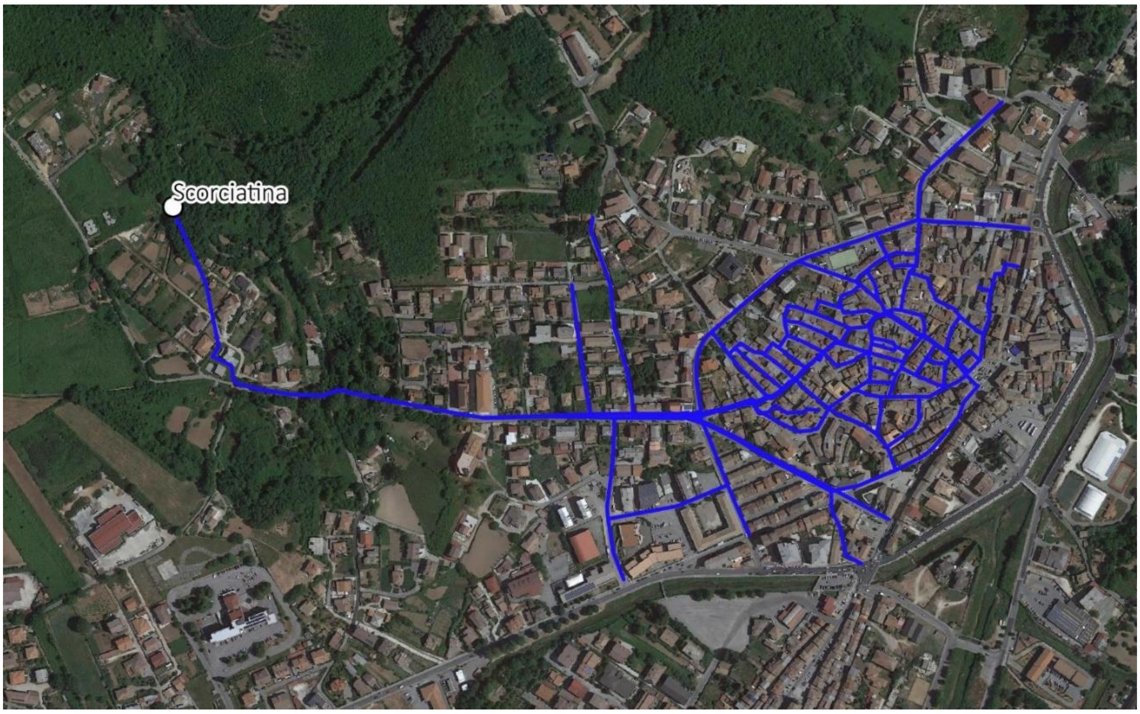

Figure 4.1.3 DMA01 plan view, Google Satellite background.

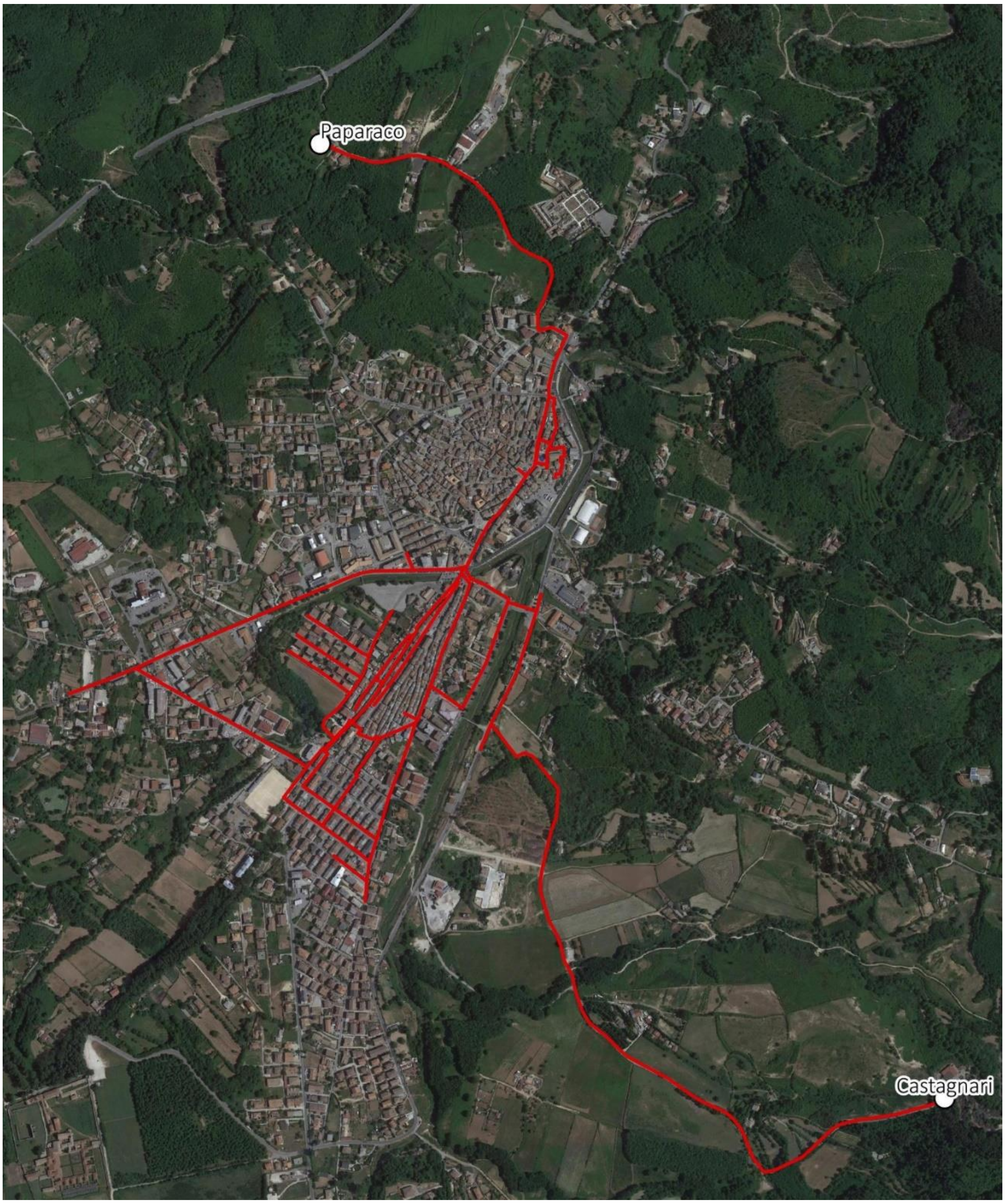

Figure 4.1.4 DMA02 plan view, Google Satellite background.

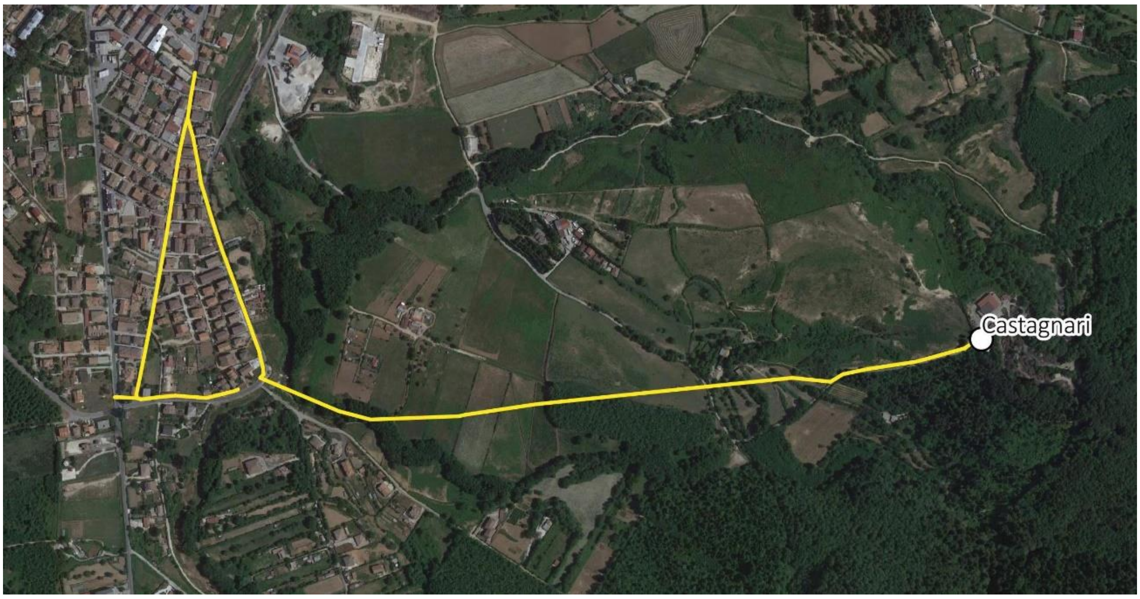

Figure 4.1.5 DMA03 plan view, Google Satellite background.

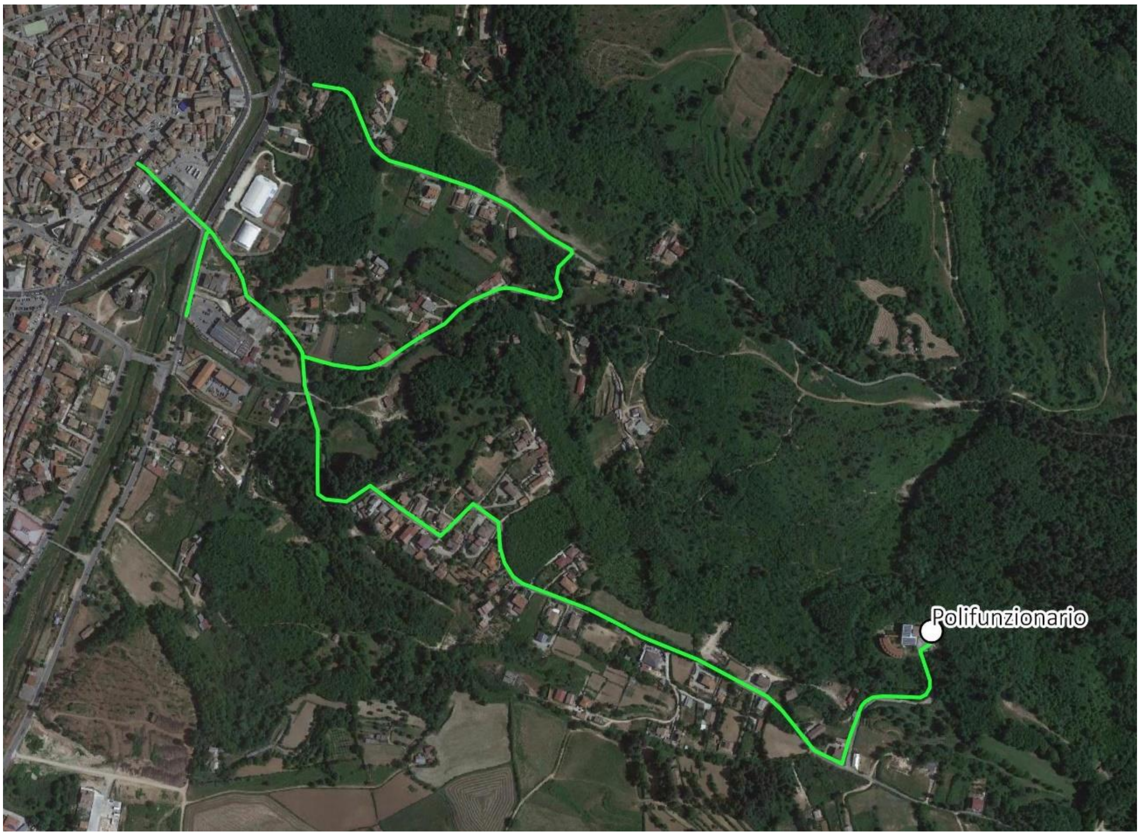

Figure 4.1.6 DMA04 plan view, Google Satellite background.

4.1.2 AQUEDUCTS AND TANKS SUPPLYING THE NETWORK

As for the previous section, the WDN counts four DMAs served by the respective tanks, Table 4.1.1. The water resource used in the network comes in part from wells and springs present in the municipal area, Figure 4.1.7. *The regional water resources company, So.Ri.Cal. owns Paparaco* tank. The tank is supplied by the regional network aqueduct. Nine springs and three wells supply *Castagnari, Polifunzionario and Scorciatina* tanks (Table 4.1.2).

Tank Name	Manager	Water source	Elevation [m.a.s.l.]	Volume [m3]
Scorciatina	Municipality	Spring Well	839.87	Undefined
Paparaco	So.Ri.Cal.	Well	859.73	1600
Castagnari	Municipality	Spring Well	926.03	500
Polifunzionario	Municipality	Well	897.97	11000

Table 4.1.1 Tanks outgoing flow and volume summary.

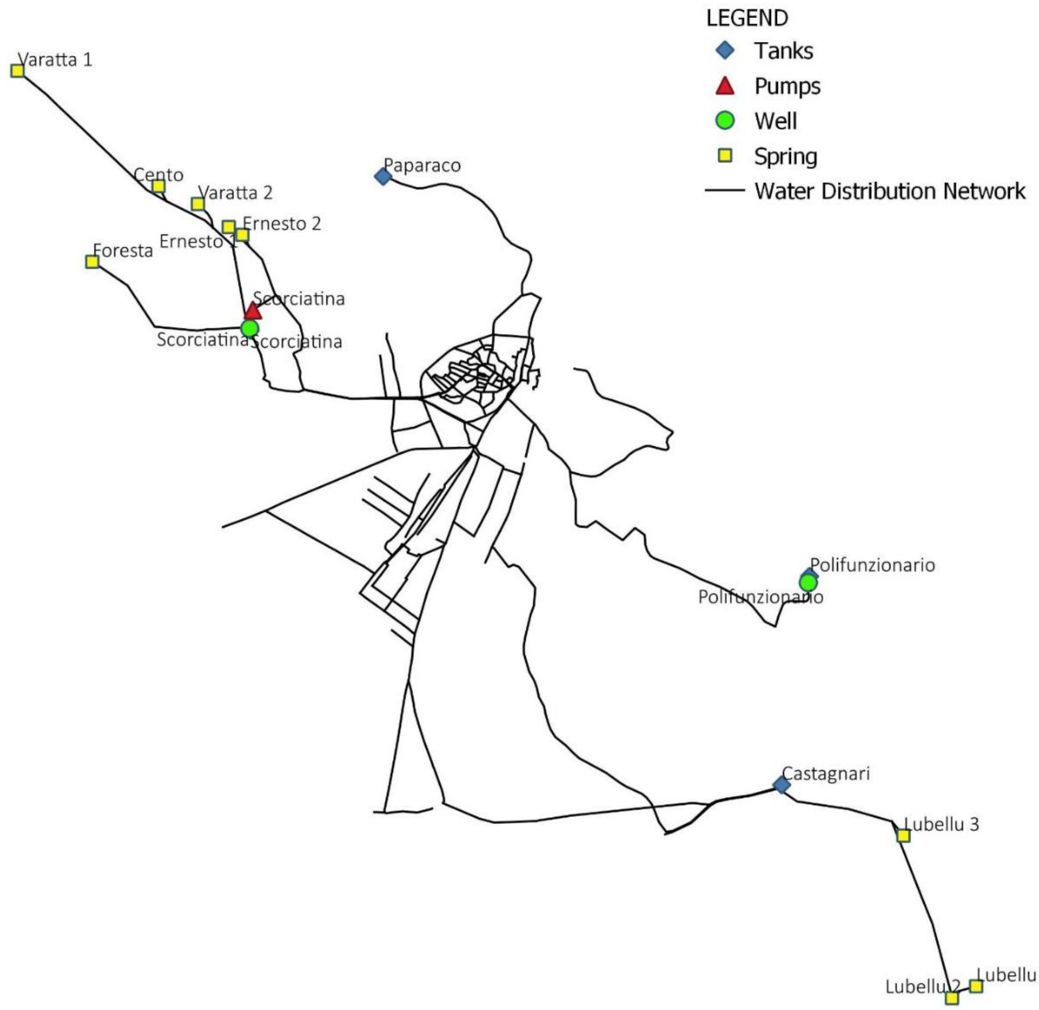

Figure 4.1.7 S erra San Bruno water supply system scheme.

Name	Type	Elevation [a.s.l.]	Supplied tank
Castagnari 1	Well	-	*Castagnari*
Polifunzionario	Well	-	*Polifunzionario*
Scorciatina	Well	-	*Scorciatina*
CENTO	Spring	893.2	*Scorciatina*
VARATTA_1	Spring	925.3	*Scorciatina*
VARATTA_2	Spring	875.2	*Scorciatina*
ERNESTO_1	Spring	850.4	*Scorciatina*
ERNESTO_2	Spring	850.3	*Scorciatina*
LUBELLU_1	Spring	1120.5	*Castagnari*
LUBELLU_2	Spring	1110.5	*Castagnari*
LUBELLU_3	Spring	980.5	*Castagnari*
FORESTA	Spring	875.3	*Scorciatina*

Table 4.1.2 Summary of the wells and springs supplying the system.

4.1.3 WDN PIPES

The hydraulic modelling involves the urban part of the system (the WDN). The pipes connecting the springs and wells to tanks are excluded from the modelling due to a lack of data. The following network statistics refer to the characteristics of the modelled network. The WDN consists of 23.3Km of pipes divided between the four DMAs, Table 4.1.3.

	Pipe length [km]	Pipe number	Junction number	Main Tank
DMA01	7.4	224	190	*Scorciatina*
DMA02	10.6	125	119	*Paparaco*
DMA03	2.5	5	4	*Castagnari*
DMA04	2.8	8	8	*Polifunzionario*

Table 4.1.3 DMA characteristics summary.

The network was built in different periods. The areas serving the historic centre are characterized by great diameters and materials variability, due to the maintenance, pipe replacement, and subsequent city expansion. Table 4.1.4 shows the distribution of nominal diameters for each DMA, and Table 4.1.5 and Figure 4.1.8, respectively, show the length and percentage of each material constituting the pipes (PE - Polyethylene; FZ - Galvanized Iron; AC - Steel; GH - Cast Iron).

Diameter	DMA01	DMA02	DMA03	DMA04	WDN
1/2"	83.3	-	-	-	83.3
1 1/4"	25.2	736.2	-	-	761.3
20mm	358.7	-	-	-	358.7
50mm	584.1	794.8	-	927.6	2306.5
60mm	528.1	-	-	364.9	893.0
63mm	246.1	241.0	-	124.9	611.9
75mm	-	-	2559.1	1417.3	3976.4
80mm	1078.3	562.3	-	-	1640.6
100mm	2900.0	2420.7	-	-	5320.7
120mm	-	2317.8	-	-	2317.8
125mm	917.3	625.6	-	-	1543.0
150mm	-	1304.0	-	-	1304.0
200mm	666.5	620.7	-	-	1287.1
250mm	-	55.2	-	-	55.2
300mm	-	904.7	-	-	904.7
Total	7387.5	10583.0	2559.1	2834.8	23364.4

Table 4.1.4 Length [meter] of pipes divided for nominal pipe diameter.

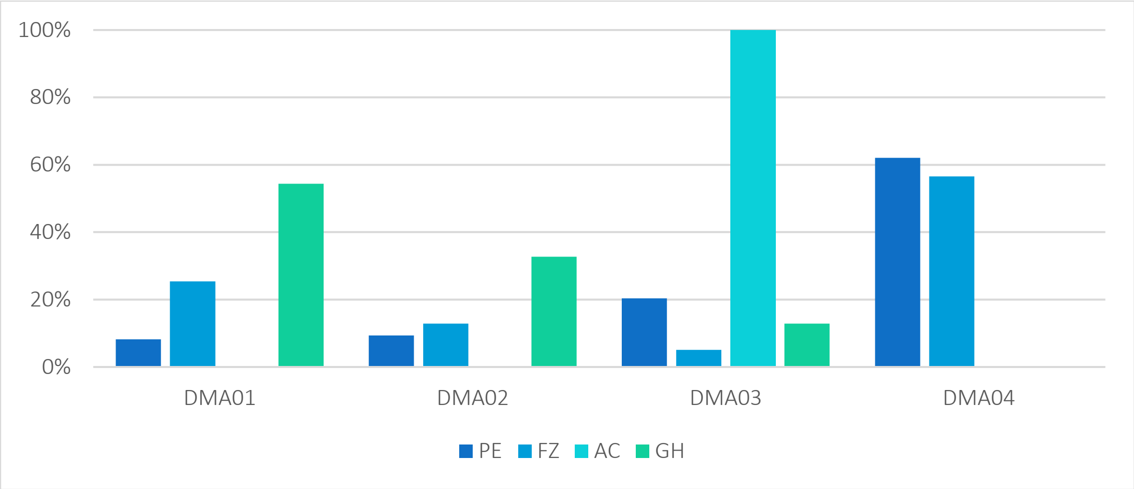

Figure 4.1.8 Length percentage of pipes divided for constituting materials for each DMA.

Material	DMA01	DMA02	DMA03	DMA04	WDN
PE	604.8	2690.0	0.0	1542.2	4837.1
FZ	692.6	1363.9	0.0	927.6	2984.1
AC	1501.9	542.4	2559.1	364.9	4968.4
GH	4588.2	5986.6	0.0	0.0	10574.8
Total	7387.5	10583.0	2559.1	2834.8	23364.4

Table 4.1.5 Length [meter] of pipes divided for constituting materials.

4.2 WATER DISTRIBUTION NETWORK DIGITIZATION

A private engineering services company, for a mapping project regarding the ATO[1] Calabria n.4, Vibo Valentia, surveyed the WDN data. The project has the objective of network mapping, the creation of a complete and updated database, and the creation of GIS support for the networks belonging to *ATO*. The information collected is organized in detailed monographs:

- Wells and devices: Contains detailed information on manholes, springs, wells and regulation devices. The information collected is encoded in a hand-filled field card. In some cases the information is accompanied by hand-drawn hydraulic detailed diagrams;
- Leaks: Contains information deriving from a leak detection campaign (02/04/2009 to 12/05/2009). Seven medium and small leaks were identified. For each detected leak a field form contains detailed information;
- Modelling: The monograph contains the WDN scheme and operating regime data. There are insights on:
  - Hydraulic scheme;
  - Water demand;
  - Districtization;
  - Model simulation and calibration;
  - Water balance.
- Flows and pressures: contains monitoring data on pressures and flows. Temporary instrumentation allowed monitoring for a period ranging from 2 to 4 days starting from 12/06/2009. The document shows flow and pressure values measured in four manholes and the tanks outgoing flow and level (level measurements are available for two of the tanks);
- Final report: This document summarizes and organizes the information obtained and in the monographs.

For digitization, in this work, the information encoded in the monographs is available (pressure and flow measurements, location of leaks). The topological and planimetric scheme of the network is available in CAD thematic cartographic drawings.

4.2.1 GIS DIGITAL NETWORK MODEL CONSTRUCTION

Similarly to what was done for the Rende network model construction in **Chapter 3**, the digital CAD model was converted into a GIS compatible format. The network CAD drawing is divided into four tables that were merged and projected. The drawing contains information on network planimetry, pipe material and diameter, Figure 4.2.1. The scaling and georeferencing procedure required the correction of errors generated in the overlapping table zones. The correction and validation of the planimetric layout used the technical cartography at a scale of 1: 5000[2] .

[1] ATO are territorial management areas defined by current Italian/European legislation, detailed in **Chapter 2.**

[2] http://geoportale.regione.calabria.it/opendata

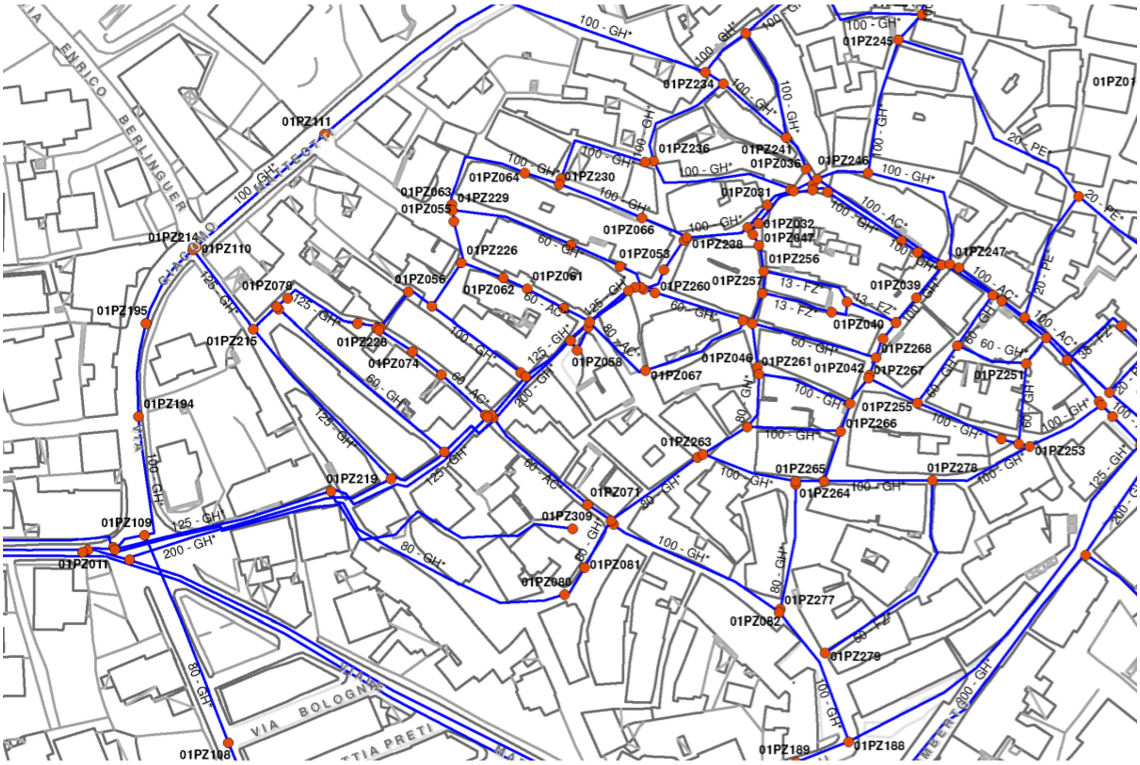

Figure 4.2.1 Planimetric map extract containing material and diameter information. Background cartography map (DBTR *Carta Tecnica* 5000)

4.2.2 Network planimetric and topologic scheme

Following the plano-altimetric layout definition, it is necessary to validate the network topology. The CAD drawing used is subject to graphic simplification that affects the topology representation. It is necessary to discern which pipe intersections are effective connections and which are crossings without connections. These criticalities are eliminated by evaluating the consistency of the water scheme represented and using the monograph detailed schemes.

4.2.3 Pipe characteristics

The pipe characteristics are encoded in the available cartography. Both the material and the nominal diameter are reported in a label adjacent to the pipe. Pipe characteristics are manually assigned. The entry requires a verification and correction phase of any entry errors. The map scale prevents the correct assignment for a cluster of small elements, and, in some areas, there are multiple indications for a single pipe section, Figure 4.2.2. The characteristics assignment for elements, in which the indications were absent or ambiguous, took place through the integration of the detailed scheme reported in the monographs.

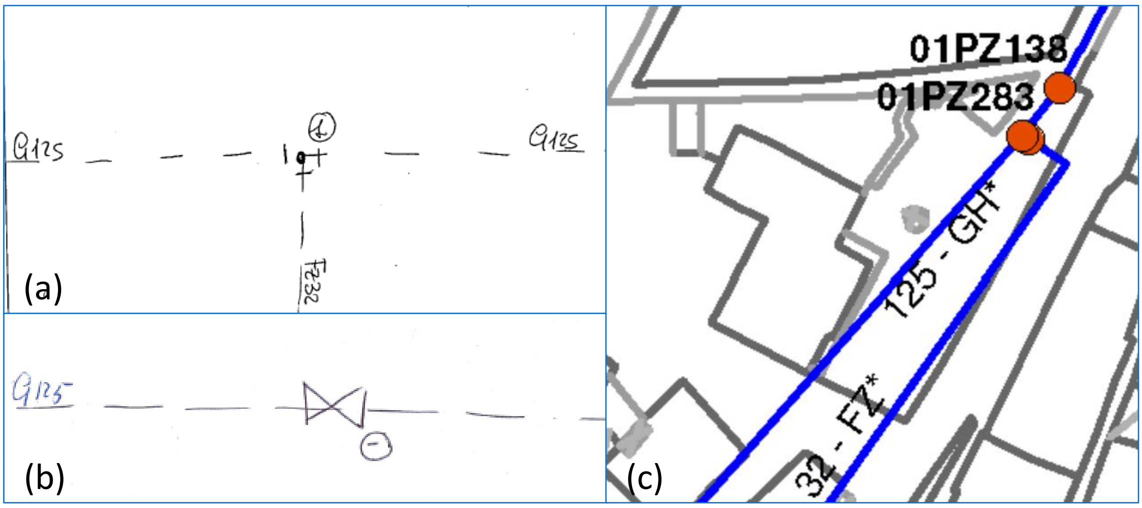

Figure 4.2.2 CAD planimetric map and monography extracts comparison. (a) Detail of field sheet (Regulation device monography) manhole N.138 (b) Detail of field sheet (Regulation device monography), manhole N.283 (c) detail of CAD planimetric map containing both manholes N.283 and N.138.

In the absence of specific indications on the pipes internal diameter and condition it is necessary to define the internal diameter and the roughness. An indicative roughness was defined depending on the material (Williams and Hazen, 1908, Williams and Hazen, 1914).

Material	Tag	Hazen-Williams Roughness
Steel	AC	140
Cast Iron	GH	80
Galvanized Iron	FZ	130
Polyethylene	PE	140

Table 4.2.1 Hydraulic roughness values assigned depending on the pipe material.

Similarly, to **Chapter 3**, pipes internal diameters comply with the UNI EN standards:

- *UNI EN 10255:2007 Non-Alloy steel tubes suitable for welding and threading - Technical delivery conditions*;
- *UNI EN 545:2010 Ductile iron pipes, fittings, accessories and their joints for water pipelines - Requirements and test methods*;
- *UNI EN 12201-1:2012 Plastics piping systems for water supply, and for drainage and sewerage under pressure - Polyethylene (PE) - Part 1: General*;
- *UNI EN 10240:1999 Internal and/or external protective coatings for steel tubes - Specification for hot dip galvanized coatings applied in automatic plants*.

4.2.4 Network altimetry

The company that collected the data, used a simplified criterion to define the elevation of the network elements. The pipes altimetry layout consider a constant slope defined based on the depth of the starting and ending point of the surveyed pipe sections. The CAD model has no indications of the pipes burial depth. The missing information is recovered from a DEM[3] with 5m square cells, Figure 4.2.3. In the absence of specific indications, junction burial depth is set to1 meter below the ground level.

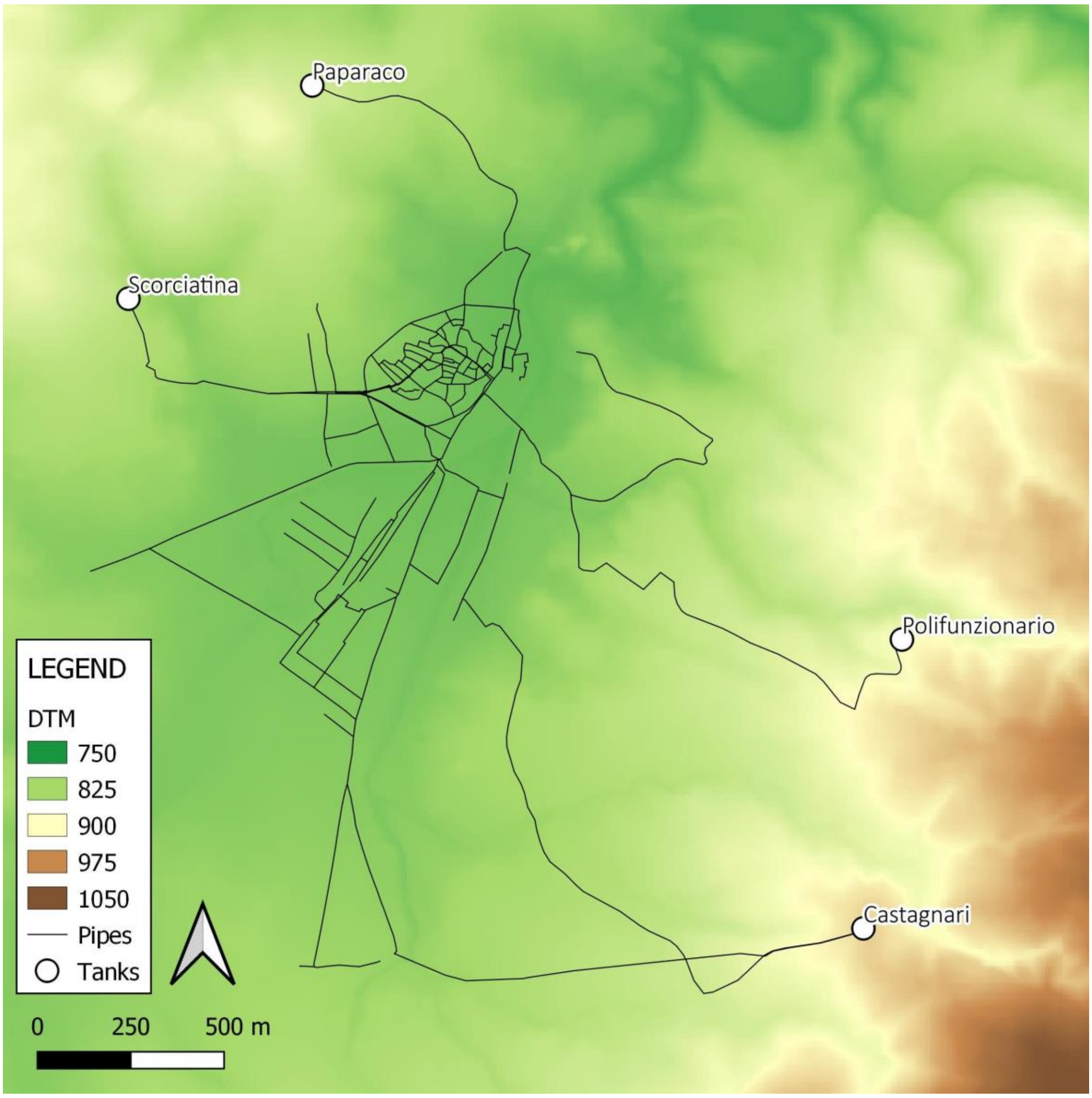

Figure 4.2.3 Digital elevation model of the network area.

[3]http://geoportale.regione.calabria.it/opendata

4.2.5 End-users water demand assessment and Demand distribution criterion

The water demand allocation is one of the constituents of hydraulic modelling subject to a high degree of uncertainty. The water supply of domestic and commercial users used in this work is assessed as part of the network digitalization project (2009) and is 122.1 litres/inh/day.

As part of network digitization, the company has used an assignment criterion that takes into account the areal extension of the inhabited areas. The demand is assigned proportionally to the area of the Thiessen-Voronoi polygon associated with the junction. This work case study uses a similar criterion. The delimitation of the areas with different population density (Figure 4.2.4) allows defining a weight to be assigned to each demand junction. The normalized weight is used to distribute the flow outgoing from each tank.

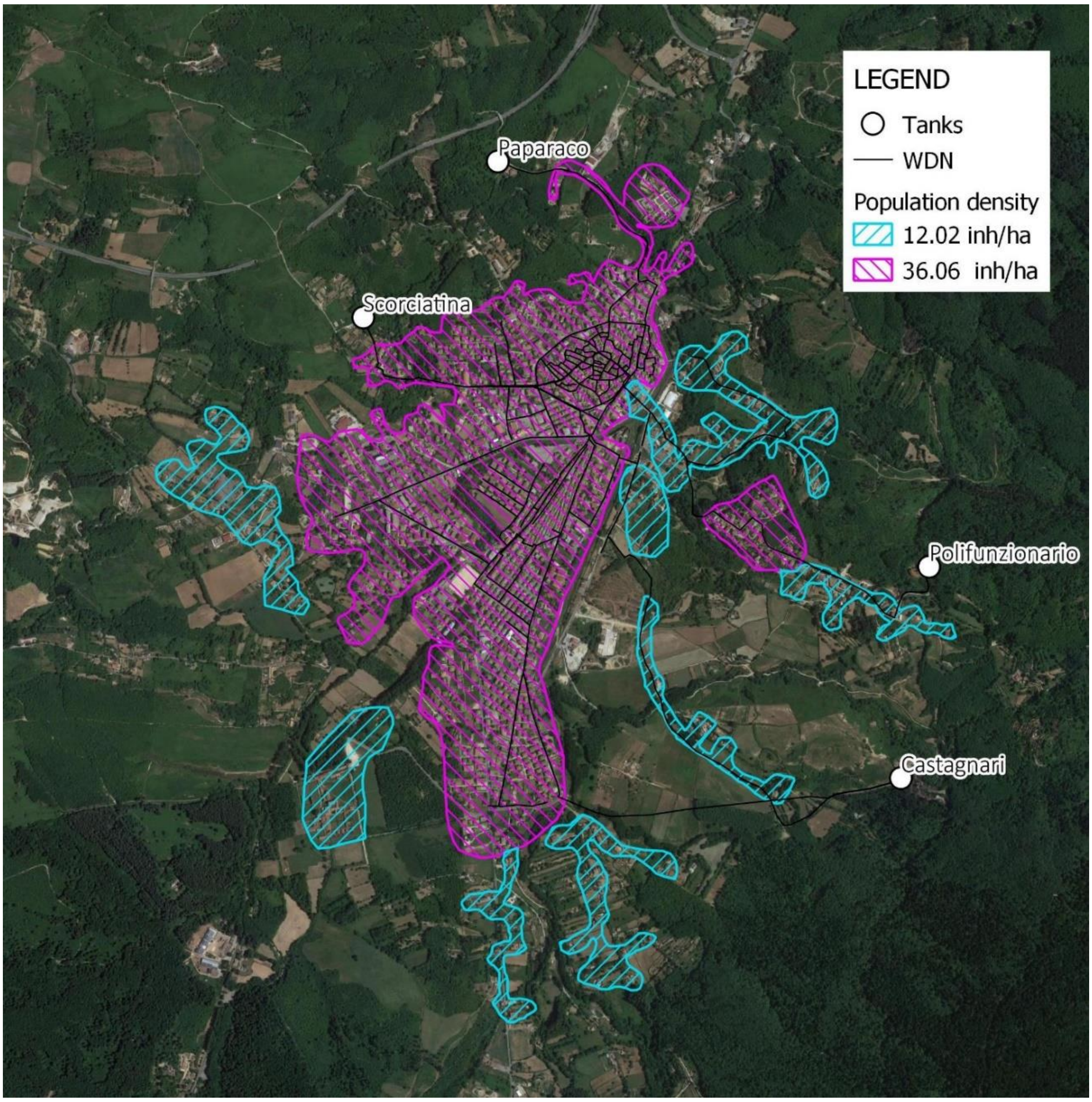

Figure 4.2.4 *Serra San Bruno* inhabitants density map. Google Satellite background.

The zones served by the WDN are divided into two categories:

- High-density areas: 36.06 inh/ha;
- Low-density areas: 12.02 inh/ha.

Thiessen-Voronoi polygons have been generated for each junction inside the network. The overall area covered by the polygons coincides with the known-density areas. Each junction area of influence falls into one or more density zones. Note the junction polygon area and its density, it is possible calculating the equivalent population. The water demand assignment does not use the monograph per-capita dotation value but uses an inhabitants-weight criterion. The weight of each junction is calculated proportionally to the equivalent population assigned to the junction compared to the total population served in the DMA. For a generic Node i:

$$\delta_i = \frac{A_i Den(A_i)}{A_{DMA} Den(A_{DMA})} \quad \text{Eq. 4.2.1}$$

where:

- δ_i Junction weight;
- A_i Junction Thiessen-Voronoi polygon area;
- $Den(A_i)$ Value of the population density in the area A_i(If area A_i covers different population densities zones, the density value is calculated as an average area-weighted value);
- A_{DMA} Total area of the district containing the junction;
- $Den(A_{DMA})$ Average inhabitants density for the district containing the junction.

The weight calculated in Eq. 4.2.1 allows assigning the junction water demand as:

$$q_i(t) = \delta_i \, Q_{DMA}(t) \quad \text{Eq. 4.2.2}$$

in which:

- $Q_{DMA}(t)$ Outgoing flow rate from the tank serving the district containing the junction;
- $q_i(t)$ Junction water demand.

Numerical example

For each DMA the equivalent population esteem depends on the area covered by the overall Thiessen-Voronoi polygons area of the DMA's junctions, Table 4.2.2. To better define the demand assignment procedure, the application for the DMA03 is shown. The DMA count five junctions. The weight is obtained with Eq. 4.2.1, as shown in Table 4.2.2.

DMAs	Eq. Inhabitants
DMA01	1440
DMA02	3234
DMA03	1064
DMA04	545
Total	6283

Table 4.2.2 Assessed equivalent inhabitants for each DMA

ID	Density	Area	Eq Inh	δ_i	q_i
-	inh/ha	ha	Inh	-	l/s
Junc_303	36.06	0.686	24.7	0.023249	0.829124
Junc_304	36.06	11.373	410.1	0.385499	1.266824
Junc_319	36.06	7.935	286.1	0.268965	0.688852
Junc_305	36.06	4.315	155.6	0.146253	1.815699
Junc_70	36.06	5.194	187.3	0.176035	0.109501
Total		29.5	1063.9	1	4.7

Table 4.2.3 Water junctions weight and water demand assigned to each DMA03 junctions.

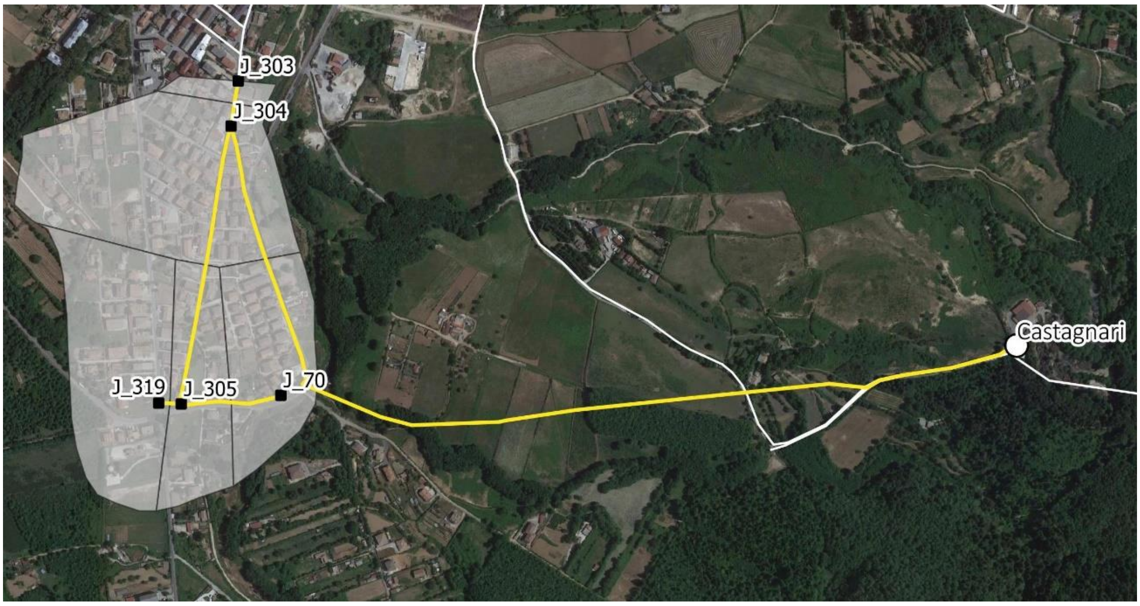

Figure 4.2.5 Thiessen-Voronoi polygons associated with the DMA03 junctions. Google Satellite background.

4.2.6 Requested pressure values for performance assessment

The WDN model is built to be used in applications that concern the network performance regime. The network performance indices involve the use of design conditions, Chapter 7. The definition of the project/requested conditions presupposes the knowledge of target values to be achieved for flow and pressures, during the operation of the network. The features of the inhabited centre served allows characterizing the requested pressure or the requested piezometric head. For the *Serra San Bruno* network, the served buildings height is used as a reference to define the required pressure value. The city is divided into blocks consisting of buildings of uniform height. Eq. 4.2.3 define the pressure as a function of the blocks building storeys, allocating 3 meters for each floor plus a 10 meter.

$$h^* = 3 * N_B + 10 \; [m] \qquad \text{Eq. 4.2.3}$$

Where:

- h^* Block requested pressure;
- N_B Block building storeys.

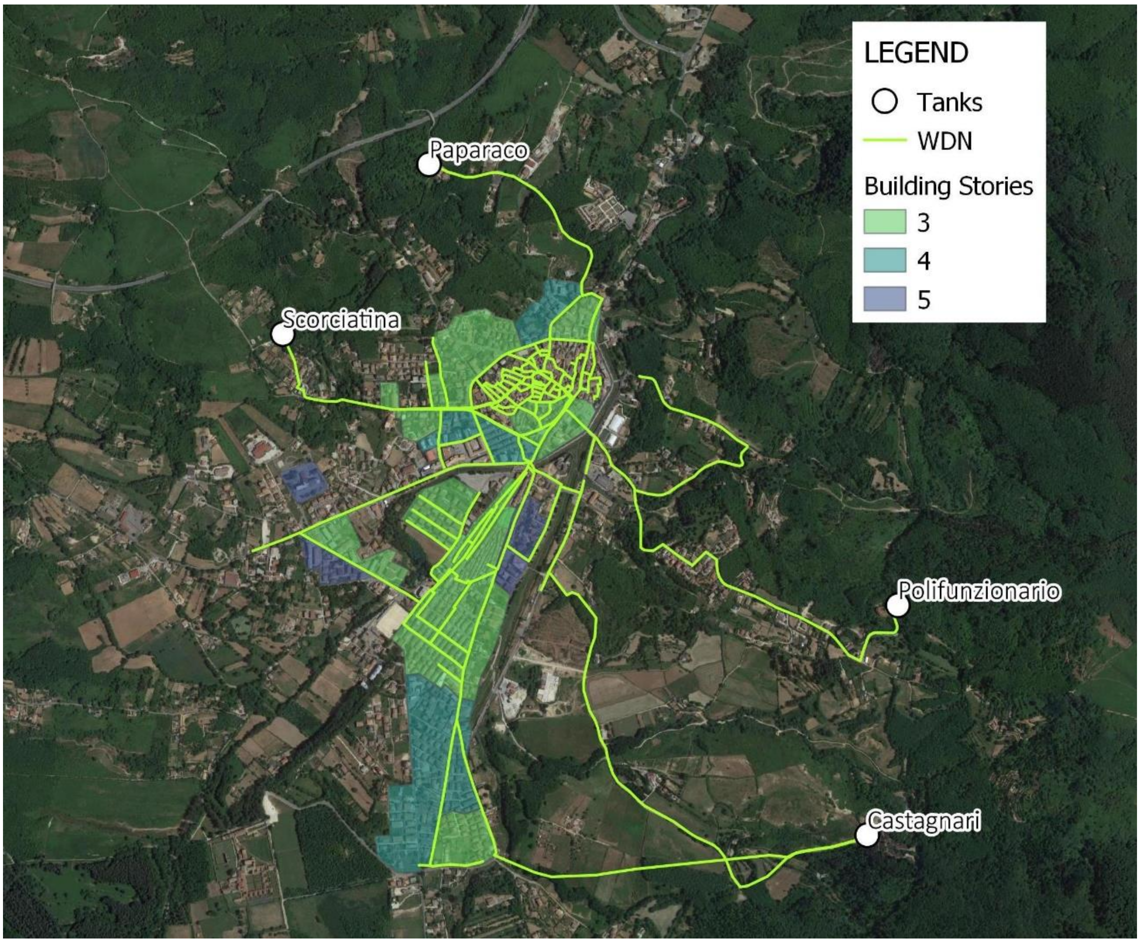

Figure 4.2.6 Building height characterization for *Serra San Bruno* city area. Google Satellite background.

The requested pressure assignment is carried out according to a proximity criterion. Each junction is associated with the maximum value of h^* of the blocks found in its vicinity. The building storeys survey uses the Google DSM. The DSM does not cover most of the modelled area. The storeys data were recovered by information obtained from the ground view (Street View, Google).

Figure 4.2.6 shows the blocks map containing the average storeys for the structures for the inhabited centre of *Serra San Bruno*. The peripheral areas and the old town are characterized by houses of limited height, for which a height of 2 storeys has been assigned.

4.2.7 Pressure and flow metering

The network digitalization campaign reports a series of measurements necessary for the hydraulic model calibration and construction. The WDN is not equipped with telemetry instrumentation. The metering surveys used temporary instruments. The metering campaign sampled the tank level and outgoing flow and pressure in some network manholes. The surveys have a sampling of 5 minutes, and a duration of at least two days, Table 4.2.4 and Table 4.2.5.

	Castagnari	*Polifunzionario*	*Paparaco*	*Scorciatina*
Log start time	12/06/2009 11.00	12/06/2009 11.30	12/06/2009 12.40	12/06/2009 11.00
Log end time	15/06/2009 9.20	15/06/2009 9.40	16/06/2009 9.20	15/06/2009 8.30
Mean flow	4.14	0.57	14.12	3
Maximum flow	4.71	1.51	25.83	5.63
Minimum flow	3.28	-0.08	4.39	0.99
Metered variable	Level, flow	Level, flow	Level, flow	Flow

Table 4.2.4 Tank temporary metering logs details summary.

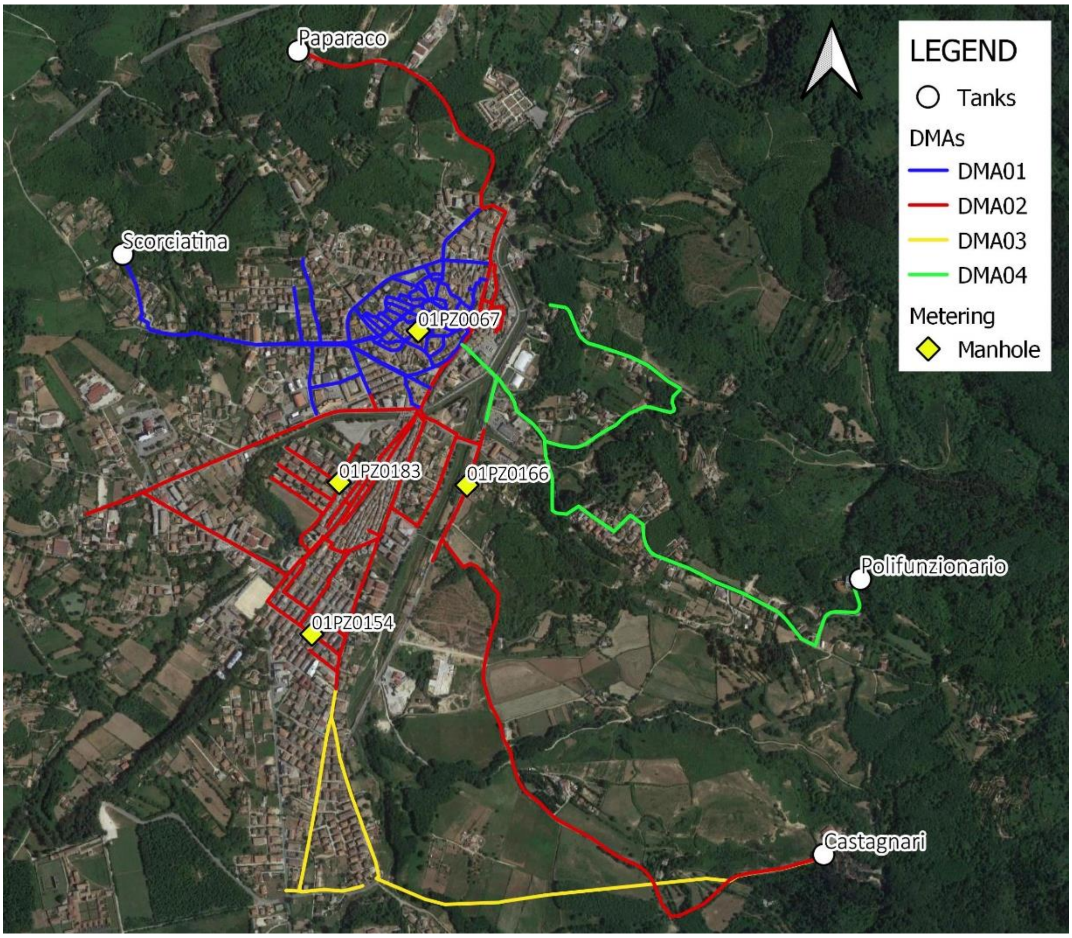

Figure 4.2.7 Map of the manholes containing the pressure meters. Google Satellite background.

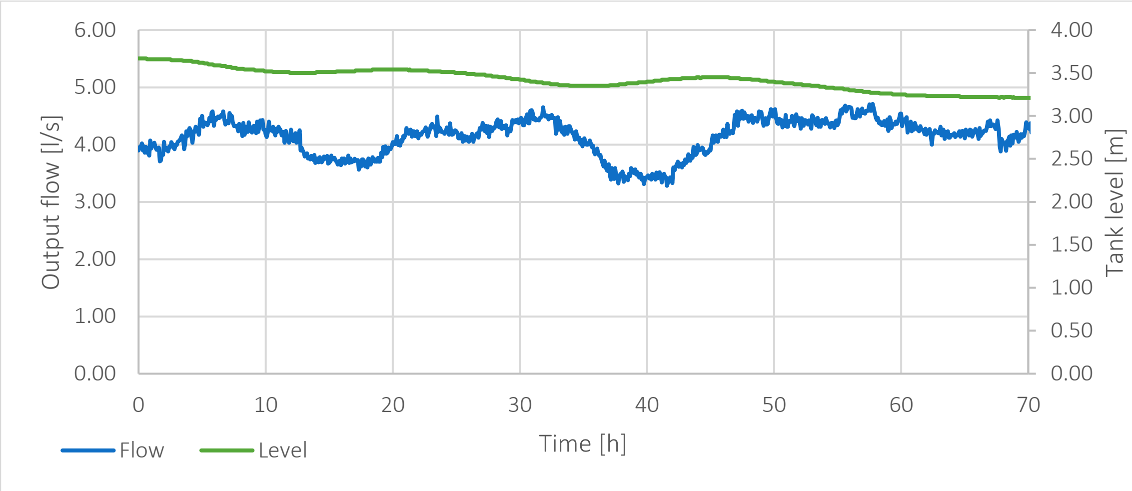

Figure 4.2.8 Outgoing flow and level metered values plot, *Castagnari*.

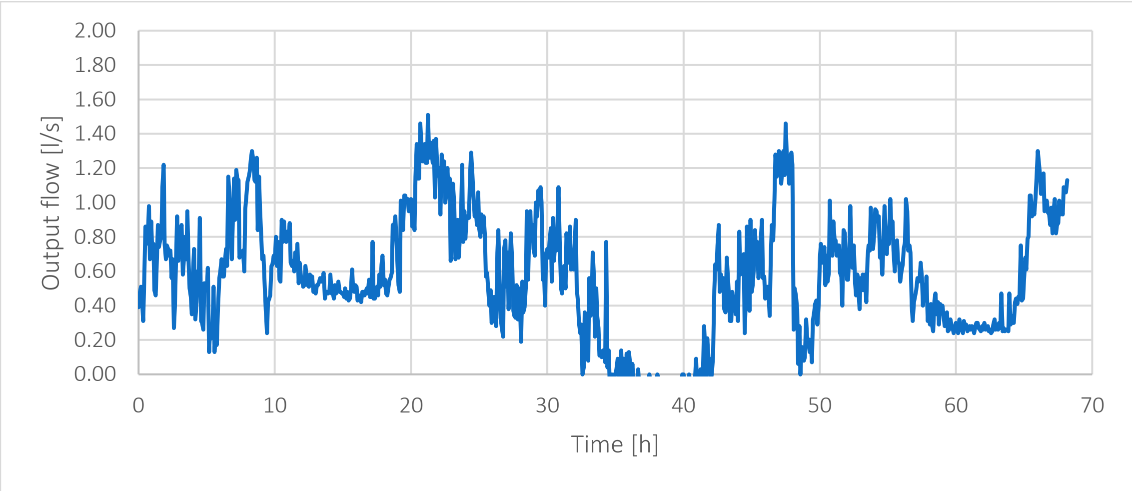

Figure 4.2.9 Metered flow values plot, *Polifunzionario*.

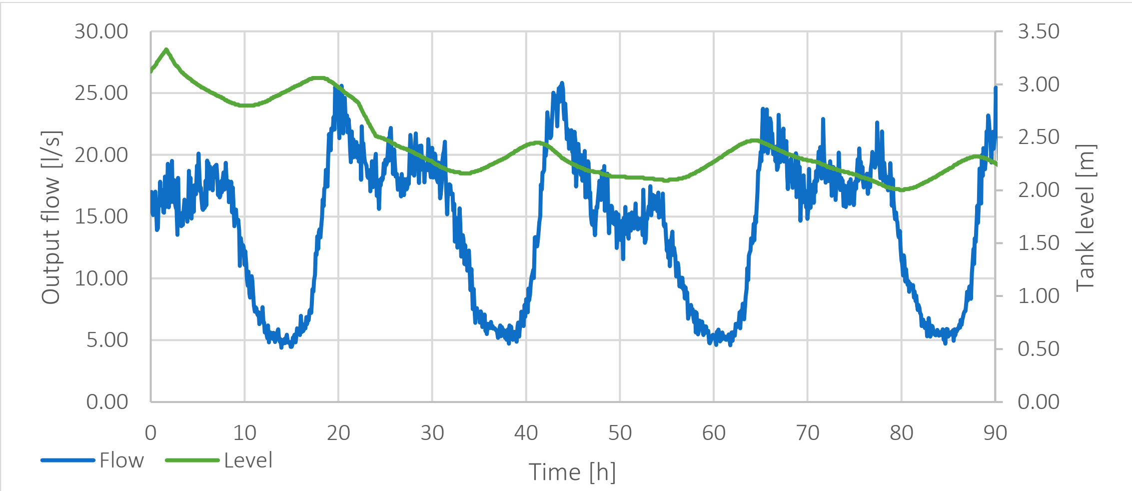

Figure 4.2.10 Outgoing flow and level metered values plot, *Paparaco*.

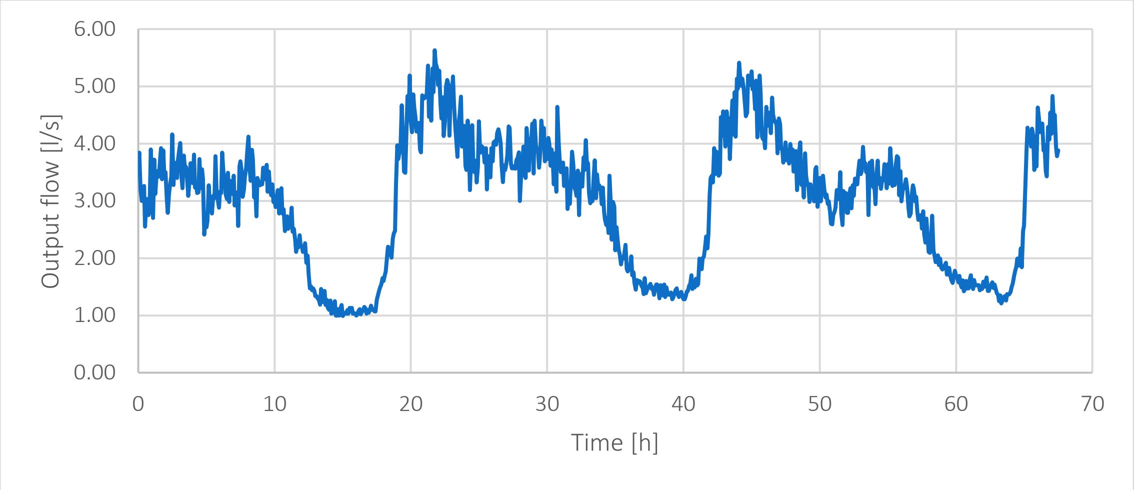

Figure 4.2.11 Metered flow values plot, *Scorciatina*.

Manhole ID	Log start time	Log end time
01PZ67	12/06/2009 14.00	15/06/2009 8.30
01PZ154	12/06/2009 14.00	15/06/2009 8.30
01PZ166	12/06/2009 14.00	15/06/2009 8.30
01PZ183	12/06/2009 14.00	15/06/2009 8.30

Table 4.2.5 Manhole pressure logs details summary.

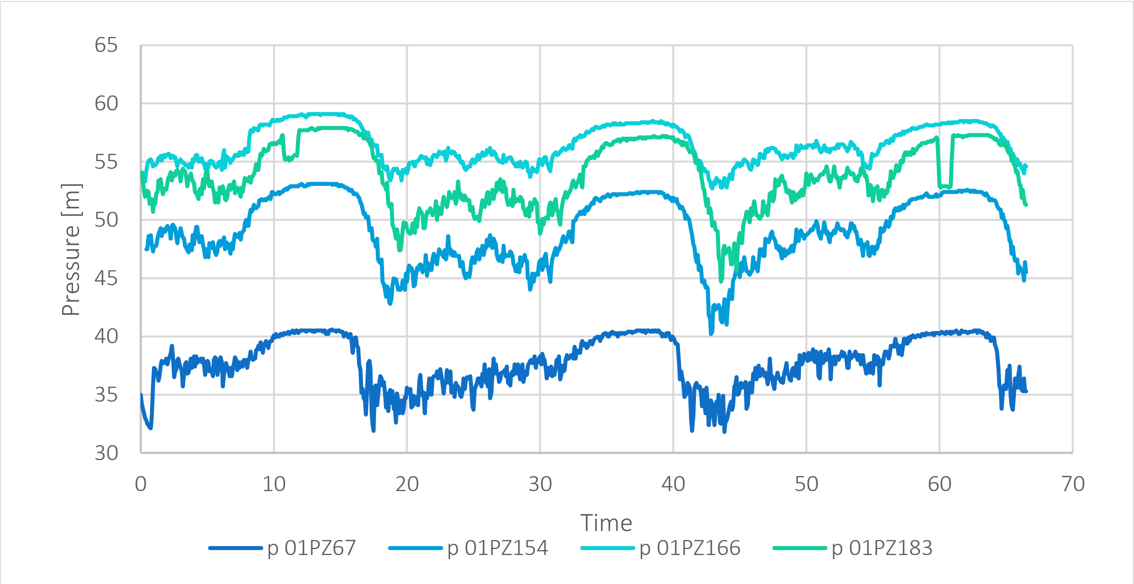

Figure 4.2.12 Metered pressure values plot.

4.3 WDN HYDRAULIC MODEL CONSTRUCTION

The monograph data and the digital CAD drawing allowed the construction of the network hydraulic model. The digital GIS model, after the correction of the projection, and the topology ambiguities, allowed building the EPANET file. The model, Figure 4.3.1, consists of four independent networks served by their respective tanks. The connection between *Paparaco* and the Castagnari tanks is set closed because it is not used under normal operating conditions.

Figure 4.3.1 EPANET network model

4.3.1 SIMULATION SCENARIOS

The metered outgoing flow time series allow characterizing the network operating regime in the period corresponding to the surveys. To assess the model accuracy, the operation of the network is simulated in two scenarios:

- Average flow;
- Peak flow.

The steady-state modelling scenarios represents a single time instant. The average and maximum demand values refer to the values detected at the tank outlet, defined in Table 4.3.1 according to the surveyed values, Table 4.2.4. The tanks are modelled as Reserviour whose levels are fixed at the surveyed value at the time corresponding to the average and peak flow.

Tank	DMA	Qmin	Qmax
Scorciatina	DMA01	3	5.63
Paparaco	DMA02	14.12	25.83
Castagnari	DMA03	4.14	4.71
Polifunzionario	DMA04	0.57	1.51

Table 4.3.1 Flow used in the average and peak consumption scenarios.

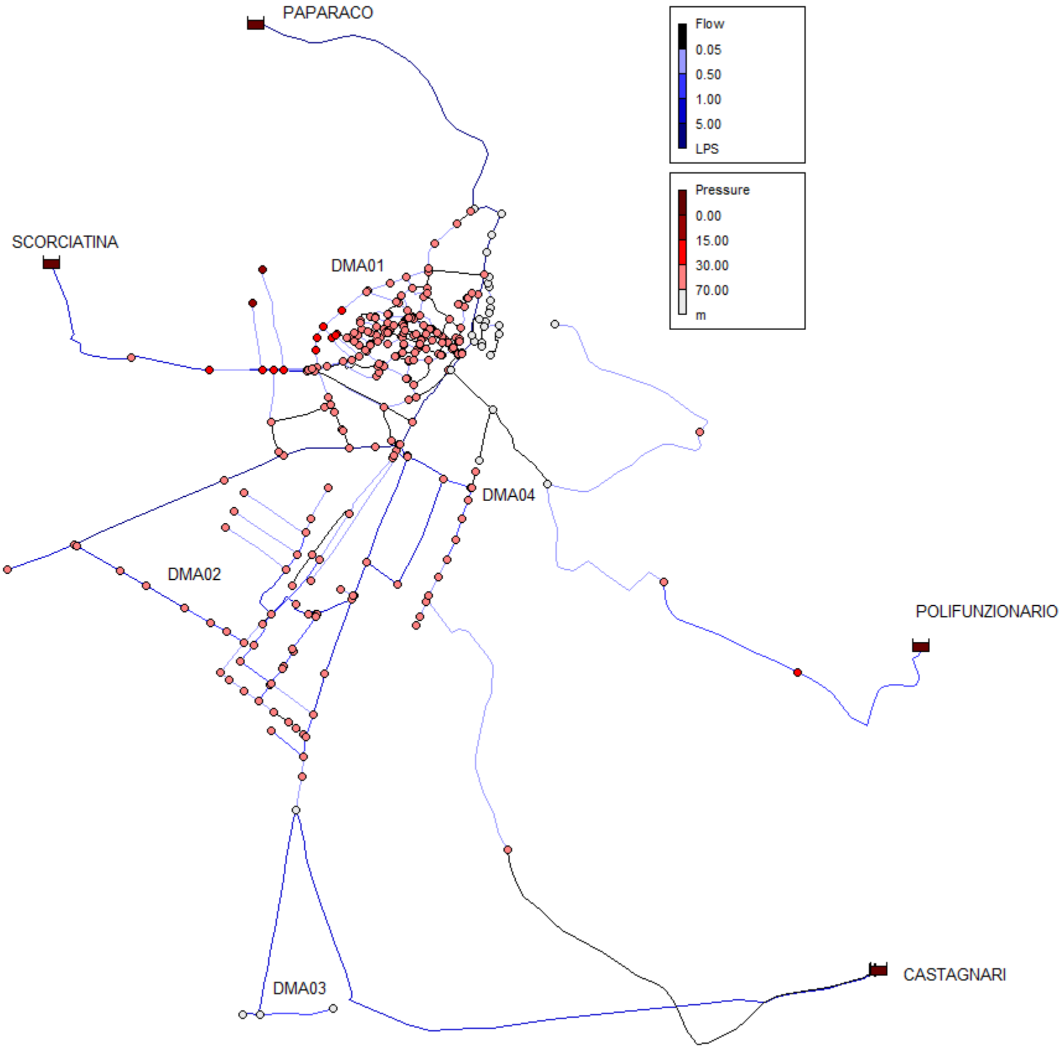

Figure 4.3.2 Average flow scenario simulation. Nodal pressure and pipe flow map.

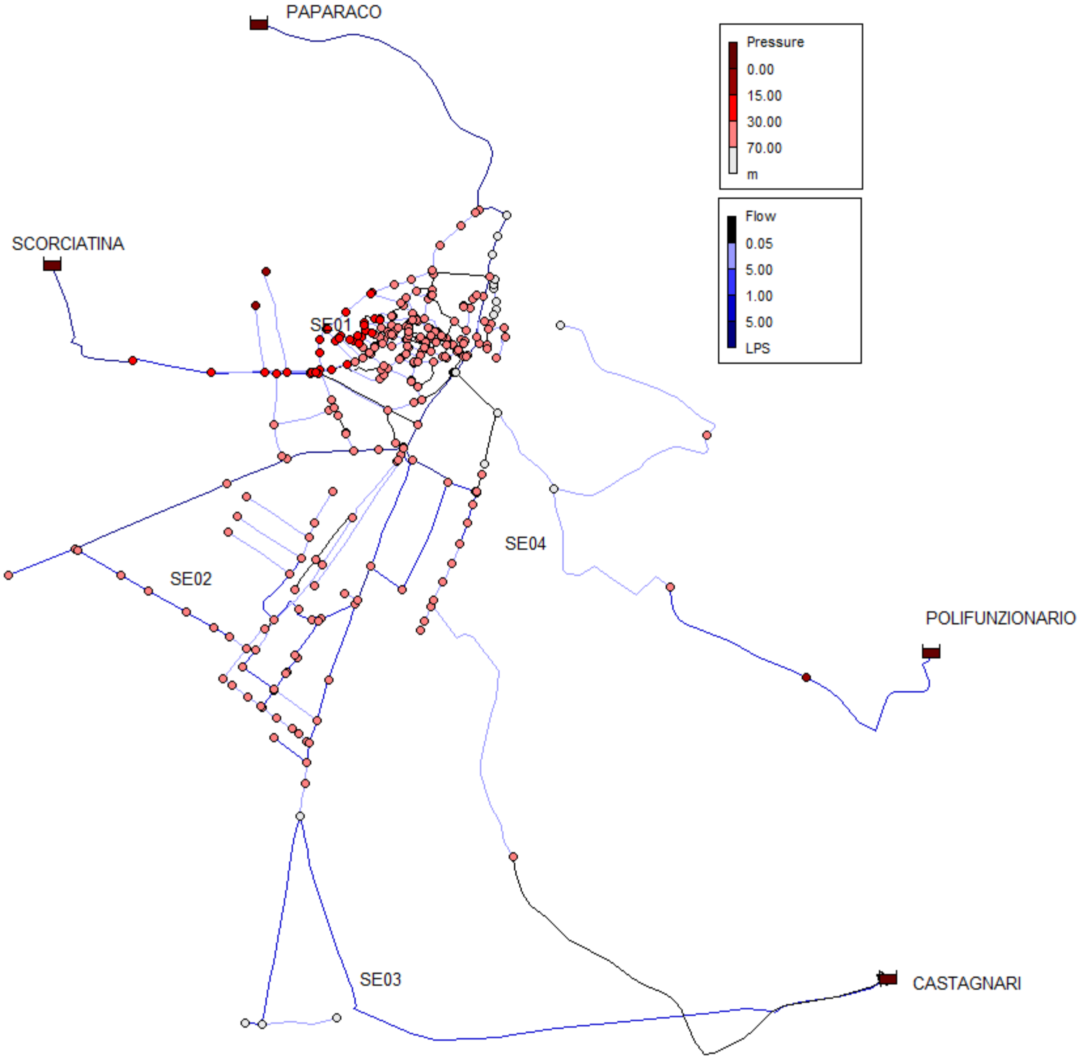

Figure 4.3.3 Peak flow scenario simulation. Nodal pressure and pipe flow map.

The simulation results shown in Figure 4.3.2 and Figure 4.3.3 refer to the hydraulic model with the roughness values assumed in Table 4.2.1. To assess the accuracy of the hydraulic model, the pressure values relating to the average and maximum consumption scenarios are compared with the values modelled in the Junctions corresponding to the metered manholes, Figure 4.2.12 and Table 4.2.5. Of the four measurement points available, three fall into the DMA02 (01PZ154, 01PZ166, 01PZ183). The 01PZ67 falls into the DMA01.

According to Table 4.3.2 and Table 4.3.3, the hydraulic model tends to overestimate the WDN pressure. The roughness coefficient values used for the network (Table 4.2.1) should be suitably calibrated.

DMA01		Average pressure [m]	Peak pressure [m]
01PZ67	Metered	33.8	38.5
	Modeled	35.7 Higher	39.2 Higher

Table 4.3.2 DMA01 manhole metered and modelled pressure comparison.

DMA02		Peak pressure [m]	Average pressure [m]
01PZ154	Metered	41	48.3
	Modeled	45.3 Higher	54.5 Higher
01PZ166	Metered	53.2	57.5
	Modeled	50.6 Lower	59.8 Higher
01PZ183	Metered	47.3	52
	Modeled	58.6 Higher	63.4 Higher

Table 4.3.3 DMA02 manholes metered and modelled pressure comparison.

4.4 STATE OF THE ART AND FUTURE DEVELOPMENTS

The network serving the city of *Serra San Bruno* has a limited extension and is correlated by a fair amount of data and measurements. The simulations initial results, representative of average and peak flow scenarios, show the need for the hydraulic model calibration. To further understand the network operating regime, it is necessary to extend the simulation to the entire metered period. The characterization of the city structures and the definition of the requested conditions will allow characterizing network performance using the indices, detailed in **Chapter 7**.

4.5 BIBLIOGRAPHY

- Williams, G.S.; Hazen, A. (1914), Hydraulic tables: the elements of gagings and the friction of water flowing in pipes, aqueducts, sewers, etc., as determined by the Hazen and Williams formula and the flow of water over sharp-edged and irregular weirs, and the quantity discharged as determined by Bazin's formula and experimental investigations upon large models. (2nd revised and enlarged ed.), New York: John Wiley and Sons

5 Santarém Water Distribution Network digital model

5.0 Summary

5.1 GEOGRAPHICAL FRAMEWORK

Santarém is a Portuguese city located near the *Tejo* River, northeast of *Lisbon*, Figure 5.1.1. The entire municipal area hosts about 60,000 inhabitants. The modelled area serves a portion of the inhabited centre that counts 30,000 inhabitants and extends for 12 Km^2, Figure 5.1.2. The administration of the network is entrusted to a local company, *Águas de Santarém*.

The WDN is partially districted. There are ten DMAs supplied by a central network directly connected to the tank. An elevated tank, 35 meters above the ground (Figure 5.1.3), supplies water to the entire network.

Figure 5.1.1 Santarém municipality geographical location.

Figure 5.1.2 Santarém municipality map. Google Satellite background.

Figure 5.1.3 Santarém raised tank. Photo by Nuno Moura Neves, Google photos.

5.1.1 DISTRICT METERED AREAS

The Santarém WDN is partially districted. This portion of the network is divided into 11 districts, of variable extension and elevation, Figure 5.1.3 and Table 5.1.1. The tank supplies directly the old city and arena area, here called "*OldCity*". The *OldCity* area is directly connected to the DMAs: STR05, STR06, STR07, STR08, STR09, STR10 and STR012. Each DMA has only one metered entry point.

District metered areas		Junction number	Pipe number	Total length	Average elevation	Median building storeys
Code	Name	-	-	Km	m	-
-	Old City	264	258	13.06	101.59	3
STR05	Atamarma	25	26	1.43	95.56	4
STR06	Portas do Sol	29	29	1.56	103.7	5
STR07	GNR	45	48	4.01	94.18	3
STR08	Campo Leãµes	55	59	3.93	98.71	6
STR09	Choupal	51	59	4.18	96.53	5
STR10	Av Combatentes	104	111	8.92	88.97	3
STR11	Caneiras	16	16	7.00	14.04	2
STR12	Av Forcados Amadores	67	70	4.37	97.23	7
STR13	Ginestal	49	51	3.38	95.22	5
STR14	CNEMA	22	19	2.56	33.04	2
Total		**727**	**746**	**54**	**93.7***	**4***
* Assessed accounting the entire junctions sample						

Table 5.1.1 Santarém DMAs characteristics summary.

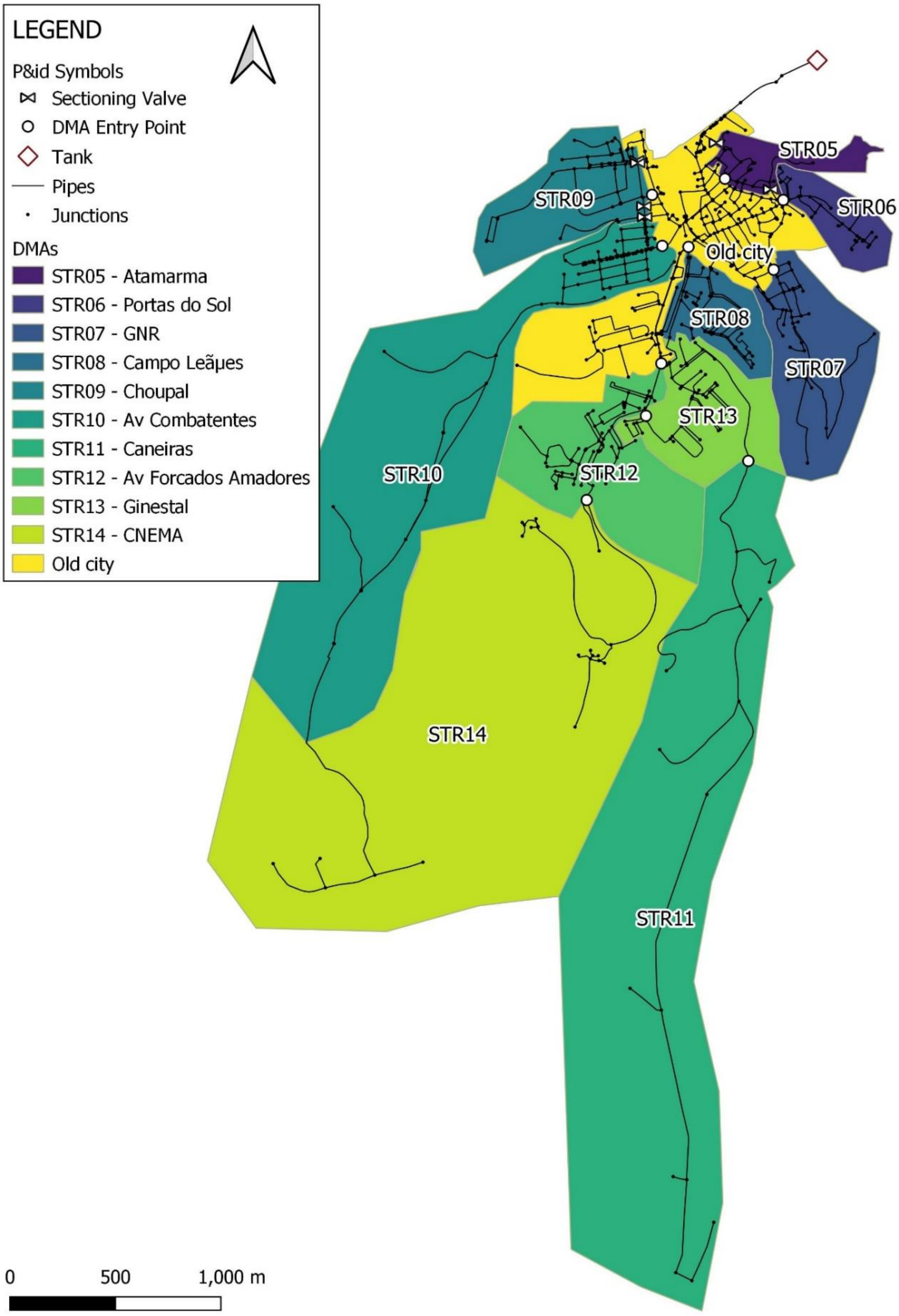

Figure 5.1.4 DMAs of the Santarém' network.

5.1.2 WDN PIPES

The hydraulic modelling is focused on the *OldCity* area; despite this, all the network pipe and node characteristics are defined. The entire network counts 727 junctions and 746 pipes that extend for about 54km. The model uses a skeletonized network that excludes distribution pipes with smaller diameters and service connections. Even if the network serving the *OldCity* covers a small area, it has a greater extension than the other DMAs characterized by high variability in diameters and materials. Table 5.1.2 and Table 5.1.3 show the type of material and its length divided by DMA. The most recent parts of the network use PVC and High-Density PolyEthylene pipes. About 74% of the pipes are in PVC, of the remaining 14.8% are in Fiber-cement.

Material	Material	*Old* City	ZMC STR05	ZMC STR06	ZMC STR07
			Atamarma	*Portas do Sol*	*GNR*
Ductile Iron	FD	1796.1	-	267.6	-
Iron	FF	480.1	-	-	-
PVC type 1	MPVC	7634.3	999.9	709.1	1659.9
Fibre-cement	FC	1995.2	435.1	581.5	1346.2
High-density polyethylene	PEAD	217.1	-	-	1003.7
PVC type 2	PVC	937.6	-	-	2.6
Total Length		**13060.4**	**1435.0**	**1558.2**	**4012.4**

Table 5.1.2 Length [meter] of pipes divided for constituting materials. DMAs: Old Town, Atamarma, Portas do Sol, GNR.

Material	ZMC STR08	ZMC STR09	ZMC STR10	ZMC STR11	ZMC STR12	ZMC STR13	ZMC STR14
	Campo Leões	*Choupal*	*Av Combatentes*	*Caneiras*	*Av Forcados Amadores*	*Ginestal*	*CNEMA*
FD	-	-	-	-	-	-	-
FF	-	-	-	-	-	-	-
MPVC	2634.2	3981.1	5782.8	6349.9	3892.9	3892.9	2564.7
FC	1295.4	201.1	1374.3	-	275.7	275.7	-
PEAD	-	-	1758.3	-	131.6	131.6	-
PVC	-	-	-	650.9	66.9	66.9	-
Total Length	3929.6	4182.1	8915.4	7000.7	4367.1	4367.1	2564.7

Table 5.1.3 Length [meter] of pipes divided for constituting materials. DMAs: Campo Leões, Choupal, Av Combatentes, Caneiras, Av Forcados Amadores, Ginestal, CNEMA.

Table 5.1.4 and Table 5.1.5 summarizes the nominal diameter and its length divided by DMA. The *OldCity* zone and the neighbouring DMAs, serving the oldest part of the network, are characterized by a higher variability of diameters.

Material	*Old* City	ZMC STR05 *Atamarma*	ZMC STR06 *Portas do Sol*	ZMC STR07 *GNR*	ZMC STR08 *Campo Leões*	ZMC STR09 *Choupal*
25	-	21.5	-	-	-	-
32	62.83	-	-	1003.67	-	-
50	157.07	-	812.47	-	163.77	-
63	237.21	394.08	-	-	-	111.26
80	302.92	126.7	-	-	-	201.06
90	2137.99	86.6	-	1088.63	432.51	1423.24
100	1021.06	57.72	745.77	-	1002.5	-
110	3330.81	497.69	-	572.55	1356.57	1966.43
125	475.13	250.68	-	-	90.62	-
140	374.08	-	-	-	-	318.94
150	112.11	-	-	1346.21	-	-
160	785.35	-	-	1.31	754.48	-
175	64.09	-	-	-	129.13	-
200	1825.91	-	-	-	-	161.2
250	45.59	-	-	-	-	-
300	2128.27	-	-	-	-	-
Total Length	**13060.42**	**1434.97**	**1558.24**	**4012.37**	**3929.58**	**4182.13**

Table 5.1.4 Length [meter] of pipes divided for nominal pipe size. DMAs: Old Town, Atamarma, Portas do Sol, GNR, Campo Leãµes, Choupal.

Diameter	ZMC STR10 *Av Combatentes*	ZMC STR11 *Caneiras*	ZMC STR12 *Av Forcados Amadores*	ZMC STR13 *Ginestal*	ZMC STR14 *CNEMA*
25	44.25	-	-	-	-
32	714.47	66.64	-	-	-
50	62.03	-	131.62	-	-
63	5295.6	5817.67	1508.25	-	945.36
80	964.51	-	186.05	1687.04	-
90	836.56	1116.43	144.3	932.98	-
100	348.73	-	89.64	316.2	32.42
110	649.25	-	1466.02	28.81	334.66
125	-	-	49.69	273.69	-
140	-	-	-	-	-
150	-	-	-	-	-
160	-	-	-	-	-
175	-	-	154.87	15.04	-
200	-	-	636.68	-	1252.26
250	-	-	-	123.52	-
300	-	-	-	-	-
Total Length	**8915.4**	**7000.74**	**4367.12**	**3377.28**	**2564.7**

Table 5.1.5 Length [meter] of pipes divided for nominal pipe size. DMAs: Av Combatentes, Caneiras, Av Forcados Amadores, Ginestal, CNEMA.

5.2 WATER DISTRIBUTION NETWORK DIGITIZATION

Águas de Santarém made available the network data. The data are organized in a CAD drawing file, Table 5.2.1. The drawing is scaled, projected and contains information on:

- Altimetry: spot elevation and contour lines;
- Planimetric layout, material and the nominal diameter of the main pipes;
- Trace of the secondary pipes;
- Building location and perimeter;

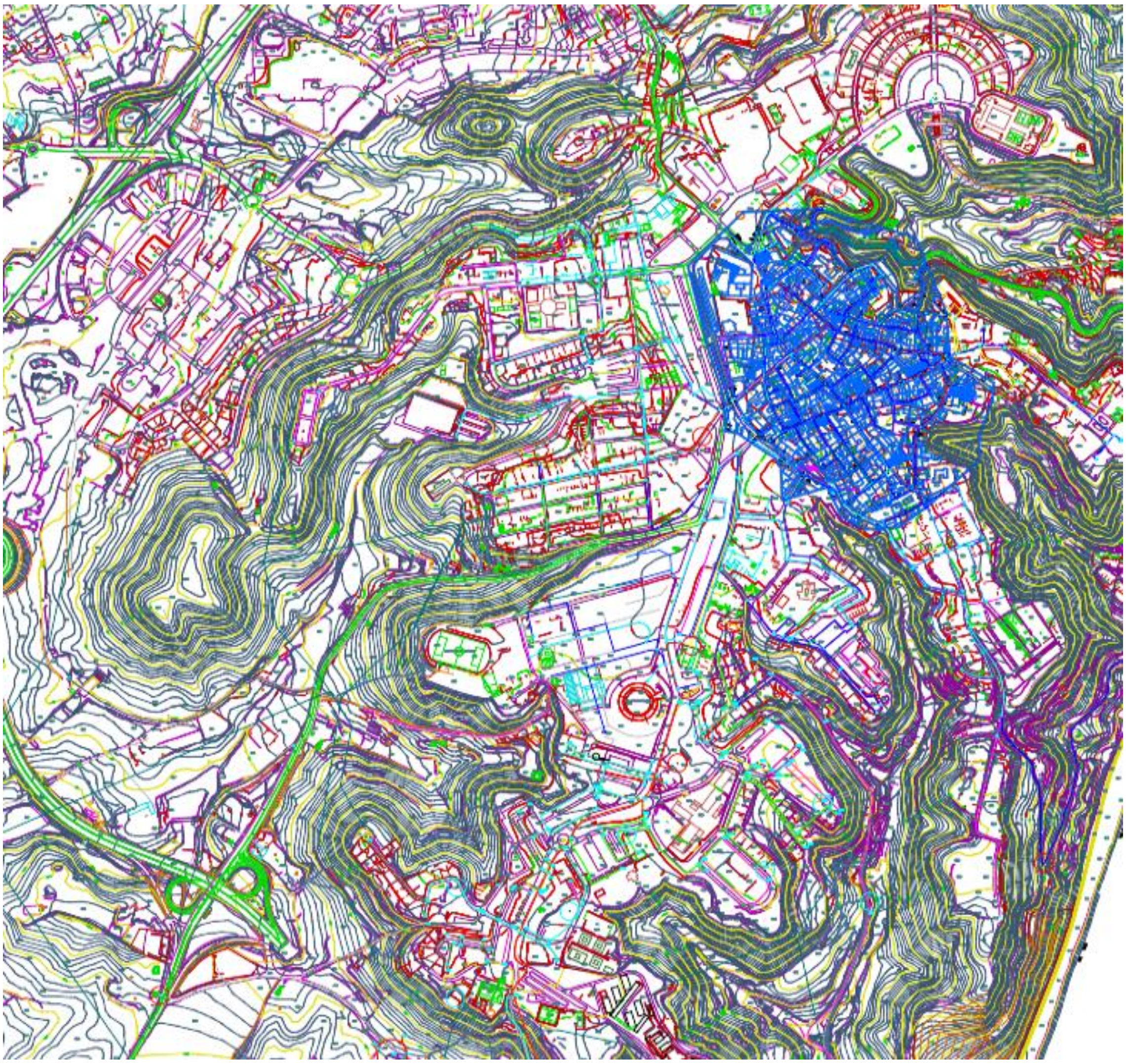

Table 5.2.1 Network CAD planimetric map.

5.2.1 GIS DIGITAL NETWORK MODEL CONSTRUCTION

Similarly to the previous chapters, the digital CAD model was converted into a GIS project. The drawing scale simplified the phase of assigning the DATUM and the coordinate system. The information on junctions and pipes (length, height, material and other management notes) are organized in the attribute table of the shapefiles obtained from the CAD.

5.2.2 TOPOLOGY

The working environment change made it possible to recover the pipes planimetric layout. Despite the junctions correct positioning in the CAD, it was necessary to validate the network topology. At each material and diameter change or the ends of each pipe, there must be a junction. As shown in Figure 5.2.1, for example, it was necessary to integrate the junctions by inserting all the end nodes of the pipes.

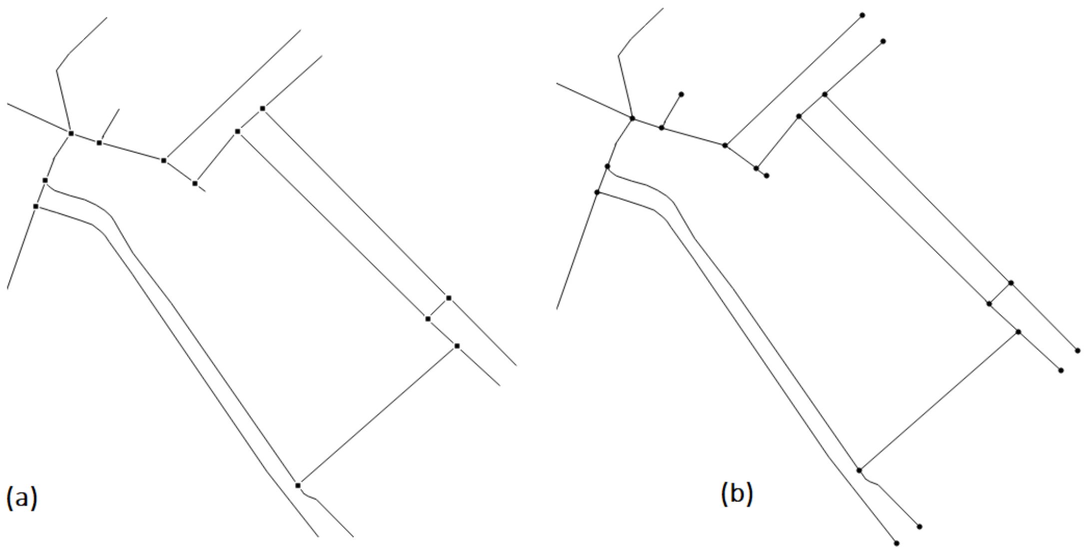

Figure 5.2.1 Topology comparison (a) CAD (b) GIS

5.2.3 PIPE CHARACTERISTICS

The pipe characterization involves the definition of internal diameter, length, roughness and topology. The nominal diameter and material assignment were automatic thanks to the CAD data. The diameter setup required a correction phase. The network technicians suggested changes to update the diameter of the material of some pipes. The material allows defining an indicative roughness for the pipes. Table 5.2.2 shows the Hazen-Williams roughness value used for each material (Williams and Hazen, 1908, Williams and Hazen 1914).

Pipes are characterized by their internal diameter value for hydraulic modelling. Similarly, to the previous chapters case studies, it was necessary to obtain this diameter from standard pipe indications:

- ***UNI EN 545:2010*** *Ductile iron pipes, fittings, accessories and their joints for water pipelines - Requirements and test methods;*
- ***UNI EN 12201-1:2012*** *Plastics piping systems for water supply, and for drainage and sewerage under pressure - Polyethylene (PE) - Part 1: General;*
- ***UNI EN 10240:1999*** *Internal and/or external protective coatings for steel tubes - Specification for hot dip galvanized coatings applied in automatic plants;*
- ***UNI EN 512:2003*** *Fibre-cement products - Pressure pipes and joints.*

Material	Tag	Hazen-Williams Roughness
Fibre-cement	FC	135
Ductile iron	FD	120
Iron	FF	100
PVC	MPVC and PVC	140
High-density polyethylene	PEAD	140

Table 5.2.2 Hydraulic roughness values assigned depending on the pipe material.

5.2.4 Network altimetry and tank elevation

Pipe slope and position is assumed depending on the elevation of the terminal junctions. The junctions elevation is not among the CAD listed data. The elevation is sampled from a DTM of 10-meter square cells, Figure 5.2.2. The DTM is obtained from the interpolation of the CAD drawing contour lines and spot elevation. The interpolation has generated some artefacts (i.e. high altitude areas STR 06, Figure 5.2.2).

The Santarém WDN is located in an elevated area with an average altitude of 100 m a.s.l. The elevation does not vary remarkably for most of the network area. The *Caneiras* and *CNEMA* DMAs (STR 11, STR 14) cover the areas located further downstream and are characterized by a much lower average altitude. The elevation assigned to the junction is validated by checking the consistency with the surrounding areas. The DTM does not cover the entire network area. *Av Combatentes, Caneiras* and *CNEMA* (STR 10, STR 11, STR 14) do not completely fall within the area covered by the DTM. The elevation for the junctions outside the DTM area is sampled using the Google DSM. In the absence of specific indications, the burial depth of the junctions is placed 1 meter below the ground level.

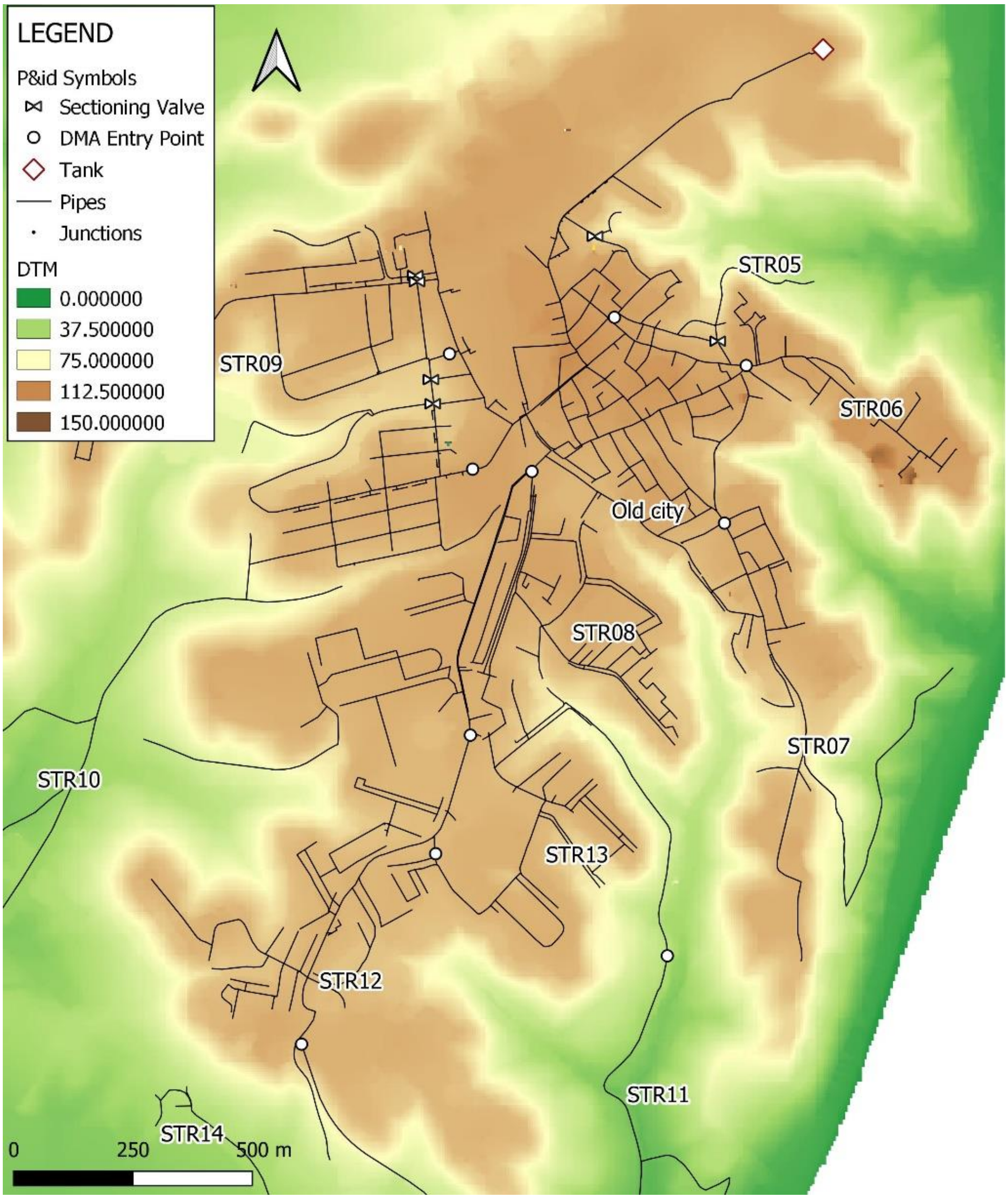

Figure 5.2.2 Digital elevation model of the network area.

5.2.5 End-users water demand assessment and demand distribution criterion

As pointed out in the previous paragraphs, the WDN serving the city is partially districted. Each district has a single metered entry point. There is no meter on the tank outlet. The lack of a meter that quantifies the total network consumption of the network makes it impossible to draw up a hydraulic balance for the *OldCity* zone

In Bonora *et al*. (2020) the network modelling involved the *OldCity* area. *Águas de Santarém* has made available the end-users consumption data, for the whole municipality. The meter readings are provided as suitably anonymized data organized in tables, by address. To simulate the operating regime it is necessary to estimate the drinking water consumption of the network despite the absence of a meter.

The consumption data should be assigned to the network junctions. The assignment relies on a manual procedure. All the addresses that fall within the modelled area have been isolated from the provided data tables. The addresses are identified according to their position, Figure 5.2.3.

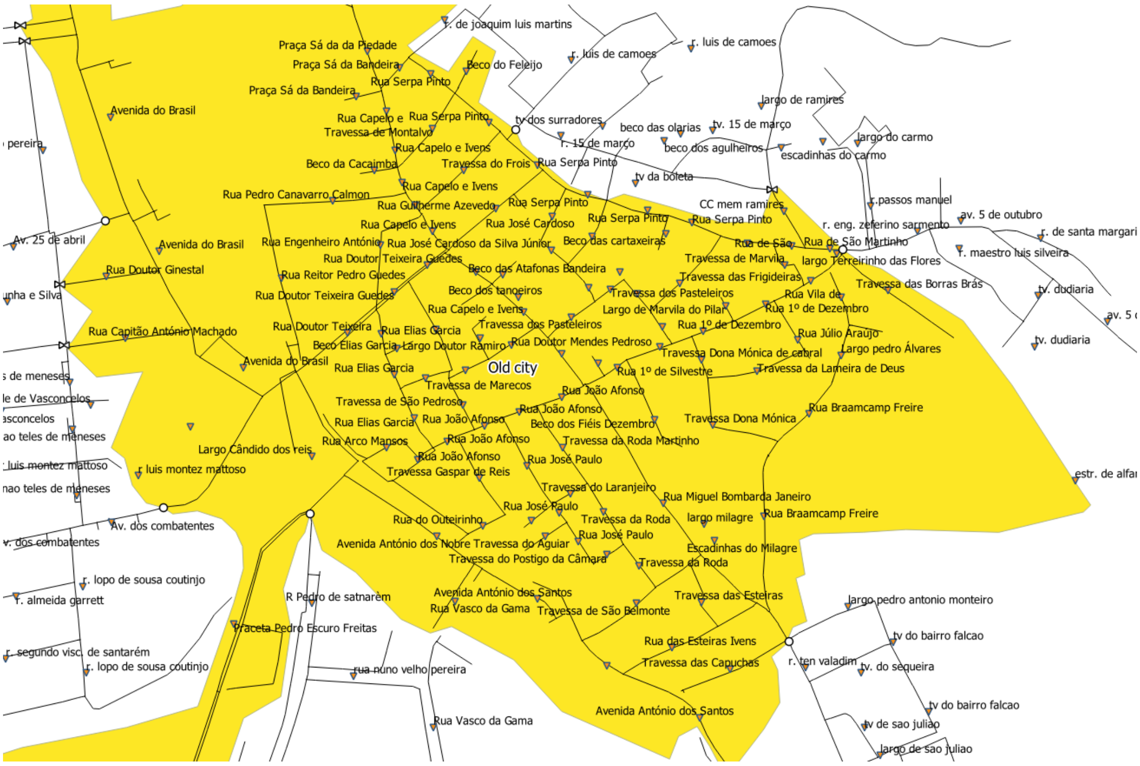

Figure 5.2.3 Santarém *OldCity* addresses positioning

- For short alleys or streets, multiple addresses can share the same ID and be associated with the same pipe;
- In the case of short streets or long pipes, some pipes can be split adding junctions. The split prevent a single pipe from covering more than one address;
- For addresses that cover large areas, the address ID can be assigned to several pipes.

Downstream of the address-pipe coupling, each pipe has assigned a numerical indicator bound to one or multiple addresses. The cumulative users' consumption value for each address is assigned to the corresponding pipe. For addresses assigned to multiple pipes, the consumption is distributed proportionally to the pipe length. In the hydraulic model, the demand is assigned to the junctions. The value assigned to each pipe divided equally to the junctions placed at the ends of the pipe, Eq. 5.2.1.

$$d_i = \sum_{j \in P_i} \frac{D_j}{2} \qquad Node\ i \qquad \text{Eq. 5.2.1}$$

in which:

- d_i water demand for the ith junction;
- D_j Demand assigned to the jth pipe flowing into/from node i;
- P_i List of pipes flowing into/from node i.

The presence of a distributed leak is associated with the drinking water demand assigned according to the described criterion. From the infrastructure knowledge, a value of 5 m^3/h (1.4 l/s) is assumed. The water loss was distributed in the network junctions, proportionaly to the length of the pipes, similar to the water demand, Eq. 5.2.1.

Numerical example

Figure 5.2.4 shows an example of demand assignment. The figures cover an area in which there are 8 addresses and 8 pipes. Table 5.2.3 shows the address assignment criterion. *Rua Serpa Pinto (7)* is assigned to two different pipes (P_218 and P_219). The associated demand value is distributed proportionally to the length of the pipes. Address *(4)*, *Largo Manuel Antonio das Neves*, can be assigned to P_696 or P_190. In both cases the pipe is already linked to another address, in this case, it is necessary to consolidate the address by associating it with another one (I.e. *Travessa dos Pasteleiros, 3*).

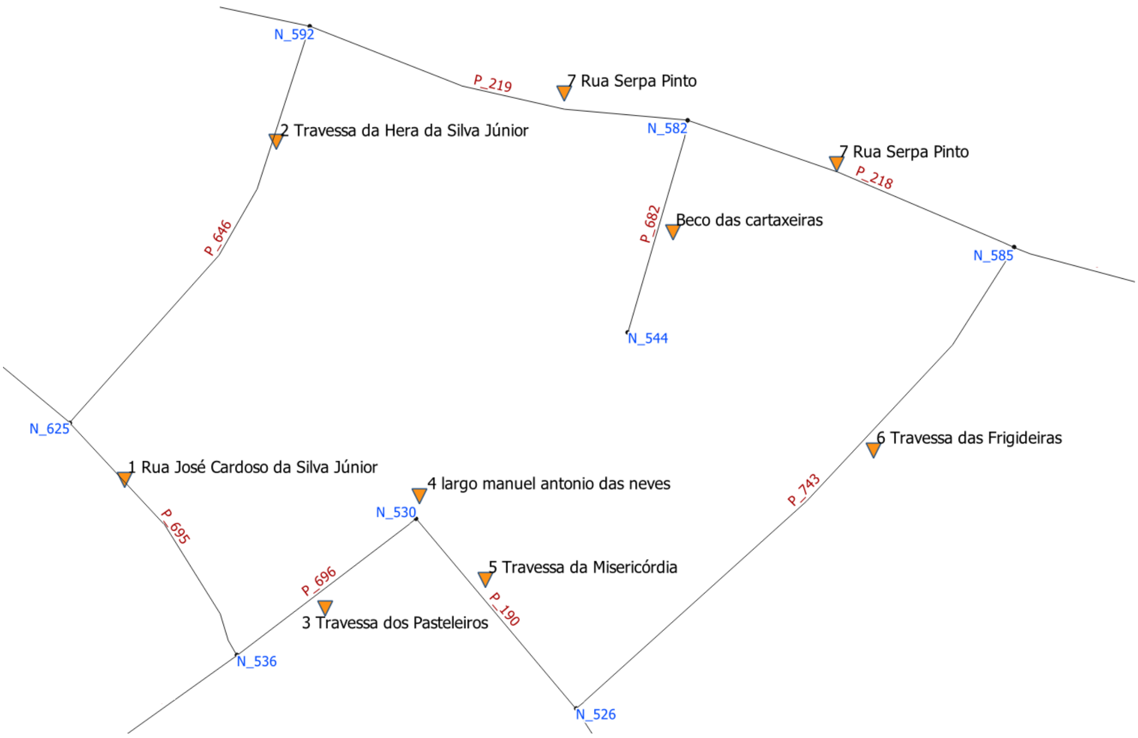

Figure 5.2.4 Demand assigning criteria example, GIS map extract.

Pipe	ID address	ID Consolidated	Address
P_695	1	1	*Rua José Cardoso da Silva Júnior*
P_646	2	2	*Travessa da Hera da Silva Júnior*
P_696	3+4	3	*Travessa dos Pasteleiros+Largo Manuel Antonio das Neves*
P_190	5	5	*Travessa da Misericórdia*
P_743	6	6	*Travessa das Frigideiras*
P_218	7	7	*Rua Serpa Pinto*
P_219	7	7	*Rua Serpa Pinto*
P_682	8	8	*Beco das cartaxeiras*

Table 5.2.3 Demand assigning criteria example. Pipe-address matching.

DMAs inlet flow metering

For the hydraulic model construction, in addition to defining the user water demand, it is necessary to quantify the flow provided by the network to the DMAs. The *OldCity* network is directly connected to the DMAs: STR05, STR06, STR07, STR08, STR09, STR10 and STR012. The network manager has made available the measurements for one day of consumption at the entrance of the 7 DMAs, Table 5.2.4 and Figure 5.2.5.

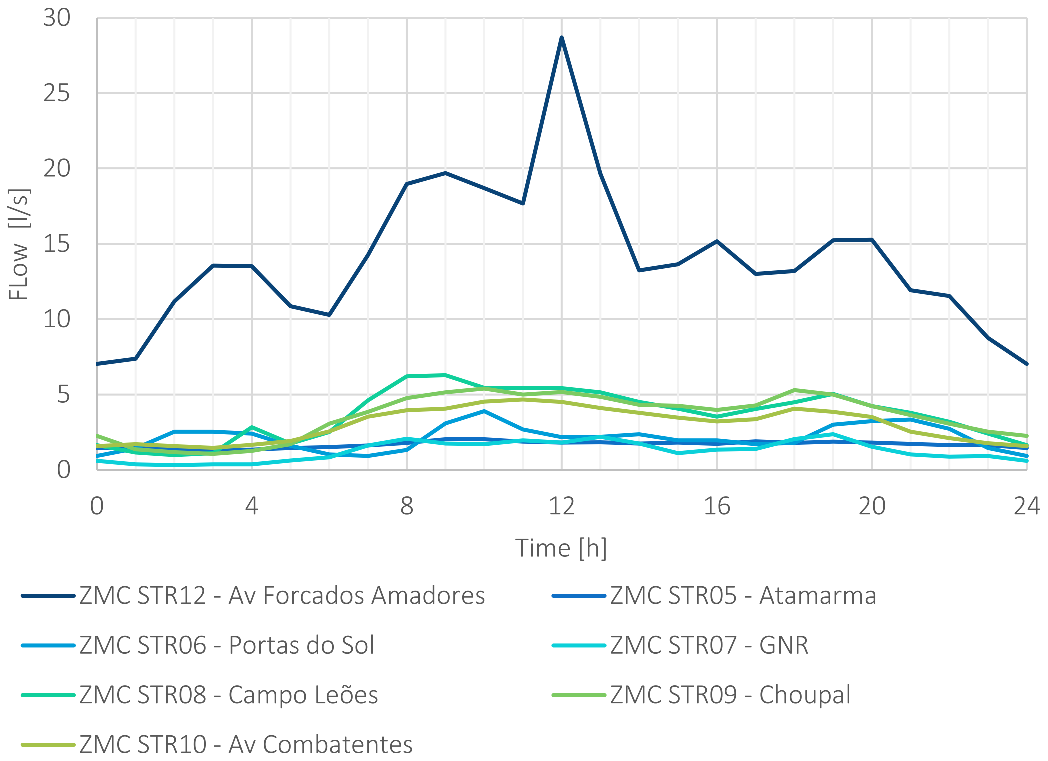

Figure 5.2.5 DMAs inlet flow measurements time plots. DMAs: Atamarma, Portas do Sol, GNR, Campo Leões, Choupal, Av Combatentes, Av. Forcados Amadores.

Time	STR05	STR06	STR07	STR08	STR09	STR10	STR12	Total dma demand
h	l/s	l/s	l/s	l/s	l/s	l/s	l/s	l/s
0	1.444	0.917	0.583	1.639	2.250	1.581	7.028	15.442
1	1.444	1.417	0.361	1.139	1.361	1.697	7.361	14.780
2	1.333	2.528	0.306	0.972	1.167	1.575	11.167	19.048
3	1.306	2.528	0.361	1.111	1.056	1.456	13.556	21.374
4	1.333	2.389	0.361	2.833	1.250	1.656	13.500	23.322
5	1.444	1.583	0.611	1.750	1.694	1.919	10.861	19.862
6	1.500	1.028	0.833	2.500	3.056	2.539	10.278	21.734
7	1.611	0.917	1.611	4.611	3.833	3.517	14.250	30.350
8	1.778	1.306	2.056	6.194	4.750	3.944	18.972	39.000
9	2.028	3.083	1.750	6.278	5.139	4.058	19.694	42.030
10	2.028	3.889	1.694	5.444	5.389	4.519	18.694	41.657
11	1.861	2.667	1.944	5.417	5.000	4.664	17.667	39.220
12	1.806	2.167	1.806	5.417	5.167	4.503	28.694	49.560
13	1.833	2.194	2.194	5.139	4.833	4.094	19.639	39.926
14	1.750	2.361	1.750	4.500	4.306	3.778	13.222	31.667
15	1.806	1.944	1.111	4.056	4.250	3.467	13.639	30.273
16	1.722	1.944	1.333	3.528	3.972	3.214	15.167	30.880
17	1.889	1.694	1.389	4.028	4.278	3.353	13.000	29.631
18	1.778	1.778	2.028	4.472	5.278	4.047	13.194	32.575
19	1.861	3.000	2.361	5.028	5.000	3.839	15.222	36.311
20	1.806	3.222	1.528	4.222	4.222	3.494	15.278	33.772
21	1.722	3.333	1.028	3.778	3.639	2.522	11.917	27.939
22	1.639	2.722	0.861	3.194	3.056	2.108	11.528	25.108
23	1.639	1.444	0.917	2.389	2.528	1.756	8.750	19.423
24	1.444	0.917	0.583	1.639	2.250	1.581	7.028	15.442
Mean Value	**1.672**	**2.119**	**1.254**	**3.651**	**3.549**	**2.995**	**13.972**	29.213

Table 5.2.4 DMAs inlet flow measurements. DMAs: Atamarma, Portas do Sol, GNR, Campo Leões, Choupal, Av Combatentes, Av. Forcados Amadores.

The overall average user consumption estimated from the readings for the *OldCity* zone is 9.37 l/s. For an extended period simulation, it is necessary to assign a daily consumption variation pattern. It has been hypothesized that the behaviour of the *OldCity* area is similar to that of the other DMAs. The pattern is estimated as an average of DMAs consumption patterns. Figure 5.2.6 shows the patterns plots for the DMAs directly connected to the *OldCity* network. The average demand pattern excludes the DMAs *Av Forcados Amadores* (STR6) and *Portas do Sol* (STR12), due to very different behaviour than the others. The average pattern assigned to the *OldCity* demand nodes is represented as a thick black line. The overall DMAs, network and *OldCity* consumption is represented in Figure 5.2.7.

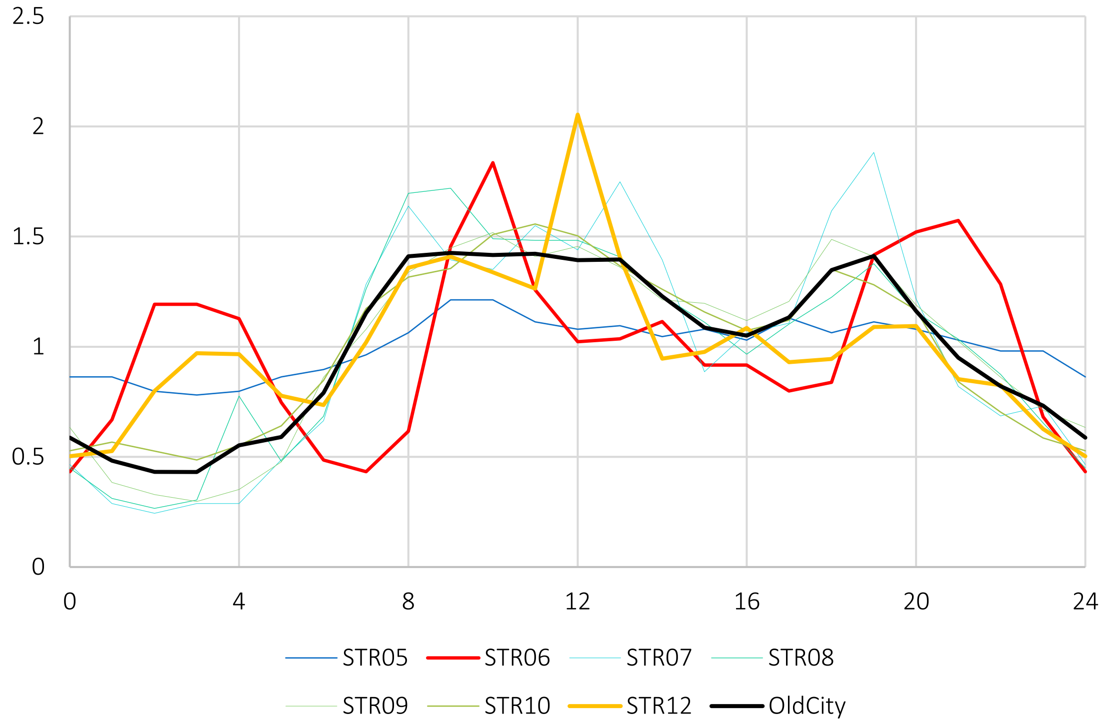

Figure 5.2.6 Daily demand patterns. DMAs: Atamarma, Portas do Sol, GNR, Campo Leões, Choupal, Av Combatentes, Av Forcados Amadores.

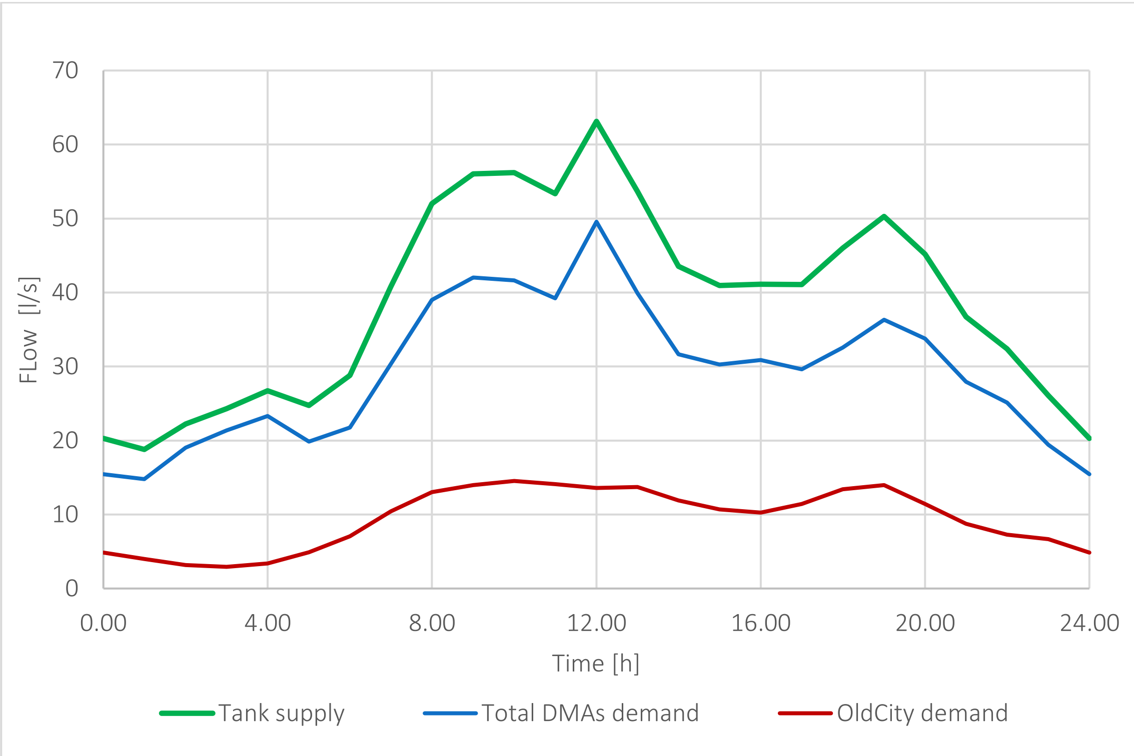

Figure 5.2.7 Daily *OldCity* demand, DMAs demands and tank supply plot.

Requested pressure values for performance assessment

The WDN supplying OldCity zone was used in Bonora *et al*. (2020) to assess some performance indices, **Chapter 7**. Performance indices often refer to design/requested conditions. These conditions represent goal values of pressure and demand to be met. In the construction of a digital model, it is possible to obtain the required pressure values depending on the number of storeys of the buildings supplied. Similarly to the Serra San Bruno WDN case study, **Chapter 4**, the area served is divided into blocks containing buildings of similar height, Figure 5.2.8.

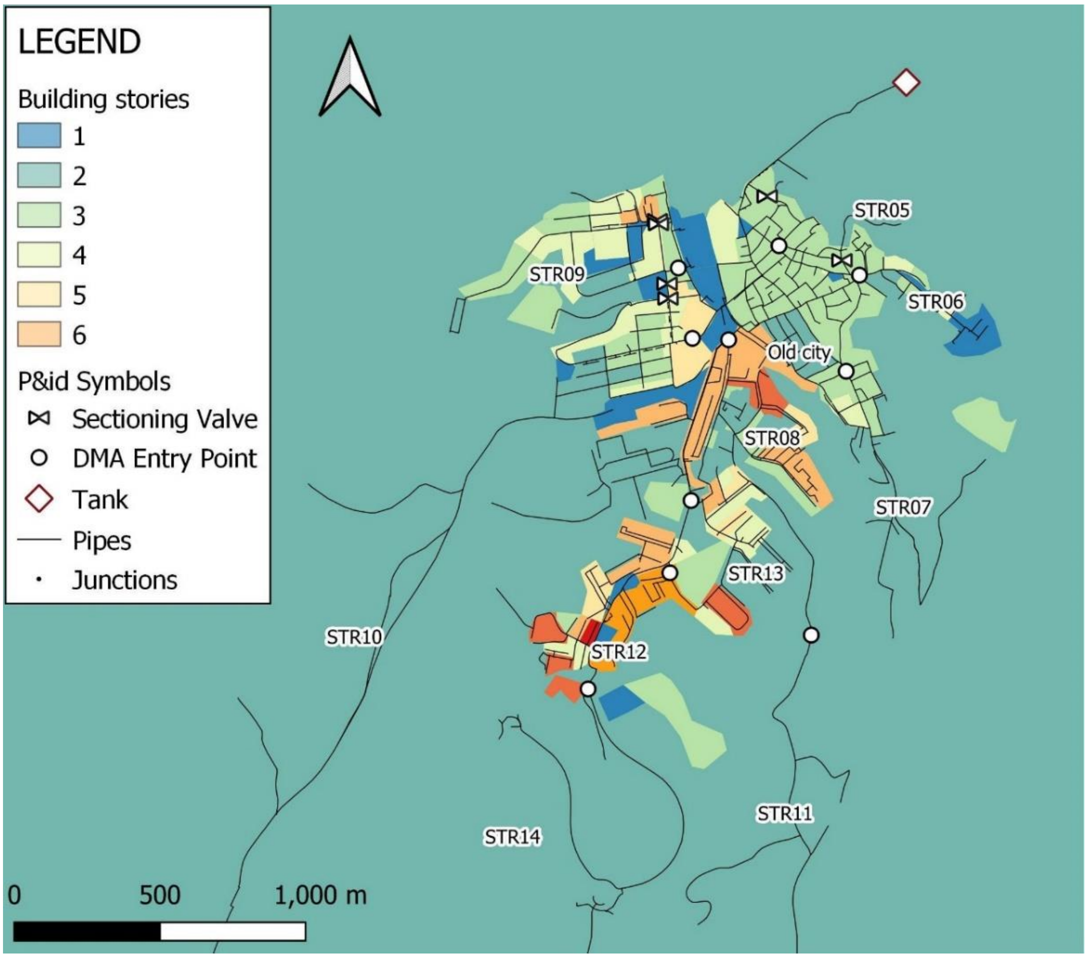

Figure 5.2.8 Santarém city area uniform-storeys block partitioning.

The sub-urban areas are characterized by scattered houses of limited height. These zones have been assigned two storeys. Table 5.1.1 shows, for each DMA, the median value of the number of storeys assigned to the junctions. The formula that expresses the storeys-design pressure dependence is provided by Portuguese legislation:

$$\hbar^{*}=100+40*\mathrm{N} \quad [\mathrm{kPa}], \qquad \text{Eq. 5.2.2}$$

where:

- $\hbar^{*}$ Pressure design value;
- N Supplied building storeys number (above the ground).

5.3 Hydraulic model construction

The Santarém WDN was used in Bonora *et al*. (2020). The hydraulic simulation involved the *OldCity* area. Part of the results of the 24-hour extended period simulation is reported in **Paragraph 7** of **Chapter 7**. In the city, the tallest buildings are commonly equipped with private small tanks and pumping stations. For this reason, the areas serving blocks with buildings with 4 or more storeys above the ground have been assigned a required pressure equivalent to that of a 2-storey building. Figure 5.3.1 and Figure 5.3.2 2 show the network operating regime (nodal pressure and pipe flow rate corresponding to the time of minimum consumption (1:00) and maximum consumption (noon). During the peak consumption periods, the *OldCity* area of the network is characterized by a low-pressure regime.

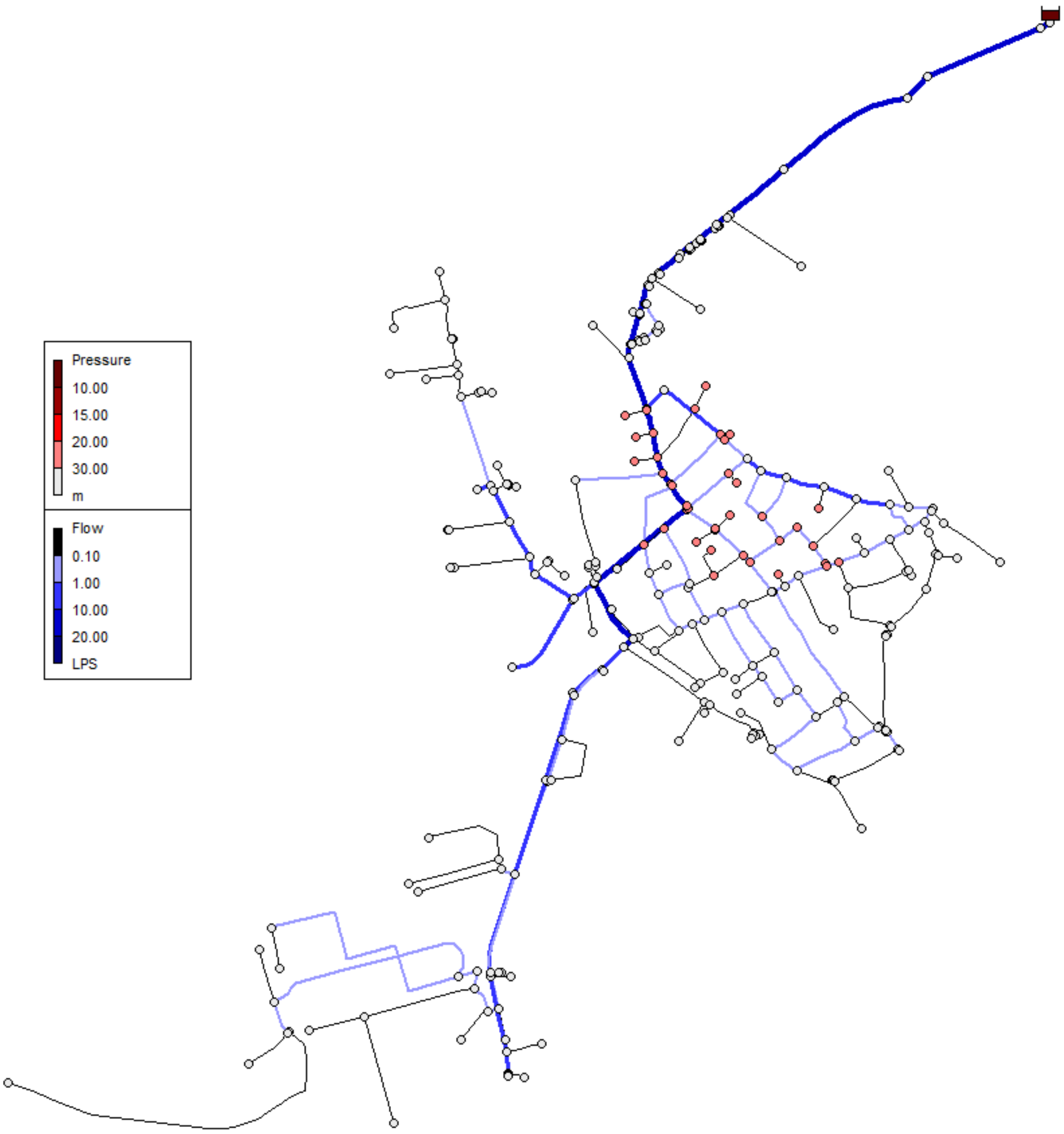

Figure 5.3.1 Minimum demand scenario simulation. Nodal pressure and link flow map.

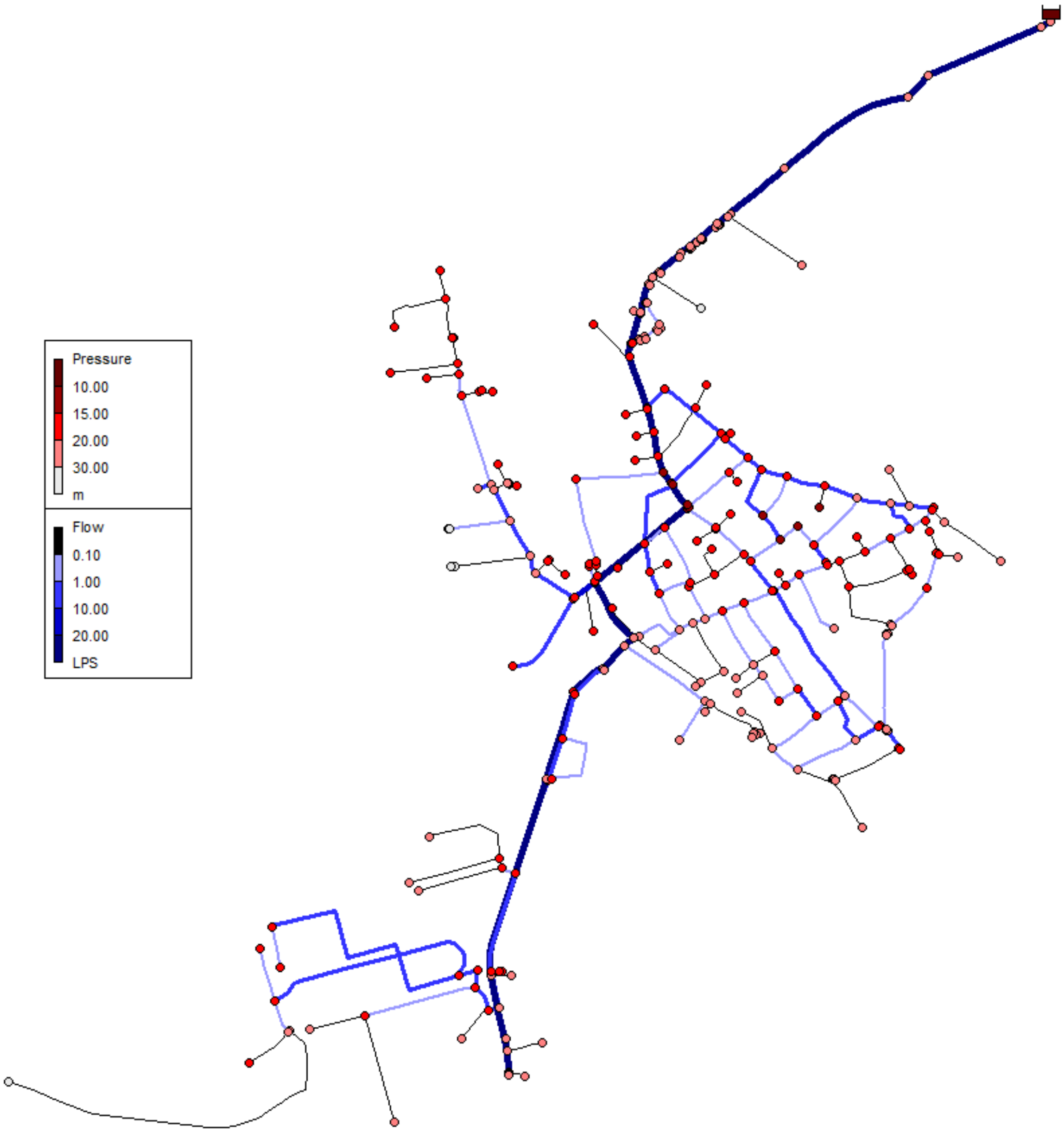

Figure 5.3.2 Peak demand scenario simulation. Nodal pressure and link flow map.

5.4 State of the art and future developments

The simulation showed that the central area of the *OldCity* is characterized by a low-pressure regime during peak demand. The model construction allowed deepening the definition of the design/request conditions in the study of the performance indices.

The Santarém network model is currently under development. The network manager is setting up the installation of a fixed flow meter on the tank outlet. This would allow quantifying the actual *OldCity* district supply. The water demand in the districts connected to the central network can be distributed according to the population density and the extension of the inhabited centre. It is also necessary to characterize the DMAs consumption. The private tanks filling/emptying cycle influences the daily consumption pattern. The presence of the numerous private tanks can also cause an accumulation of water losses due to tank overflows.

5.5 BIBLIOGRAPHY

- Bonora, M. A., Caldarola, F., Maiolo, M., Muranho, J., & Sousa, J. (2020). The New Set-Up of Local Performance Indices into WaterNetGen and Application to Santarém's Network. In Environmental Sciences Proceedings (Vol. 2, No. 1, p. 18). Multidisciplinary Digital Publishing Institute.
- Williams, G. S., & Hazen, A. (1908). Hydraulic Tables: The Elements of Gagings and the Friction of Water Flowing in Pipes, Aqueducts, Sewers, Etc. as Determined by the Hazen and Williams Formula and the Flow of Water Over Sharp-edged and Irregular Weirs, and the Quantity Discharged, as Determined by Bazin's Formula and Experimental Investigations Upon Large Models. J. Wiley & sons.
- Williams, G.S.; Hazen, A. (1914), Hydraulic tables: the elements of gagings and the friction of water flowing in pipes, aqueducts, sewers, etc., as determined by the Hazen and Williams formula and the flow of water over sharp-edged and irregular weirs, and the quantity discharged as determined by Bazin's formula and experimental investigations upon large models. (2nd revised and enlarged ed.), New York: John Wiley and Sons

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6 CASTEL SAN GIORGIO WATER DISTRIBUTION NETWORK DIGITAL MODEL

6.0 SUMMARY

6.1 GEOGRAPHICAL FRAMEWORK

Castel San Giorgio is a *Campanian* municipality located in the *Salerno* Province, Figure 6.1.1. The municipal territory extends for 13.6Km^2 in the flat areas surrounding *Vesuvius*. The municipality hosts a population of 13411 inhabitants (ISTAT 2018). The infrastructure management is entrusted to *GORI S.p.A. GORI* deals with the management of the integrated water service of the *Sarnese-Vesuviano* District of *Campania* (ATO, **Chapter 1**).

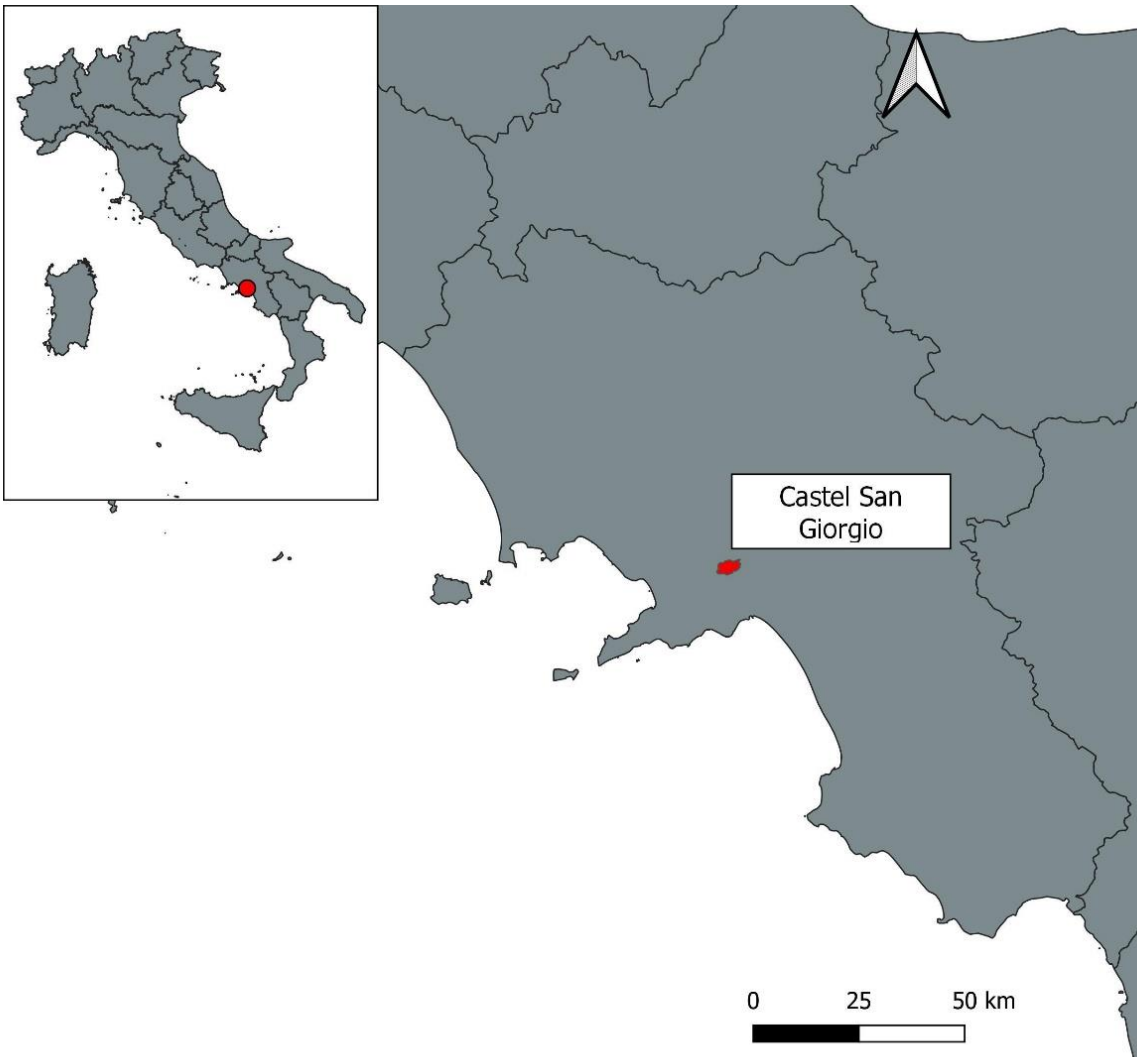

Figure 6.1.1 Castel San Giorgio municipality geographical location.

6.1.1 DISTRICT METERED AREAS

The WDN serving the municipal area is organized in three DMAs, Figure 6.1.2. The DMA02, Figure 6.1.3, supplies the southwest network area. This area includes part of the residential area and some production plants. The DMA03, Figure 6.1.4, supplies the central municipality area, mainly residential. The DMA04 supplies a limited area located north of the inhabited centre. This area is located at a higher altitude than the tank and requires a pumping station. Each district is isolated and supplied by a tank. Table 6.1.1 summarizes the characteristics and extent of each district. The network is part of an extensive urbanized territory and borders on areas served by adjacent networks. To the north, DMA01 "*Siano*" borders the DMA04 and DMA03. The DMA01 is connected to the network with a secondary pipe, but is commonly supplied by another WDN. To the south is the "*Sant'Eustacchio*" area, which is supplied by one of the network tanks with a dedicated pipe, Figure 6.1.5. This area is referred to as "*EXT*", for external.

Code	Name	Pipe length [km]	Pipe number	Junction number	Average elevation	Main Tank
DMA02	*Santa Croce*	22.19	170	600	86.5	*Santa Croce*
DMA03	*Torello Cortedomini*	26.24	36	666	91.6	*Torello Cortedomini*
DMA04	*Torello ZA*	1.21	602	31	134.1	*Torello Cortedomini*
EXT	*S. Eustachio*	2.45	715	2*	83.3	*Torello Cortedomini*
UTILITIES	-	7.35	26	191	108.9	-
Total		59.43	1549	1504**		*Traiano****
* Most of the EXT pipe junction is listed as Utilities because the served zone is outside the WDN area ** 14 nodes are not listed because counts as DMA boundary nodes *** The Traiano tank supplies water to other tanks						

Table 6.1.1 Castel San Giorgio DMAs characteristics summary.

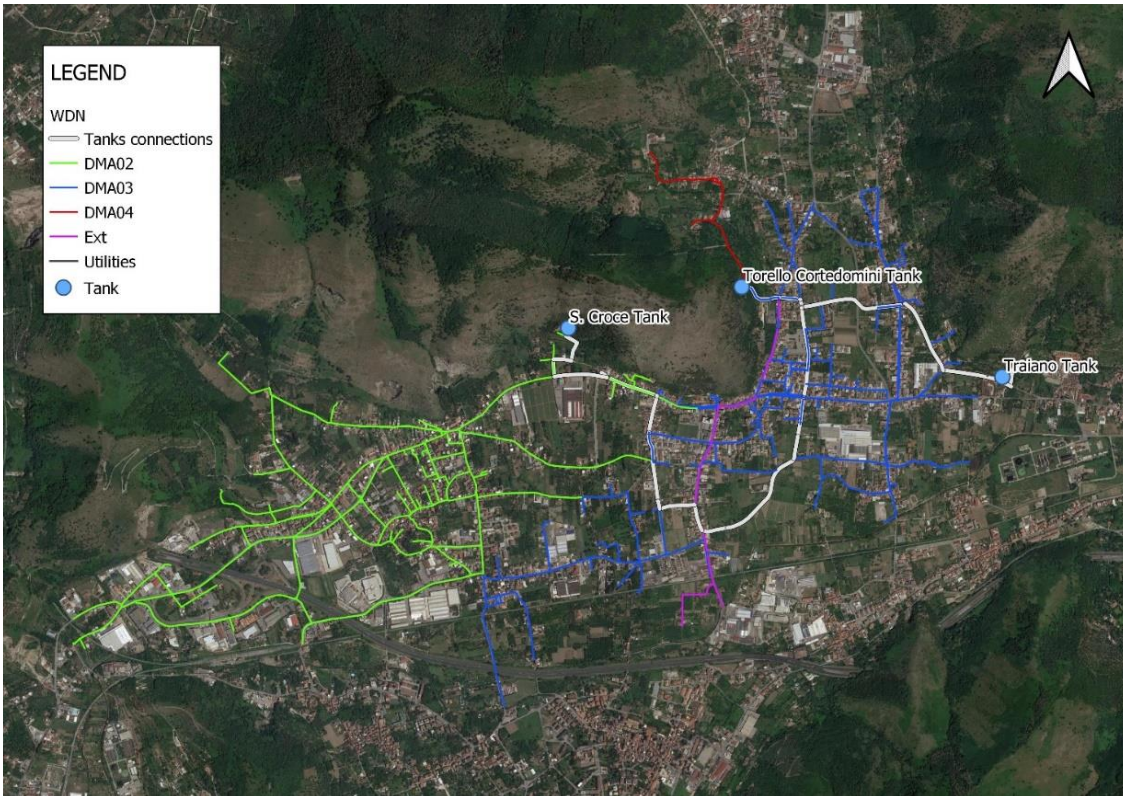

Figure 6.1.2 Castel San Giorgio municipality map. Google Satellite background.

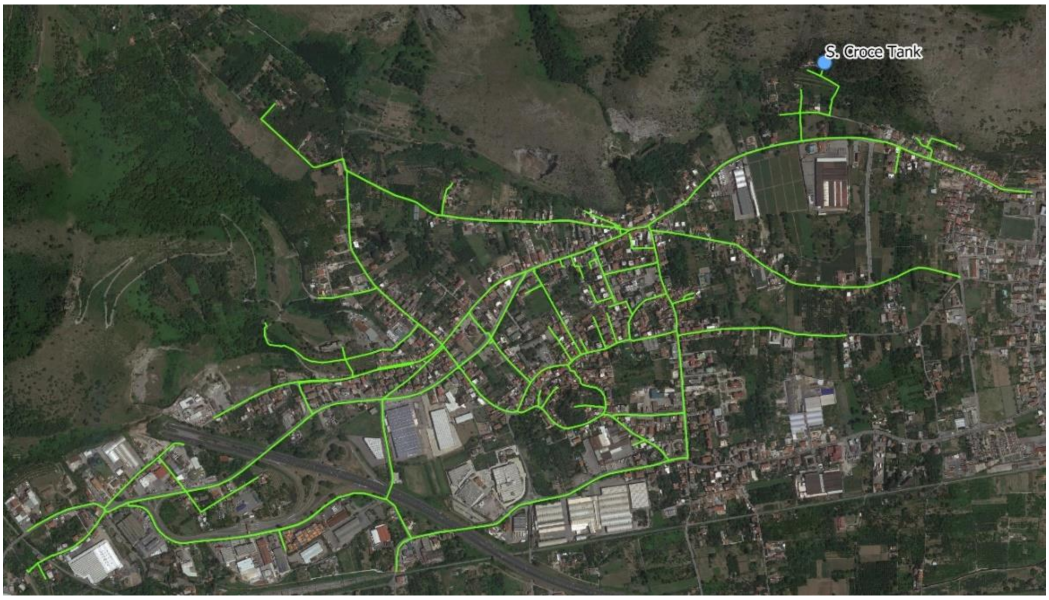

Figure 6.1.3 DMA02 plan view, Google Satellite background.

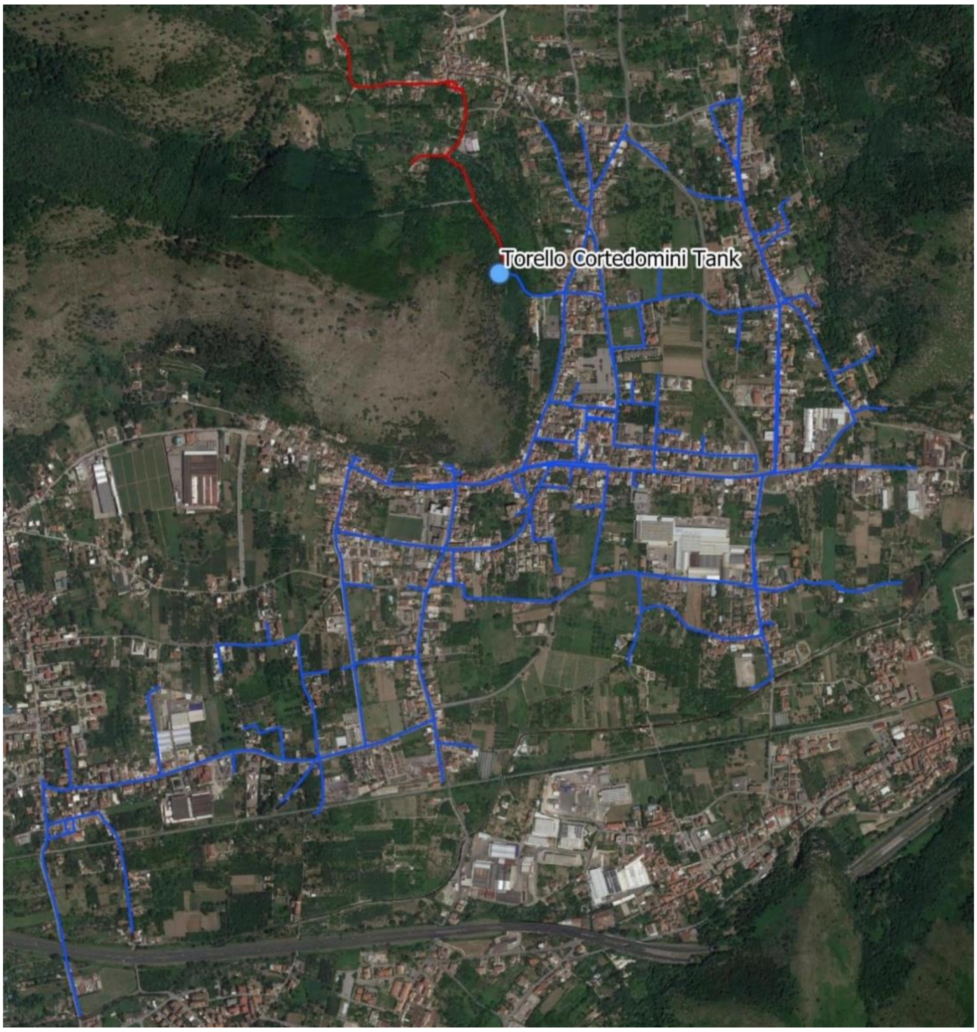

Figure 6.1.4 DMA03 and DMA04 plan view. Google Satellite background.

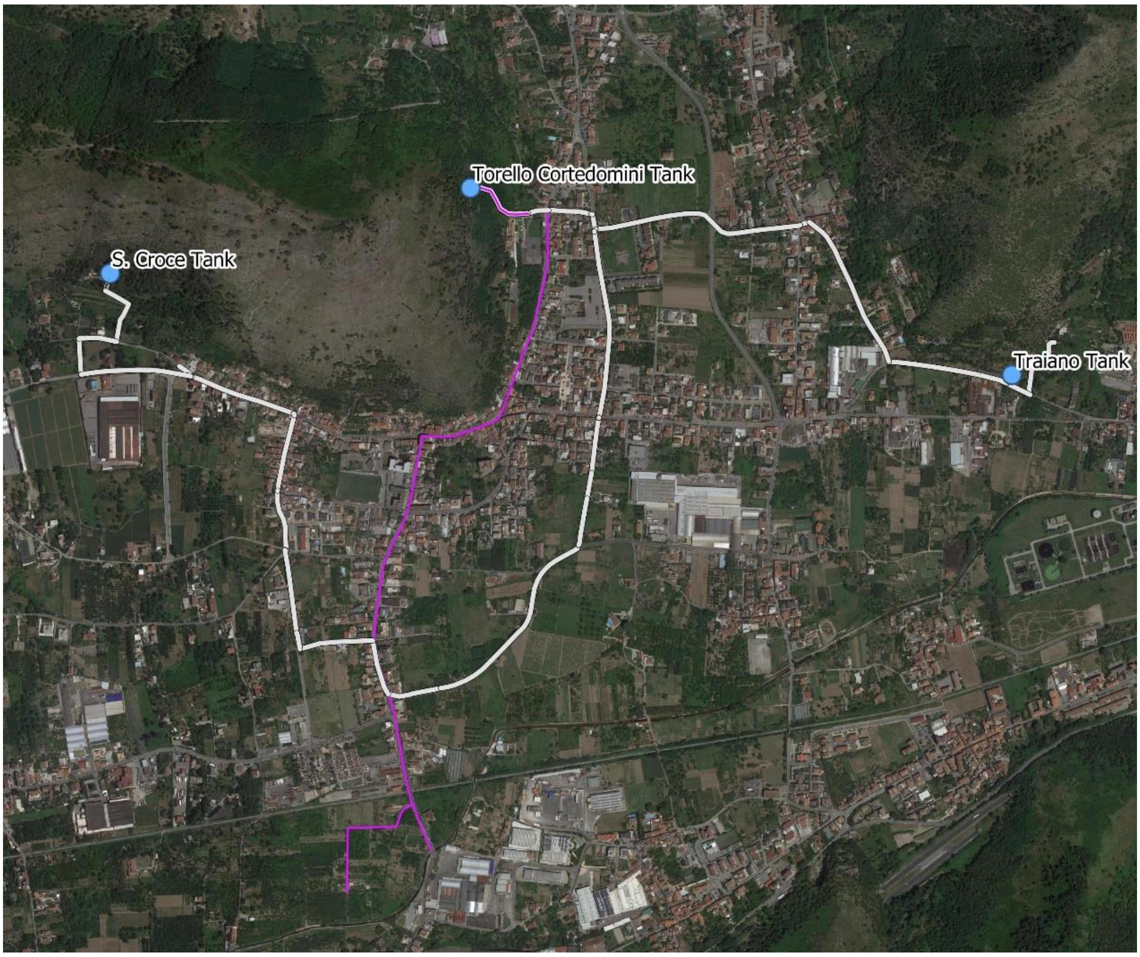

Figure 6.1.5 Connection between tanks and EXT DMA plan view. Google Satellite background.

6.1.2 TANKS SUPPLYING THE NETWORK

The network is divided into three DMAs and supplies water to two external zones. In the municipal area, there are three wells and three tanks. The WDN has a complex operating scheme and requires a schematic to ensure a correct understanding of the relationships that exist between tanks, wells, and the DMAs.

Traiano tank

Traiano is the main network tank. The tank is located to the east, Figure 6.1.5. Despite having a very limited storage volume, the tank supplies the other network tanks. Table 6.1.2 summarized some tank characteristics. The data refers to an equivalent cylindrical tank, which has a volume and base area equal to the sum of the existing tanks. Figure 6.1.6 schematizes the tank connections with the network and the other tanks. The *Traiano* tank is fed by two wells located in its vicinity (*Traiano_1* and *Traiano_2*). The water taken from the wells is distributed to the other tanks using three pumps. Two pipelines branch off from the tank, the first supplies the *Torello Cortedomini* tank using two parallel pumps (P_6 and P_7); the second supplies the *Santa Croce* and *Torello Cortedomini* tanks using a pump (P_89). Figure 6.1.5. shows the connections between tanks and network.

Base elevation	100	m
Maximum Level	3.11	m
Equivalent Base area	29	m^2
Equivalent Diameter	6.1	m
Maximum storage Volume	90.3	m^3

Table 6.1.2 *Traiano* tank characteristic summary.

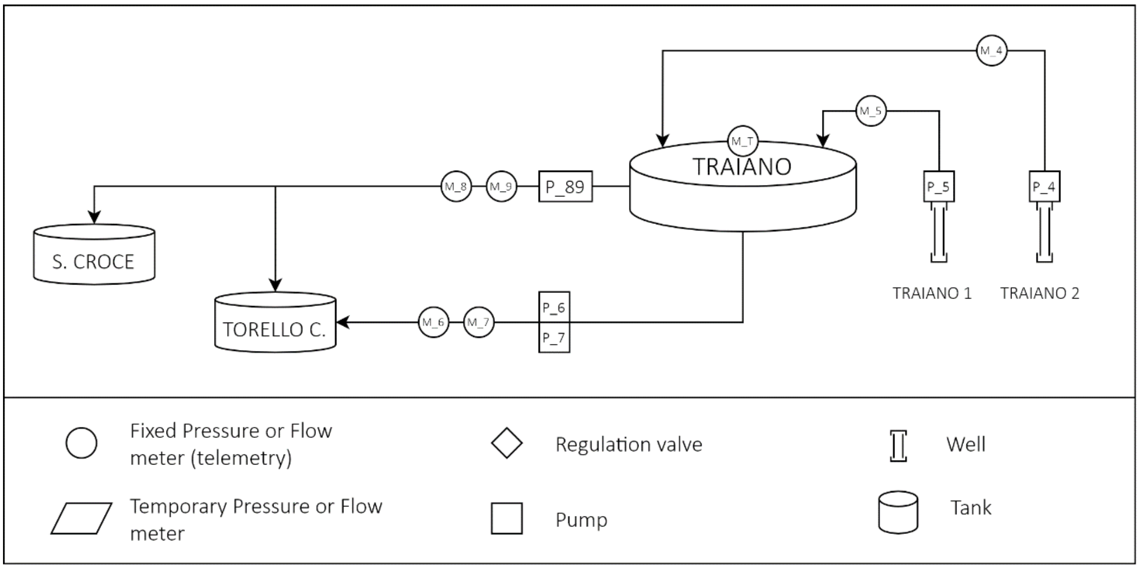

Figure 6.1.6 *Traiano* tank connections diagram.

Torello Cortedomini tank

Torello Cortedomini is in a central position for the WDN. The tank supplies DMA03, DMA04 (wich feeds DMA01) and *EXT* zone. Table 6.1.3 gives summary information on the tank. Unlike *Traiano*, *Torello Cortedomini* has a high storage volume. Figure 6.1.7 schematises the connections and interdependencies of the tank. The figure shares the legend of Figure 6.1.6.

Base elevation	165	m
Maximum Level	4.4	m
Equivalent Base area	270	m^2
Equivalent Diameter	18.53	m
Maximum storage Volume	1188	m^3

Table 6.1.3 *Torello Cortedomini* tank characteristic summary.

As previously mentioned, the tank is fed by two pipes coming from the *Traiano* tank. The volume of water is distributed to the DMA03 and the *EXT* area by gravity. The gravity distribution is regulated by a valve (V_3). DMA01 is connected to DMA04, but commonly there is no water exchange. The DMA04 is supplied through a pumping station (P_2).

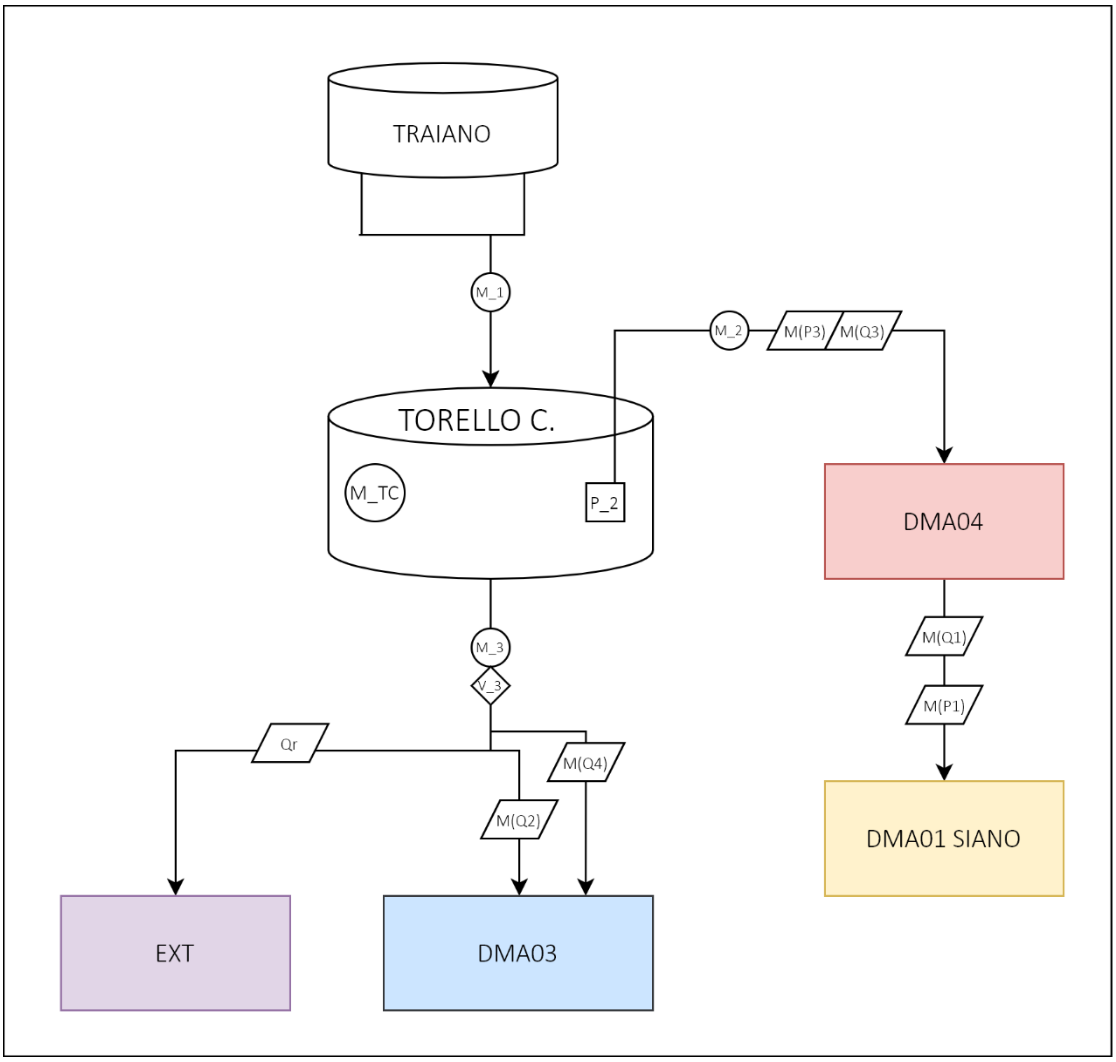

Figure 6.1.7 *Torello Cortedomini* tank connections diagram.

Santa Croce tank

The *Santa Croce* tank serves the DMA02. Table 6.1.4 shows the summary information on the tank. The tank volume allows a compensation function. Figure 6.1.8 maintains the same legend as the previous ones and shows the tank operating diagram. The tank is supplied by the pipe coming from *Traiano* and the well (*Santa Croce*) located in its vicinity. On the tank outlet pipe, there is a pressure regulation valve (V_13).

Base elevation	125	m
Maximum Level	4	m
Equivalent Base area	232.7	m^2
Equivalent Diameter	17.2	m
Maximum storage Volume	930.7	m^3

Table 6.1.4 *Santa Croce* tank characteristic summary.

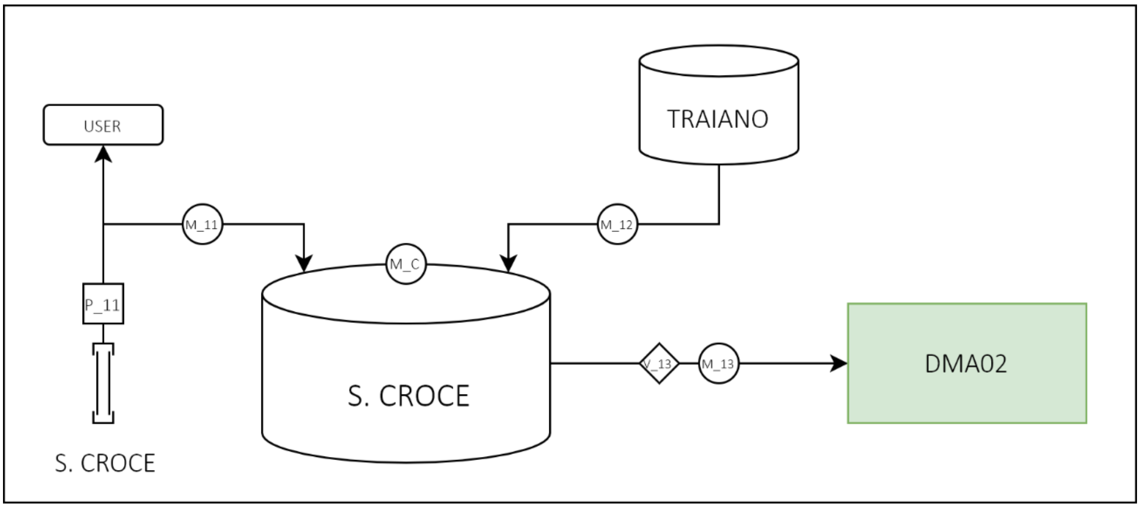

Figure 6.1.8 *Santa Croce* tank connections diagram.

Network pumping stations

The network serving Castel San Giorgio relies on the abstraction of water from various wells. The abstracted water is distributed from *Traiano* using pumping stations. Table 6.1.5 summarizes the pumps information (model, nominal flow, nominal speed). The Name column refers to the ID used in Figure 6.1.6, Figure 6.1.7, and Figure 6.1.8.

Name	Zone	Type	Pump Model	Nominal Flow (l/s)	Nominal Speed (rpm)	No. Of Stages
P_11	*Santa Croce*	Well	*CAPRARI E8R40/19*	14	2905	19
P_5	*Traiano*	Well	*CAPRARI E9S50/5A+MC840*	27	2890	5
P_4	*Traiano*	Well	*LOWARA Z8125 06*	34.72	2900	6
P_2	*Torello Cortedomini (DMA04)*	Distribution	*FELSOM AP6E3*	6.67	2900	1
P_6	*Traiano*	Distribution	*CAPRARI PM80/2A*	30	3500	2
P_7	*Traiano*	Distribution	*CAPRARI PM80/2A*	30	3500	2
P_89	*Traiano*	Distribution	*CAPRARI HV80/2F*	40	2900	2

Table 6.1.5 WDN pumps/pumping stations characteristic summary.

6.1.3 Pressure and flow metering

The WDN is equipped with telemetry metering devices. The devices sample hourly the flows entering and leaving the tanks and the pressure downstream the pumps. The network manager has made hourly measurements available for a period that covers the years 2019 and 2020. The meters and valves are represented respectively by circles and lozenges in the diagrams (Figure

6.1.6, Figure 6.1.7 and Figure 6.1.8). Table 6.1.6 shows the nomenclature, positioning, type of meter or valve and a brief description of the detected variable.

The flow entering the *Traiano* tank, abstracted from *Traiano_1* and *Traiano_2* wells, is measured by M_4 and M_5. The flows outgoing from the tank and the pressures downstream of the pumps positioned on the pipes directed towards the *Santa Croce* and *Torello Cortedomini* tanks are monitored by M_8 + M_9 and M_6 + M_7. All the flows entering and exiting the tank are monitored and it is possible to obtain a hydraulic balance on an hourly scale.

The *Santa Croce* is fed by the *Traiano* and the *Santa Croce* well. M_11 and M_12 monitor the overall tank inlet flow. The tank outgoing flow rate and the setting of the valve located on the pipe are also detected by M_13 and V_13. For *Santa Croce,* it is possible to obtain the hydraulic balance on an hourly scale.

Name	Unit	TANK	Description
M_C	Level meter [m]	*Santa Croce*	*Santa Croce* tank level
M_12	Flow meter [l/s]	*Santa Croce*	Ingoing flow from *Traiano* Tank
M_13	Flowmeter [l/s]	*Santa Croce*	Outgoing flow to DMA02
M_11	Flowmeter [l/s]	*Santa Croce*	Ingoing flow from *Santa Croce* Well
V_13	Valve setting [%]	*Santa Croce*	Outgoing flow (to DMA02) valve setting
M_TC	Level meter [m]	*Torello Cortedomini*	*Torello Cortedomini* tank level
M_3	Flowmeter [l/s]	*Torello Cortedomini*	Outgoing flow to DMA03
M_1	Flowmeter [l/s]	*Torello Cortedomini*	Ingoing flow from *Traiano* tank
M_2	Pressure meter [bar]	*Torello Cortedomini*	*Torello Cortedomini* pump (P_2) pressure (flow to DMA04)
V_3	Valve setting [%]	*Torello Cortedomini*	Outgoing flow (to DMA03) valve setting
M_T	Level meter [m]	*Traiano*	*Traiano* tank level
M_5	Flowmeter [l/s]	*Traiano*	Ingoing flow from *Traiano_1* Well
M_4	Flowmeter [l/s]	*Traiano*	Ingoing flow from *Traiano_2* Well
M_7	Flowmeter [l/s]	*Traiano*	Outgoing flow to *Torello Cortedomini* Tank
M_9	Flowmeter [l/s]	*Traiano*	Outgoing flow to *Torello Cortedomini* and *Santa Croce* Tanks
M_6	Pressure meter [bar]	*Traiano*	*Traiano* pumps (P_6 and P_7) pressure (flow to *Torello Cortedomini* Tank)
M_8	Pressure meter [bar]	*Traiano*	*Traiano* pump (P_89) pressure (flow to *Torello Cortedomini* and *Santa Croce* Tanks)

Table 6.1.6 Pressure,tank level , and flow measurement characteristics, telemetry meter network.

Torello Cortedomini has the most complex operating scheme, Figure 6.1.7. The tank supplies directly two DMAs and the *EXT* zone. Meter M_1 measures the incoming flow from the Traiano tank. The meter M_2 samples the pump outlet pressure on the pipe that supplies the DMA04 (and DMA01). The supply of the DMA03 and the EXT zone takes place through a single pipe in which there is a valve (V_3) and a flow meter (M_3). The pipe branches after the meter and the valve. With the telemetry data, it is not possible to obtain a hydraulic balance because there is no measurement of the flow directed towards the DMA04. It is not possible to distinguish the share of water supplied to the DMA03 and the EXT since the meter is located upstream of the pipe branch.

To integrate the missing data, the infrastructure manager set up a survey campaign that uses the temporary flow and pressure meters. The measurements cover a period of approximately one week with a sampling interval of 10 minutes, Table 6.1.7.

Name	Unit	Metering log start*	Metering log end**	Zone	Description
M(P1)	Pressure meter [bar]	11:40:00	11:10:00	DMA01 border	Manhole pressure, flow from DMA04 to DMA01
M(P3)	Pressure meter [bar]	14:40:00	12:50:00	*Torello Cortedomini*	*Torello Cortedomini* pump (P_2) pressure (flow to DMA04)
M(Q1)	l/s	11:20:00	11:00:00	DMA01 border	Manhole flow from DMA04 to DMA01
M(Q2)	l/s	14:10:00	11:40:00	*Torello Cortedomini*	Outgoing flow to DMA03
M(Q3)	l/s	14:30:00	11:40:00	*Torello Cortedomini*	Outgoing flow to DMA04
M(Q4)	l/s	12:40:00	11:50:00	*Torello Cortedomini*	Outgoing flow to DMA03
* 07/02/2020 ** 14/02/2020					

Table 6.1.7 Pressure and flow measurement characteristics, temporary meters.

Two temporary meters are placed in the border area of DMA01 and DMA04. The meters M(P1) and M(Q1) detect the pressure and the flow rate exchanged between the districts. Using the values detected by the temporary meters it is possible to draw up an hydraulic balance of *Torello Cortedomini* (The flow rate consumed by the DMA04 is measured by M(P3)). The meters allow quantifying the water supplied to the DMA3 and the *EXT* zone. There are no meters on the pipe directed towards the EXT zone but the presence of the other meters allows to obtain the residual flow rate (Qr) using a difference (Qr = M_3- M(Q2) - M(Q4)).

6.1.4 WDN PIPES

Network modelling requires knowledge of the pipes hydraulic and geometric characteristics. The network manager has made available a model in which defines the pipe nominal diameters, internal diametera, material and roughness. In the following tables and graphs, the pipes are organized into five groups. Three of the groups contain the pipes within the DMAs. The pipes that start from the *Torello Cortedomini* tank and supply the *EXT* area are treated as a further group. The *Utilities* group includes the set of pipes connecting the wells to the tanks, the tanks to each other and pipes closed to isolate the DMAs. Table 6.1.8 shows the distribution of nominal diameters for each pipe group.

Table 6.1.9 and Figure 6.1.9, respectively, show the length and the percentage of each material constituting the pipes. To simplify the Figure 6.1.9 readability, the materials are re-organized into four groups: Steel and Galvanized steel, Iron, Extruded Cast-Iron and Cast Iron, Polyethylene and

HDPE. About half of the pipes in the network are Extruded Cast-Iron pipe, 28% are iron and 19.5% are HDPE.

Diameter	DMA02	DMA03	DMA04	EXT	UTILITIES	WDN
1/2"	211.8	598.2	-	1.0	184.7	995.7
3/4"	419.1	990.1	0.8	-	40.2	1450.2
1"	1523.6	3251.2	-	362.0	103.9	5240.9
1" 1/4	1023.7	932.0	-	-	0.2	1955.8
1" 1/2	2301.1	1988.2	325	-	-	4614.2
50mm	2701.9	2146.4	67.4	-	-	4915.7
2"	417.2	174.3	-	-	-	591.5
2" 1/2	1772.8	6194.6	128.9	-	-	8097.2
75mm	966.3	88.7	-	-	-	1055.0
90mm	1076.9	-	-	-	-	1076.9
80mm	2.5	666.5	5.8	-	0.3	675.0
110mm	283.7	680.6	678.6	-	-	1642.3
100mm	4974.9	5121.1	-	1.2	791.8	10889.5
125mm	2245.8	752.9	-	-	173.4	3172.2
150mm	1243.2	2470.6	-	2084.2	852.9	6650.9
200mm	1026.9	180.7	-	-	5197.8	6405.4
Total	**22191.5**	**26236.1**	**1206.4**	**2448.4**	**7346.1**	**59428.4**

Table 6.1.8 Length [meter] of pipes divided for nominal pipe diameter.

Material	Tag	DMA02	DMA03	DMA04	EXT	UTILITIES	WDN
Steel	AC	781.7	376.6	-	137.7	860.9	2156.9
Galvanized steel	AZ	-	363.8	-	-	-	364.0
Iron	FER	7304.4	8600.7	389.9	1.0	225.3	16521.1
Extruded Cast-Iron	GG	10511.4	12470.6	130.9	1947.7	1768.9	26829.4
Cast Iron	GS	0.0	1073.0	-	-	51.8	1124.7
Polyethylene	PE	432.2	342.6	-	-	69.4	844.2
HDPE	PEAD	3161.8	3008.8	685.6	362.0	4369.7	11588.0
Total		**22191.5**	**26236.1**	**1206.4**	**2448.4**	**7346.1**	**59428.4**

Table 6.1.9 Length [meter] of pipes divided for constituting materials.

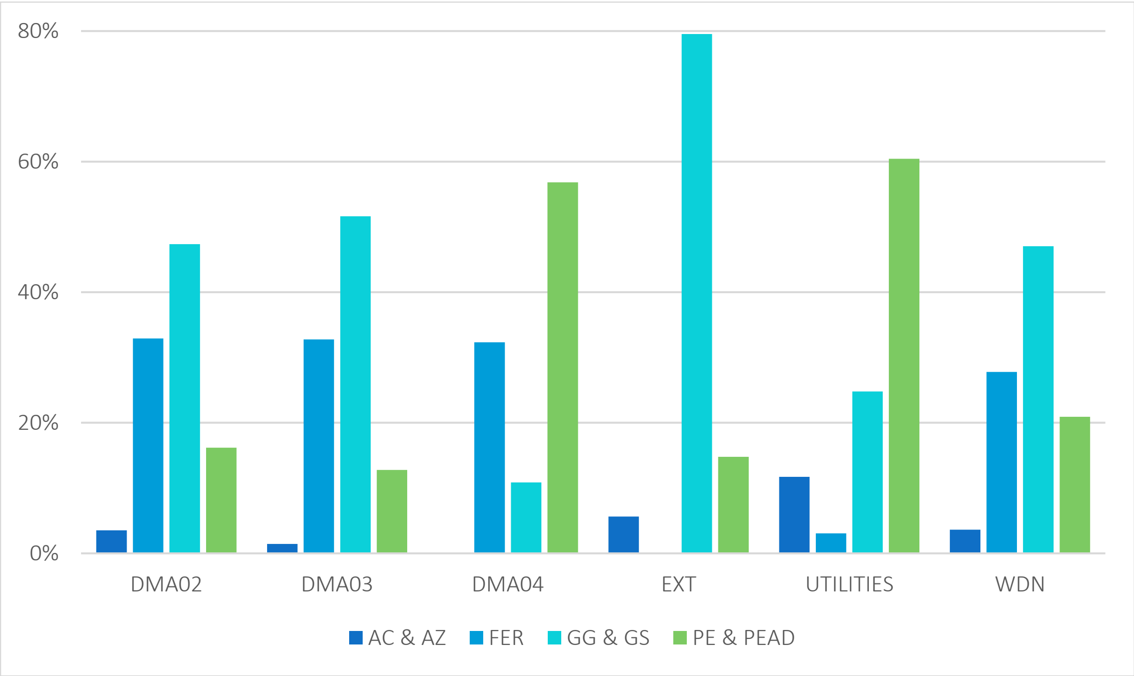

Figure 6.1.9 Length percentage of pipes divided for constituting materials for each DMA.

Table 6.1.10 reports the roughness assigned in the model according to the material. Unlike the other cases studies, the network manager defines the pipe roughness directly in the model.

Material	Abbreviation	Hazen-Williams Roughness
Steel	AC	120
Galvanized steel	AZ	120
Iron	FER	120
Galvanized Iron	FZI	120
Extruded Cast-Iron	GG	100
Cast Iron	GS	130
Polyethylene	PE	145
HDPE	PEAD	145

Table 6.1.10 Pipe material list and corresponding hydraulic roughness values.

6.2 WATER DISTRIBUTION NETWORK DIGITIZATION

The network manager provided a network digital model correlated by a series of elements data and measurements. The information on pumps, tanks and pipes are outlined in the previous paragraphs. The network digital model is extracted from specialized management software. The model was provided in EPANET inp format, shapefile and textual database. All the diagrams are georeferenced and accompanied by detailed information. The information provided is sufficient for the construction of the hydraulic model.

The EPANET scheme presents some criticalities due to the presence of a large number of isolation valves, schematized as valve elements, Figure 6.2.1. In EPANET, the isolation valves are not modelled, as it is possible to close the pipe elements. The EPANET schematization is detailed in Chapter 2. A further network scheme criticality is the absence of the element "geometries" of many elements. The valve and pump elements are links that connect two nodes elements. In the model provided, the end nodes of these links coincide. Most of the valve and pump elements present in the model have no length.

Figure 6.2.1 Network manager EPANET network model.

The network topology has been reorganized starting from the textual database. The elements are recompiled into well-known text (WKT) vectors. WKT elements are developed by the Open Geospatial Consortium (OGC) and allow representing simple geometric elements (Point, MultiPoint, LineString, MultiLineString, Polygon, MultiPolygon, Triangle, PolyhedralSurface, TIN). The WKT format is directly compatible with GIS software.

By reorganizing the model in WKT format and importing it into GIS it was possible to include the attributes of the element in the textual database. The model counts 548 valves, 7 pumps and 14 meters. For each device, there is a group of two overlapping junctions and a zero-length link. These elements are recompiled using three criteria:

- Isolation valves are excluded from the model. The junctions and the valve corresponding to each isolation valve haave been reduced to a single junction. Of the 548 isolation valves, 169 are closed, Figure 6.2.2. Closed valves mainly affect terminal sections of the pipe and some pipes inside the network. The valve status assignment involves one of the pipes adjacent to the new "isolation valve" junctions. The valve's closure allowed the isolation of the DMAs consistently with the district boundaries.

- EPANET does not have a meter element. Measurements refer directly to pipes or junctions. Meter elements are excluded from the model. Corresponding links and junctions have been organized merged similarly to the isolation valves.
- EPANET models the pumps as links. Pump elements without geometry or with a very short length have been corrected.

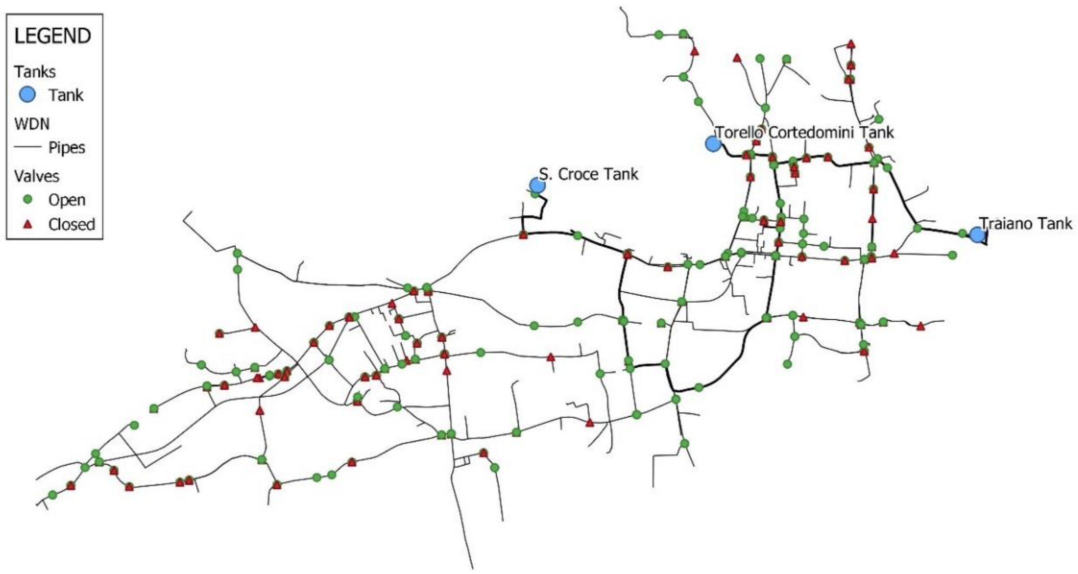

Figure 6.2.2 WDN map and valves status.

6.2.1 End-users water demand assessment and demand distribution criterion

The assignment of water demand to junctions is one of the modelling phases characterized by uncertainty. The original network model contains a layer with location and information on the end-users average annual consumption, Figure 6.2.3. The average water demand obtained from the users provides information only on the revenue water (**Paragraph 9.3.1**). The overall water demand includes the unbilled authorized consumption and the water losses (apparent and real). According to ISTAT estimates (2018), the municipality of Castel San Giorgio is characterized by significant amount of non revenue water; approximately 59% of the water fed into the network does not reach the final users.

To characterize the total water demand of the network, it is necessary to integrate the end-users consumption with additional data. ISTAT makes available territorial census information in the form of a textual and cartographic database. The database divides the Italian territory in sections. The sections are homogeneous territorial zones of variable extension. The sections are divided into inhabited areas and productive locations. The database classifies the inhabited localities in *Case Sparse* (*Sparse Houses*), *Centri Abitati* (*Inhabited Centers*) and *Nuclei Abitati* (*inhabited areas*).

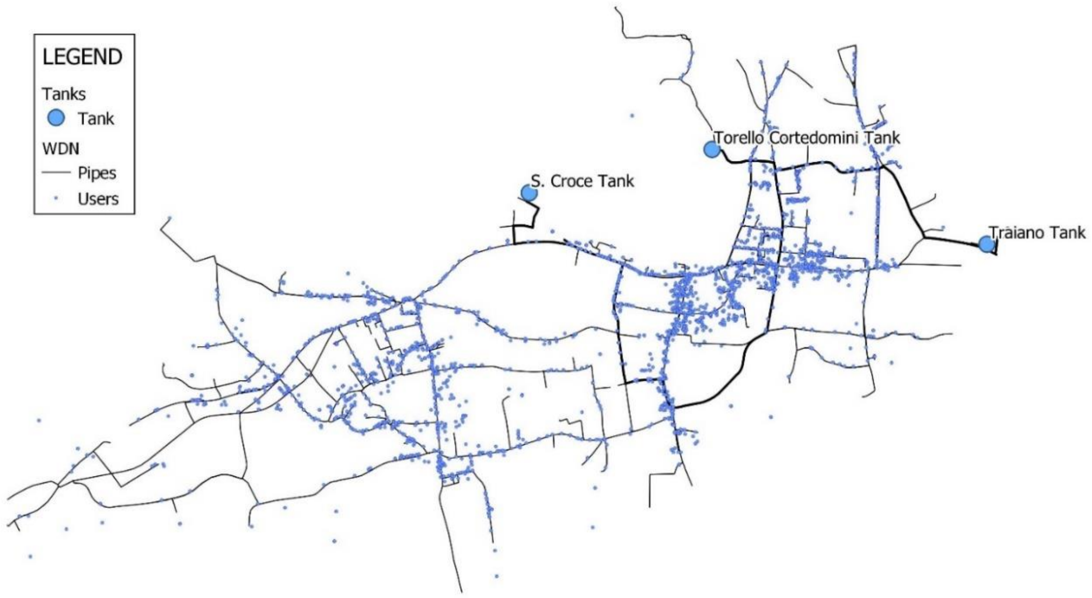

Figure 6.2.3 End- users' private water meter location map.

The classification is based on the density of the houses. The Italian territory subdivision into localities and the subdivision criteria are detailed in the document "*Descrizione dei dati geografici e delle variabili censuarie delle Basi territoriali per i censimenti: anni 1991, 2001, 2011*" (*Description of geographic data and census variables of the territorial bases for censuses: years 1991, 2001, 2011*) (25/02/2016). For each location, the map database contains information on:

- Resident population:
  - Classification by age groups;
  - Classification by civil state;
  - Classification by education title;
  - Classification by employment.
- Buildings:
  - Classification by use purpose;
  - Classification by construction type;
  - Classification by construction age.

The population and employees of the municipal area were extracted to characterize the inhabitants' distribution and, consequently, the water demand distribution. The knowledge of the number of employees and residents for each section allowed estimating the population and workers density for each section. Figure 6.2.4 shows the ISTAT classification of the municipal area.

Table 6.2.1 reports the number of sections and the number of inhabitants in each category. The ISTAT zoning data refer to the 2011 census. The resident population in the municipality in 2011 was 13,689 inhabitants. The municipal population remained stable. The last surveyed value in 2019 is 13,405 inhabitants (2.07% decrease).

ISTAT class	SEZ2011 Number	Area [ha]	Employees	Inhabitants
Case sparse	3	1035.9	9	384
Centro abitato	21	258.7	542	12710
Località produttiva	3	65.3	546	267
Nucleo abitato	1	2.4	1	50
Total	28	1362.3	1098	13411

Table 6.2.1 *Castel San Giorgio* surveyed Inhabitants and employees number.

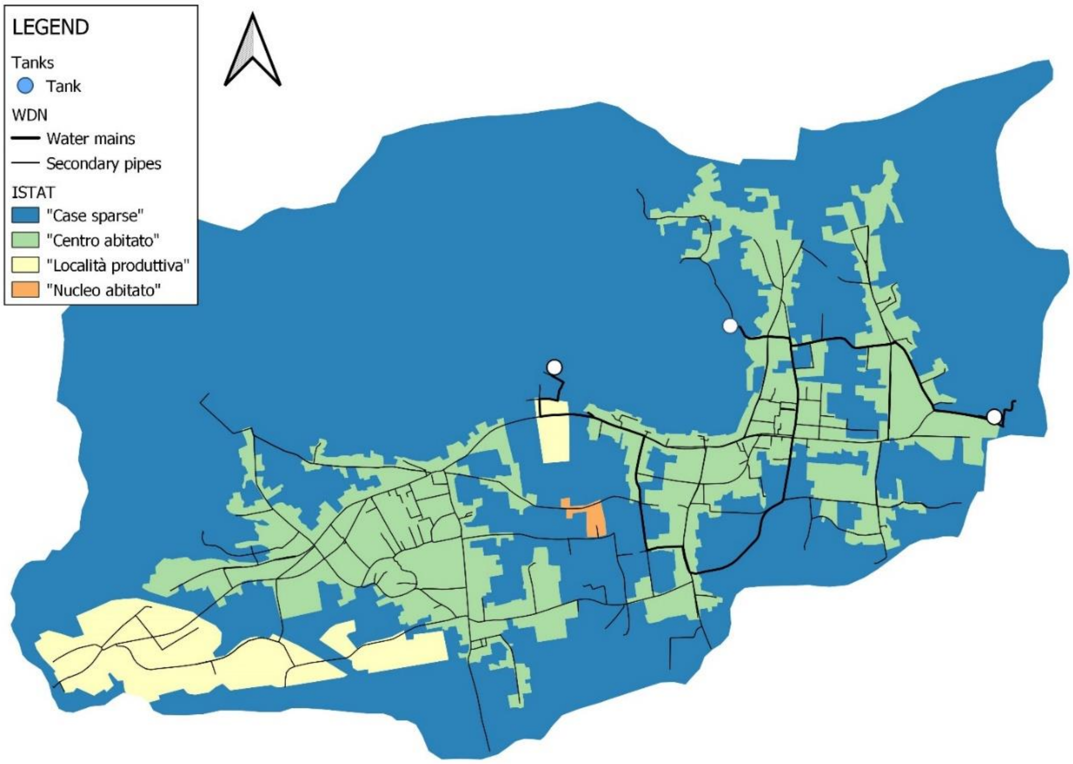

Figure 6.2.4 Urban fabric distribution, ISTAT classification and mapping

The extension and the number of inhabitants and workers surveyed in each section allowed obtaining the map of the population density, Figure 6.2.5. Using the same criterion described for the network serving the municipality of *Serra San Bruno* (**Paragraph 4.2.1**) it is possible to distribute the demand on the junctions.

DMA	Inhabitants	Employees
DMA03	6268.2	248.5
DMA02	5973.3	773.2
DMA04	142.3	1.5
DMA01	1027.1	74.7
Total	13411	1098

Table 6.2.2 Inhabitants distribution per DMAs

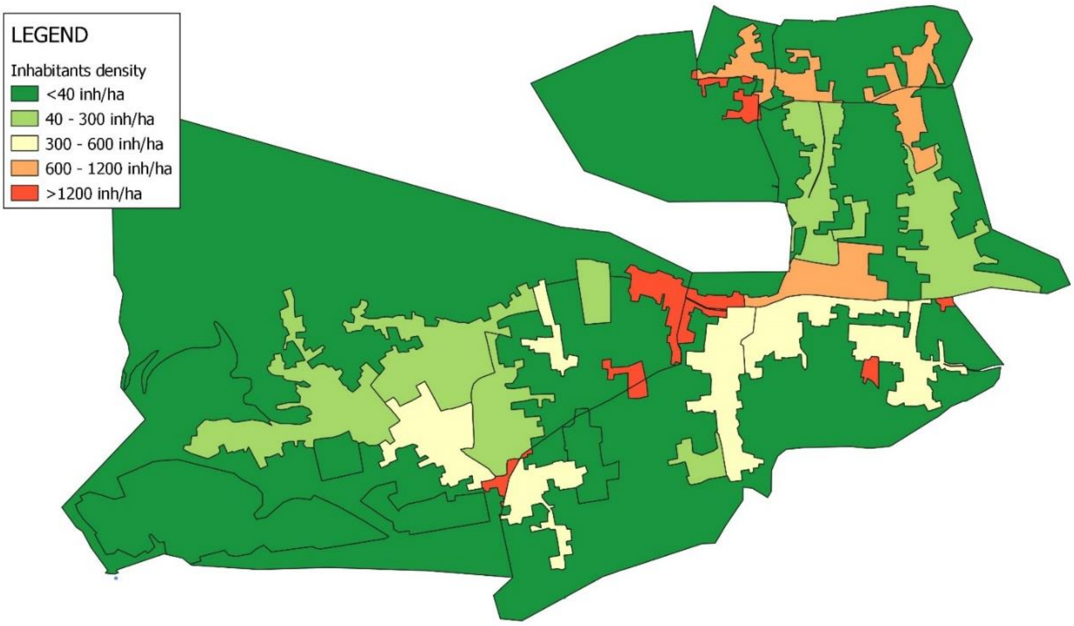

Figure 6.2.5 *Castel San Giorgio* sections Inhabitants density.

6.3 State of the art and future developments

The WDN serving municipality of Castel San Giorgio is particularly complex and rich in information. Understanding the connections between the network elements and the different areas required an in-depth study and a dialogue with the network technicians. The presence of telemetry meters makes available a large number of readings. The very high rate of non-revenue water and the absence of continuous readings on the end-user meters makes it difficult to characterize the water demand. The construction of the hydraulic model is still ongoing.

The network is supplied by water abstracted from three wells. Two of these wells supply the central tank of the network that distributes the water through pumping stations. The presence of several pumps makes the network suitable for studying the dependence of the water distribution infrastructure on the electricity network. This study would allow an in-depth study of the interconnections between critical infrastructures.

7 WATER DISTRIBUTION NETWORK RELIABILITY AND SYNTHETIC PERFORMANCE INDICES

7.0 SUMMARY

7.1 Introduction

Modern times are characterized by an increase in the need for water resources due to the development of inhabited areas, socio-economic changes and production processes. Concomitantly, there is a progressive reduction in the availability of water resources due to climate change. Many areas of the planet face periods of resources lack that continue over time, causing inconvenience and problems for the human settlements development and maintenance. Due to the greater demand and less availability, the regulations (local and superordinate) support the need for more rational and sustainable resource use.

The need for optimization and improvement of the infrastructure functioning regime has prompted the designers, the managers and the scientific community to refer to synthetic performance indicators. These indicators numerically describe one or more intrinsic characteristics of a distribution network. In addition to evaluating the performance of existing infrastructures, indexes are often used as a criterion to be maximized (or minimized) in the design. Very often WDNs designer refers to the concept of Reliability. The design goal is to define an infrastructure that is reliable in the largest number of possible operating scenarios.

7.1.1 Water Distribution Network reliability

Kaufmann *et al*. (1977) define reliability as the probability that the system will perform its specified tasks under specified conditions and during a specified time. Cullinane *et al*. (1992) and Goulter (1995) define the WDN reliability as the ability of the system to meet the demands that are placed on it. In several studies, it is defined as the weighted time-averaged value of the ratio of the flow delivered to the flow required by the users (Setiadi *et al*. 2005, Tanyimboh 1993, Tanyimboh and Sheahan 2002).

Setiadi *et al*. (2005) refer that to have an effective estimate of reliability, all possible operating and failure scenarios must be taken into account. This kind of characterization is very complex and difficult to implement for large networks. The authors consider WDN entropy as a surrogate measure of reliability. The WDN entropy assessment is based on the methodology presented by Tanyimboh and Templeman (1993). The paper shows a correlation between entropy and reliability. Furthermore, the correlation increases if PDAs (Pressure-Driven Analysis) are used in modelling hydraulics.

Tanyimboh and Templeman (1993a, 1993b) use a probabilistic approach based on the concept of entropy in communications theory presented in Shannon (1948). The authors in Tanyimboh and Templeman (1993a) use entropy to derive the operating regime (the distribution of flow in the pipes) in networks with incomplete or insufficient data. Tanyimboh and Templeman (1993b) show that the entropy maximization in WDNs design allows defining networks resilient to breakage and anomalies without a substantial cost increase.

Ciaponi *et al*. (2011) define reliability as the ability of a WDN to satisfy users in all possible operating conditions. Reliability is assessed using the ratio between the volume of water delivered to users and the one requested in a given period. The proposed methodology estimates a series of performance indices for different operating scenarios with a probability of occurrence. The operating scenarios take into account failures or interruptions of mechanical elements (pumps and pipes) and anomalous variations in hydraulic factors (increase in water demand, variations in roughness). The operating scenarios are defined per what is reported in Bertola *et al*. (2004), Khomshi *et al*. (1996) and Tanymboh *et al*. (2001).

Todini (2000) considers the concept of reliability as not completely defined and influenced by numerous factors that are difficult to define. The author introduces the concept of resilience as the system's ability to overcome failures. The formulation allows estimating resilience without the need to analyze all types and combinations of possible failures. An increase in resilience leads to an increase in reliability.

Di Nardo *et al*. (2010) develop a tool to support the WDNs districtization. Resilience and entropy indices are used in the definition of the district to identify the most effective pipe set to be closed to isolate the districts. The authors find no correlation between resilience and entropy indices. Entropy is not related to any of the indices used (Root Mean Square of Pressure Deviations, Mean Pressure Deviation, Di Nardo *et al*. 2006) (Resilience Index, Todini 2000).

Greco *et al*. (2012) use a definition of reliability similar to the Kaufmann *et al*. (1977) one. This definition presents applicative issues in practical scenarios, due to the intrinsic complexity of WDNs and the great variability of operating conditions. The authors analyze the effectiveness of entropy and resilience indices as reliability surrogate measures. The reliability esteem to a large number of possible operating configurations (including pipe failure) for two different case studies did not identify any correlation between the resilience and entropy indices. Resilience indices quantify the network strength in the event of breakage.

Gargano and Pianese (2000) present a methodology for the WDN design that allows defining a scheme maximum reliability scheme. The methodology is partially presented in Pianese and Villani (1994) and Pianese (1995). It consists of seven steps and allows esteem the overall reliability. The overall reliability is the weighted probability of satisfying the water demand of the users in the event of normal or abnormal operating conditions of the WDN components.

Prasad *et al*. (2004) present multiobjective genetic algorithms for the WDNs design. The algorithm minimizes the cost and maximizes resilience simultaneously. The authors consider the network resilience to be representative of reliability. Network resilience is based on the resilience index proposed by Todini (2000). The resilience index has been modified to reward the presence of loops of similar diameter pipes. The network resilience used increases the reliability of a WDN in conditions of failure.

Raad *et al*. (2010) use the definition of reliability proposed by Cullinane *et al*. (1992) and Goulter (1995). The study compares four different reliability measures: resilience index (Todini 2000), network resilience (Prasad *et al*. 2004), flow entropy (Tanyimboh and Templeman 1993a, 1993b) and a new index obtained combining the flow entropy and the resilience. This index should be more effective in representing reliability because it combines several aspects.

Di Nardo *et al*. (2012) consider reliability as an indicator difficult to define, due to the uncertainties affecting the WDNs operating conditions knowledge. The authors consider the robustness a better metric. Robustness is defined as the ability of the system to maintain a certain level of service in the presence of unfavourable operating conditions. The study compares the flow entropy (Tanyimboh and Templeman 1993a, 1993b) and the resilience index (Todini 2000) as measures of robustness. The result shows no correlation between resilience and entropy. Networks with higher resilience are found to be more robust concerning breakages or malfunctions.

Liu *et al*. (2014) propose a new formulation for the flow entropy (Tanyimboh and Templeman 1993a, 1993b) to better represent reliability. The new formulation takes into account the impact of the pipe diameter uniformity in the assessment of the flow entropy.

Muranho *et al*. (2018) define reliability as the ability to satisfy the water demand with sufficient pressure, even in the case of critical operating scenarios. The authors present a comparison between surrogate measures of reliability: resilience (Todini 2000), network resilience (Prasad *et al*. 2004), flow entropy (Tanyimboh and Templeman 1993a, 1993b, Liu *et al*. 2014). A new reliability surrogate measure is presented, the WNG Index (WaterNetGen Index). The index represents the ability to satisfy the water demand in the presence of a pipe failure. The authors present a design methodology that identifies the solution with the maximum reliability form a certain budget. The study shows no strong correlations between the analysed indices. Entropy maximization shows an improvement in reliability.

7.2 FLOW ENTROPY

As stated in the previous section, Tanyimboh and Templeman (1993b) use the maximization of entropy as a design criterion. Flow entropy has the advantage of being easy to calculate and integrate into optimization codes. The entropy maximization design criterion leads to the preference for looped schemes with a balanced distribution of the flow rates.

Entropy is calculated as

$$S = S_0 + \sum_{i=1}^{n} P_i S_i$$ Eq. 7.2.1

- S network entropy;
- S_o entropy of the sources;
- S_i entropy of node i;
- n total number of nodes.

P_i is the ratio of the total flow arriving at the node to the sum of flow which is supplied by all sources

$$P_i = \frac{q_i^{IN}}{Q_{IN}}$$ Eq. 7.2.2

$$q_i^{IN} = \sum_{j \in IN} q_{i\,j}$$ Eq. 7.2.3

$$Q_{IN} = \sum_{j=1}^{k} Q_j$$ Eq. 7.2.4

- q_i^{IN} flow arriving at node i;
- Q_{IN} total flow supplied by the sources;
- $q_{i\,j}$ flow of the jth pipe arriving at node i;
- IN list of pipes arriving at node i;
- k total number of sources.

S_0 represents the overall sources (tanks and reservoirs) entropy:

$$S_0 = -\sum_{j=1}^{k} \frac{Q_j}{Q_{IN}} ln\left(\frac{Q_j}{Q_{IN}}\right)$$ Eq. 7.2.5

- Q_j network inflow from source j.

Similarly S_i represent the demand node (junction) entropy:

$$S_i = -\frac{q_i}{q_i^{IN}} ln\left(\frac{q_i}{q_i^{IN}}\right) - \sum_{z \in OUT} \frac{q_{i_z}}{q_i^{IN}} ln\left(\frac{q_{i_z}}{q_i^{IN}}\right) \quad \text{Eq. 7.2.6}$$

- q_i water demand at node i;
- q_{i_Z} flow of the z^{th} pipe emanating from node i;
- OUT list of pipes emanating from node i.

The network entropy can be calculated as:

$$S = -\sum_{j=1}^{k} \frac{Q_j}{Q_{IN}} ln\left(\frac{Q_j}{Q_{IN}}\right) + \sum_{i=1}^{n} \left(\frac{q_i^{IN}}{Q_{IN}}\right) \left[-\frac{q_i}{q_i^{IN}} ln\left(\frac{q_i}{q_i^{IN}}\right) - \sum_{z \in OUT} \frac{q_{i_z}}{q_i^{IN}} ln\left(\frac{q_{i_z}}{q_i^{IN}}\right)\right] \quad \text{Eq. 7.2.7}$$

Diameter sensitive flow entropy

The flow entropy characterizes the network's pipe flow uniformity. Eq. 7.2.8 is insensitive to diameter variation. Diameters have a significant impact on reliability. Liu *et al*. (2014) propose an alternative formulation of flow entropy. The demand node (Eq. 7.2.6) is modified introducing a dimensionless parameter that takes into account the variability of the diameters.

$$S_i = -\frac{q_i}{q_i^{IN}} ln\left(\frac{q_i}{q_i^{IN}}\right) - \sum_{z \in OUT} \frac{C}{v_{i_z}} \frac{q_{i_z}}{q_i^{IN}} ln\left(\frac{q_{i_z}}{q_i^{IN}}\right) \quad \text{Eq. 7.2.8}$$

- v_{i_z} velocity of the z^{th} pipe arriving at node i;
- C arbitrary velocity constant (for example, 1m/s).

The diameter sensitive flow entropy is:

$$S = -\sum_{j=1}^{k} \frac{Q_j}{Q_{IN}} ln\left(\frac{Q_j}{Q_{IN}}\right) - \sum_{i=1}^{n} \left(\frac{q_i^{IN}}{Q_{IN}}\right) \left[\frac{q_i}{q_i^{IN}} ln\left(\frac{q_i}{q_i^{IN}}\right) + \sum_{z \in OUT} \frac{C}{v_{i_z}} \frac{q_{i_z}}{q_i^{IN}} ln\left(\frac{q_{i_z}}{q_i^{IN}}\right)\right] \quad \text{Eq. 7.2.9}$$

With this formulation, pipes with velocity bigger than C (their capacity is surpassed) have a lower entropy value, while pipes with velocity lower than C (their capacity isn't fully used) have higher entropy. Maximum entropy design tends to reward network configurations in which there is a more uniform distribution of flow connections and diameters.

7.3 Resilience and robustness

Todini (2000) introduces the concept of resilience as a surrogate measure of robustness. Robustness is a measure of the system's ability to overcome failures. The author defines the resilience index and the failure index as design metrics. The optimal design scheme is achieved by maximizing resilience and limiting the cost. Todini (2000) builds the resilience index from an energy balance.

The Todini resilience index, like many other known ones, refers to the "requested" or "design" conditions. These conditions are water demand and piezometric head values that must be reached to ensure proper network functioning. The requested conditions and variables are indicated by an asterisk apex.

The formulation is based on the concept that a network that has a pressure surplus is more robust in case of breakages or anomalous hydraulic events.The resilience index, I_r, is structured as the complement to the ratios between the power/energy dissipated in the WDN (P_D*) and the maximum dissipable value (P_{Dmax}) to meet the target/design values.

$$I_r = 1 - \frac{P_D^*}{P_{D\,max}} \qquad \text{Eq. 7.3.1}$$

The total available power (P_{tot}) at the entrance of a WDN is:

$$P_{tot} = \gamma \sum_{k=1}^{r} Q_k H_k + \sum_{j=1}^{p} P_j \qquad \text{Eq. 7.3.2}$$

in which:

- γ water specific weight;
- r number of sources (tanks, reservoirs);
- Q_k source discharge (flow entering the network);
- H_k source piezometric head;
- p number of pumps;
- P_j pump power.

The global minimum output power (P_{Emin}) is the global sum of the power that must be delivered at each demand node to satisfy the design piezometric head and demand:

$$P_{E\,min} = \sum_{i=1}^{n} p_i^* = \gamma \sum_{i=1}^{n} q_i^* h_i^* \qquad \text{Eq. 7.3.3}$$

- n number of network nodes;
- p_i^* design power of the i^{th} node;
- q_i^* design water demand of the i^{th} node ;
- h_i^* design piezometric head of the i^{th} node.

The maximum dissipable power is the highest power that can be used without compromising the accomplishment of the design values:

$$P_{D\,max} = P_{tot} - P_{E\,min} = \left(\gamma \sum_{k=1}^{r} Q_k H_k + \sum_{j=1}^{p} P_j\right) - \gamma \sum_{i=1}^{n} q_i^* h_i^* \qquad \text{Eq. 7.3.4}$$

The total amount of actually delivered power (P_E) to the demand nodes is:

$$P_E = \gamma \sum_{i=1}^{n} q_i h_i \qquad \text{Eq. 7.3.5}$$

- q_i water delivered to the i^{th} node;
- h_i piezometric head of the i^{th} node.

The total amount of power dissipated in the network to satisfy the total demand is:

$$P_D^* = P_{tot} - \gamma \sum_{i=1}^{n} q_i^* h_i \qquad \text{Eq. 7.3.6}$$

The resilience index can be written as:

$$I_r = \frac{\sum_{i=1}^{n} q_i^* (h_i - h_i^*)}{\sum_{k=1}^{r} Q_k H_k + \sum_{j=1}^{p} \frac{P_j}{\gamma} - \sum_{i=1}^{n} q_i^* h_i^*} \qquad \text{Eq. 7.3.7}$$

Todini (2000) also introduces the failure index. This index evaluates the effect of pipe failures:

$$I_f = \frac{I_{fi}}{\sum_{i=1}^{n} q_i^* h_i^*} \qquad \text{Eq. 7.3.8}$$

$$I_{fi} = \begin{cases} 0 & h_i \geq h_i^* \\ q_i^* (h_i^* - h_i) & h_i < h_i^* \end{cases} \qquad \text{Eq. 7.3.9}$$

Di Nardo *et al.* alternative resilience index

Di Nardo *et al*. (2010b, 2011, 2014a, 2015) present an alternative formulation of the resilience index:

$$I_R = 1 - \frac{P_D}{P_{D\,max}} \qquad \text{Eq. 7.3.10}$$

The index uses the total dissipated power (P_D) instead of the amount of power dissipated in the network (Eq. 7.3.6). The total dissipated power is obtained as:

$$P_D = \gamma \sum_{j=1}^{m} q_j \Delta h_j \qquad \text{Eq. 7.3.11}$$

- m total number of network pipes;
- Δh_j piezometric head dissipated along the j^{th} pipe;
- q_j flow along the j^{th} pipe.

The total dissipated power can be obtained as:

$$P_D = P_{tot} - P_E \qquad \text{Eq. 7.3.12}$$

The resilience index is:

$$I_R = 1 - \frac{P_D}{P_{D\,max}} = \frac{\sum_{i=1}^{n}(q_i h_i - q_i^* h_i^*)}{\sum_{k=1}^{r} Q_k H_k + \sum_{j=1}^{p} \frac{P_j}{\gamma} - \sum_{i=1}^{n} q_i^* h_i^*} \qquad \text{Eq. 7.3.13}$$

Recalling the hydraulic modelling described in **Chapter 1**, the resilience index of Di Nardo et al. coincides with the Todini index (2000) in the case of DDA. The two indices differ for PDA models. The difference between PDA and DDA simulations and their influence on resilience indices is discussed in **Section 7.5.1.**

The use of resilience indices in WDN design rewards networks with an energy surplus that can be dissipated in the event of a failure or an increase in user demand. The limitation in resilience indices structure is that their esteem does not take into account the network topology. In some cases, a tree-like network topology, obviously not very resilient to failure, with a high enough piezometric head surplus can obtain high resilience values.

Network resilience index

Prasad and Park (2004) present an alternative formulation of the Todini resilience index (I_r) which reward the presence of loops in the network, penalizing sudden changes in diameter. To take into account the variability of the diameter, the authors define a uniformity coefficient:

$$C_i = \frac{\sum_{j=1}^{npi} D_j}{npi * \max(D_j)} \qquad \text{Eq. 7.3.14}$$

- C_i uniformity coefficient for the i^{th} node;
- npi number of pipes connected to node i;
- D_j diameter of pipes connected to node i.

The coefficient gets value $C = 1$ if pipes connected to a node have the same diameter and $C < 1$ if pipes connected to a node have different diameters. The weighted surplus power combines the effect of surplus power and nodal diameter uniformity. The weighted surplus power for node i is:

$$X_i = C_i p_i = C_i \gamma q_i (h_i - h_i^*) \qquad \text{Eq. 7.3.15}$$

- p_i power of the i^{th} node.

The total weighted surplus power is:

$$X = \sum_{i=1}^{n} X_i = \sum_{i=1}^{n} C_i \gamma q_i (h_i - h_i^*) \qquad \text{Eq. 7.3.16}$$

The network resilience is:

$$I_r = 1 - \frac{X}{X_{max}} = \frac{\sum_{i=1}^{n} C_i q_i (h_i - h_i^*)}{\sum_{k=1}^{r} Q_k H_k + \sum_{j=1}^{p} \frac{P_j}{\gamma} - \sum_{i=1}^{n} q_i h_i^*} \quad \text{Eq. 7.3.17}$$

where X_{max} is the maximum surplus power (Eq. 7.3.4). It is assumed that the nodal design demand is fully sdatisfied ($q_i^* = q_i$).

An alternative formulation of the resilience index

Creaco *et al*. (2016) expand the work developed in Todini (2000). The work clarifies some definitions and indicates the resilience and failure index esteem for simulations using PDAs.

The resilience index (Eq. 7.3.7) for DDA becomes:

$$I_r = \frac{\sum_{i=1}^{n} \max[q_i^* (h_i - h_i^*), 0]}{\sum_{k=1}^{r} Q_k H_k + \sum_{j=1}^{p} \frac{P_j}{\gamma} - \sum_{i=1}^{n} q_i^* h_i^*} \quad \text{Eq. 7.3.18}$$

The failure one becomes:

$$I_f = \frac{\sum_{i=1}^{n} \min[q_i^* (h_i - h_i^*), 0]}{\sum_{i=1}^{n} q_i^* h_i^*} \quad \text{Eq. 7.3.19}$$

For PDAs the resilience index gets a structure similar to the resilience index proposed in Di Nardo *et al*. (2010b, 2011, 2014a, 2015):

$$I_r = \frac{\sum_{i=1}^{n} \max[\sum_{i=1}^{n} (q_i h_i - q_i^* h_i^*), 0]}{\sum_{k=1}^{r} Q_k H_k + \sum_{j=1}^{p} \frac{P_j}{\gamma} - \sum_{i=1}^{n} q_i^* h_i^*} \quad \text{Eq. 7.3.20}$$

The PDA failure index is:

$$I_f = \frac{\sum_{i=1}^{n} \min[(q_i h_i - q_i^* h_i^*), 0]}{\sum_{i=1}^{n} q_i^* h_i^*} \quad \text{Eq. 7.3.21}$$

With this formulation, the resilience index can assume only values between 0 and 1. The authors specialize the resilience index to be the only representative of the network redundancy. Pressure deficient nodes do not contribute to the resilience reduction but contribute to the increase of the failure index (in absolute value). The failure index can only assume non-positive values, between -1 and 0. Networks characterized by a sufficient pressure regime have a null failure index. The indices are respectively non-negative and non-positive. The authors have introduced the generalized resilience/failure index:

$$GRF = I_r + I_f \quad \text{Eq. 7.3.22}$$

7.4 LOCAL SURPLUS INDICES

Caldarola and Maiolo (2019) present a set of local indices and a mathematical framework. The indices proposed works as elementary building bricks to build local and global indices and can be useful to recover the well-known global indices ordinarily used in WDN analysis. The presented indices describe the local surplus (related to nodes) of quantities representative of the network operating regime concerning their design value.

Local discharge surplus index:

$$q_i^s = \frac{q_i}{q_i^*} - 1 = \frac{q_i - q_i^*}{q_i^*} \qquad \text{Eq. 7.4.1}$$

Local pressure head surplus index:

$$\hbar_i^s = \frac{\hbar_i}{\hbar_i^*} - 1 = \frac{\hbar_i - \hbar_i^*}{\hbar_i^*} \qquad \text{Eq. 7.4.2}$$

Local piezometric head surplus index:

$$h_i^s = \frac{h_i}{h_i^*} - 1 = \frac{h_i - h_i^*}{h_i^*} \qquad \text{Eq. 7.4.3}$$

where $\hbar$ refers to the pressure head defined as $\hbar = h - z$ in which z is the nodal elevation.

Local power surplus index:

$$p_i^s = \frac{p_i}{p_i^*} - 1 = \frac{q_i h_i}{q_i^* h_i^*} - 1 = \frac{q_i h_i - q_i^* h_i^*}{q_i^* h_i^*} \qquad \text{Eq. 7.4.4}$$

The quantities describing the hydraulic variables of the network can be grouped in n-element arrays:

- water delivered to demand nodes $q = (q_1, \dots, q_i, \dots, q_n)$;
- nodal design water demand $q^* = (q_1^*, \dots, q_i^*, \dots, q_n^*)$;
- nodal piezometric head $h = (h_1, \dots, h_i, \dots, h_n)$;
- nodal design piezometric head $h^* = (h_1^*, \dots, h_i^*, \dots, h_n^*)$;
- nodal pressure head $\hbar = (\hbar_1, \dots, \hbar_i, \dots, \hbar_n)$;
- nodal design pressure head $\hbar^* = (\hbar_1^*, \dots, \hbar_i^*, \dots, \hbar_n^*)$;
- nodal elevation $z = (z_1, \dots, z_i, \dots, z_n)$;
- nodal power $p = (p_1, \dots, p_i, \dots, p_n)$;
- nodal design power $p^* = (p_1^*, \dots, p_i^*, \dots, p_n^*)$.

For sources (tanks e reservoirs) there are r-element arrays:

- source discharge $Q = (Q_1, \dots, Q_k, \dots, Q_r)$;
- source piezometric head $H = (H_1, \dots, H_k, \dots, H_r)$.

Even the local surplus indices (Eq. 7.4.1-Eq. 7.4.4) can be written as:

- Local discharge surplus index$q^s = (q_1^s, \dots, q_i^s, \dots, q_n^s)$

- Local pressure head surplus index $\hbar^s = (\hbar_1^s, \dots, \hbar_i^s, \dots, \hbar_n^s)$;
- Local piezometric head surplus index $h^s = (h_1^s, \dots, h_i^s, \dots, h_n^s)$;
- Local power surplus index $p^s = (p_1^s, \dots, p_i^s, \dots, p_n^s)$.

The authors show how the array formulation for the local surplus indices allows rewriting a multitude of indices commonly known and used in literature. For example, the Todini resilience index (Eq. 7.3.7) in the absence of pumps is:

$$I_r = \frac{p^s \circ p^*}{\gamma(Q \circ H - q^* \circ h^*)} \qquad \text{Eq. 7.4.5}$$

The operator ∘ represents the array scalar product.

The Di Nardo *et al*. (Eq. 7.3.13) resilience index is:

$$I_R = \frac{h^s \circ p^*}{\gamma(Q \circ H - q^* \circ h^*)} \qquad \text{Eq. 7.4.6}$$

Caldarola and Maiolo (2019) present the alternative formulation for the modified resilience index (Jayaram and Srinivasan, 2008), network resilience index (Prasad and Park, 2004), failure index (Todini, 2000), mean pressure surplus and mean pressure deficit (Di Nardo *et al*. 2015) and others.

7.4.1 RESILIENCE AND LOCAL INDICES STUDY

The local surplus indices presented in Caldarola and Maiolo (2019) are under study. This section reports the scientific advances regarding local surplus indices and resilience indices (Todini 2000, Di Nardo *et al*. 2010b, 2011, 2014a, 2015). The work focuses on application cases, to define the potential of local indices and the best procedures for the use of resilience indices. The following paragraphs show applications on the network presented by Kang and Lansey (2012) and on the network serving the city of *Santarém* (described in Chapter 5).

To date, practical applications have involved only the Kang and Lansey and the *Santarém* networks since the indices assessment requires a certain level of maturity of the hydraulic model. Paragraphs 7.5 and 7.6 presents the elaboration on the Kang and Lansey network published in Bonora *et al*. (2019) and Bonora *et al*. (2020a). Paragraph 7.7 describes an application on the network of Santarém (Bonora *et al*. 2020b).

Of the networks described in the previous chapters, some require further refinement of the hydraulic model. The *Rende* WDN (Chapter 3) presents some criticality due to the indeterminacy of water consumption and relations with adjacent networks. The model of the *Serra San Bruno* (Chapter 4) and *Castel San Giorgio* (Chapter 6) WDNs will be the object of further study and future development. The requested pressure values for the Serra San Bruno network have been defined, but it is necessary to calibrate the model. The *Castel San Giorgio* network is accompanied by a large amount of data. The large database of pressure and flow measurements makes the *Castel San Giorgio* network a case study of particular interest and complexity.

7.5 Numerical experimentations for a new set of local indices of a water network

In Bonora *et al*. (2019) an application of the local performance indices (Caldarola and Maiolo, 2019) is presented. The authors analyse the necessary hypotheses to estimate the local indices and some resilience indices. The relevance of the hydraulic modelling approach is investigated. The work esteem the indices for a WDN known in the literature and compare the results deriving from different modelling approaches.

7.5.1 Solution approaches

In this work, particular attention is paid to the influence of the solution model on the indices resulting from the simulations. Two solution approaches are studied, Demand Driven Analysis (DDA) and Pressure Driven Analysis (PDA). In DDA modelling, the amount of water supplied to the demand nodes is a model input. The solver identifies an operating regime compatible with the assigned water request. In PDA modelling there is the possibility that, in the event of pressure deficit conditions, the supply is lower than the requested demand. In the absence of deficient pressure conditions the results from PDA modelling are identical to those from DDA.

A Demand-Driven approach is typical of software such as EPANET (Rossman 2000). This software allows modelling the hydraulic regime of WDNs and to carry out water quality analysis. EPANET 2, developed by the EPA (Environmental Protection Agency) is one of the most popular software for the WDN hydraulic simulation. In EPANET the user water demand in the nodes is a model known term. The most recent version (EPANET 2.2, July 2020) introduces the possibility of using PDA modelling (Rossman *et al*., 2020).

Hydraulic PDA modelling is performed using WaterNetGEN software (Muranho *et al*. 2012,2014), a modified version of EPANET. The new features introduced use both approaches to model a network under different stress conditions to study the behaviour of local and resilience indices.

Design condition

The definition of the design conditions is one of the criticalities identified in the indices estimation for existing networks. Design conditions are used in numerous studies (Todini 2000, Di Nardo *et al*. 2010b, 2011, 2014, 2015, Prasad and Park 2004) but the assessment method is rarely specified or detailed. The water demand (q^*) and piezometric head (h^*) design values help to characterize the operating regime of the analysed network. Some authors use a reference design piezometric head value for the entire WDN (Todini 2000, Di Nardo *et al.* 2010b, 2011, 2014a, 2014b, 2015, 2017). None of the analysed publications directly refers to the water demand design values. Commonly no distinction is made between supply and demand for utilities (Prasad and Park 2004, Di Nardo *et al*. 2010b, 2011, 2014a, 2014b, 2015, 2017).

Modelling hypothesis, Demand Driven Analisis

In hydraulic modelling with a DDA model, the water demand value assigned to the nodes is an input value. The identified WDN operating regime satisfies the assigned demand even in the event of a severely deficient pressure regime. In the assessment of resilience indices and local surplus indices, in the case of DDA it is assumed that supply and demand coincide:

$$q_i = q_i^* \qquad i = 1, \dots, n. \qquad \text{Eq. 7.5.1}$$

This hypothesis implies that the local discharge surplus index, defined in Eq. 7.4.1, is always null:

$$q_i^s = \frac{q_i}{q_i^*} - 1 = 0 \qquad i = 1, \dots, n. \qquad \text{Eq. 7.5.2}$$

And the local power surplus index coincides with the local head surplus one:

$$p_i^s = \frac{p_i}{p_i^*} - 1 = \frac{q_i h_i}{q_i^* h_i^*} - 1 = \frac{h_i}{h_i^*} - 1 = h_i^s \qquad i = 1, \dots, n. \qquad \text{Eq. 7.5.3}$$

No assumptions can be made on the hydraulic piezometric head or the pressure local surplus indices. These indices depend on the resulting operating regime. The pressure design value is not included in the simulation but only in the indices estimate. The Eq. 7.5.1 hypothesis implies that the Todini (Eq. 7.3.7) and Di Nardo *et al*. (Eq. 7.3.13) resilience indices coincide.

Modelling hypothesis, Pressure Driven Analisis

Solvers using a PDA approach models a possible discrepancy between users required and supplied demand. In case of insufficient pressure, the nodal water supply can be lower than the assigned water demand. The relationship that models the partial supply (Wagner *et al*. 1988, Muranho *et al*. 2012, 2014) is:

$$q_i^{avl} = q_i^{ref} \begin{cases} 1 & \mathrm{h}_i \geq \mathrm{h}_i^{ref} \\ \left(\dfrac{\mathrm{h}_i - \mathrm{h}_i^{min}}{\mathrm{h}_i^{ref} - \mathrm{h}_i^{min}}\right)^{\alpha} & \mathrm{h}_i^{min} < \mathrm{h}_i < \mathrm{h}_i^{ref} \\ 0 & \mathrm{h}_i \leq \mathrm{h}_i^{min} \end{cases} \qquad \text{Eq. 7.5.4}$$

in which:

- q_i^{avl} available flow in the i^{th} node;
- h_i piezometric head of node i;
- q_i^{ref} water demand in the i^{th} node;
- h_i^{min} minimum pressure below which there is no supply in the i^{th} node;
- h_i^{ref} service pressure (necessary to fully satisfy the demand) in the i^{th} node;
- α exponent of the pressure-demand relationship.

In the indices assessment, it is assumed that the service pressure h_i^{ref} corresponds to the required pressure (design) h_i^*. The relationship in Eq. 7.5.4 can be written as:

$$q_i = q_i^* \begin{cases} 1 & h_i \geq h_i^* \\ \left(\dfrac{h_i - h_i^{min}}{h_i^* - h_i^{min}}\right)^{\alpha} & h_i^{min} < h_i < h_i^* \\ 0 & h_i \leq h_i^{min} \end{cases} \qquad \text{Eq. 7.5.5}$$

The water supply can differ from the design value, this means that the hypothesis in Eq. 7.5.2 and Eq. 7.5.3 does not stand in the case of PDAs. As for Eq. 7.5.5, the local discharge pressure index (Eq. 7.4.1) can assume non-positive values.

Two scenarios can occur in the context of modelling a WDN with PDA. If the network is characterized by a good piezometric head regime the results are identical to those of a DDA simulation:

$$(\underline{h_i} \geq \underline{h_i^*}),\ q_i = q_i^*. \qquad q_i^s = \frac{q_i}{q_i^*} - 1 = 0 \qquad \text{Eq. 7.5.6}$$

If the network is in pressure deficit conditions in part the water supplied to users is less than that necessary to satisfy the requested demand:

$$\begin{cases} q_i = q_i^* & h_i \geq h_i^* \\ q_i < q_i^* & h_i \leq h_i^* \end{cases} \qquad \text{Eq. 7.5.7}$$

7.5.2 CASE STUDY

Local surplus indices and resilience indices were calculated for the network proposed by Kang and Lansey (2012). The network counts 935 nodes and 1274 pipes and has a single source (reservoir) that models a pump station output. 623 nodes have a non-zero water demand. The average total demand is 177 l/s (2808 gal/min). The WDN is located in an area characterized by limited altitude variability, Figure 7.5.1. The minimum altitude is 391.15 m.a.s.l., the maximum one is 407.6 m. The reservoir piezometric head is 413.3 m.a.s.l. To account for the hourly peaks, Kang and Lansey provide a peak coefficient of 1.75, Figure 7.5.2. The authors indicate the requested pressure in conditions of average and peak consumption. The requested pressure is approximately 28m (40 psi). The minimum head threshold (h_i^{min}) is set equal to the piezometric head corresponding to a pressure of 15 meters.

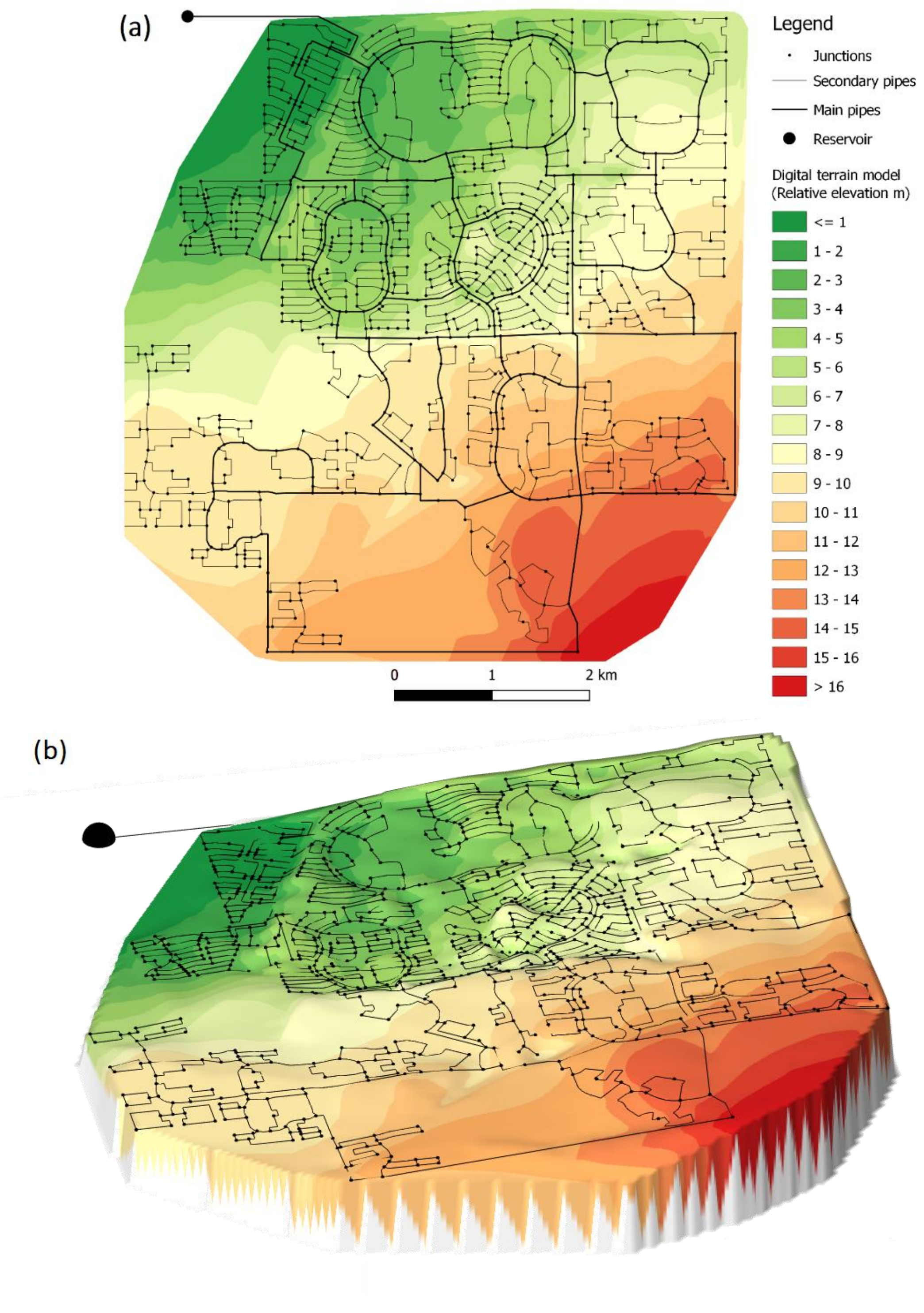

Figure 7.5.1 Scheme of Kang and Lansey (KL) network. The colour scheme represents the relative altimetry, zero is set at 391.15 meters above sea level. (a) Plan view (b) 3d view, with a 50 vertical magnifying factor, to better show the elevation variability.

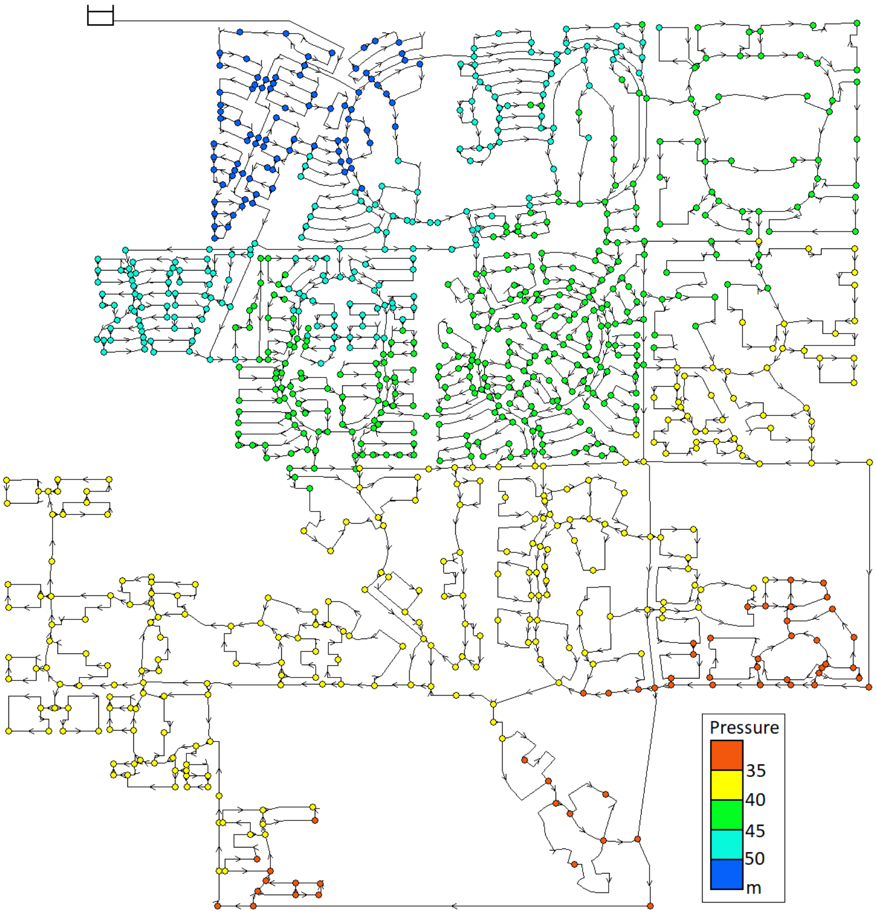

Figure 7.5.2 KL network pressure regime. Simulation with a Peak coefficient $P_c = 1.75$,$Q_{max} = 310l/s$.

In this work applications, the authors use a higher hourly peak coefficient than the one suggested. The peak coefficient is set at 2.5 (Milano 1996) bringing the total peak demand to 442.5 l/s. The chosen peak coefficient ensure the establishment of a supply deficit condition. The deficit allows highlighting the differences between the DDA and PDA approaches in the local surplus indexes and resilience indices estimation.

The I_R and I_r resilience indices values calculated for the network are shown in Table 7.5.1. As expected the values coincide for DDA simulation.

	h_i^{min} [m]	h_i^* [m]	I_R	I_r
DDA	15	28	0.0532	0.0532
PDA	15	28	0.448	1.449

Table 7.5.1 Simulations h_i^{min}e h_i^* values. Assessed resilience indices for PDA e DDA simulations.

Figure 7.5.3 and Figure 7.5.4 show the four local surplus indexes values. It is useful to remind that in the event of a surplus the indices have a positive value, in the event of a deficit they have negative values, and values close to zero in conditions close to those of design. The figures use a traffic light colour scale:

- Red: Deficit conditions;

- o Yellow: Design-close conditions;
- o Green: Surplus condition.

The colour classification is organized in membership bands. For the Local Discharge Surplus Index and the Local Pressure Head Surplus Index, the bands' boundaries are:

- o [-1, -0.1) Deficit conditions, for values that are lower than the 90% of the design value;
- o [-0.1, 0.1] Design conditions, for values that do not differ more than 10% from the design value;
- o [-1, -0.1) Surplus conditions, for values that are greater than 110% of the design value.

For the Local Power Surplus Index and the Local Head Surplus Index, the membership bands differ since the presence of the elevation reduces the indices variability:

- o [-1, -0.01) Deficit conditions, for values that are lower than the 99% of the design value;
- o [-0.01, 0.01] Design conditions, for values that do not differ more than 1% from the design value;
- o [-1, -0.01) Surplus conditions, for values that are greater than 101% of the design value.

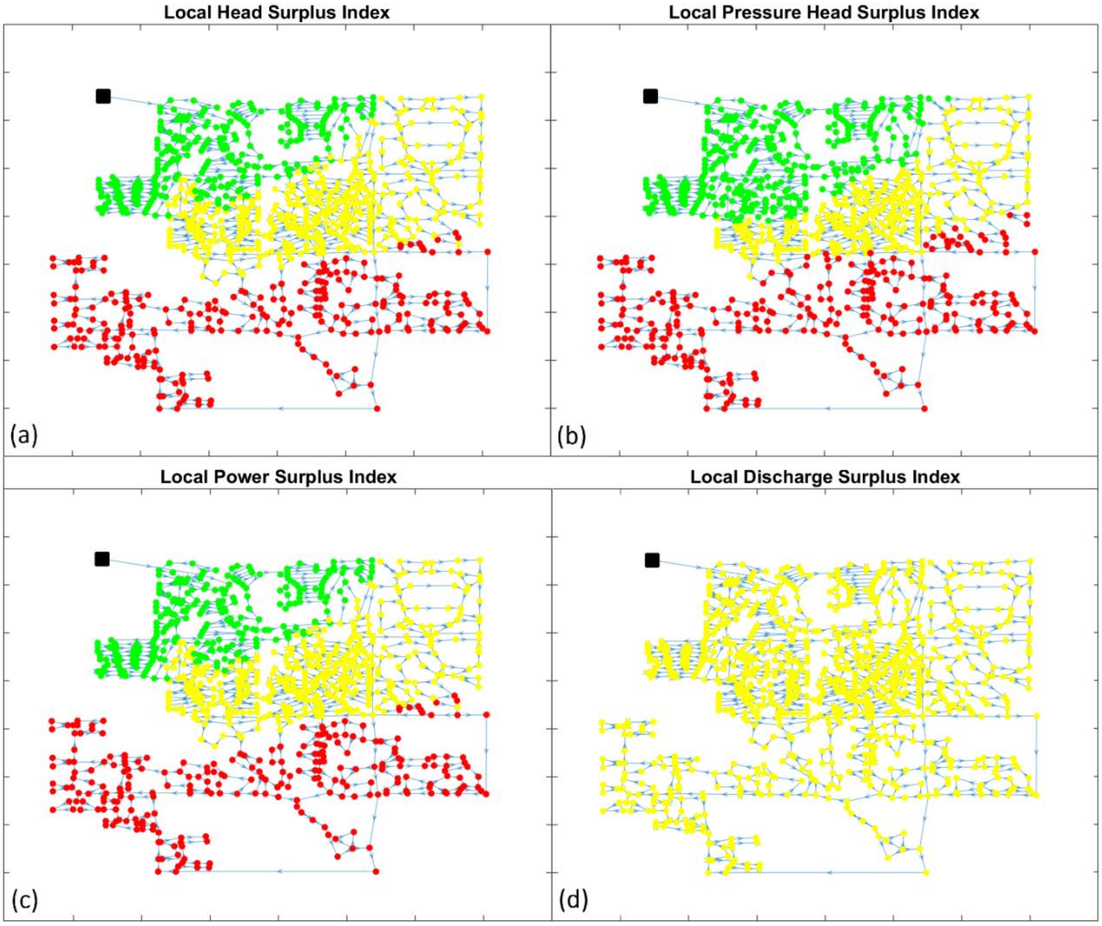

Figure 7.5.3 Local surplus indices for KL network. DDA simulation result.

The use of a demand peak coefficient of 2.5 establishes a deficit pressure regime in comparison to the target pressure defined in Table 7.5.1. Figure 7.5.3 shows the values of the local surplus indices for the DDA simulation results. As for Eq. 7.5.2, the local discharge surplus index gets null values (d). The local power surplus index (c) coincides with the local head surplus index (a) as for Eq. 7.5.3. The local piezometric head (a) and the local pressure head surplus index (b) provide immediate graphical information on the network operating regime. The deficit concerns the peripheral areas of the network.

The local surplus indices obtained from the PDA simulation are shown in Figure 7.5.4. These indices differ from the previous ones. The local discharge surplus index (d) shows the nodes with supply deficits, in red. The Local piezometric head (a) and the local power surplus index (c) do not coincide. Finally, from the local pressure head (b) it is noticeable that the operating regime of the network resulting from a PDA simulation is less deficient than the DDA simulation one. PDA simulations, modelling a supply reduction, are characterized by lower flow passing through the pipes and therefore lower head losses.

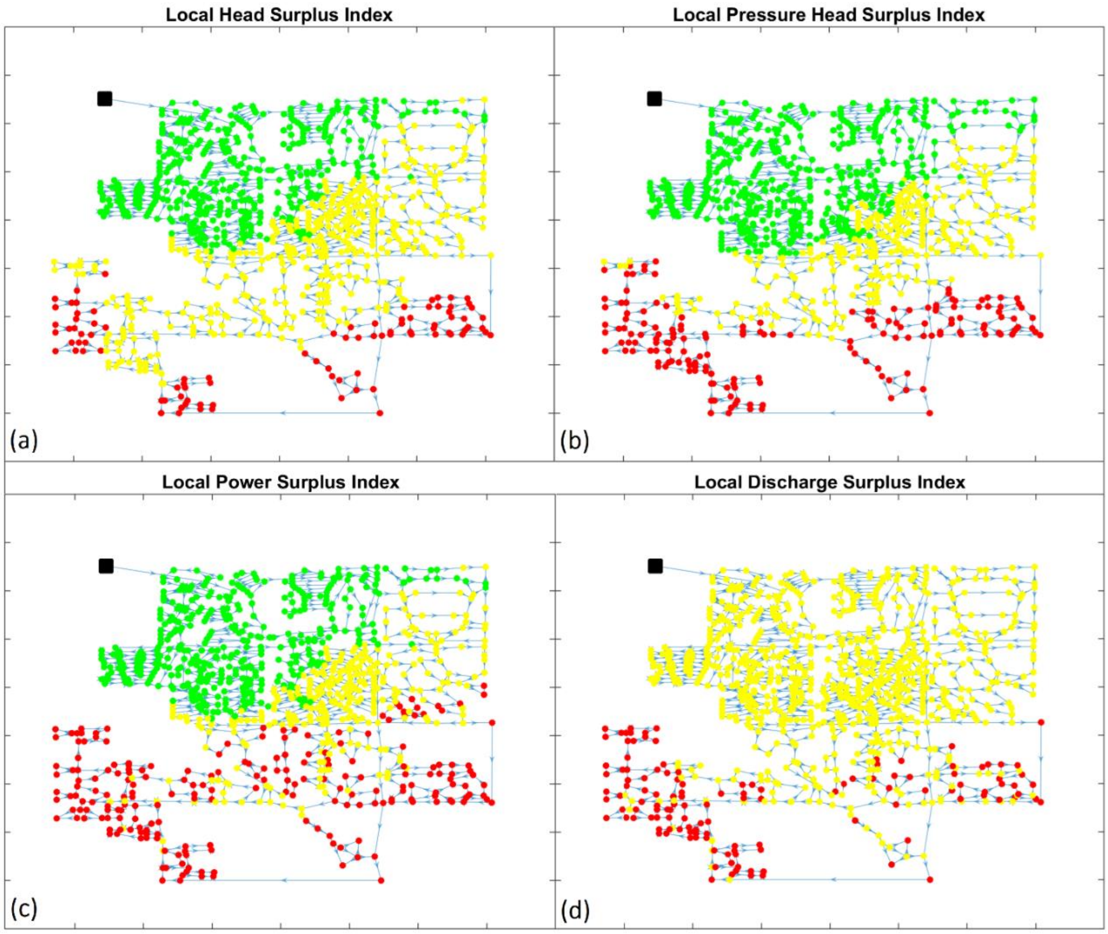

Figure 7.5.4 Local surplus indices for the KL network. PDA simulation result.

7.5.3 CONSIDERATIONS

The local surplus indices, presented in Caldarola and Maiolo (2019) were used in the assessment of the operating regime modelled for the KL network. The mathematical framework, implemented in an automatic code, made it possible to simplify the calculating procedure for the resilience indices. Local surplus indices have proved useful as standalone indicators in presenting various aspects of the network's operating regime. The use of a practical case study allowed the authors to identify some limits and hypothesis that need clarification in subsequent studies. The lack of an objective and easy definition for the requested/design conditions leads to a degree of indeterminacy in the results. In some situations, the hydraulic solution model strongly influences the indices values (both local and resilience).

7.6 A New Set of Local Indices Applied to a Water Network through Demand and Pressure Driven Analysis

Bonora *et al*. (2020a) present an in-depth analysis of the same case study analysed in Bonora *et al*. (2019). The new surplus indices (Caldarola and Maiolo, 2019) and the resilience indices are evaluated, in the case of both DDA and PDA modelling, in a series of scenarios characterized by critical operating regimes.

7.6.1 Case study

To generate a series of simulations characterized by a different degree of criticality, the demand scenarios uses a series of incremental peak coefficients. The nine peak coefficients are:

$$P_c = (1.5, 1.75, 2, 2.25, 2.5, 2.6, 2.7, 2.8, 2.9) \qquad \text{Eq. 7.6.1}$$

To define the range of variation of the peak coefficients, the population that the KL network could serve was assessed. Assuming a water supply of 250 litres per day (Lamberti *et al*. 1994), the population served by the KL network is approximately 60,000 inhabitants.

For networks of this size, the daily peak flow can reach values of 2 or 3 times higher than the average one. In the simulations, the minimum head threshold in the node h_i^{min} coincides with that corresponding to a null pressure, $\mathrm{h}_i^{min} = z_i$.

Resilience indices

The estimated values for the Todini (I_r) and Di Nardo *et al*. (I_R) resilience indices are listed in Table 7.6.1 (DDA simulations) and Table 7.6.2 (PDA simulations). Figure 7.6.1 shows the variability of the resilience indices for both approaches. The indices are plotted as a function of the peak coefficient. It is immediate to observe how in the absence of pressure (and therefore supply) deficits in the network ($P_c \leq 1.75$) the values of the resilience indices coincide for all simulations. With high demand scenarios, which cause high-pressure deficits, the indices obtain unrealistic values. With a high peak coefficient ($P_c \geq 2.6$) the resilience index I_r for DDA simulations and I_r for PDA simulations get negative values.

Peak coefficient	I_r I_R
1.50	0.632
1.75	0.511
2.00	0.373
2.25	0.221
2.50	0.053
2.60	-0.018
2.70	-0.092
2.80	-0.168
2.90	-0.247

Table 7.6.1 Resilience index values assessed with different peak coefficients, using a DDA simulation.

Peak coefficient	I_r	I_R
1.50	0.632	0.629
1.75	0.511	0.511
2.00	0.375	0.371
2.25	0.261	0.152
2.50	0.204	-0.482
2.60	0.187	-1.134
2.70	0.177	-2.842
2.80	0.193	-17.969
2.90	0.135	7.503

Table 7.6.2 Resilience index values assessed with different peak coefficients, using a PDA simulation.

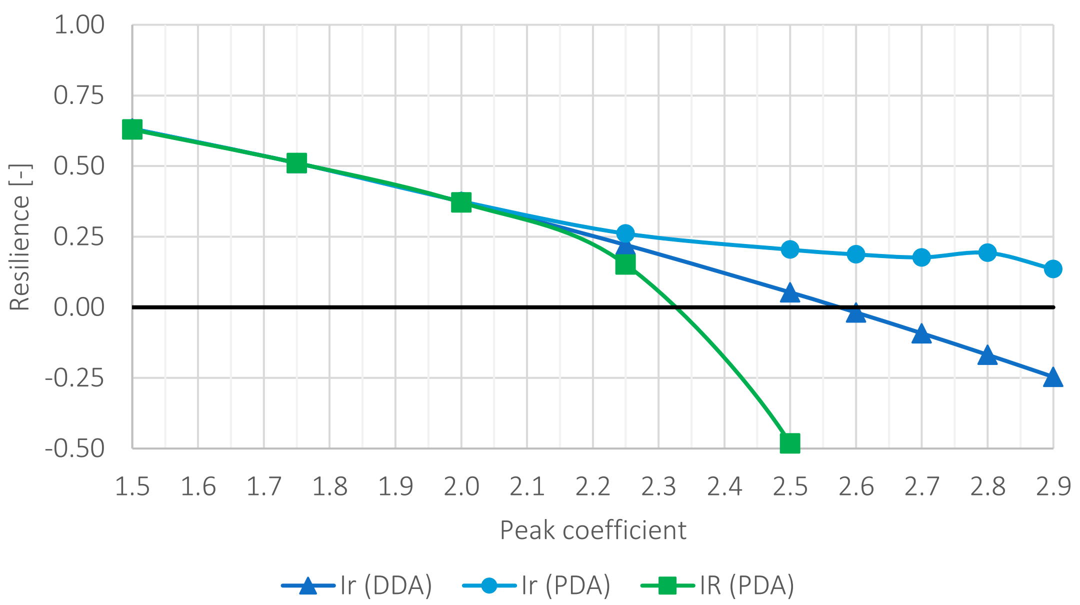

Figure 7.6.1 Resilience index values plotted as a peak coefficient function. Curves obtained by interpolation.

The values of I_R in the interval $2.8 \leq P_c \leq 2.9$ get a vertical asymptote and a change of sign. The sign change is due to the achievement of a condition in which the minimum energy required to satisfy the design conditions is greater than the one observed:

$$P_{E\,min} > P_E$$
$$P_{E\,min} < 0 \qquad \text{Eq. 7.6.2}$$

Eq. 7.6.2 can represent a scenario in which the WDN is operating under conditions of excessive demand and/or pressure deficit. Such a scenario may depend on an actual increase in water demand or an incorrect choice of design/requested conditions. In this application, the most likely hypothesis is that the achievement of the conditions described in Eq. 7.6.2 is due to an excessive peak coefficient value.

Local surplus indices

Local surplus indices, as shown in Bonora *et al*. (2019), can be used as synthetic performance indicators of the network operating regime, providing immediate information on pressure, piezometric head, water supply and power deficits (or surplus). The figures below show results for simulations (DDA and PDA) with four peak coefficients: 1.75, 2, 2.25, 2.5.

As said, the variability of the local power surplus index and the piezometric head surplus index is reduced by the presence of the elevation in their formulation. The reduced variability makes them less effective as graphical indicators. To reduce the amount of graphics they have been excluded. The graphs show the local pressure head surplus index values for the four peak coefficients and the two solution approaches (Figure 7.6.2, Figure 7.6.3, Figure 7.6.4, and Figure 7.6.5). The local discharge surplus index can assume non-zero values only for PDA simulations (Eq. 7.5.2). Only the graphs relating to the local discharge surplus indices with PDA simulations have been reported (Figure 7.6.6 and Figure 7.6.7).

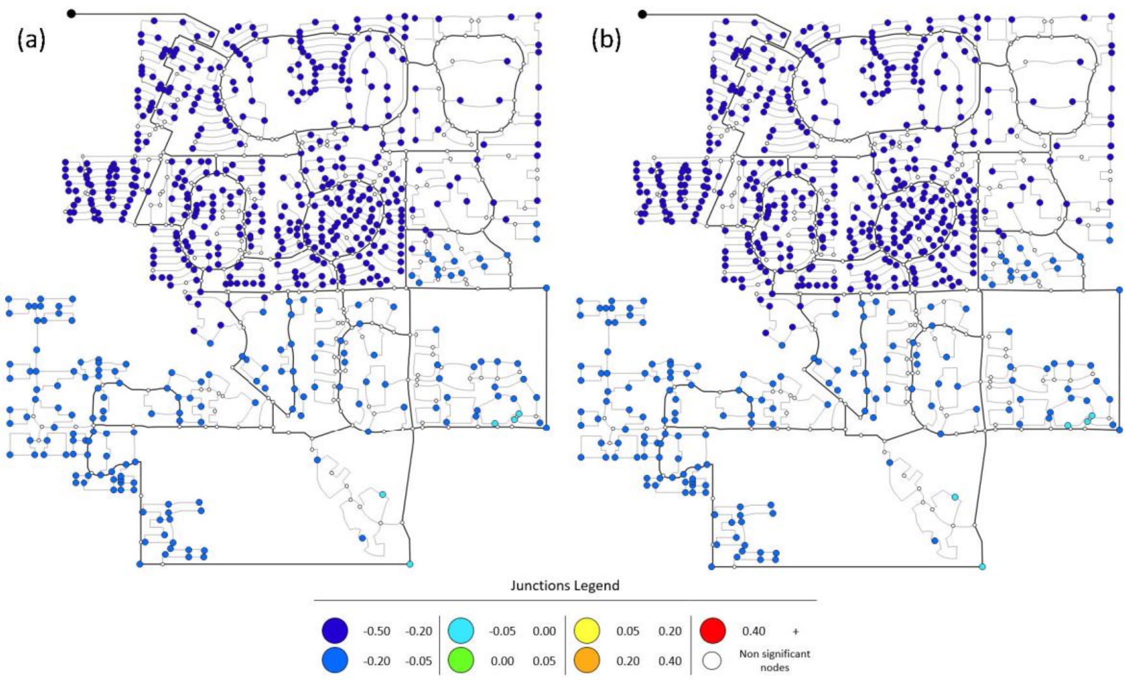

Figure 7.6.2 Local pressure head surplus index, Pc = 1.75. (a) DDA simulation result. (b) PDA simulation result.

In all graphs, part of the nodes is labelled as "non significant". These nodes are characterized by no water demand. If the not significant nodes have assigned null surplus indices, these would have made the figures less legible, presenting nodes with zero local discharge surplus in areas characterized by pressure or supply deficits (i.e Figure 7.5.4). Figure 7.6.2 and Figure 7.6.6a report the local indices for the simulations with $P_c = 1.75$. The peak coefficient does not impose deficit conditions in any area of the network. The absence of deficit means that the local pressure head surplus index assumes positive values and the local discharge surplus index null ones. In the absence of a deficit, the simulated operating regime with PDA and DDA models coincides. This implies that the local pressure head surplus index coincides, Figure 7.6.3a and Figure 7.6.3b.

Figure 7.6.3 and Figure 7.6.6b report the local indices for the simulations with $P_c = 2$. The peak coefficient increase involves the modification of the network operating regime which reaches, in the peripheral areas, design-like conditions. Deficit conditions characterize only one node. The output of the PDA and DDA simulations is practically identical (except for the supply and pressure of the deficit node).

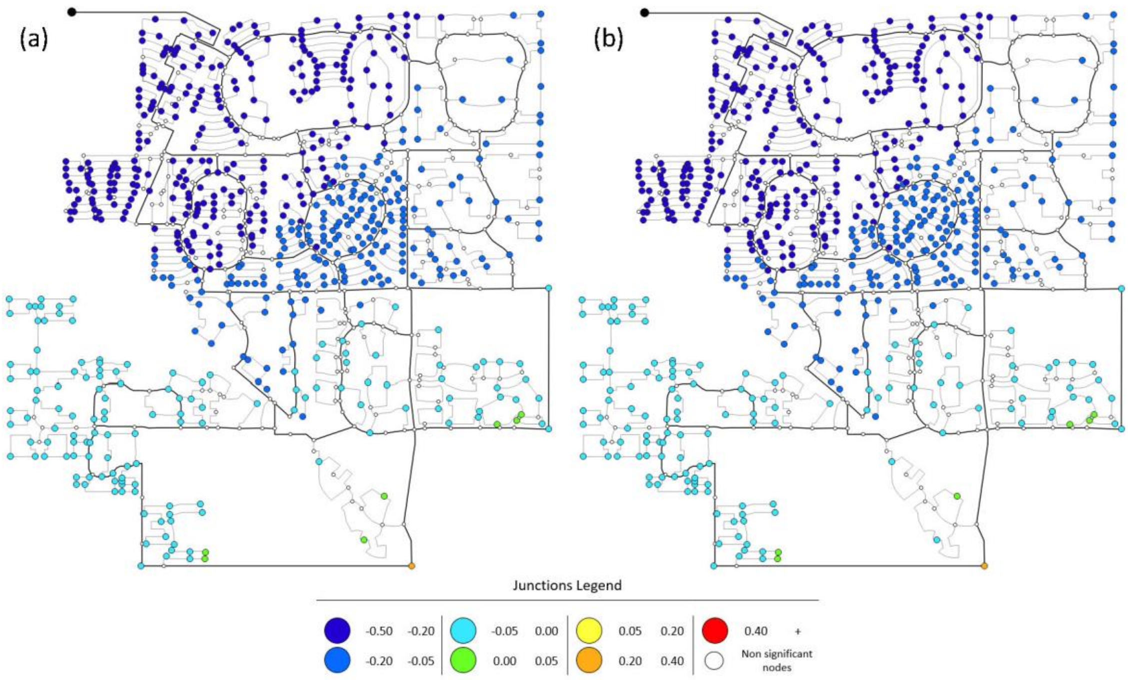

Figure 7.6.3 Local pressure head surplus index, Pc = 2. (a) DDA simulation result. (b) PDA simulation result.

Figure 7.6.4 and Figure 7.6.7a report the local indices for the simulations with $P_c = 2.25$. The use of a higher peak coefficient imposes deficits in the peripheral areas of the network. The network central area achieves a design-like operating regime. The presence of large areas characterized by pressure and supply deficits makes the difference between DDA and PDA simulations results appreciable. The supplied flow reduction (Figure 7.6.7a) induces lower head losses, so the resulting pressure regime of the PDA simulations is characterized by lower pressure deficits.

Figure 7.6.5 and Figure 7.6.7b report the local indices for the simulations with $P_c = 2.5$. The use of a very high peak coefficient imposes a deficit regime in a very large area of the network. The flow rates supplied to the users are notably reduced (Figure 7.6.7b). The supply reduction affects the pressure regime of the PDA simulation, increasing the difference from the DDA simulated regime.

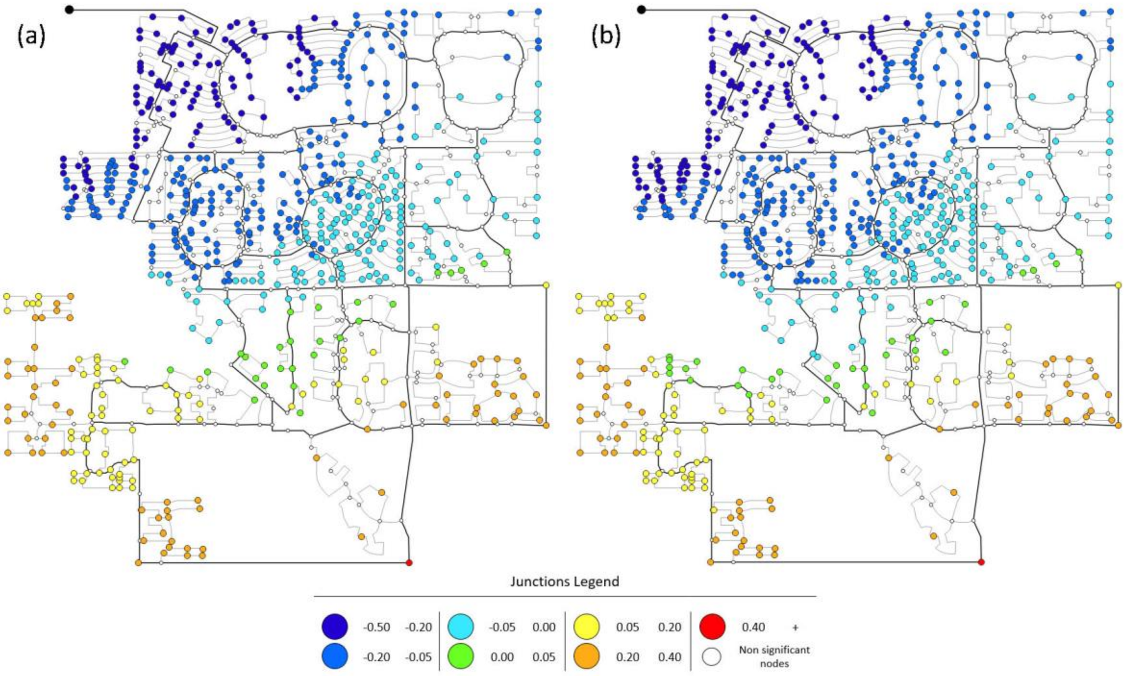

Figure 7.6.4 Local pressure head surplus index, Pc = 2.25. (a) DDA simulation result. (b) PDA simulation result.

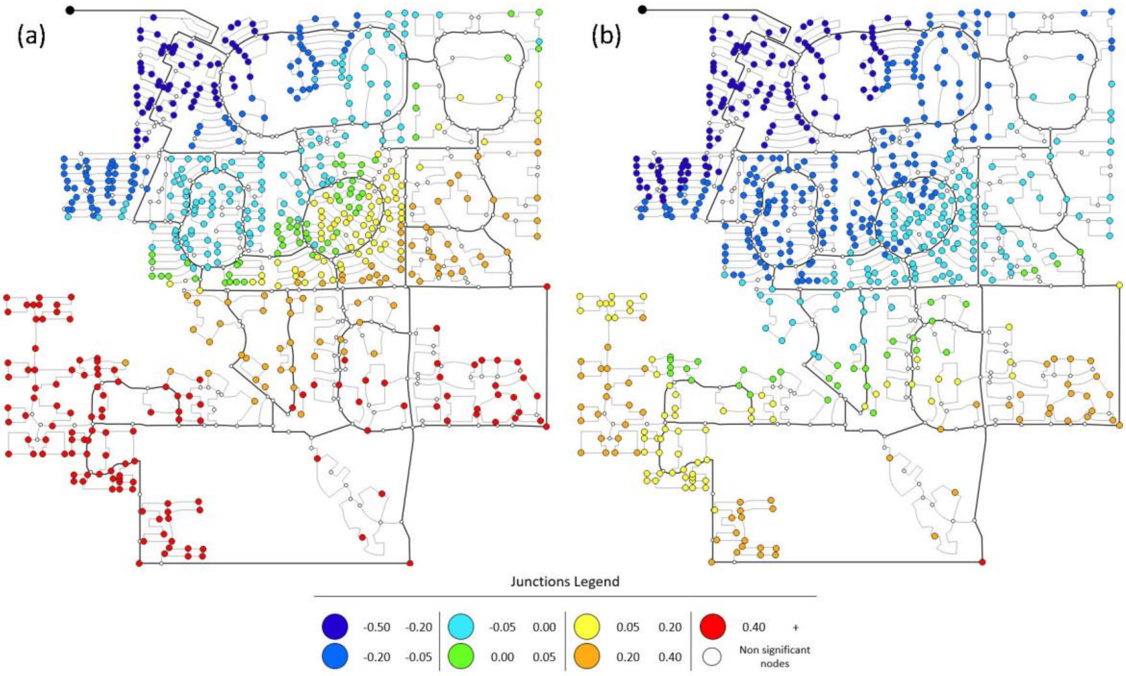

Figure 7.6.5 Local pressure head surplus index, Pc = 2.5. (a) DDA simulation result. (b) PDA simulation result.

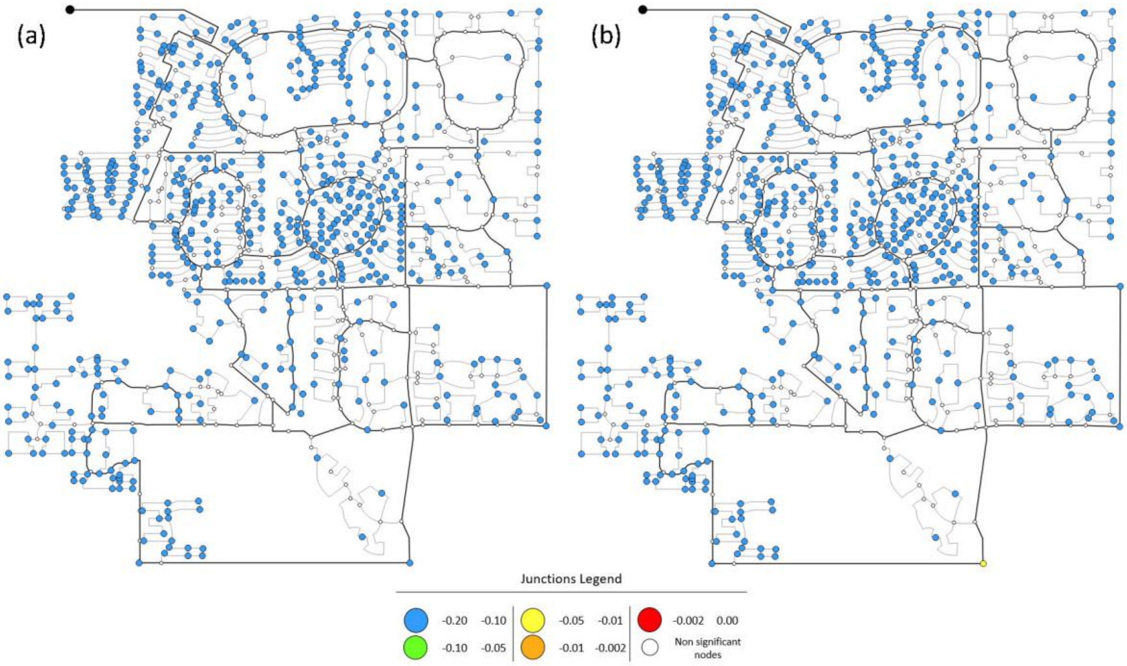

Figure 7.6.6 Local discharge surplus index, PDA simulation result. (a) Pc = 1.75 (b) Pc = 2.

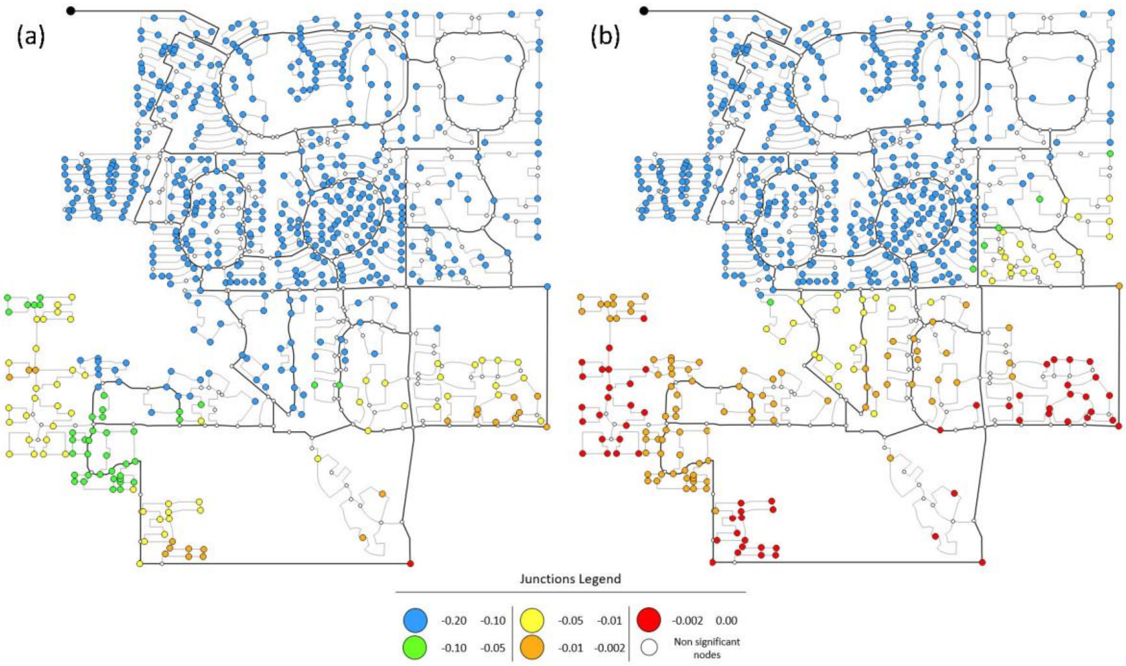

Figure 7.6.7 Local discharge surplus index, PDA simulation result. (a) Pc = 2.25 (b) Pc = 2.5.

7.6.2 CONSIDERATIONS

The elaboration carried out in Bonora *et al*. (2020a) and reported in the previous paragraphs allowed evaluating the usefulness of the local surplus indices, presented in Caldarola and Maiolo (2019) and previously analyzed in Bonora *et al*. (2019). The estimate of local surplus and resilience indices for more application scenario made it possible to better assess their limits and potential. The definition of the design or requested conditions was a particularly delicate phase.

The local pressure head surplus index and the local discharge surplus index were found to be very effective in graphically representing the operating regime of the network. The local power surplus index and the piezometric head surplus index were not very effective as standalone graphic indicators due to their limited variability.

7.7 THE NEW SET-UP OF LOCAL PERFORMANCE INDICES INTO WATERNETGEN AND APPLICATION TO SANTARÉM'S NETWORK

Bonora *et al*. (2020b) present the hydraulic model building and the calculation of the local indices (Caldarola and Maiolo 2019) and some resilience indices for a medium-sized network serving the city of Santarém (Portugal). During the model construction, particular attention was paid to the definition of the design/requested conditions, to be used in the indices calculation. Hydraulic modelling compare the results of DDA and PDA approaches. The work uses an experimental version of the hydraulic software WaterNetGEN[1]. The software integrates the calculation and graphic display of local surplus indices and resilience indices.

7.7.1 CASE STUDY

The city of Santarém WDN is supplied by a raised tank that is 35 meters above the ground. The WDN is partially districtized. The data collection and the digital model construction process are detailed in Chapter 5. The core network supplies 11 DMAs, of which 7 directly. In this work, the hydraulic modelling and the estimation of the indices involve the area of the network directly supplied by the tank, called "OldCity", of about a square kilometre. The sub-network counts 285 pipes extending for 13km and 264 junctions.

Requested value assessment

The hypothesis already reported in the previous paragraphs hold (Eq. 7.5.1 to Eq. 7.5.7) for the indices calculation. The minimum pressure threshold h_i^{min} is 0 and so the minimum piezometric head coincides with the altitude of the served point, z_i. The required pressure is defined along a relationship provided by the Portuguese legislation:

$$\hbar^{*}=100+40*\mathrm{N} \quad [\mathrm{kPa}], \qquad \text{Eq. 7.7.1}$$

The relation allows obtaining an indicative value of the required pressure ($\hbar_i^*$) as a function of the number of storeys above ground from the buildings. To assess the requested pressure, the served area is divided into uniform blocks. Each block contains buildings of similar height, Figure 7.7.1. The design pressure for each block is obtained as a function of the number of storeys of the tallest building inside, Eq. 7.7.1.

Each junction has assigned the design pressure value that characterizes the block in which is contained. For a junction close to the border between several blocks, the maximum value of the adjacent blocks is assigned.

For isolated buildings with an outlier number of storeys, the pressure value is associated only with the closest junction. As specified in Paragraph 5.3, due to the presence of private pumping stations, buildings with four or more floors are characterised by a required pressure equivalent to a two-storey building.

[1] Development, non-public version

Figure 7.7.1 OldCity area uniform-storeys block partitioning.

The OldCity sub-network directly supplies seven DMAs. The entry point of the DMAs is equipped with flow meters. The measured flow is modelled as a concentrated demand and assigned to the junctions placed at the entrance of the DMAs.

There is no meter on the pipe exiting the tank. The flow is assessed using the end-users water consumption (Chapter 5). The total water supply contains the user overall consumption and the network water losses. The hypothesized losses are 5m^3/h (1.4 l/s). The losses were distributed proportionally to the pipe length. The assessed OldCity consumption is time-averaged on the user's survey period. The temporal variation pattern is obtained depending on the consumption patterns of the other DMAs, except DMAs Forcados Amadores and Portas do Sol as they behave very differently from all the others.

Results

The DDA and the PDA simulations have a duration of 24 hours and a timestep of 1 hour. The simulation results, Figure 7.7.2, show the occurrence of 3 demand peaks (10:00, 12:00, 19:00). PDA modelling does not influence the demand value assigned to the nodes entering the DMAs, being a metered value. The 10:00 peak corresponds to the maximum consumption in OldCity. The noon peak corresponds to the overall consumption peak in the network. The demand peaks establish deficit condition only at 10:00 and 12:00. Figure 7.5.2 shows the supply reduction in the PDA model.

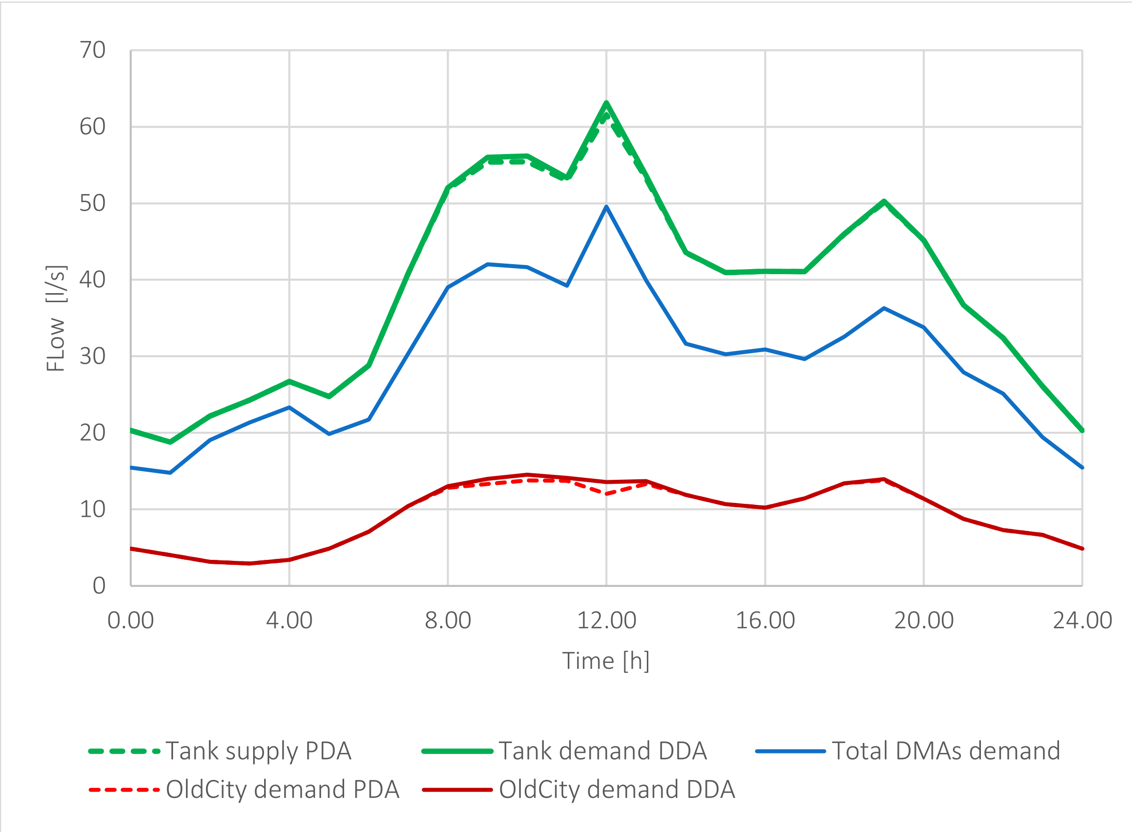

Figure 7.7.2 DDAs and PDAs result comparison. Daily OldCity consumption, DMAs consumption and tank supply plot.

Figure 7.7.3 shows the time plot of the Todini (Eq. 7.4.5) and Di Nardo *et al*. (Eq. 7.4.6) resilience indices. The indices coincide when used in a DDA simulation. Todini index was estimated for both simulations. In the PDA simulation, the index values are higher, due to the better pressure regime. In high consumption conditions, the network reaches very low resilience values.

The following figures (Figure 7.7.4, Figure 7.7.5, and Figure 7.7.6) show the local pressure head surplus index and the local discharge surplus index corresponding to the maximum daily consumption conditions.

Figure 7.7.4 shows the local pressure head surplus index corresponding to the peak demand occurring at 10:00. The 10:00 demand peak corresponds to the maximum demand value of the modelled area. The pressure deficit affects the areas corresponding to the OldCity. The difference in the operating regime between DDA (a) and PDA (b) is not evident. Figure 7.7.5 shows the local pressure head surplus index graph corresponding to the peak demand that occurs at noon. The midday peak corresponds to the overall maximum demand of the network. The pressure deficit affects mainly the OldCity area. The difference between the DDA and PDA simulation results are manifest. Figure 7.7.6 shows the graphical scheme of the local discharge surplus index, for the PDA simulation, corresponding to peak demand occurring at 10 (a) and 12 (b). Pressure deficits significantly reduce the water supply in the OldCity area.

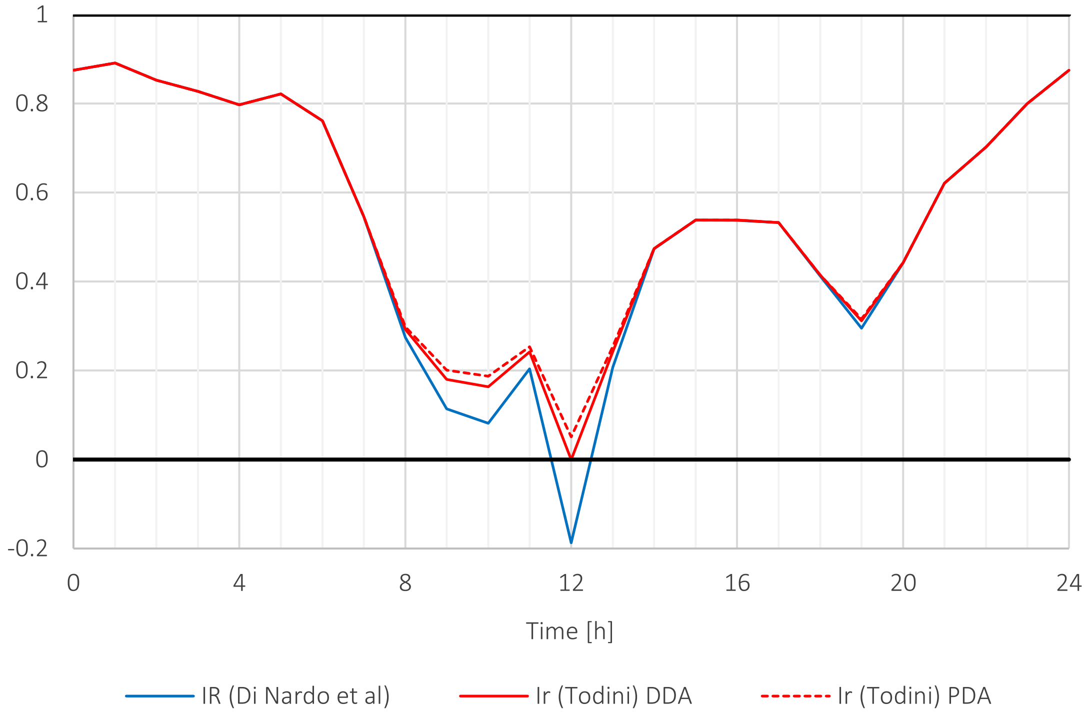

Figure 7.7.3 DDAs and PDAs result comparison. Resilience indices 24-hour simulated plot.

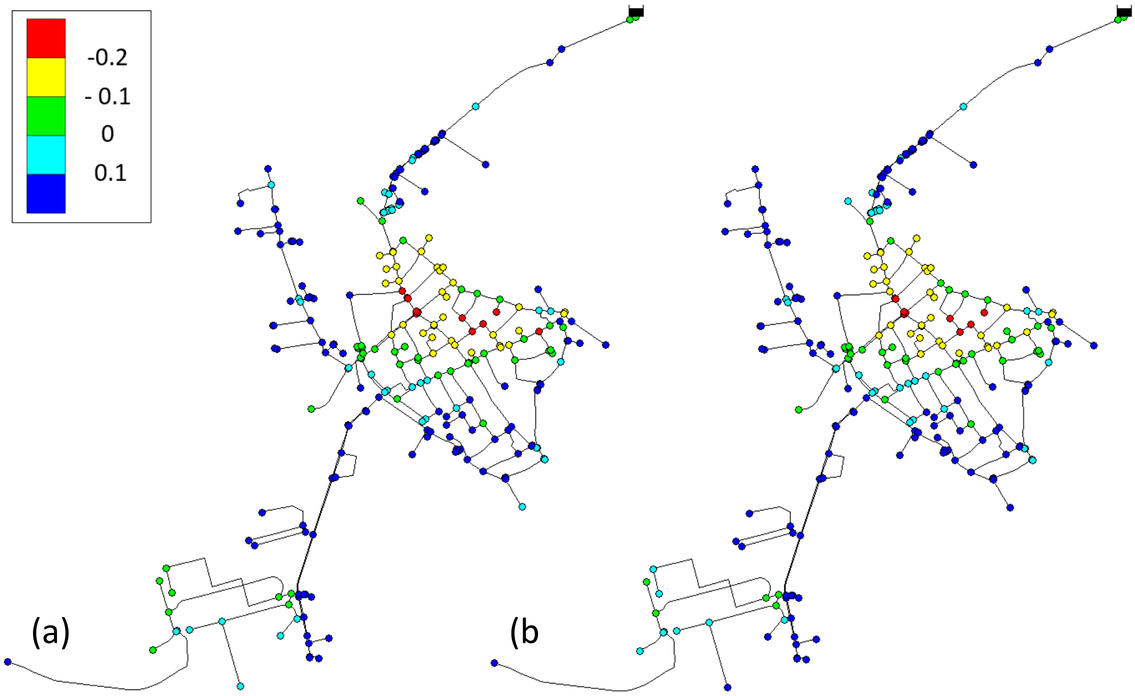

Figure 7.7.4 Graphical views of the local pressure head surplus index, obtained along with the peak condition, at 10:00. (a) DDA (b) PDA.

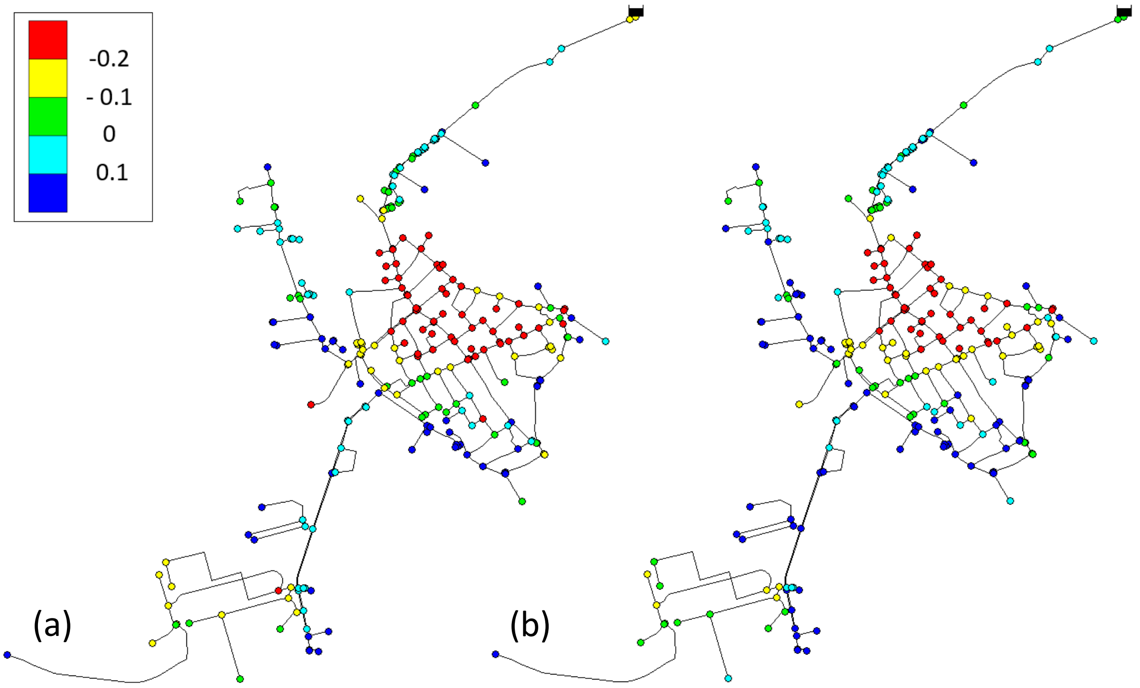

Figure 7.7.5 Graphical views of the local pressure head surplus index, obtained along with the peak condition, at noon. (a) DDA (b) PDA.

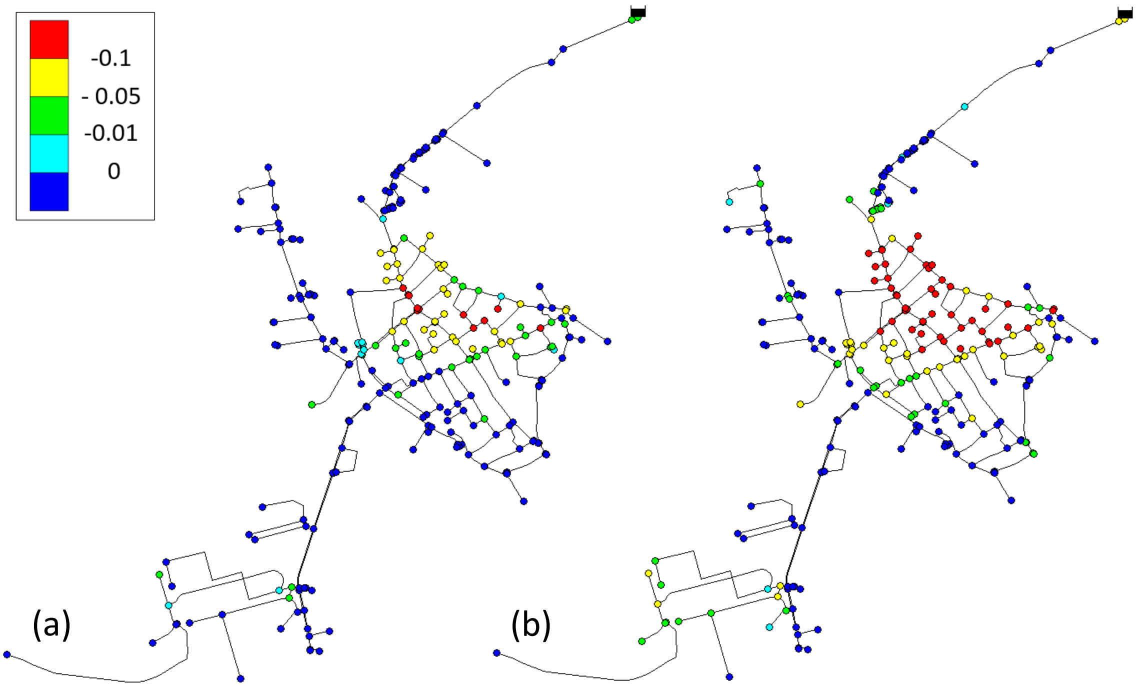

Figure 7.7.6 Graphical views of the local discharge surplus index, obtained whit the PDA model. Values obtained along the peak condition at: (a) 10:00 (b) 12:00.

7.7.2 Considerations

Local surplus indices and two resilience indices were calculated for a portion of the WDN serving the city of Santarém. The network digital model construction allowed obtaining enough information to characterize the requested conditions used by the indexes. The local pressure head surplus index and the local discharge surplus index were useful as immediate graphical indicators.

The capability to calculate the local surplus indices and the resilience indices within the WaterNetGen software has made it easier and faster to have an indication of network performance and evaluate the influence of many variables on the indices.

7.8 STATE OF THE ART, GENERAL CONSIDERATIONS AND FUTURE DEVELOPMENT

In WDNs study and management, synthetic performance indicators is a topic of interest. The ambiguity and variety of definitions of concepts such as reliability have made it difficult to define a commonly accepted procedure for its estimation. Surrogate reliability measures are often used in scientific literature. A framework, such as the one presented in Caldarola and Maiolo (2019), allows identifying recurring analytical patterns in the structure and relationships in many commonly used indices.

The use of resilience as a surrogate measure of reliability brings a series of issues related to the definition of the variables involved in the calculation, the scenarios to be taken into account and the conditions to consider as requests. Resilience evaluates the robustness of a network to failures. A weakness of the resilience index proposed by Todini (2000) or Di Nardo *et al*. (2010b, 2011, 2014a, 2015) is the lack of topology within the definition. Unlike resilience, flow entropy (Tanyimboh and Templeman, 1993b) or its sensitive to diameters variant (Liu *et al*. 2014) implicitly takes into account the presence of internal connections to the network and the diameter uniformity. Prasad and Park (2004) propose a formulation to overcome the limitations of resilience indices by developing a variant sensitive to the uniformity of the diameter. Raad *et al*. (2010) combine resilience and flow entropy indices to reduce the limitations of individual components.

In future works, the possibility of including the network topology, without excessively complicating the calculation procedure in the formulation of the resilience indices, will be studied. A formulation that rewards the interconnections within the networks would allow having a more realistic assessment of the WDNs resilience (as a surrogate measure of reliability).

7.9 BIBLIOGRAPHY

- Bonora, M. A., Caldarola, F., & Maiolo, M. (2020a). A new set of local indices applied to a water network through Demand and Pressure Driven Analysis (DDA and PDA). Water, 12(8), 2210.
- Bonora, M. A., Caldarola, F., Maiolo, M., Muranho, J., & Sousa, J. (2020b). The New Set Up of Local Performance Indices into WaterNetGen and Application to Santarém's Network. In Environmental Sciences Proceedings (Vol. 2, No. 1, p. 18). Multidisciplinary Digital Publishing Institute.
- Bonora, M. A., Caldarola, F., Muranho, J., Sousa, J., & Maiolo, M. (2019). Numerical experimentations for a new set of local indices of a water network. In International Conference on Numerical Computations: Theory and Algorithms (pp. 495-505). Springer, Cham.
- Caldarola, F., & Maiolo, M. (2019). Local indices within a mathematical framework for urban water distribution systems. Cogent Engineering, 6(1), 1643057.
- Ciaponi, C., L. Franchioli, & S. Papiri (2011), Simplified procedure for water distribution networks reliability assessment, Journal of Water Resources Planning and Management, 138(4), 368-376.
- Creaco, E., Franchini, M., & Todini, E. (2016). Generalized resilience and failure indices for use with pressure-driven Modelling and leakage. Journal of Water Resources Planning and Management, 142(8), 04016019.
- Cullinane, M. J., Lansey, K. E., & Mays, L. W. (1992). Optimization-availability-based design of water-distribution networks. Journal of Hydraulic Engineering, 118(3), 420-441.
- Di Nardo, A., & Di Natale, M. (2010b). A design support methodology for district metering of water supply networks. In Water Distribution Systems Analysis 2010 (pp. 870-887).
- Di Nardo, A., & Di Natale, M. (2011). A heuristic design support methodology based on graph theory for district metering of water supply networks. Engineering Optimization, 43(2), 193-211.
- Di Nardo, A., Di Natale, M., & Santonastaso, G. F. (2014a). A comparison between different techniques for water network sectorization. Water Science and Technology: Water Supply, 14(6), 961-970.
- Di Nardo, A., Di Natale, M., Giudicianni, C., Musmarra, D., Varela, J. R., Santonastaso, G. F., ... & Tzatchkov, V. (2017). Redundancy features of water distribution systems. Procedia Engineering, 186, 412-419.
- Di Nardo, A., Di Natale, M., Greco, R., & Iervolino, M. (2006). Controllo differenziato delle pressioni per la riduzione delle perdite in una rete idrica distrettualizzata. Atti del XXX Convegno di Idraulica e Costruzioni Idrauliche, 1-11.
- Di Nardo, A., Di Natale, M., Santonastaso, G. F., Tzatchkov, V. G., & Alcocer-Yamanaka, V. H. (2015). Performance indices for water network partitioning and sectorization. Water Science and Technology: Water Supply, 15(3), 499-509.
- Di Nardo, A., Di Natale, M., Santonastaso, G. F., Tzatchkov, V. G., & Alcocer-Yamanaka, V. H. (2014b). Water network sectorization based on graph theory and energy performance indices. Journal of Water Resources Planning and Management, 140(5), 620-629.
- Di Nardo, A., Greco, R., Di Natale, M., & Santonastaso, G. F. (2012). Resilienza ed entropia come indici di robustezza delle reti di distribuzione idrica. In Quinto seminario su "La diagnosi e la gestione dei sistemi idrici" (pp. 225-232).
- Di Nardo, A., Greco, R., Santonastaso, G. F., & Di Natale, M. (2010a, September). Resilience and entropy indices for water supply network sectorization in district meter areas. In Proceedings of the 9th International Conference on Hydroinformatics, Tianjing, China (Vol. 711).
- Gargano R., Pianese D. (2000). Reliability as tool for hydraulic network planning. Journal of Hydraulic Engineering, 126 (5), 354–364.
- Goulter, I. (1995). Analytical and simulation models for reliability analysis in water distribution systems. In Improving efficiency and reliability in water distribution systems (pp. 235-266). Springer, Dordrecht.
- Greco, R., Di Nardo, A., & Santonastaso, G. (2012). Resilience and entropy as indices of robustness of water distribution networks. Journal of Hydroinformatics, 14(3), 761-771.
- Jayaram, N., & Srinivasan, K. (2008). Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing. Water resources research, 44(1).

- Kang, D., & Lansey, K. (2012). Revisiting optimal water-distribution system design: issues and a heuristic hierarchical approach. Journal of Water resources planning and management, 138(3), 208-217.
- Kaufmann, A. (1977). Mathematical models for the study of the reliability of systems.
- Khomsi, D., Walters, G. A., Thorley, A. R. D., & Ouazar, D. (1996). "Reliability Tester for water distribution networks." J. Computing in Civil Eng., 10(1), 10–19.
- Lamberti, P., Maiolo, M., Mazzola, R., & Veltri, P. (1994) Rapporto sui consumi idropotabili sul finire degli anni '80. In I Quaderno del Gruppo Nazionale "Consumi idropotabili"; Taglialatela, L., Bertola, P., Eds.; CUEN Editrice: Napoli, Italy.
- Liu, H., Savić, D., Kapelan, Z., Zhao, M., Yuan, Y., & Zhao, H. (2014). A diameter-sensitive flow entropy method for reliability consideration in water distribution system design. Water resources research, 50(7), 5597-5610
- Milano, V. (1996). Acquedotti. Hoepli Editore.
- Muranho, J., Ferreira, A., Sousa, J., Gomes, A., & Marques, A. S. (2014). Pressure-dependent demand and leakage modelling with an EPANET extension–WaterNetGen. Procedia Engineering, 89, 632-639.
- Muranho, J., Ferreira, A., Sousa, J., Gomes, A., & Sá Marques, A. (2012). WaterNetGen: an EPANET extension for automatic water distribution network models generation and pipe sizing. Water science and technology: water supply, 12(1), 117-123.
- Muranho, J., Sousa, J., Marques, A. S., & Gomes, R. (2018, September). Water distribution network reliability: are surrogate measures reliable?. In 13th International Conference on Hydroinformatics (HIC 2018) (Vol. 3, pp. 1470-1461). EPiC Series in Engineering.
- Pianese, D. (1995). Affidabilita idraulica delle reti idriche in pressione. Proc., Spec. Conf. on Affidabilita dei sistemi di adduzione e di distribuzione idrica, 30–41
- Pianese, D., & Villani, P. (1994). Verifica di affidabilita delle reti idriche in pressione. Parte prima: Valutazione mediante indici locali. Proc., XXIV Convegno Nazionale di Idraulica e Costruzioni Idrauliche, Vol. 2, T3b, 67–80
- Prasad, T. D., & Park, N. S. (2004). Multiobjective genetic algorithms for design of water distribution networks. Journal of Water Resources Planning and Management, 130(1), 73-82.
- Raad D.N., Sinske A.N., & van Vuuren J.H. (2010). Comparison of four reliability surrogate measures for water distribution systems design. Water Resources Research, 46 (5), W05524.
- Rossman, L., H. Woo, M. Tryby, F. Shang, R. Janke, & T. Haxton. (2020) EPANET 2.2 User Manual. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-20/133.
- Rossman, L.A. (2000) EPANET 2: Users Manualus Environmental Protection Agency; Water Supply and Water Resources Division, National Risk Management Research Laboratory: Cincinnati, OH, USA.
- Setiadi, Y., Tanyimboh, T. T., & Templeman, A. B. (2005). Modelling errors, entropy and the hydraulic reliability of water distribution systems. Advances in Engineering Software, 36(11-12), 780-788.
- Shannon, C. E. (1948). A mathematical theory of communication. The Bell system technical journal, 27(3), 379-423.
- Tanyimboh, T. T. (1993). An entropy-based approach to the optimum design of reliable water distribution networks (Doctoral dissertation, University of Liverpool).
- Tanyimboh, T. T., & Templeman, A. B. (1993a), Calculating maximum entropy flows in networks, The Journal of the Operational Research Society, 44(4), 383-396.
- Tanyimboh, T. T., & Templeman, A. B. (1993b). Optimum design of flexible water distribution networks. Civil Engineering Systems, 10(3), 243-258.
- Tanyimboh, T., & Sheahan, C. (2002). A maximum entropy based approach to the layout optimization of water distribution systems. Civil Engineering and Environmental Systems, 19(3), 223-253.
- Tanymboh, T. T., Tabesh, M., & Burrow, R. (2001). "Appraisal of source head methods for calculating reliability of water distribution networks." J. Water Resour. Plann. Manage., 127(4), 206–213.
- Todini, E. (2000). Looped water distribution networks design using a resilience index based heuristic approach. Urban water, 2(2), 115-122.
- Wagner, J. M., Shamir, U., & Marks, D. H. (1988). Water distribution reliability: analytical methods. Journal of Water Resources Planning and Management, 114(3), 253-275.

8 Support model for gravity water networks design in a realistic orography

8.0 Summary

8.1 Introduction

Climate change associated with population growth and production development is negatively affecting the state of available water resources. A society with growing needs finds itself facing an availability reduction of good quality and easy to use resources. The degradation of the resources state and availability requires more careful management, which aims at conservation, reuse and mainly optimization. Large international associations have focused their attention on the need to achieve sustainability goals on water use and the need to improve its accessibility to a large number of people. The *UN 2030 agenda* defines the objectives for sustainable development to be achieved, hopefully, by 2030 (*Sustainable Development Agenda: GOAL 6*)

Part of the water-related targets defined in the agenda are:

- *By 2030, achieve universal and equitable access to safe and affordable drinking water for all.*
- *By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.*
- *By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.*
- *By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.*
- *By 2030, expand international cooperation and capacity-building support to developing countries in water and sanitation related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.*

Other international associations such as the *European Water Stewardship* [1] (EWS) and the *International Water Association* [2] (IWA) focus on water saving and the achievement of sustainability and efficiency objectives. The *EWS* emphasizes the need to quantify and monitor all water uses to improve the exploitation of the resource efficiency:

- *The total and the net water abstraction shall be quantified and monitored by source.*
- *Actions taken to improve water efficiency, reduce water losses and mitigate detected and potential impacts of water abstraction shall be described and implemented. All actions should be integrated in the Water Management Strategy.*
- *Water losses are identified. Type and destination of losses are described.*
- *A strategy is in place and described to achieve optimized water efficiency.*
- *Water consumption per unit is quantified.*

The overall commitment to improve the water resources usage includes the definition of methodologies and criteria for better and correct distribution. Sustainable management implies that, regardless of the availability of the resource, it is necessary to exploit it in a conservative and optimized way. Defining optimal consumption criteria is a common engineering problem. On a territory, there are different users with conflicting water resources needs (irrigation, drinking water, industrial use). The resource optimal allocation problem for a limited set of users and

[1] https://ews.info/
[2] https://iwa-network.org/

sources is explored in several papers (Li *et al*. 2020, Davijani *et al*. 2016, Zhanping and Juncang 2012).

Maiolo and Pantusa (2015) and Carini *et al*. (2017) Maiolo *et al*. (2017, 2018) propose an approach that treats the optimal allocation of water resources, in the presence of multiple sources and users, as a minimum cost optimization problem. The goal is to minimize the infrastructure building cost (ex-Novo or expansions) to obtain an optimal and cost-efficient distribution of the resource to all users.

The use of a minimum cost problem implies the definition of a cost function for the infrastructure element to be built. The cost function, defined in Maiolo and Pantusa (2015) and Carini *et al*. (2017), parameterizes the cost of the pipeline. The cost function depends on the water flow, the pipe geometric characteristics (length and diameter) and the path characteristics (difference in height and length). The authors use an approximation in the planimetric path and length estimation, using the Euclidean distance between sources and users. This approximation negatively affects the price estimate of the evaluated design solution. The objective of the in-depth study published by Maiolo *et al*. (2019) is the definition of an advanced criterion for source-user nodes distance assessment. The work presents a methodology to estimate the distance between two points placed on a topographical surface while ensuring that the identified path is compatible with a realistic gravity water pipe.

8.2 Topological surfaces modelling and distance definition

The distance assessment on a topological surface has many practical applications in robotics, path planning, texture mapping, and computer graphics (Porazilova 2007). A possible approach in topographic surface minimal paths search is to consider the surface as an undirected graph using the tools provided by operations research (OR) to identify optimal solutions (Balasubramanian *et al*. 2008, Surazhsky *et al*. 2005, Kanai *et al*. 2000). A geodesic curve is commonly referred to as the shortest curve that joins two points on a surface.

The proposed methodology aims to identify optimal paths laying on a topological surface. The degree of novelty lies in identifying the shortest path that respects some physical limitations linked to the work goal. Since the paths represent the pipes route, these will have to comply with the limits and conditions imposed by the hydraulics and should preferably avoid uphill sections to guarantee an adequate hydraulic head along the entire path.

A three-dimensional topological surface can be represented as a polyhedral surface. A polyhedral surface is a set of polygonal faces that approximate the starting surface. The real surface approximation with a sufficient degree of detail (dimension of the elements) introduces an approximation that does not affect the representativeness, Figure 8.2.1.

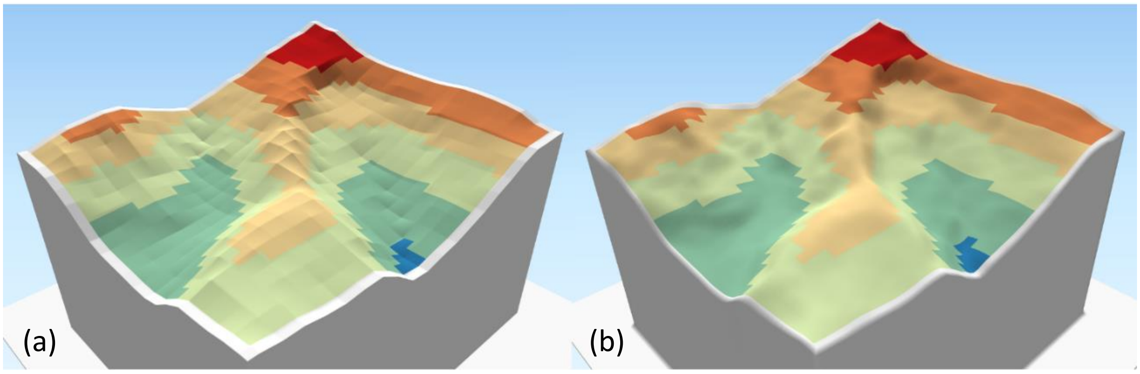

Figure 8.2.1 Polyhedral surface example, 3D view. (a) Large cell size, low resolution (b) Small cell size, high resolution.

8.2.1 Geodesic curves and constrained paths

A polyhedral surface can be represented by a graph.

$$S = (E, V)$$

$$E = \{e_1,\ e_2,\ e_3, \dots\ e_i\ \dots\ e_l\} \qquad \text{Eq. 8.2.1}$$

$$V = \{v_1,\ v_2,\ v_3, \dots v_i\ \dots\ v_n\}$$

The surface elements are represented by point elements (vertices or nodes), the adjacency of the elements is represented by line elements (edges or links), Figure 8.2.2.

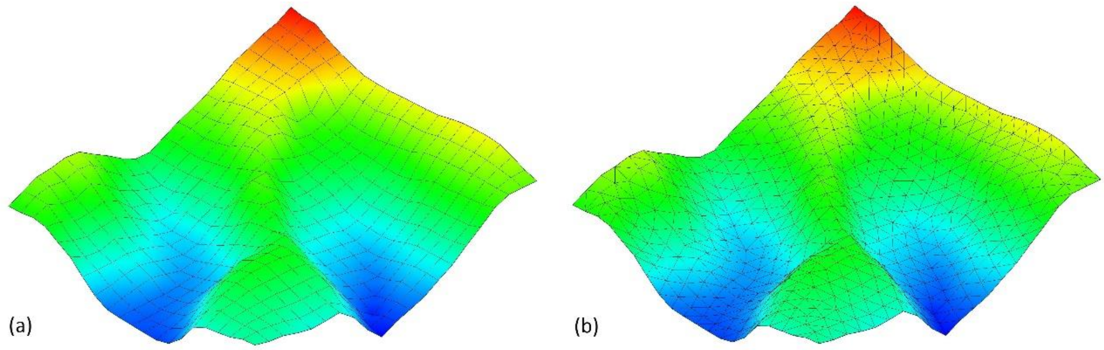

Figure 8.2.2 Polyhedral surface graph example (a) Surface with square elements (b) Triangulated irregular network (TIN) surface.

A Polyhedral surface can be represented by an undirected graph with non-negative weights. Given a pair of adjacent vertices, there is only one edge connecting them. The weight of the edge is set equal to the Euclidean distance between the two vertices.

$$e_1, e_2 \in E$$
$$v_{12} = v_{21} \in V \qquad \text{Eq. 8.2.2}$$
$$\varepsilon_{12} = \varepsilon_{21}$$

The minimum distance between two non-adjacent graph vertices is approximate to the geodetic distance between these vertices on the surface. In the quest for the optimal paths that connect two non-adjacent vertices, the methodology takes into account an hydraulic criterion, which should guarantee the gravity water distribution through the pipes. The criterion implementation imposes the need to discriminate some paths considered less "preferable".

To take into account a hydraulic-gravity constraint, it is necessary to differentiate the uphill and downhill connections. Under these constraints, an undirected graph is not sufficient to represent the surface. A directed graph with non-negative weights considers two connections between two adjacent vertices. The links weight is set equal to the Euclidean distance between the vertices. The use of two different connections for the uphill and downhill edges allows increasing the weight for uphill ones to make them "inconvenient".

For an hydraulically constrained geodesic:

$$e_1, e_2 \in E$$
$$z_{n_1} > z_{n_2} \qquad \text{Eq. 8.2.3}$$
$$\varepsilon_{12} < \varepsilon_{21}$$

The minimum distance between two non-adjacent vertices, calculated using the directed graph defined in Eq. 8.2.3, in the absence of price increments for inconvenient paths, provides a geodesic distance between the vertices. For a graph with a cost increase for uphill edges, the optimal path differs from a geodesic. For the path length, hold the relation:

$$d_{euclidean} \leq d_{geodesic} \leq d_{hydraulic\,constrained} \qquad \text{Eq. 8.2.4}$$

The Dijkstra algorithm allows identifying the shortest surface paths. Dijkstra's algorithm is a minimum paths search algorithm. Given two graph vertices, the algorithm identifies the path with the minimum cost that connects them. It works on directed or undirected, non-negative-weights graphs. A variant of the algorithm allows obtaining the distance of all the graph edges from the chosen source vertex.

8.2.2 Data format and setting

The graph construction requires the use of a reference polyhedral surface. The presented methodology uses a Digital Terrain Model (DTM) in raster format as a database. The raster format is a matrix structure that represents a rectangular grid of pixels. This structure can be used to store topographic information and is a common-use format in GIS software.

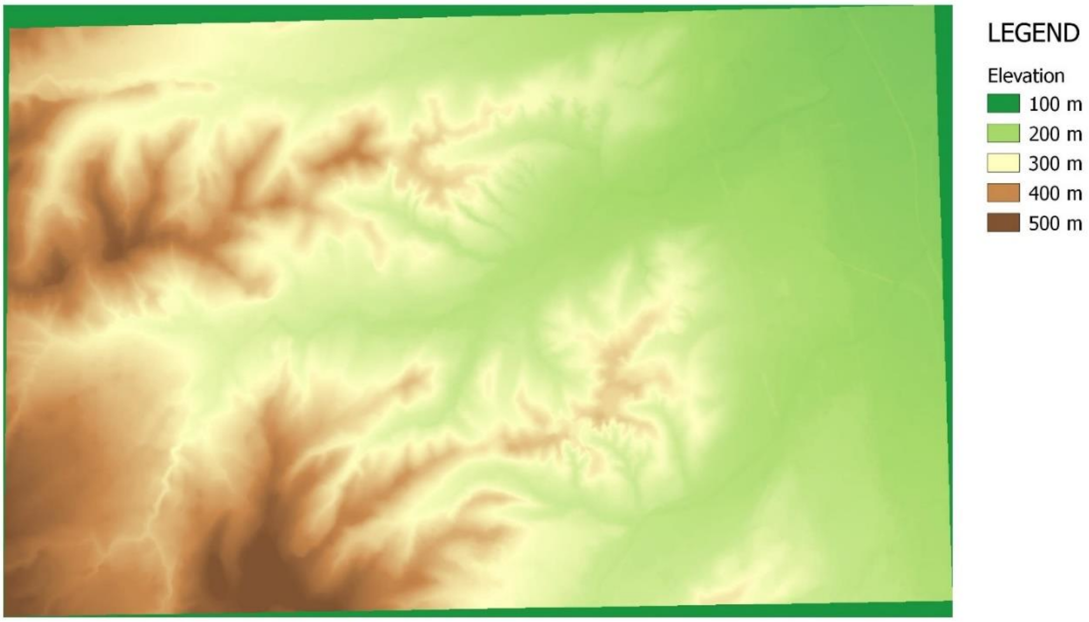

Figure 8.2.3: Digital terrain model, raster format.

DTM stores information about altimetry. Each raster cell corresponds to the mean elevation of the area covered by that cell (e.g. Figure 8.2.2a). Each cell is associated with a pair of coordinates of a geodetic Datum. Chosen the datum, the coordinates are defined only for one of the corners (i.e. top left corner). The remaining cell coordinates are derived from the known corner coordinates and the cell size. To construct an oriented graph using a DTM, it is necessary to define the vertices generation and positioning criterion and the edges connection criterion.

Vertices

Each graph vertex is associated with a DTM cell. The vertices are positioned in the centre of the cells. A triplet of space coordinates, Eq. 8.2.5, characterizes each vertex:

$$E = \{e_1,\ e_2,\ e_3, \dots\ e_i \dots\ e_l\}$$

$$e_1 : (x_1, y_1, z_1)$$

Eq. 8.2.5

For a DTM in which the top left corner has coordinates (x_0, y_0) and cells dimension (dx, dy), the coordinate triplet associated with the cell $(i; j)$ can be derived as:

$$x_i = x_0 + (i-1)dx + \frac{1}{2}dx$$

$$y_j = y_0 - (j-1)dy - \frac{1}{2}dy$$

$$z_i = Cell(i,j)_{DTM}$$

Eq. 8.2.6

The graph vertices associated with a DTM surface are organized in an ordered grid, with a spacing that depends on the raster cells size. A pair of indices indicate their distance (in cells) from the upper left corner. For the graph construction, it is necessary to define a unique index for the vertices. The numbering follows a lexicographic convention, according to which the vertices are numbered by proceeding from left to right, top to the bottom. Table 8.2.1 report the range of variation and the nomenclature of the matrix and vertex indices.

Matrix indices	Rows	$i = \{1 \dots R\}$
	Columns	$j = \{1 \dots C\}$
Vertices index		$n = \{1 \dots N\}$

Table 8.2.1: Matrix indices and vertices nomenclature.

For the vertices management and positioning it is useful to define a formula to convert the vertex index to the DTM matrix indices and vice versa. For a DTM cell (i, j) the corresponding vertex index is:

$$n = (i-1) * C + j$$

Eq. 8.2.7

For the vertex index n the corresponding matrix indices pair is:

$$i = INT\left(\frac{n}{C}\right) + 1 \qquad j = MOD\left(\frac{n}{C}\right)$$

Eq. 8.2.8

Where MOD() function returns the remainder after division. The INT() function returns only the integer part of a decimal number.

Links

In the representation of the polyhedral surface as a graph, the edges represent the proximity between the vertices. Adjacent vertices belong to DTM cells that share a side or a (geometric) vertex, Figure 8.2.4.

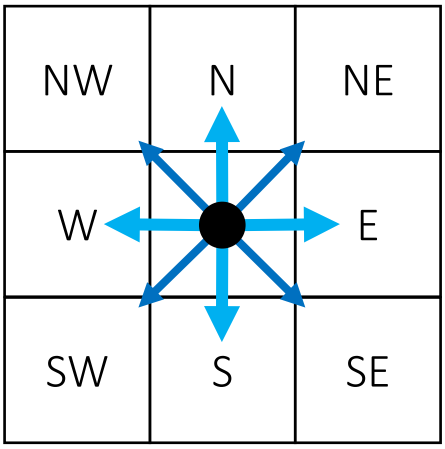

Figure 8.2.4: Edge generation criterion.

As regards the linking criterion, there are eight possible connections along with the directions: North, South, East, West, North-West, South-West, North-East, South-East, Figure 8.2.4. These connections can be automatically generated whether the position of the cell in the matrix (i, j) or the node index (n) is used, Table 8.2.2.

Direction	Matrix indices		Vertices indices
N	i-1	j	n-C
S	i+1	j	n+C
W	i	j-1	n-1
E	i	j+1	n+1
NW	i-1	j-1	n-C-1
NE	i-1	j+1	n-C+1
SW	i+1	j-1	n+C-1
SE	i+1	j+1	n+C+1

Table 8.2.2 Edge generation criteria, matrix indices and vertices index formulae.

Edge cost

As for Eq. 8.2.4, the edges cost assignment criterion affects the type of path identified by the shortest path search algorithm. The link cost is set equal to the Euclidean distance between cell centres. For a DTM with square cells, the length depends only on the connection type (straight or diagonal) and on the elevation difference between starting and ending node, Figure 8.2.5.

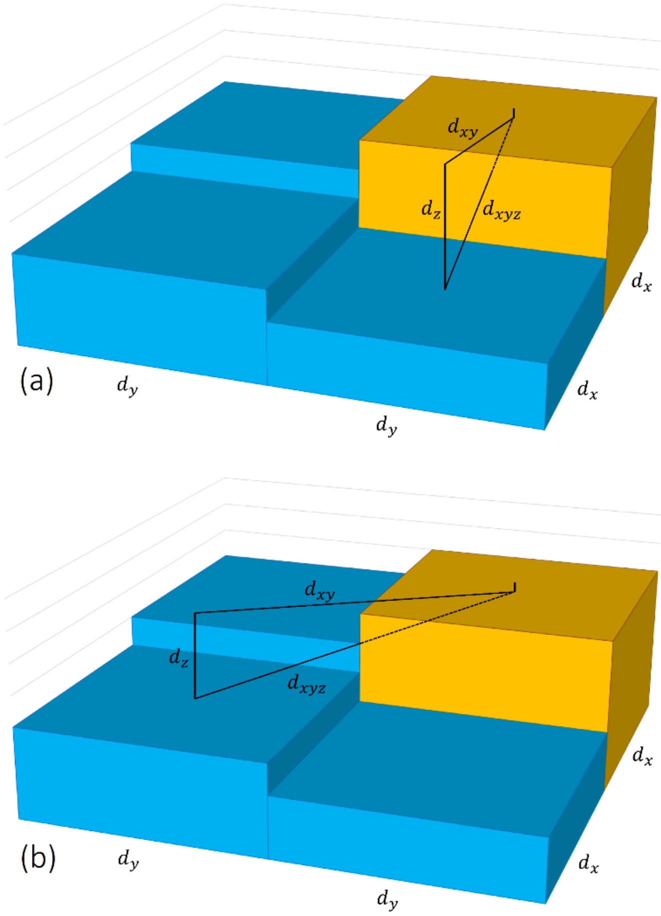

Figure 8.2.5 Link length calculation: a) North, South, East, West links. b) North-West, South-West, North-East, South-East links.

The distance between two adjacent nodes is:

$$d_{xyz} = \sqrt{(dx)^2 + (dy)^2 + (dz)^2} \quad \text{Eq. 8.2.9}$$

For square cells DTM:

$$dx = dy = dl \quad \text{Eq. 8.2.10}$$

Hence, for N, S, E, W links:

$$d_{xy} = dl$$

$$d_{xyz} = \sqrt{(dl)^2 + (dz)^2} \qquad \text{Eq. 8.2.11}$$

In addition, for NW, SE, NE, SW links:

$$d_{xy} = \sqrt{(dl)^2 + (dl)^2} = \sqrt{2}\,dl$$

$$d_{xyz} = \sqrt{2(dl)^2 + (dz)^2} \qquad \text{Eq. 8.2.12}$$

The distance function becomes:

$$d_{xyz} = \sqrt{{d_{xy}}^2 + dz^2} \qquad \text{Eq. 8.2.13}$$

The weight defined in Eq. 8.2.13 characterizes a graph which does not differentiate descending and ascending links, Eq. 8.2.2. A gravity flow pipe path must be characterized by a preferably descending path, to guarantee that the piezometric surface does not intersect the pipe. The formulation that discriminates uphill routes, as defined in Eq. 8.2.3, needs a criterion to impose an additional cost for uphill edges. The chosen criterion add a synthetic length to the edges for which the elevation difference is positive (uphill edges):

$$d_{xyz} = \sqrt{{d_{xy}}^2 + dz^2} + Pen * dz \qquad \text{Eq. 8.2.14}$$

$$Pen \geq 0$$

If *Pen* is equal to zero, the graph considers only the Euclidian distance between the centres of the cells. For uphill links, the penalty is positive, for others null. In a graph with no cost increasing the shortest path algorithm gives as result a simple geodesic path.

8.3 HYDRAULIC CONSTRAINTS

The proposed methodology seeks to include series of constraints in the search for the minimum paths that make the identified pipe route representative of the possible plano-altimetric route of a pipe transporting the water resource from a source to an user. To ensure that a path is compatible with a gravity flow pipe, assuming that there are no territorial constraints, it is necessary to solve the correlated hydraulic problem. The hydraulic formulas use the geometric and hydraulic characteristics of the pipes. A pipe layout can operate by gravity if the piezometric surface does not intercept the pipe, always guaranteeing a positive pressure.

The proposed path-finding methodology application takes place before the application of the works cost-minimizing algorithms (Maiolo and Pantusa 2015, Carini *et al*. 2017). In this phase, it is only necessary to know the length of the hydraulically possible connections between a set of sources and users. The presence of the connections and the actual flow conveyed in their result from the optimization procedure. At this stage, the hydraulics formulas cannot be used to assess the validity of the pipe paths, since the pipe flow rate is not known.

The path-find algorithm uses a synthetic cost increase, Eq. 8.2.14, to reward the hydraulically feasible routes. However, the use of a penalty for uprising paths is not a sufficient condition to guarantee an hydraulically verified path.

8.3.1 EXCLUSION AND DISADVANTAGE TERRITORIAL CRITERIA

The construction of the oriented weighted graph constraints allows excluding not suitable pipe paths. To reduce the computational weight linked to the graph generation and the one for the path-finding algorithm, all areas with an elevation greater than that of the source node are excluded from the domain, Figure 8.3.1.

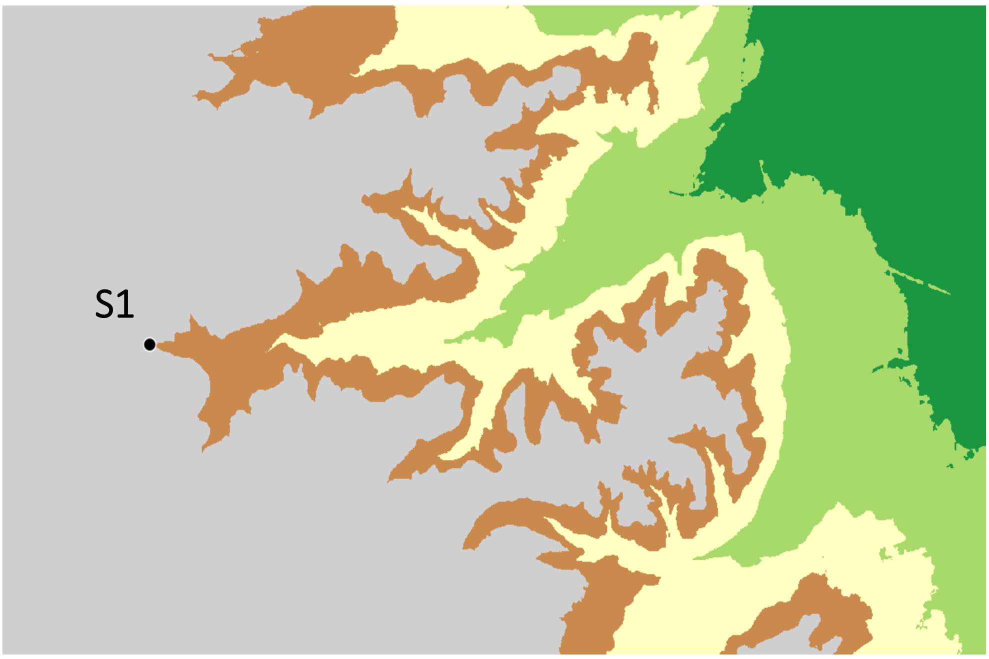

Figure 8.3.1 Reduced DTM for path-searching algorithm from source node S1.

Specific areas can be excluded from the path-search domain using the same logic. The pipe may do not get through lakes, rivers, cities or areas subject to naturalistic constraints. During the domain construction phase, it is possible to set additional constraints that make areas less preferable (or impossible) for the passage of pipe routes. These domain constraints are classified into two categories:

Criterion: it is possible to represent the constraint with an equation. The graph generation algorithm excludes or increases the cost of the vertices that do not comply with the imposed condition. The example of Figure 8.3.1 is a constraint that excludes from the graph all vertices with an elevation value greater than a set threshold.

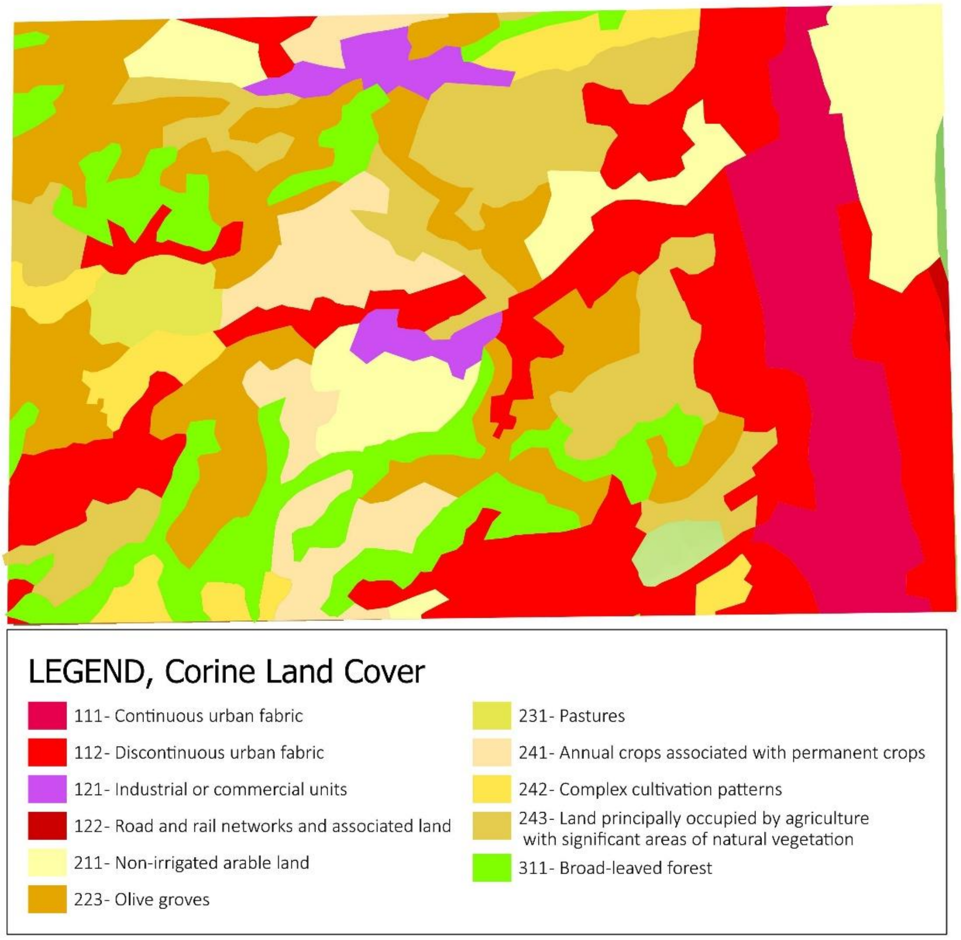

Figure 8.3.2 Territorial area masks. Corine Land Cover[3] gives information on the territory usage allowing to discern suitable from unsuitable areas for aqueduct traces.

Masks: Irregular shapes represent the areas excluded or unsuitable for the aqueduct trace. Since it is not possible to define a criterion (i.e an equation) to exclude a node of the graph according to its characteristics (position, elevation), it is necessary to check whether the vertex falls within the constrained areas. To reduce the computational cost deriving from the area needing verification, it is possible to use a raster that has the extension and position of the same cell as the DTM. The raster cells contain the numerical information (weight increase or exclusion of the cells) to be assigned to the graph vertices. The example of Figure 8.3.2 shows an overlap in the

[3] https://land.copernicus.eu/pan-european/corine-land-cover

calculation domain of the cultivated areas (Corine Land Cover). These areas can be considered as more expensive to cross in the definition of the planimetric layout of the pipelines since they involve expropriation costs, which are modelled as an additional distance (multiplicative coefficient) in the edges generation.

8.3.2 HYDRAULIC CONSTRAINT

The impossibility of assessing the feasibility of the identified paths using hydraulic formulas requires identifying an alternative assessment criterion. It has been assumed that a pipe can operate under gravity if it ensures a minimum slope.

The constant slope line follows the geodesic curvilinear abscissa. If the curve intersects the topographic surface then the verification is not satisfied. A triplet of coordinates defines the constrained geodesic, which represents the pipeline trace:

$$gc = (x_i, y_i, z_i) \qquad i = 1 \dots n; \qquad \text{Eq. 8.3.1}$$

The constant slope curve, necessary for validating the path, follows the planar trace of the line defined as:

$$s_i = \sum_{j=2}^{i} \sqrt{\left(x_{j-1} - x_j\right)^2 + \left(y_{j-1} - y_j\right)^2} \qquad \text{Eq. 8.3.2}$$

The curve starts from x_1, y_1, z_1 with the following equation:

$$\begin{cases} xi \\ yi \\ z_i^{tg} = z_1 - s_i * slope_{tg} + E \end{cases} \qquad \text{Eq. 8.3.3}$$

Where:

- E Possible excavation depth.
- $slope_{tg}$ Target slope.

A pipe path passes the slope check if:

$$z_i^{tg} \geq z_i \qquad i = 1 \dots n; \qquad \text{Eq. 8.3.4}$$

8.4 Computational resource cost

The presented methodology builds an oriented graph representing the polyhedral surface. The Dijkstra algorithm, applied to the graph, search for the shortest paths connecting sources to user nodes. The graph generating procedure and the minimum paths search can be very expensive in terms of computational resources. The search for an optimal configuration of connections between water sources and users can involve very large areas.

The number of DTM cells, and consequently graph vertices, depends on the extent of the area and the size of the cells. A DTM that covers an area of a square kilometre, with 5-meter square cells, counts 40,000 cells. The associated graph is made up of 40,000 nodes and about 320000 connections (In an oriented graph, in which the arcs are differentiated according to the direction, each node within the domain has 8 connections). The application of exclusion criteria (Paragraph 8.3.1) may reduce the overall computational cost. The application of cost-increase criteria or domain area exclusion can adversely affect the domain generation performance. The algorithm must check whether each vertex falls into a particular area characterized by increased cost or signed as "excluded".

The shortest-paths search algorithm is applied to a list of sources present in the modelled territory to identify all the hydraulically possible paths between every source and user. Some tweaks allow reducing the computational load related to the algorithm application.

8.4.1 Domain data pre-treatment

The search for hydraulically constrained geodesics can involve areas of considerable extension. A DTM representing these areas if uses small cells can contain millions of elements. To limit the surface graph size associated with large areas, the algorithm can reduce the DTM quality by merging adjacent cells into larger cells. Having defined a reduction factor, S_f (Shrink Factor), the algorithm merges the $S_f \cdot S_f$ adjacent cells. This procedure allows to quadratically reducing the number of vertices and edges of the graph, Figure 8.4.1.

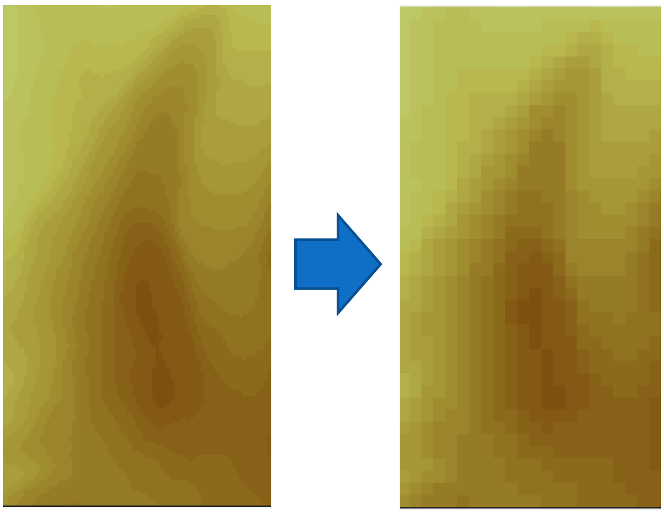

Figure 8.4.1: DTM with 5m cells example. Using $S_f = 4$ reduces the number of DTM cells to 1/16 of the starting number (20m wide).

8.4.2 Multi-cost polyhedral surface graph

The use of an increased coefficient for upward links, Eq. 8.2.14, and a threshold for the minimum slope, involves the need to calibrate the algorithm thresholds. The Eq. 8.3.4 slope ($slope_{tg}$) and excavation depth (E) must be defined before the surface graph construction.

The slope check follows the constrained geodesics quest. The penalty associated with uprising links affects the surface-graph construction. With penalty increases, the identified constrained geodesics lengthen. It is necessary to find the path that respects the check of 4 while minimizing the length increase (minimizing the assigned penalty).

For each water source, it is necessary to generate a graph and apply the path-search algorithm. An iterative procedure allows identifying the path with the minimum penalty that respects the slope check. An iterative procedure that builds multiple graphs for each source was too expensive in computational terms for application on a workstation.

A more efficient simplified methodology uses a vector containing k values of increasing penalties. The algorithm computes k matrices of costs simultaneously for each water source. The algorithm checks the k constrained geodesic with the chosen penalties. The check starts from a simple geodesic and then increase the penalty until the constrained geodesic passes the imposed slope check, Figure 8.4.2.

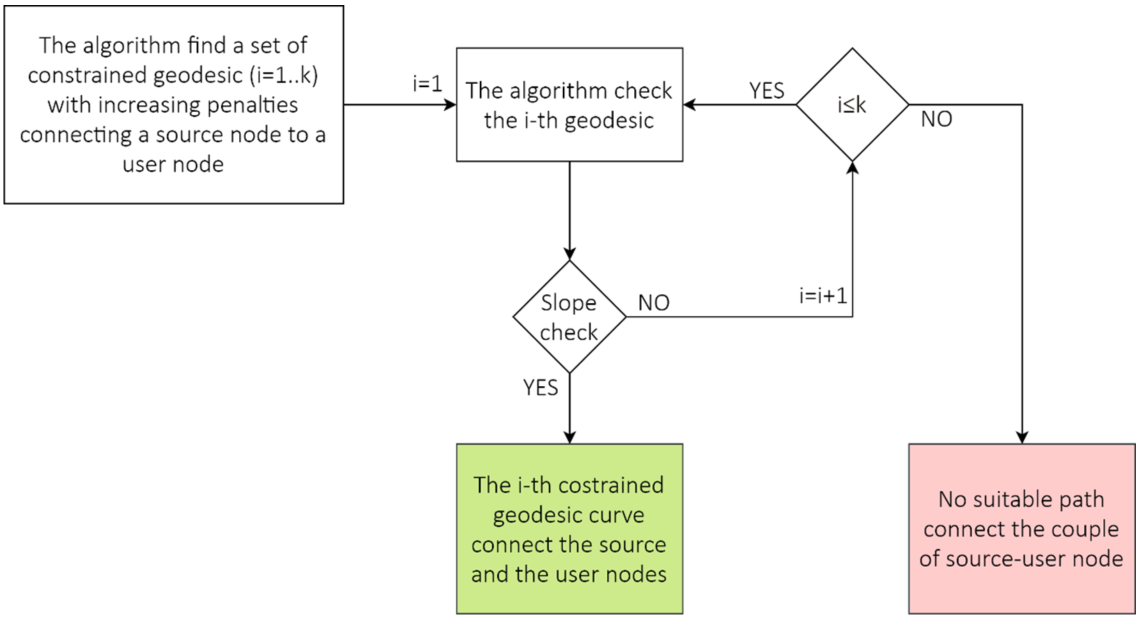

Figure 8.4.2: Slope check procedure with an increasing-penalty geodesic curve set.

8.5 SYNTHETIC CASE STUDY

To assess the effectiveness of the proposed methodology, the authors (Maiolo *et al*. 2019) applies the algorithm to a polyhedral surface representing a portion of the real territory, Figure 8.5.1. The area modelled by the DTM contains 5 sources and 4 users. The DTM has 5m square cells and extends for about 36 km^2, Table 8.5.1.

	Length/Area	Number of cells
Columns	7485m	1497
Rows	4825m	965
DTM	36.115 km^2	1444605

Table 8.5.1: DTM characteristics summary.

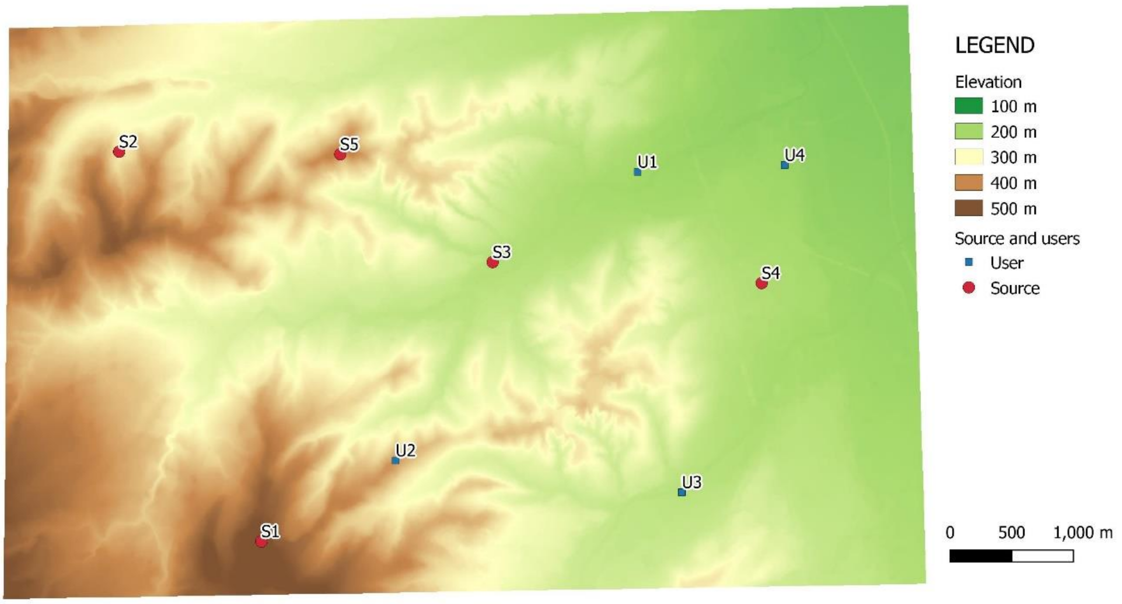

Figure 8.5.1 DTM elevation and sources and users positions.

The DTM elevation ranges between 170 and 563m a.s.l. The sources and the users have been synthetically positioned to assess the algorithm ability to adapt to different configurations. Sources S1 and S5 are located in elevated areas, S3 and S4 are located in low elevation and mainly flat areas. Source S2 is surrounded by elevated areas that prevent a complete downhill path to the users. The surface graph is generated using a $S_f = 2$. The resolution reduction lowered the graph edge count from 1.44 million vertices and 11.55 million edges to about 360 thousand cells and 2.87 million edges.

The penalties for the slope check are:

$$Pen = 0, 5, 10, 50, 100 \qquad \text{Eq. 8.5.1}$$

The target slope and the maximum excavation depth are:

$$E = 2\ m$$
$$slope_{tg} = 0.025$$
Eq. 8.5.2

Table 8.5.2 summarizes the graph computational cost and resource usage for various shrink factors. The actual number of edges of each graph is lower than the theoretical number since the algorithm excludes any border cells with unassigned elevation and all the vertices which elevation exceeds the source one. The algorithm constructs a graph for each chosen penalty value, Eq. 8.5.1. Resource consumption refers to the five surface graphs generated for a source:

Shrink factor	Node Maximum number	Link Maximum number	Link number	Memory usage*	Generating time*
1	1444605	11542076	9730316	797.47 MB	17s
2	360536	2876916	2420574	198.42 MB	4s
3	160179	1276520	1082348	88.88 MB	2s
4	90134	717390	608868	49.89 MB	1s
*Performance refers to a Matlab code using a specific workstation (CPU: AMD Ryzen 5 3600; GPU: AMD Radeon RX 5700; RAM: 16Gb Cl16 3200mhz)					

Table 8.5.2 Cost graph characteristics and computational cost with different shrink factors

Results

The algorithm identifies a geodesic curve and four constrained geodesic curves for each source-user pair. The case study counts 5 sources and 4 users. There are 20 possible (constrained) geodesic paths. For null penalties, the algorithm identifies the simple geodesic connecting the vertices. As the penalty increases, the resulting constrained geodesic, tend to reward downhill paths avoiding uphill areas, departing from the geodesic path, Figure 8.5.2. The slope check allows choosing a suitable geodesic curve for the path of a supply pipe.

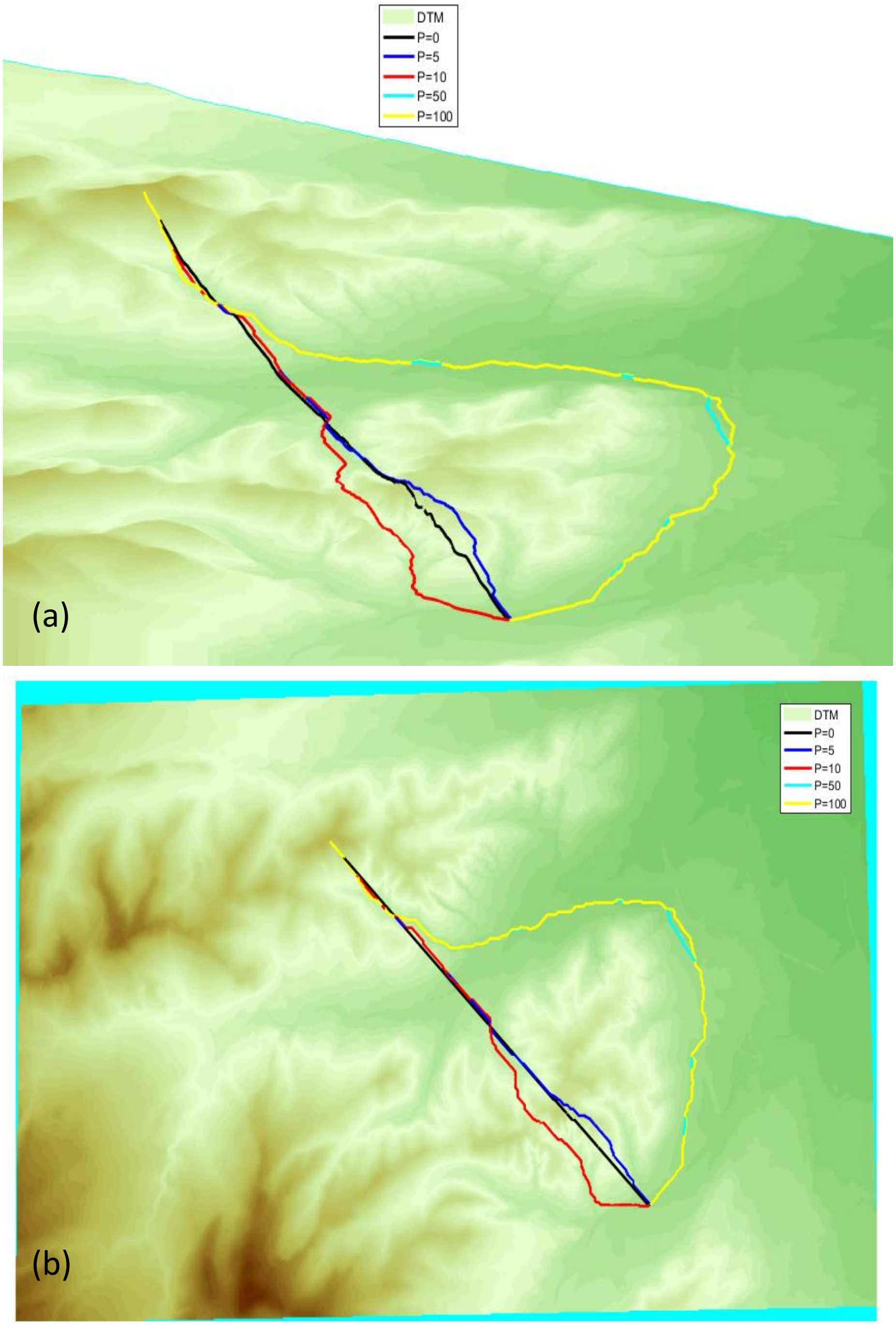

Figure 8.5.2: Set of 5 geodesic curves with increasing penalties found from source S3 to user U3. (a) 3D view (b) plan view.

Slope check

Each set of geodesics that connects a source-user vertices pair is subjected to the slope check. Figure 8.5.3 and Figure 8.5.4 shows the slope check for the geodesic curves. Figure 8.5.3 shows a section view that follows the curvilinear abscissa of the constrained geodesic paths. The simple geodesic and the $Pen = 5$ curve do not satisfy the check. The procedure in this case defines the geodesic with a $Pen = 10$ as the connection between the source node and the user node.

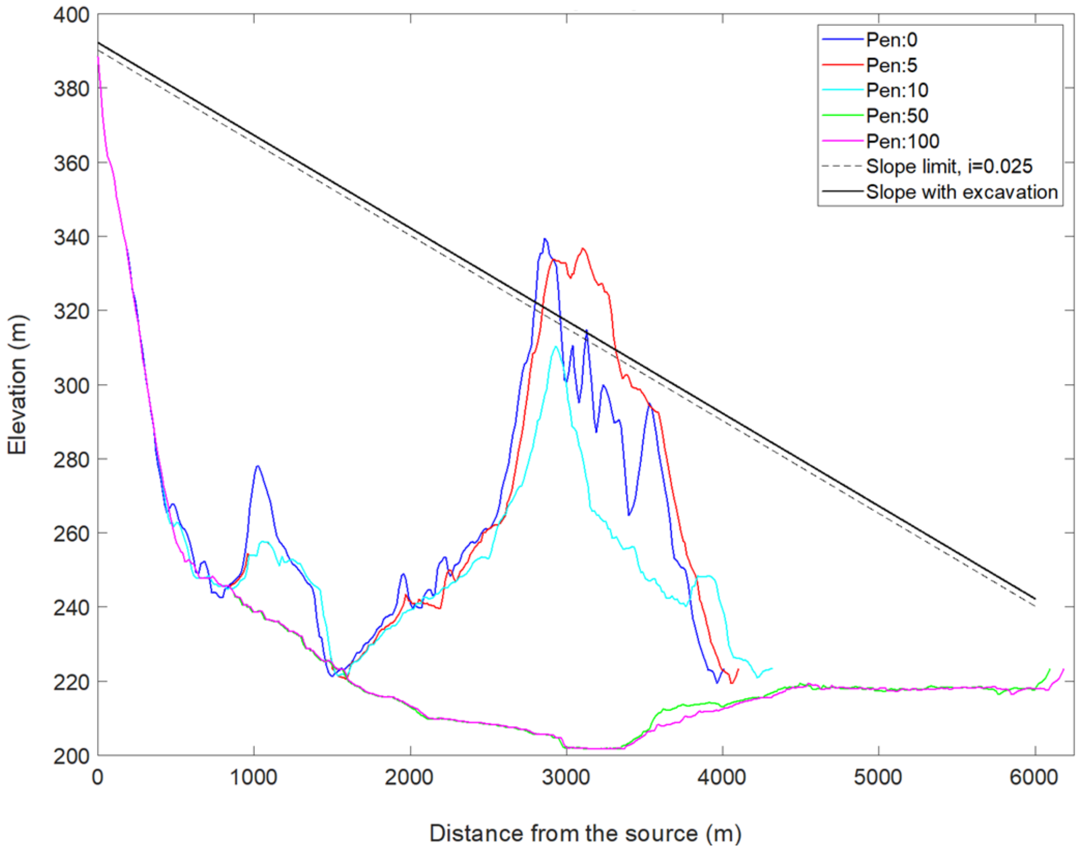

Figure 8.5.3: Section view (along the curvilinear abscissa) of the 5 geodesic curves connecting Source S3 to user U3 with the slope check curve (minimum slope).

Figure 8.5.4 shows a three-dimensional view of the constrained geodesics that connect the source S3 to the user U3. Figure 8.5.4a shows the constant slope curve following the path of the $Pen = 100$ geodesic. Figure 8.5.4b shows the constant slope curve following the simple geodesic. As for Figure 8.5.3, the curve intersects the topological surface, labelling the curve as unsuitable for the pipe route, according to the hypothesized criteria.

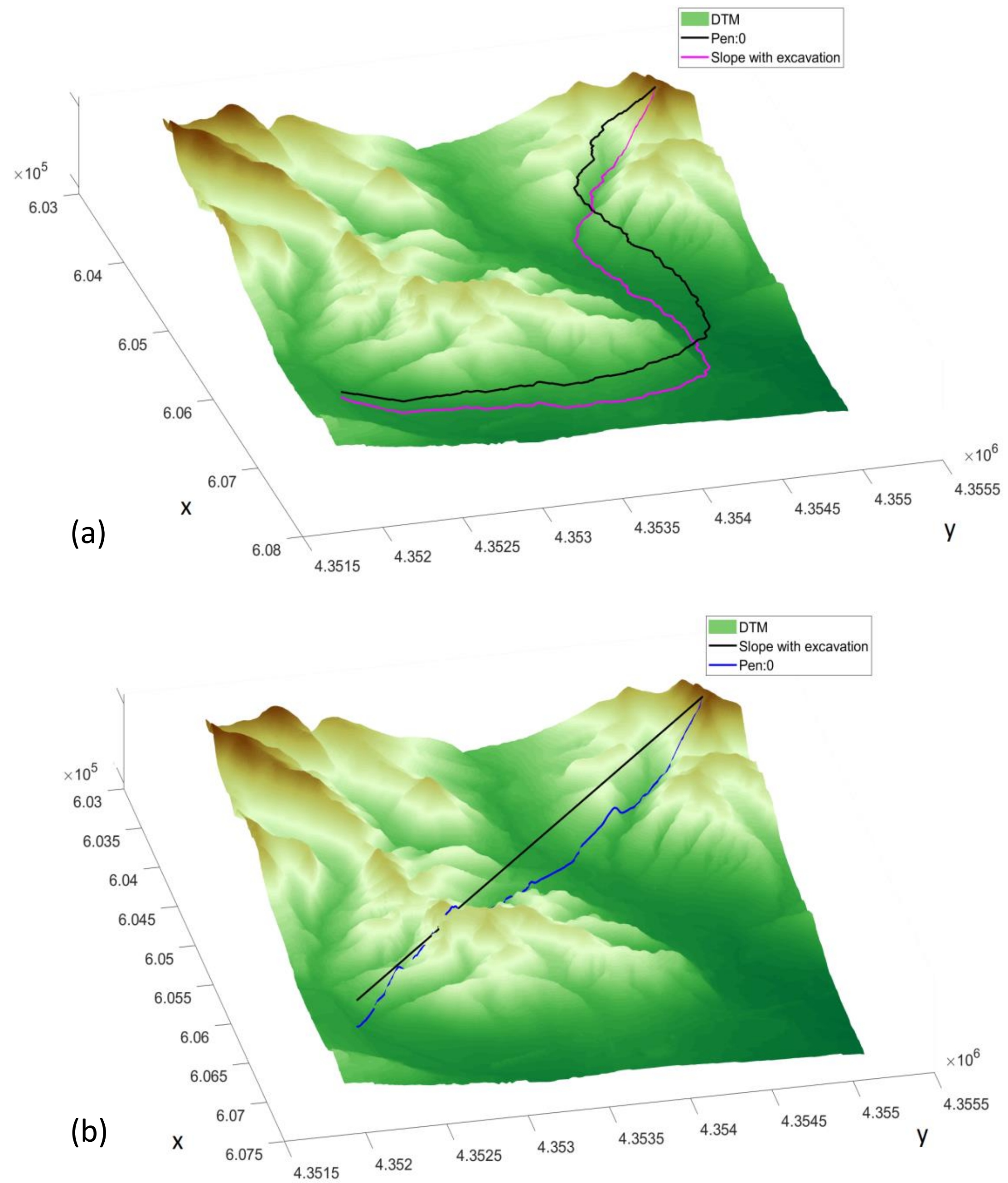

Figure 8.5.4: 3D view of an slope check for Source S3 to user U3. (a) Penalty 100 (b) Penalty 0.

Table 8.5.3 and Table 8.5.4 shows the results for the entire set of user nodes and source nodes. The table compares the constrained geodesics with the Euclidean path length. It is immediately noticeable that for the Euclidean connection, the only existence condition is that the source node is higher than the user one. In constrained geodesics, this condition is necessary but not sufficient; this reduces the number of possible connections. The use of (constrained or simple) geodesics also implies a length increase. The higher the penalty the greater is the path length increase, Table 8.5.4.

Connection matrix: Constrained Geodesic length [m]				
Source\User	U1	U2	U3	U4
S1	4351.6	1386.6	3620.7	5562.1
S2				
S3				
S4				1035.5
S5	2510.4		4316.1	3682.2
Connection matrix: Euclidean line length [m]				
Source\User	U1	U2	U3	U4
S1	4292.9	1279.1	3446.0	5241.1
S2	4211.3		5338.0	5401.3
S3	1386.7			2497.2
S4	1351.9			977.7
S5	2425.3	2527.7	3904.4	3612.2

Table 8.5.3 Algorithm comprehensive results. The possible geodesic path from each source to every user. Comparison between hydraulically constrained geodesic and Euclidean length.

Geodesic penalty information				
Source\User	U1	U2	U3	U4
S1	Pen 0	Pen 0	Pen 0	Pen 0
S2	SC*	IP**	SC	SC
S3	SC	IP	IP	SC
S4	SC	IP	IP	Pen 0
S5	Pen 0	SC	Pen 10	Pen 0
Length increase using constrained geodesics				
Source\User	U1	U2	U3	U4
S1	1.37%	8.40%	5.07%	6.13%
S2				
S3				
S4				5.91%
S5	3.51%		10.54%	1.94%
*SC: Slope check not passed. **IP: Impossible path, the source node is lower than the demand node.				

Table 8.5.4 Algorithm comprehensive results. The possible geodesic path from each source to every user. Information on the slope check and length percentage increase.

8.6 REAL CASE STUDY

The proposed methodology is applied to a real case study. The case study is the province of *Crotone*, in the *Calabria* region (Italy), Figure 8.6.1. The availability of water in this area is sufficient to satisfy the users' demand but the water distribution is unbalanced and uneven.

The analyzed area includes 27 municipalities and has an extension of 1734km^2, Figure 8.6.2. The municipality water needs are modelled as points placed in the centre of gravity of the municipal areas. The province area counts 29 springs, 3 river intakes, and 7 wells, for an overall water availability of about 1.535 m^3/s while the municipalities have an overall demand of approximately 0.923 m^3/s.

Figure 8.6.1 *Calabria* (Italy) geographical location.

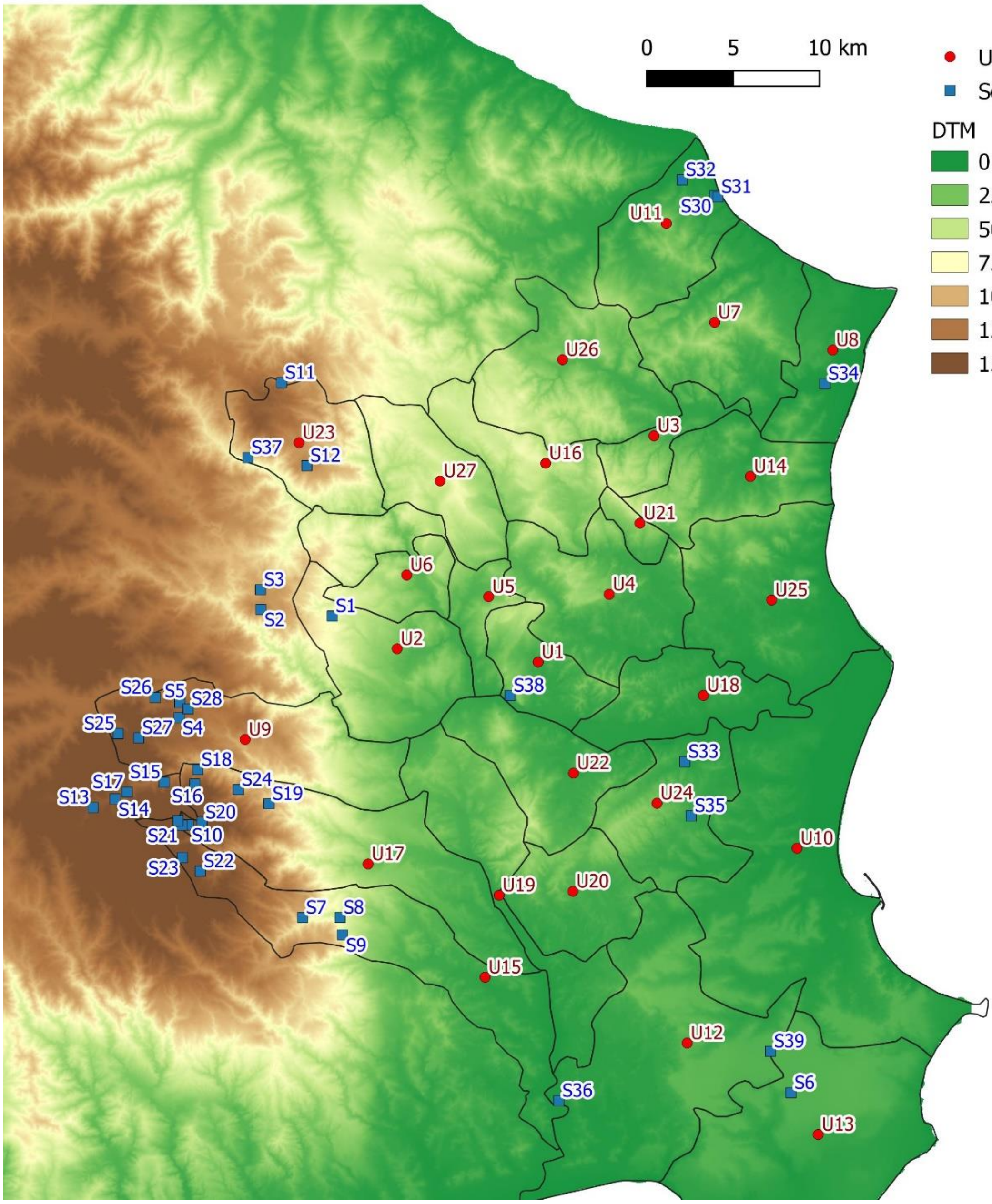

Figure 8.6.2 Case study area DTM. Water sources and users positioning. Each user point corresponds to the municipality area centre of gravity.

DTM covers an area of $4200km^2$ and counts more than 10 million square cells (20m), Table 8.6.1.

	Length/Area	Number of cells
Columns	60km	3000
Rows	70 km	3500
DTM	4200 km^2	10500000

Table 8.6.1: Case study DTM characteristics summary.

To reduce the memory occupied by the corresponding surface graph, the DTM resolution used is reduced by a factor of 2 (1/4 of the total cells, 40m). For the slope-check uses 5, identical to those of the previous case, Eq. 8.5.1. The target slope and the maximum excavation depth are set to:

$$E = 2\,m$$
$$slope_{tg} = 0.002 \qquad \text{Eq. 8.6.1}$$

Possible source/user connections

A real case application requires the use of a series of simplifications. As defined in the previous paragraphs, the application result provides a list of paths and distances to be used as input data in a resources allocation algorithm (Maiolo and Pantusa 2015, Carini *et al*. 2017, Maiolo *et al*. 2017, 2018).

A real application is unlikely to be a design from scratch of a pipe network. The most likely scenario concerns the optimization or enhancement of existing infrastructure. The hypothesis that foresees the presence of connections only between source nodes and users (star connections) does not represent the design reality. To overcome this issue the case study foresees the possibility to connect user nodes to represent more effectively a possible real configuration. The following chapters present the case study results, diversifying the connections between source nodes to user nodes and connections between user nodes.

8.6.1 Methodology application: source to user connections

In the analyzed area, 39 sources should provide water to 27 municipalities. The algorithm application involves the generation of 5 (the number of penalties chosen) cost matrices for each source. The size of the surface graphs associated with a source depends on the extension of the area that does not exceed the source elevation, Figure 8.3.1. Table 8.6.2 shows the memory consumption of the surface graph associated with the highest and lowest source nodes. The graph size of the other sources is included among these boundary values.

Source	Source elevation	Link Maximum number	Link number	Graph memory usage	Graph generating time	Total path generating time	Medium path generating time
-	m	-	-	MB	s	s	s
S24	1628	3352208	2118106	177.62	4	65.9	2.53
S31	175	3352208	65436	21.01	1	6.1	0.226
Performance refers to a Matlab code using a specific workstation (CPU: AMD Ryzen 5 3600; GPU: AMD Radeon RX 5700; RAM: 16Gb Cl16 3200mhz)							

Table 8.6.2 Constrained geodesics identification algorithm performances for the maximum and minimum elevation sources.

The methodology identifies 1053 connections between users and sources. Figure 8.6.3 shows the connection types. Of these:

- 574 paths are simple geodesics;
- 291 connections are impossible, the algorithm cannot find any geodesic curve connecting the nodes;
- 51 connections do not pass the slope test with the highest penalty.

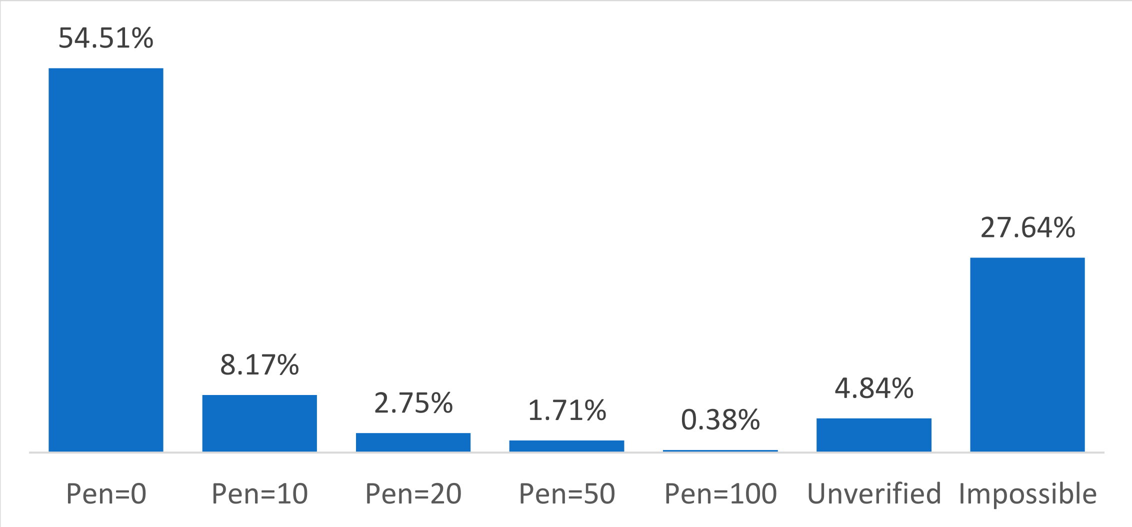

Figure 8.6.3 Source nodes to user nodes connection type histogram. Percentage of paths within each penalty class, impossible and unverified paths.

Of the 39 sources supplying the area, as summarized in Figure 8.6.4:

- 11 sources are connected to all users;
- 7 sources are not connected to any user.

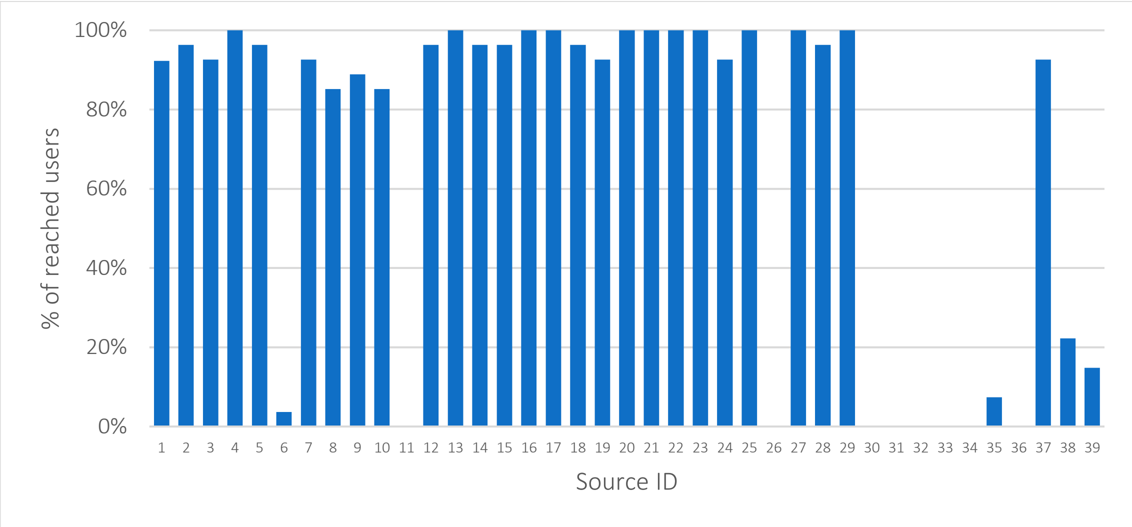

Figure 8.6.4 Sources connection degree. Percentage of reached users (for which at least a constrained geodesic passes the hydraulic test) for each source node.

On average, the sources with high elevation have a very high degree of connection. Most of the isolated sources (S11, S26, S30, S31, S32, S33, S34, S36) have low elevation or are characterized by an unfavourable plano-altimetric positioning that makes it impossible to identify a path that respects all constraints. Low-elevation sources are wells, which are excluded from the constrained geodesics identifying algorithm due to the impossibility to operate by gravity. The isolated sources are excluded. It is necessary to evaluate for which sources the exclusion is due to particular topographical conditions and for which it is due to a real impossibility of the gravity operation regime.

As it appears from a first analysis:

- The source S26 refers to an artificial basin water withdrawal. The source position prevents the identification of a descending path due to the flat lake surface.
- Source S11 is placed in a local depression. The code has excluded a priori all possible geodesic paths since the path should exceed the source altitude. The source must be moved out of the depression.

Figure 8.6.5 shows the users degree of connection. Unlike the sources degree of connection, the users one is lower but more constant. The users are connected (there is a hydraulically constrained geodesic) to about 70% of the sources. Utilities U9 and U23 have a lower degree of connection due to their higher elevation, Figure 8.6.2.

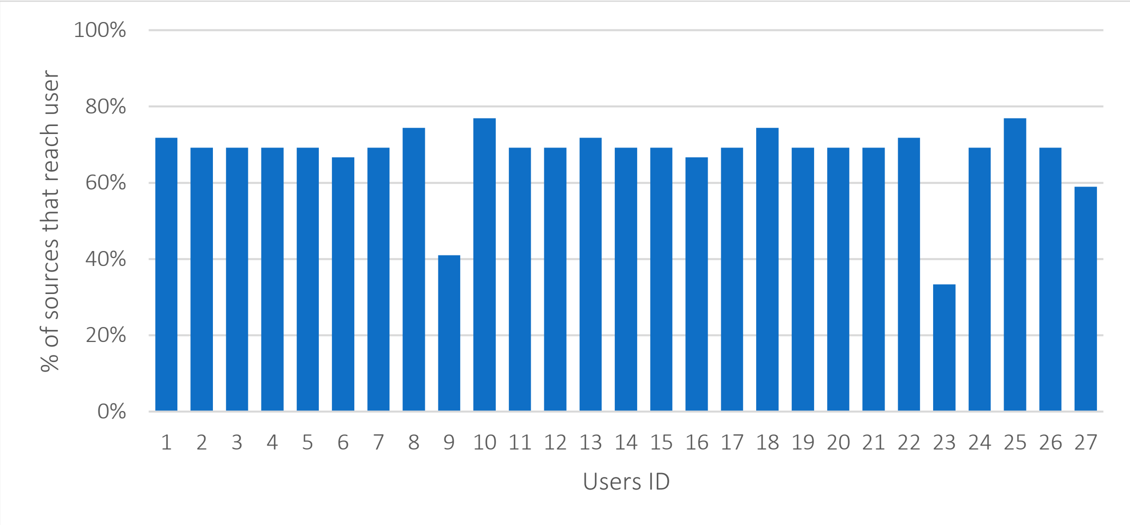

Figure 8.6.5 Users connection degree. Percentage of supplying source (for which at least a constrained geodesic passes the hydraulic test) for each user node.

Unlike the use of the Euclidean distance between sources and users, the procedure allows identifying the paths that can operate by gravity. The length of a geodesic is commonly greater than the Euclidean distance connecting two points on a surface, Eq. 8.2.4. Figure 8.6.6 summarizes the average length increase of the 711 (possible) paths obtained using simple or constrained geodesic curves, compared to the Euclidean length. More than 75% of the connections have an increase in length between 0 and 10%. The average increase is 11.1%, the maximum is 169.2%.

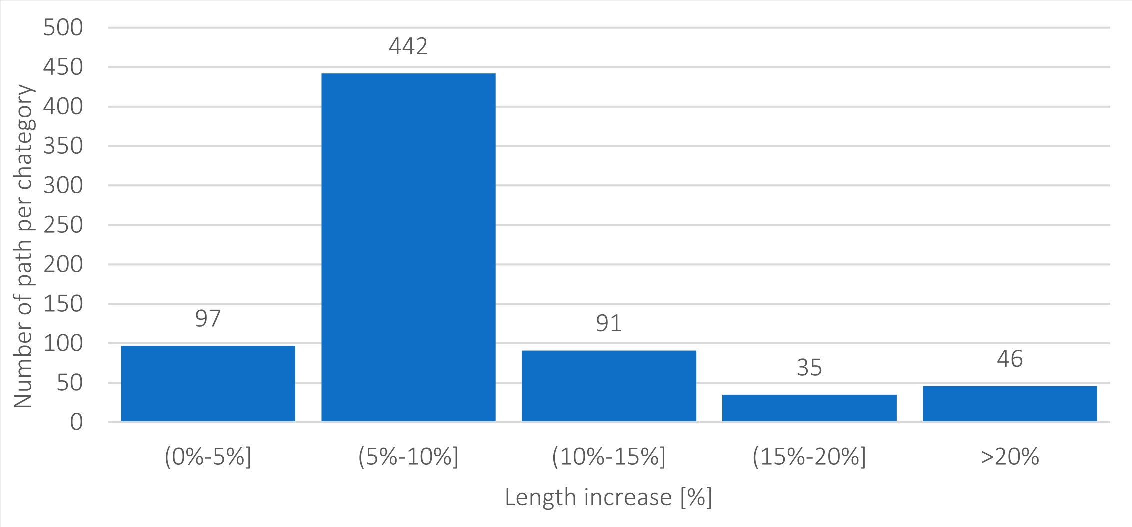

Figure 8.6.6 Length percentage increase for the possible connections (for which a constrained geodesic passes the hydraulic test) in comparison to the Euclidean distance.

8.6.2 Methodology application: user to user

The methodology is applied to model the possible connections between user nodes. To identify the connections, the users are considered fictitious sources. 729 links were identified. As shown in Figure 8.6.7. Of these:

- 127 links are simple geodesics;
- 115 links are constrained geodesics;
- 378 connections are impossible;
- 109 connections do not pass the slope test with the highest penalty.

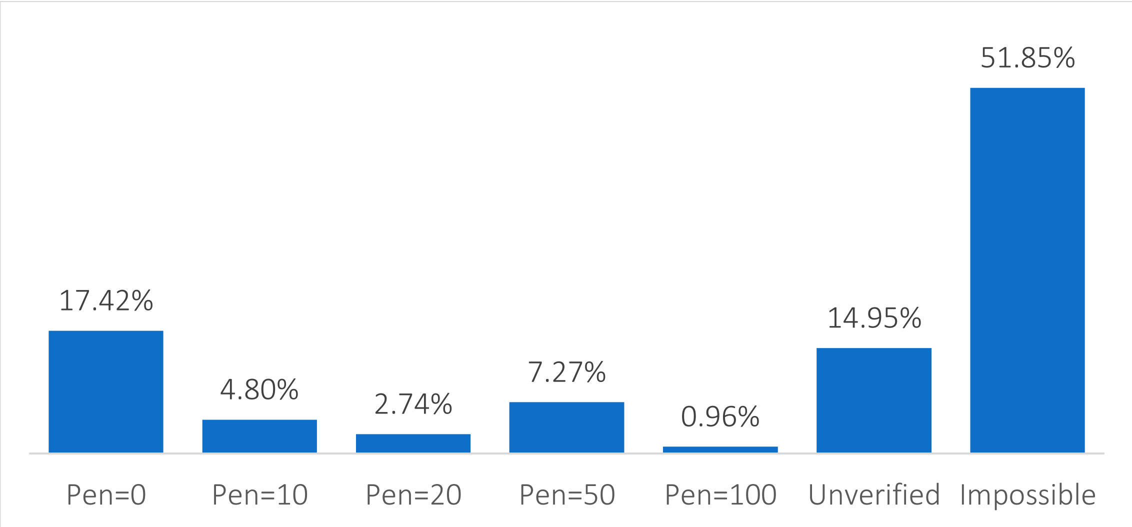

Figure 8.6.7 User-source nodes to user nodes connection type histogram. Percentage of paths within each penalty class, impossible and unverified paths.

Of the 27 users, considered as sources, as summarized in Figure 8.6.8:

- No user-sources are connected to all other users;
- 6 user-sources are not connected to any users.

The degree of interconnection of the user-sources is on average much lower than the sources one. This is mainly due to the user' nodes low elevation, which makes it difficult to identify paths that comply with the constraints.

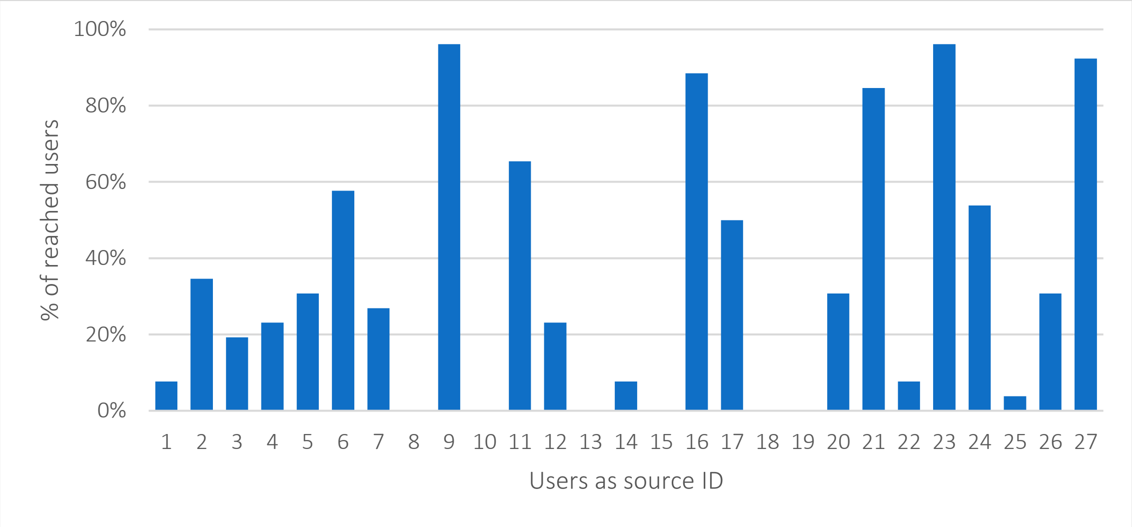

Figure 8.6.8 User-sources connection degree. Percentage of reached user for each user-source node.

Figure 8.6.9 shows the degree of connection of the users. In this case, the degree of connection is on average lower but more constant. Two of the utilities (U9 and U23, see Figure 8.6.5) are connected only to real sources due to their elevation.

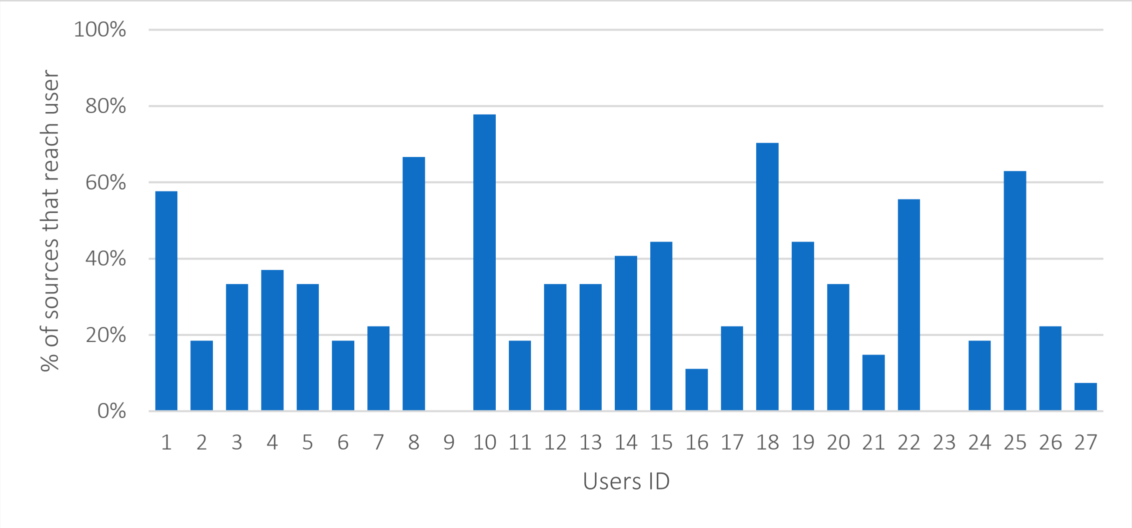

Figure 8.6.9 Users connection degree. Percentage of supplying user-source for each user node.

In this application, the procedure allowed estimating the length of the connection. Of the 729 paths, 242 (33.2%) exist and have passed the slope test. Figure 8.6.10 summarizes the average length increase in comparison to the Euclidean distance. About 70% of the path have less than a 25% length increment. The average increase is 27.4% while the maximum is 271.8%.

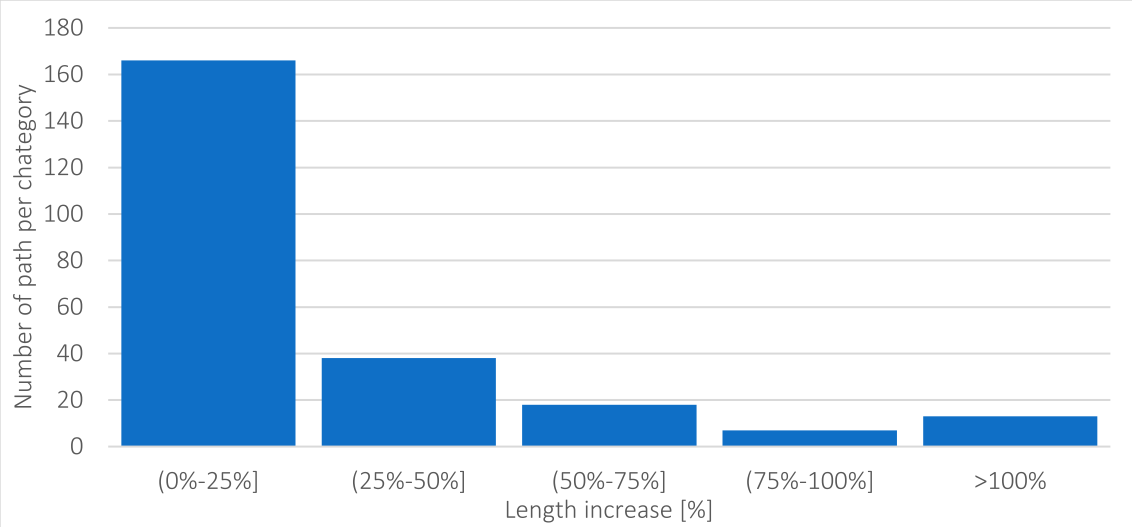

Figure 8.6.10 Length percentage increase for the possible connections in comparison to the Euclidean distance.

8.7 Considerations and future development

This chapter describes a methodology that allows identifying the shortest path that connects two points on a topological surface, under specific conditions. The algorithm provides information on the existence and the length of paths that represent pipe routes that operate by gravity. The degree of novelty of the work is linked to the improvement of the ability to represent reality.

The use of this methodology in water supply system design and optimization allows obtaining solutions that are more realistic in the subsequent design phase. The use of the methodology in a real application case made it possible to assess the effectiveness of distances estimation, comparing the geodesics and the Euclidean paths. In addition to a realistic distance estimation, which takes into account the real topography, the methodology introduces the concept of the possible existence of the connections. A methodology that does not take into account the topography considers possible (for gravity operation) all connections even with a positive elevation difference.

The methodology application encountered some critical issues. The limitations on the amount of available workstation memory dictated the necessary choices to reduce the domain size. The use of masks or functions to influence the cost of specific areas still implies an increase in computational costs, which is sometimes incompatible with the computational resources usually available.

The limitations on available resources made it necessary to use the multiple cost criterion (**Paragraph 8.4.2**). Better optimization and a possible domain parallelization can make the iterative procedure (graph generation, path identification, slope test, and possible penalty increase) feasible. The slope-check procedure, described in **Paragraph 8.3.2**, can be implemented directly integrated into the Dijkstra minimum path search algorithm. At present, the implementation needs to optimize memory consumption.

The methodology showed the ability to find the feasible connections between a set of sources and user nodes on a large scale. The hypothesis chosen for the identification of the constrained geodesics and the slope check have made the algorithm susceptible to the presence of particular topological conditions. The application to a real case, therefore, requires a phase of topology pre-processing in the areas surrounding the sources.

8.8 BIBLIOGRAPHY

- Balasubramanian, M., Polimeni, J. R., & Schwartz, E. L. (2008). Exact geodesics and shortest paths on polyhedral surfaces. IEEE transactions on pattern analysis and machine intelligence, 31(6), 1006-1016.
- Carini, M., Maiolo, M., Pantusa, D., Chiaravalloti, F., & Capano, G. (2018). Modelling and optimization of least-cost water distribution networks with multiple supply sources and users. Ricerche di Matematica, 67(2), 465-479.
- Davijani, M. H., Banihabib, M. E., Anvar, A. N., & Hashemi, S. R. (2016). Multi-objective optimization model for the allocation of water resources in arid regions based on the maximization of socioeconomic efficiency. Water resources management, 30(3), 927-946.
- Dijkstra, E.W.: A note on two problems in connexion with graphs. Numerische mathematik 1(1), 269{271 (1959)
- Kanai, T., & Suzuki, H. (2000, April). Approximate shortest path on a polyhedral surface based on selective refinement of the discrete graph and its applications. In Proceedings Geometric Modeling and Processing 2000. Theory and Applications (pp. 241-250). IEEE.
- Li, X., Wang, X., Guo, H., & Ma, W. (2020). Multi-Water Resources Optimal Allocation Based on MultiObjective Uncertain Chance-Constrained Programming Model. Water Resources Management, 34(15), 4881-4899.
- Maiolo, M., & Pantusa, D. (2016). An optimization procedure for the sustainable management of water resources. Water Science and Technology: Water Supply, 16(1), 61-69.
- Maiolo, M., Capano, G., Carini, M., & Pantusa, D. (2018). Sustainability criteria for the selection of water supply pipeline. Cogent Engineering, 5(1), 1491777.
- Maiolo, M., Mendicino, G., Pantusa, D., & Senatore, A. (2017). Optimization of drinking water distribution systems in relation to the effects of climate change. Water, 9(10), 803.
- Maiolo, M., Sousa, J., Carini, M., Chiaravalloti, F., Bonora, M. A., Capano, G., & Pantusa, D. (2019, June). Optimization Model for Water Distribution Network Planning in a Realistic Orographic Framework. In International Conference on Numerical Computations: Theory and Algorithms (pp. 545-556). Springer, Cham.
- Porazilová, A. (2007). The Geodesic Shortest Path.
- Surazhsky, V., Surazhsky, T., Kirsanov, D., Gortler, S. J., & Hoppe, H. (2005). Fast exact and approximate geodesics on meshes. ACM transactions on graphics (TOG), 24(3), 553-560.
- Zhanping W., & Juncang T. (2012) Optimal Allocation of Regional Water Resources Based on Genetic Algorithms. Journal of Convergence Information Technology (JCIT) 7(13)

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9 DECISION SUPPORT SYSTEMS AND DWSMAMI

9.0 SUMMARY

9.1 INTRODUCTION

The WDN and more generally the IWS components are considered critical infrastructures, as other energy transport systems (Monstadt and Schmidt 2019).

Modern society is heavily dependent on the reliable performance of critical infrastructures such as water, energy and transportation systems. A large number of international associations (IWA, EWA, UN, etc.) recognizes as a priority the water resources saving and the systems proper management. The identification of new sources and the interventions aimed at increasing resource availability is not a sustainable management strategy. The improvement interventions should aim at modernization of management strategies and infrastructures, often outdated and in a bad state of conservation. The level of complexity that characterizes drinking WDN and the interdependence with other critical infrastructures (Shuang *et al*. 2014), makes modernization a challenge, which requires innovative techniques (Lo *et al*. 2020).

Tools such as Decision Support Systems (DSS) can prove to be very useful to support modern and advanced management (Aiello *et al*. 2018). DSS aim to increase the effectiveness in decision-making processes, presenting and processing data and information to make them immediately available to those who access decisions. A DSS is a system that creates an interactive bond between users and the resources (e.g. data, models, documents) (Power and Sharda, 2009). These tools are support systems and do not have the objective of replacing the responsible subjects with autonomous and automatic decisions.

The DSS support the decision-maker in the evaluation of alternative strategies and scenarios. A DSS must be versatile and modular, as it should adapt to different situations and areas. The growing use of DSS for water systems management depends on several factors. The implementation of complex support systems is becoming simpler and more cost-effective thanks to scientific advances and innovation in ICT and data and information management (Capano *et al*., 2016). International associations underline the need for integrated and advanced management, and local and European legislation directs towards the use of such solutions.

In the context of the management of water systems, a DSS can involve various design and management aspects. It can support the WDNs design or the management (modernization, monitoring and management of the operating regime). An advanced management model must include an integrated vision of the objectives to be achieved and a coordinated approach of the subjects involved in management and design (Capano *et al*., 2016).

In recent years, the development of water systems management DSS has produced several solutions, which differ in approach, modelling and scope. Most of the available solutions deal with the management problem at the water system scale.

Delpla *et al*. (2014) propose a DSS with a small to medium application scale. The solution is called *ARTEM-WQ* (AwaReness Tool for the Evaluation and Mitigation of Drinking Water Quality issues deriving from environmental changes). *ARTEM-WQ* has a sequential risk analysis approach. It provides a holistic assessment of the water system while assessing the potential risks to human health.

The solution proposed in Westphal *et al*. (2003) is based on hydrological modelling, hydraulic reservoir modelling, and water quality assessment. The DSS allows aggregating, managing and exploiting climatic, hydrological and hydraulic information. Data analysis enables the production of accurate predictions of the hydrological system variables. This DSS can develop optimal operational programs in real-time and trade-off studies to examine various system targets.

Sechi and Sulis (2007) present *WARGI* (Water Resources system optimization aided by Graphical Interface). WARGI analyzes complex water systems in different scenarios. The DSS consists of an optimization module and a simulation one. The first uses hydrological and demand scenarios to characterize the decision variables adopted in the second module. These models outputs are useful for defining optimal operational strategies.

Islam *et al*. (2016) present a DSS for prognostic and diagnostic analyses of the water distribution system. The modelling allows assessing the reliability, the loss potential, and performing the water leaks localization and the water monitoring. The DSS incorporates hydraulics and water quality models.

Grimaldi *et al*. (2020) present *MC-SDSS* (Multi-criteria Spatial Decision Support System). The DSS supports the water systems economic management. The system prioritizes the interventions in terms of investment through an index that takes into account the regulatory directives.

Some DSSs have a more specific scope. Karavokiros *et al*. (2020) present *Hydronomeas*. The DSS focuses on WDN-scale management. *Hydronomeas* is based on parameterization, simulation and optimization, also studying the interaction between water flows and energy.

Fischer *et al*. (2017) present *tDSS* (tapes Decision Support System). The DSS has a more specific scope than the previous ones. *tDSS* manages the information on Contaminants of Emerging Concern (CECs), the assessments of physical/chemical characteristics, regulatory values, presence of criticalities, identification methods and risk mitigation strategies.

Boelee *et al*. (2017) present *LiSS* (LUAS "Lembaga Urus Air Selangor") which is an operational forecasting tool for monitoring tank levels. *LiSS* consists of modules that process the observed and forecasted data, estimate the tank supply and level, and provide warnings in case of criticality.

Ribeiro *et al*. (2015) present *iWIDGET* (Improved Water efficiency through ICT for integrated supply-Demand side manaGEmenT). The goal of *iWIDGET* is the promotion of energy-efficient use behaviours between end-users and managers. The DSS analyses data from smart water to extract information and processing in near-real-time.

Not all the summarized DSS solutions are characterized by modularity and scalability. Some of the solutions are case-specific, which makes them difficult to generalize.

9.2 DWSMAMI AND ORIGAMI

The innovative industrial PhD project "*Drinking water supply modelling for Advanced Metering Infrastructures*" (DWSMAMI) aims to create WDN models for the management to be integrated into a DSS management framework. The PhD project is part of a larger scope, integrating itself into the objectives of the origAMI research and development project. The name chosen for the project, origAMI, is a “pun” for *Original AMI*, in which AMI stands for Advanced Metering Infrastructure. OrigAMI is an integrated and multi-platform software system for modelling, monitoring and control of water distribution systems. It offers, in a single application, technical and management tools for network administrators and end-users.

DWSMAM is located in different thematic areas and trajectories defined by the “*Strategia Nazionale di Specializzazione Intelligente*” (National Strategy of Intelligent Specialization) and was co-financed by the *Ministero dell'Istruzione, dell'Università e della Ricerca* (Ministry of Education, University and Research (MIUR) and by the *Fondo Sociale Europeo* (European Social Fund) (FSE). The doctorate is hosted by the *University of Calabria* (UNICAL) (Cosenza, Italy) and includes periods of collaboration with the *Instituto Politécnico de Coimbra/Instituto Superior de Engenharia de Coimbra* (IPC / ISEC) (Coimbra, Portugal) and the company *NTT DATA Italia SpA* (Milan).

OrigAMI was developed in an Italian Regional Project (POR CALABRIA FESR 2014-2020) - Innovation and Competitiveness (I&C) [J48C17000170006] (01/12/2017-31/07/2019). The project is part of a funding line that supports the implementation of complex projects of research and development activities on relevant thematic areas, identified by the *Smart Specialization Strategy* (S3) of the Calabria Region and compatible with the national (*“Agenda Strategica Digitale”*, Strategic Agenda Digital, (AgID)) and international (INSPIRE Directive (2007/2 / CE)) lines of intervention.

The PhD and the origAMI research project intended to promote the application of technological solutions to increase the level of innovation in the S3 thematic areas, rewarding the collaboration between companies and research institutions. The partnership of the origAMI project includes *NTT DATA Italia S.p.A.*, the *Research Group of Sustainable Management of Water Resources* (GSRI) of the *Dipartimento di Ingegneria dell’Ambiente* (*Department of Environmental Engineering)* (DIAm) of UNICAL and d&m (design&multimedia, for the communication activities of the project).

9.2.1 THE FRAMEWORK

OrigAMI is a platform designed for managers of drinking WDNs, who want to equip infrastructures with advanced monitoring systems (Smart Metering). It provides compatibility with existing SCADA and enables the implementation of AMI.

The use of extensive near-real-time readings makes a large amount of data available to the WDN manager to improve management operations. The use of AMI allows improving data collection and transmission procedures and integrating them with automated analysis and hydraulic modelling procedures. The integration of processes allows improving management and service efficiency (Maiolo *et al*. 2019).

The platform works completely on-cloud and has WEB-GIS characteristics. It incorporates a hydraulic solver and GIS functionalities that use the network digital model. The model contains information on the topology and all the constituent elements.

The platform can integrate a water consumption forecast to model the daily demand curves, anticipating peaks and showing any operating regime anomalies. The demand-forecasting model, the predictive maintenance, and the smart meters communicate continuously with the platform.

The platform is designed to be multi-tenant. Different organizations and subjects can only access the information levels of their scope; administrators, technical staff and end-users use the same platform. Users can access the functions and information of their scope thanks to a system of credentials and permissions.

There is no universally recognized DSS classification. Power and Sharda (2009) present a DSS classification:

- **Communications-driven:** facilitate problem-solving by providing collaboration tools for a group of decision-makers;
- **Data-driven:** focus on data analysis and organization. These DSS provide tools for accessing and manipulating large databases of structured data (i.e., time series) ;
- **Document-driven:** support managers in handling and organizing unstructured documents and web pages;
- **Knowledge-driven:** provide support in the decision-making stages by suggesting possible solutions or actions. These DSSs presuppose specialist knowledge in particular domains;
- **Model-driven:** focus on the manipulation of a quantitative model. They provide simple analysis tools to support decision-makers.

OrigAMI provides tools for the analysis, organization and classification of data from the AMIs and specialized tools to support the management decisions of the infrastructure. The DSS can be classified as data-driven and knowledge-driven.

The platform aims to provide support tools for various management aspects. The main features and tools that constitute it are listed below:

- DSS in a BIM (Building Information Modelling) and GIS (Geographic information system) environment.
- Integration with hydraulic modelling software (EPANET);
- Technical and management tools for designers, network administrators and citizens;
- Priority-driven predictive maintenance (in terms of cost, impact, feasibility), prediction of failures, losses and interception of fraud;
- Consumption remote reading (user profiling, demand curve, billing automation);
- Monitoring interface with near-real-time warning and remote control;
- Modular and extensible design.

DSSs are composed of four main components (Power and Sharda 2009): user interface, database, models and analytical tools, DSS architecture and network. Each of these aspects is discussed in the next paragraphs. **Paragraph 9.3** investigate the framework structure by defining the DSS architecture and structure. Paragraph provides an overview of the DSS modules. **Paragraph 9.3.1** defines the operating logic, examines the relationships between the modules and describes the DSS links with the infrastructure, the meters and the parties involved. **Paragraph 9.4** explores the forecast models. **Paragraph 9.5** summarizes some aspects related to implementation and prototyping.

9.2.2 COMPONENTS

origAMI is structured to be able to manage the aspects that characterize WDN management, maintenance and monitoring. The platform core collects, organize and manage SCADA and AMI system data. The framework includes economic and maintenance capabilities. A framework that includes various management tools while maintaining the predisposition to add further ones requires a development based on modularity and scalability.

origAMI has a modular structure. Each module contains several controllers and allows managing one or more aspects. Controllers allow performing actions and managing specific aspects.

Some modules can be replaced or excluded for particular applications. For example, a manager could have a local solution for economic management. The possibility of excluding the economic module, and possibly adapting the proprietary software, would make the solution more organic and less impactful in overall management.

OrigAMI counts 8 main modules:

1. *Water Network Management,*
2. *Zone Analysis*
3. *Device Manager*
4. *Event Manager*
5. *IdroAnalitcs*
6. *Billing Manager*
7. *BIM Manager*

Water Network Management

Water Network Management is the framework core module. It manages element data (nodes, pipes, ...) and the network topology (network). The module organizes the network into districts. *Water Network Management* also manages the hydraulic simulation settings and execution of the EPANET simulation engine. The module contains 4 controllers:

- ***Network controller:*** is the main controller. It manages the network topological aspects. It allows importing the network component characteristics and topology from EPANET (parsing the .inp file);
- ***ParameterController:*** manages and stores the hydraulic simulation parameters, and acts as a simple registry service. The controller returns the list of supported parameters, together with their data type, boundaries and default values;
- ***SimulationController:*** manages the hydraulic simulation, the history and saves the simulation reports;
- ***AnalysisController:*** retrieves the element statistics and failure predictions, to make them available for viewing and querying.

The integration of the smart meter real-time data (*Device Manager*) and the forecasts (*Idroanalitics*) into the network model allows obtaining continuous hydraulic simulations. The platform has a dedicated interface for the hydraulic operating regime of the network.

Zone Analysis

Zone analysis defines the network logic districts on which calculate the relative performance indices (risk, sustainability, reliability). The module provides a tool to assess performance indices or Key Performance Indicators (KPIs).

The module has two controllers:

- *Zone Controller*: deals with the network partitioning into logical zones, aggregates the information and calculates the indices and KPIs. The subdivision uses imported files that describe the zones boundaries;
- *Function Controller*: enables the construction of custom functions. It allows system users to add custom indices or KPIs without requiring the intervention of the system developers.

Indices and KPIs become part of the DSS interface. Each manager can implement the indices and KPIs that deems most useful and significant. These indicators can have a very simple structure: maximum and minimum pressure during the day, maximum daily pressure variation, daily water consumption, the ratio of maximum flow to average daily flow, etc. The module can calculate complex indices that represent the network resilience (Todini 2000; Prasad and Park 2004; Di Nardo *et al*. 2011), pressure indices (Di Nardo *et al*. 2015) water flow deficit (Di Nardo *et al*. 2013; Di Nardo *et al*. 2014a, 2014b). The framework presented in Caldarola and Maiolo (2019) and detailed in Bonora *et al*. (2019, 2020a, 2020b) allows simplifying the implementation of local or general indices.

Device Manager

The Device Manager manages the network smart meters by adding or modifying the characteristics of the devices (digital twin). The module manages and stores technical information on all installed devices. It allows access to readings, measurements, and device status data. It connects the network elements to the smart meters. OrigAMI supports bidirectional communication but the implementation logics, automatic or semi-automatic, depend on the devices remote control predisposition.

Event Manager

The Event Manager manages the failures and anomalies reports, or more generally the events concerning the network, to notify any event to the entities concerned. For the decision support, it can send notification for specific events or series of events that allows you to report situations of interest in near-real-time.

Each *Event* consists of:

- Category;
- Entity concerned (e.g. System, Profile, User, Operator);
- Date;
- Description;
- Importance.

Each *Notification* consists of:

- Event to which it refers;

- Receiver (System, Profile, User, Operator, etc…);
- Creation date;
- Status (Sent/not sent, read/not read).

The manager aggregates and harmonizes the information made available by other systems. Set of notifications (maintenance alerts) can be related to a single work order, redirecting the results on the Work Force Management (WFM) systems, based on the number/type of notifications, their geolocation and the time in which they were sent.

Event Manager contains two controllers:

- *EventController*: enables CRUD (create, read, update, and delete) functionality for Event objects. The controller functionality is therefore purely for event storage;
- *NotificationController*: processes the events stored by the *Event Controller*, according to a logic defined by the manager, generates and sends notifications to the interested parties. The goal to be achieved is to be able to notify, almost in real-time, events of interest that may require quick intervention to minimize any damage to the network or inefficiencies.

IdroAnalitics

The *IdroAnalitics* module processes water measurement data to provide demand forecast curves. The module uses a forecasting model based on Artificial Neural Networks (ANNs) (See **Paragraph 9.4**)

Water Management Network uses the forecasted demand curve for the hydraulic simulation. *IdroAnalitics* retrieves consumption metering data by collaborating with the *Device Manager* module. In origAMI, Data Mining techniques based on deep machine learning (Deep Learning) are used to manage the amount of data from smart metering for the prediction of the demand curve or the functioning anomalies identification (e.g. failures and breakages).

Profile Manager

origAMI is enabled to manage the economic aspects related to the WDN administration. Rate, billing and customer management require a set of tools not commonly implemented into water system related DSS. The *Profile manager* module includes all the services to enter and retrieve information on contracts, utilities and customers. To manage billing-related services, the *Billing Manager* must communicate with the *Profile Manager*.

In economic management, the platform characterizes a user by distinguishing "*Profile*" and "*User*". The Profile represents a natural or legal person who can be the owner of one or more Utilities. The Profile contains personal data. The User, on the other hand, contains information on the Contract and details on the service. Each Profile is associated with one or more *Users* through a customer code.

Profile manager contains three controllers:

- *Contract Controller*: enables the CRUD functionalities for commercial contracts. This information allows the *Billing Manager* to show the invoices relating to a specific contract;
- *Supply Controller*: enables the CRUD functionalities for the contracts relating to a specific User. The *Billing Manager* module needs to communicate with the *Supply Controller* to return particular User invoices;

- ***Customer Controller***: Enable CRUD functionality for customers. This controller takes care of the communication with the *Billing Manager* for the consumption accounting and the invoices management.

Billing Manager

The *Billing Manager* module interfaces with the *Profile Manager* for the issuance of new invoices and the recovery of past ones. The *Billing Manager* deals with the calculation and validation of the rate according to the indications and regulations implemented by the manager.

The service is divided into two controllers:

- ***Rate Controller***: enables the rate calculation and verification (based on the constraints imposed by current legislation);
- ***Invoice Controller***: calculates and issues the invoices.

BIM Manager

BIM Manager allows importing and exporting the network digital model. It defines the data formats supported by the platform and allows the conversion between them. BIM is a model-based process that allows professionals to plan, design, build and manage facilities and infrastructures more efficiently (**Chapter 2**). The module is compatible with BIM exchange format (.ifc), EPANET format (.inp) and GIS vector (.geojson).

DSS framework layout

The DSS must connect the physical components of the network (meters) to the modules and controllers of the management software. The platform is developed in different overlapping informative layers that connect the WDN physical components to the software. The WDN is equipped with a network of smart meters that provides near-real-time data. The data is processed and stored in the cloud infrastructure.

Figure 9.2.1 clarifies data flow to/from the platform. Starting from the bottom:

- ***Physical layer***: This layer consists of the sensors connected to the physical components of the network. In addition to the network of smart meters, the platform is compatible with existing SCADAs;
- ***Wrapper layer***: The Wrapper layer is responsible for communicating with systems, modules and devices external to the platform. It represents the "digital" border. This layer enables the data exchange with the outside world. The function of the wrappers is to standardize the data model and allow bidirectional communication;
- ***Middleware layer***: this layer collects and standardizes the data coming from the underlying layers or the processed data from the upper ones. The main modules are:
    - ***Data gathering/encoding***: collects meter data and standardizes them. The presence of the wrapper layer makes the platform agnostic from the communication protocol/data format;
    - ***Notification System***: manages existing notifications and allows defining new ones. Implement notification management logic (i.e.aggregation and distribution rules);
    - ***Caching***: collects the data necessary for predictive business logic, which typically requires quick access to information;

- ***Digital twin manager***: contains metadata with information on measurements and data on device characteristics;
- ***Gateway manager***: manages any gateways that convey data from devices and systems that do not publish directly via the network (i.e., SCADAs).

• ***Business layer***: groups together the modules necessary to satisfy the development functional requirements. Includes support services for data management modules:
  - ***Data Store;***
  - ***Data Elaboration;***
  - ***Data Visualization.***

• ***Web Console and the mobile APP***: is the access points for the services offered by the platform. *Web Console* interacts with the rest of the platform to retrieve information to be shown to users. The information and processing are organized into sections that group different functions. The main modules are:
  - ***Hydraulic model***: allows the integration of hydraulic models, interfaces with storage to retrieve data on assets and use the simulation engines;
  - ***Prediction***: is responsible for consumption predictive models;
  - ***What-if analysis***: enable the platform to conduct what-if analysis, facilitating the management;
  - ***Decision Support***: offers support for the interventions and maintenance planning. It, therefore, aggregates all available information to support asset and workforce management.

A ***Vertical layer*** supports the other layers. It provides tools and services, such as

- ***Identity Manager***: manages identity and access through single log-in;
- ***Message Broker***: ensure the safe and reliable sharing of data between multiple services;
- ***Security***: define standard security protocols for data transmission (eg: SSL).

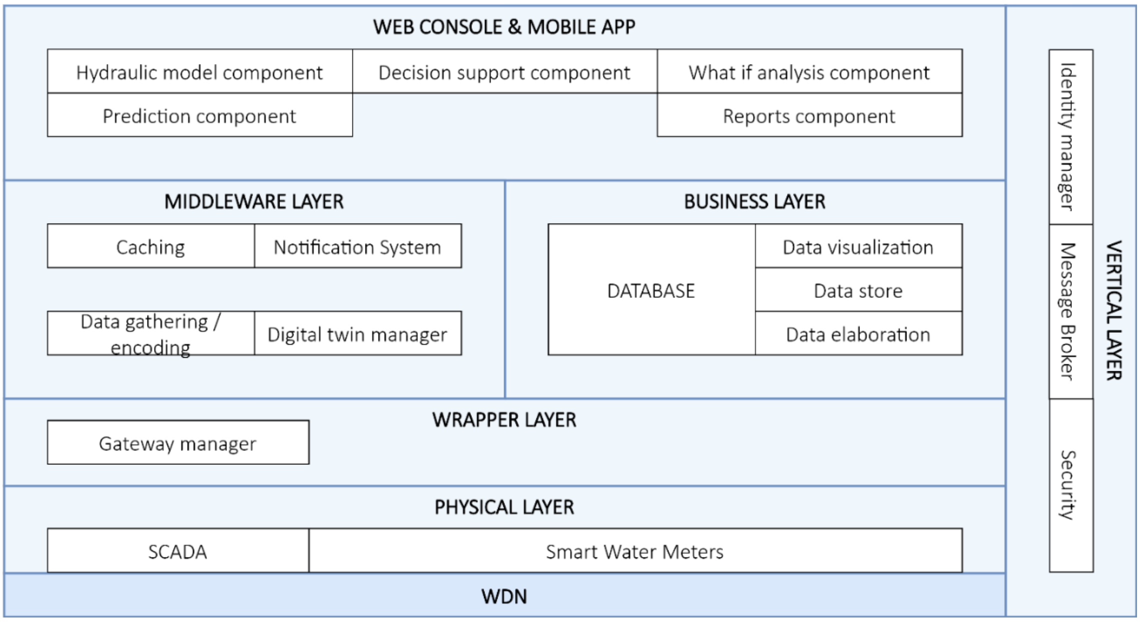

Figure 9.2.1 Information structure diagram.

Identity Manager

The platform provides a single access point for different users. There are different roles with different permissions and different levels of access to the information stored on the platform. The information relating to monitoring and warnings must be managed only by a few users legally authorized to do so. *Identity Manager* manages the user identities allowing access only to the information and features of their competence. The framework users can fill three roles:

- The ***Manager*** deals with the administration and management of one or more Networks. This role must have permissions that allow accessing all information, modifying the Network, and the roles assigned to other users;
- The ***Operator*** can operate on the network or the end-users and can be specialized in several sub-roles:
  - ***Technician***: specialized users and the workforce that operates on the network and must be able to view the information necessary for the interventions;
  - ***Administrative***: deal with the company administration and manages the water network distribution service;
  - ***Accounting***: users that take care of the accounting, billing, and end-user invoices.
- The ***User***, divided into *Profile* and *User*. (See Profile Manager)

9.3 ORIGAMI ARCHITECTURE

OrigAMI DSS is a complex platform that has a modular structure. Each module (*Manager*) manages a specific set of aspects and is divided into specialized controllers (**Paragraph 9.2.2**). The modules and controllers communicate and exchange information to operate. Figure 9.3.1 and Figure 9.3.2 schematizes that set of rules and relationships. The figures divide the origAMI *Managers* and *Controllers* into elementary blocks. Each block represents a simple element or function. In the diagrams, the arrows express the direct dependence of the block from one or more superordinate blocks (e.g. the *Demand monitoring* enables the *User bill computation,* Figure 9.3.2).

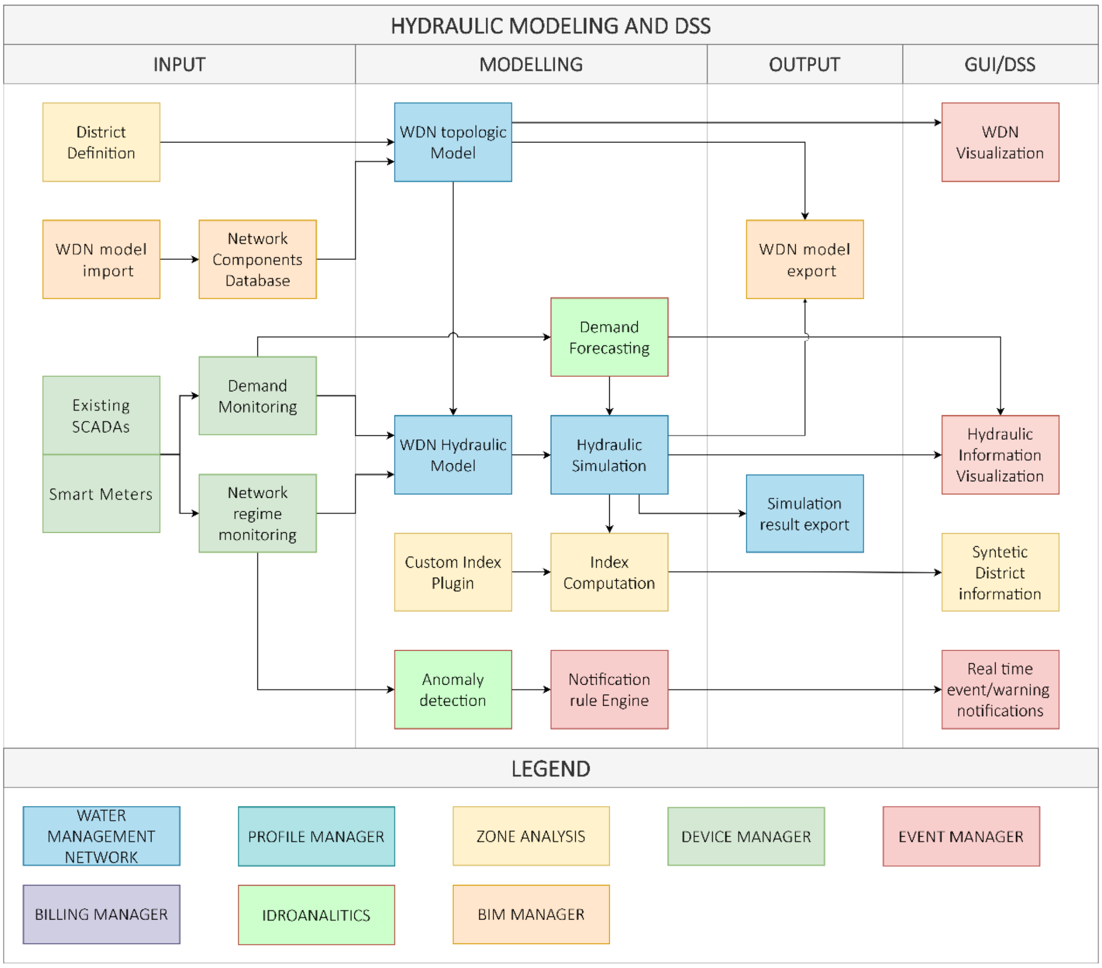

Figure 9.3.1 origAMI platform structure, Hydraulic modelling and DSS.

Figure 9.3.1 and Figure 9.3.2 are organized according to two criteria. The belonging of the blocks to a *Module* is coded by colours. The eight main origAMI managers correspond to eight block groups. Figures legend code the colour-*Modules* relationship.

The platform receives the data collected, processes them and provides outputs (e.g. reports, analysis documents) and graphic outputs. The figures organized the blocks into four macro-categories: *Input, Modelling, Output and GUI/DSS* (Graphic User Interface). The diagrams follow a horizontal logic that describes the data input (I*nput*, left), processing (*Modelling*, centre) and the output of the results (*Output* and *GUI-DSS* right). Based on the function it performs, each block has been positioned in one of the categories.

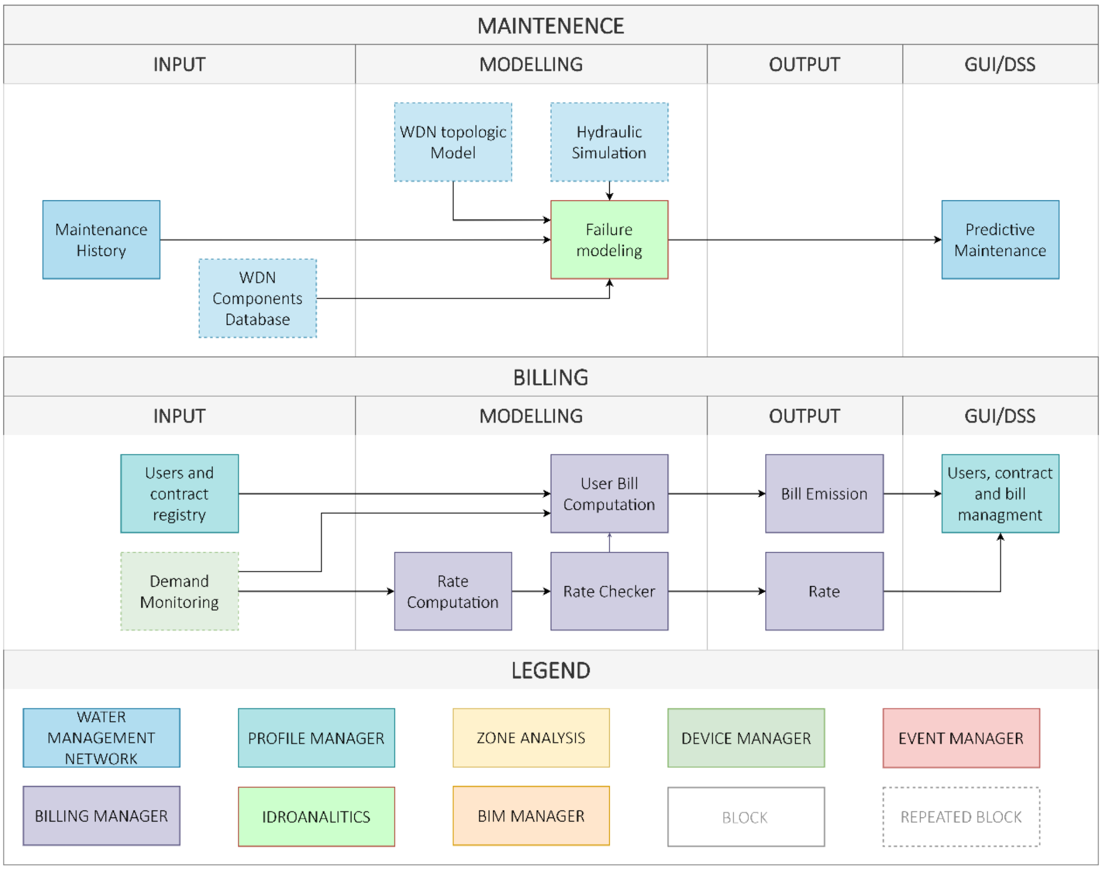

Figure 9.3.2 origAMI platform structure, Maintenance and Billing.

The platform can be conceptually divided into three macro-blocks: *Hydraulic modelling and DSS* (Figure 9.3.1), *Maintenance* and *Billing* (Figure 9.3.2). To simplify the diagram structure, some blocks are repeated. These blocks are shown in transparency in the macro-blocks to which they do not belong.

- ***Hydraulic modelling and DSS*** is the core macro-block. It contains *Water management network*, *Zone Analysis*, *Device manager*, *Event Manager*, *BIM Manager* and uses the forecasts from *Idroanalitics*. It deals with data collection, import and management in the network model, hydraulic modelling, performance indices assessment, and the warnings and notifications generation;
- ***Maintenance*** manages the predictive maintenance part of the *Water Management Network*. It uses the network model, the simulation outputs, and the *Idroanalitics* output (i.e., anomaly identification).
- ***Billing*** manages all aspects relating to the rate calculation, consumption assessment, and the issuance of the invoices. It contains *Billing Manager* which uses the readings detected by the *Device Manager* to assess the overall consumption to be billed to end-users.

9.3.1 PLATFORM USER INFORMATION FLOW

The platform is designed to be used by different users with different tasks. The I*dentity manager* manages the information content that each user can access. The users who can access the platform are divided into three categories, the *Manager*, the *Operators* and the *Users* (See **Identity Manager**). The *Operators* deal with the management of specific aspects and have access to advanced features. *Users* have an interest in accessing only personal information (bills or scheduled interruptions). origAMI is designed for both top-down and bottom-up exchange of information. *Users* can report issues, providing additional information to *Technicians* and *Managers. W*orkers can inventory the intervention and update the network model (i.e., topology and device characteristics). The ability to automate notifications and warnings contributes to the improvement of the WFM. The presence of special interfaces supports WFM and simplifies the organization of the workflow.

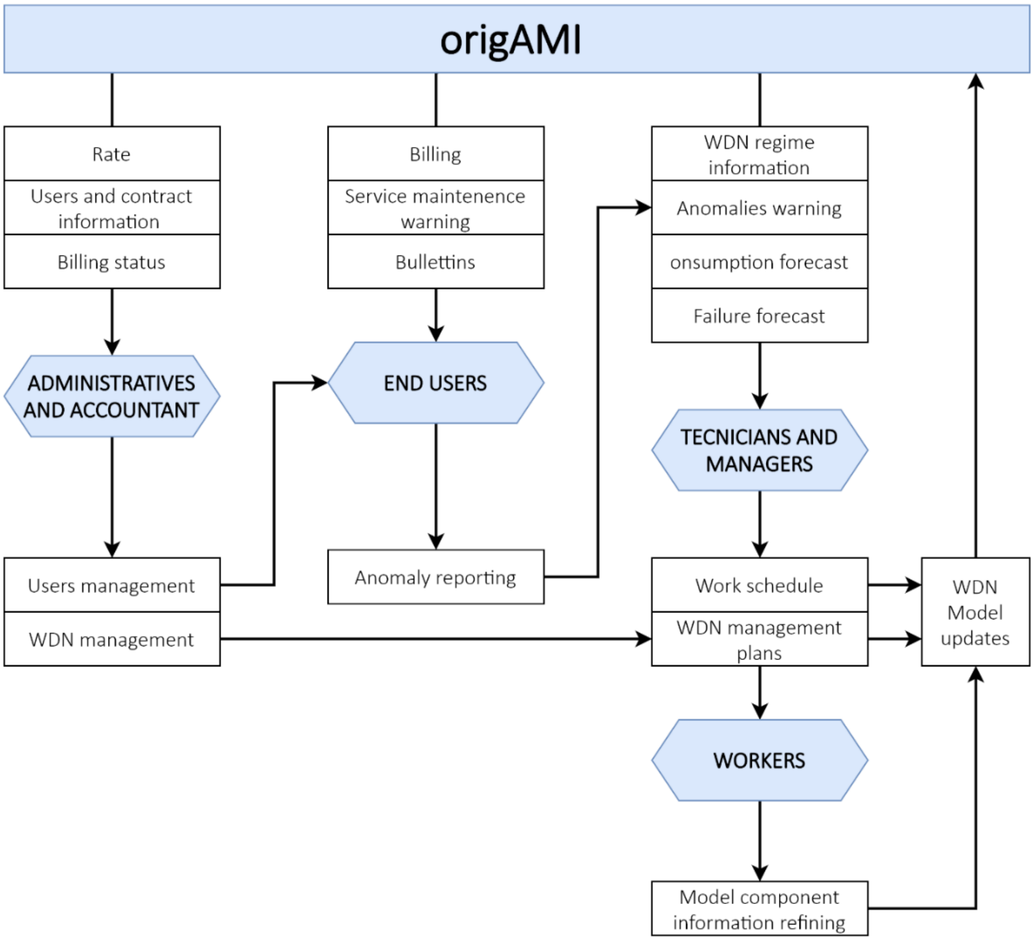

Figure 9.3.3 Information flow between platform users in origAMI

Figure 9.3.3 schematize the flow of information between the various parties involved in the WDN management and use. In the flowchart, arrows describe a passage of information; white rectangles enclose the exchanged information, while light blue hexagons represent the users. The DSS, located at the top, makes the information available to *Administrators*, *Operators* and *Users*.

The knowledge of the hydraulic operating regime and the consumption forecast enables *Operators* to make preventive management decisions. The failure detection supports the maintenance organization and reduces reaction times. The scheme involves the *Administrative* staff that deal with the management of the financial aspects and the management of the network. The *Accounting* staff and the platform communicate with the *Users* about the issue of notices and invoices. *Users* are implicitly involved in management, as they can report local issues and malfunctions. The *Users* and the field *Technicians* reports collaborate in the management of the WFM.

The *Technicians* and *Operators* who act directly on the network have the task of keeping the model updated, communicating and inventorying interventions, changes in element characteristics or topology, new meter devices, etc...

origAMI improves and organizes data collection for billing purposes, shortening the calculation and issuing times of invoices. Having the ability to manage and view information on *Users* and contracts, the *Manager* and the *Accountants* can use a single and automated platform for economic management.

9.4 WATER DEMAND AND FAILURE FORECASTING MODELS

origAMI *Idroanalitics* provides predictive tools to support DSS functions. The platform manages the data coming from the AMI meters. Data management uses data mining techniques. Data mining refers to a series of techniques for analyzing large amounts of data (bigData) to recognize intrinsic connections and significant patterns (recurring models).

The project involves the development of a model for predicting the end-user demand curve, and a model for the detection and identification of anomalous scenarios (e.g., failures, breakages).

The demand prediction model aims to predict the temporal trend of water consumption. Forecasting can support routine management manoeuvres decisions. The identification of anomalies identifies anomalies in the parameters detected and promptly report them to the subjects involved.

9.4.1 WATER CONSUMPTION SHORT TERM FORECASTING MODELS

WDNs transport the water to public and private users, fire hydrants, public fountains, devices. The inhabited centre consumption characterization is a complex procedure, mainly due to the variety of shares that constitute it. Normally a WDN satisfies the water needs of private users (sanitary water and other uses), public buildings, commercial and tourist users, artisanal and industrial agglomerations. Each user has different needs in terms of quantity and temporal distribution. In addition, the overall network water consumption includes the water losses, consumptions necessary for infrastructure maintenance (e.g., emptying and washing of tanks and pipes), and fire-fighting services.

To assess the share that characterizes the water demand, Liemberger *et al*. (2014) for the *International Water Association*, present a criterion for the construction of the water balance. Table 9.4.1 provides a criterion for the subdivision of the various share that characterize the total water consumption in a WDN.

System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed Metered Consumption	Revenue Water
			Billed Unmetered Consumption	
		Unbilled Authorized Consumption	Unbilled Metered Consumption	Non-Revenue Water
			Unbilled Unmetered Consumption	
	Water Losses	Apparent Losses	Unauthorized Consumption	
			Metering Inaccuracies and Data Handling Errors	
		Real Losses	Leakage on Transmission and/or Distribution Mains	
			Leakage and Overflows at Utility's Storage Tanks	
			Leakage on Service Connections up to Point of Customer Metering	

Table 9.4.1 Liemberger *et al*. (2014) IWA water balance components.

The difficulty in quantifying the volumes of non-revenue water increase the complexity in the overall water demand characterization. The demand has a very strong variability on a daily, weekly and annual scale.

Private and working habits of the served population influence the water consumption and its daily variability. . The daily consumption pattern remains similar to itself. The peaks occur at the beginning, the breaks and the end of work activities, while the lows occur during the night. The peaks duration and intensity depends on the type and extent of the urban centre. Numerous models characterize the weekly variability, distinguishing between weekdays and holidays. On holidays, the population activities change, affecting the intensity, duration and positioning of the peaks. Finally, it is possible to identify a long-term seasonality. Climate influences habits and water consumption. There are differences in consumption according to the season change (also depending on the type of climate).

The presence of a non-resident population rate that moves to and from the cities for work or tourism influence the consumption in some inhabited centres. The drinking water demand of an urban centre in addition to the seasonality presents a general trend. Overall consumption depends on the increase or reduction in the size of the urban centre, as well as on the evolution of the population habits and the evolution of production processes.

To build predictive modelling, it is necessary to identify the variables that directly and indirectly influence water consumption and to define the type of modelling commonly used in short-term forecasting.

Alvisi *et al*. (2007) present the Pattern-based Water Demand Forecasting (*Patt_WDF*) model. The multi-parametric model takes into account different seasonality using different simple models (i.e., AR (1) autoregressive models, Fourier series). The model uses the observed hourly flow rate to provide a 24h floating window hourly/bi-hourly forecast.

Bakker *et al*. (2014) compare the performance of models for daily and multi-day volume prediction. They evaluate an Adaptive heuristic model, a Transfer/Noise model (ARIMA and Box and Jenkins) and a Multiple Linear Regression (MLR). The authors compare the models' performance with and without the use of climatic variables.

Bougadis *et al*. (2005) assess the correlation between weather and consumption data. The authors compare three modelling approaches for weekly consumption forecast: Linear and multiple linear regression models, ARIMA and an ANN (feed-forward network, which uses the back-propagation algorithm for training). The models use the total weekly volume, the peak demand and some climatic variables (temperature, rainfall volume).

Candelieri and Archetti (2014) present a model that uses a Support Vector Regression (SRV). The data is clustered by similarity in shape, time and pattern. The model defines a SVR for each cluster and continuously acquires data (hourly flow). It uses the data relating to the first six hours of the day to choose which SVR to use to forecast the remaining 18 hours. The model takes into account some climatic variables. Clustering takes into account the forecast month and day of the week.

Candelieri (2017) presents a data-driven, scalable model suitable for the use of SCADA and AMI data. The model identifies and characterizes typical daily patterns and generates a set of forecast models for each pattern. The model uses the observed hourly flow rate data to generate a rolling 24-hour forecast.

Felfelani and Kerachian (2016) present three ANNs for the hourly demand forecast for the 14 days following the observations. The ANNs are multi-layer perceptron with a back-propagation algorithm (MLP-BP), cascade-forward (CF-BP), and radial basis functions (RBF). Hourly observations of flow rate and daily maximum and minimum temperature are used. The models differentiate the forecast based on the weekday and take into account the dates of religious holidays.

Gato *et al*. (2007) present a simple time series model that takes into account seasonality and trends. The model predicts the next day consumption. The model uses rain and temperature thresholds and differentiates the forecast according to the weekday.

Guo *et al*. (2018) compare the performance of two models for the forecast for the next 15 minutes and a daily forecast. The authors compare a GRUN model. GRUN is a Recurrent neural network (RNN) with several GRU (gated recurrent unit) layers. Models use consumption observations every 15 minutes.

Herrera *et al*. (2010) compare the performance of different approaches for the next hour demand forecast: Artificial neural networks (ANN) (feed-forward neural networks with one hidden layer and the back-propagation learning algorithm Projection pursuit regression (PPR)), Multivariate adaptive regression splines (MARS), SVR, Random forests, Weighted pattern-based model for water demand forecasting. The models use the metered hourly flow, climatic variables (i.e. Average temperature, wind speed, rainfall volume and pressure atmospheric) and differentiate between the weekdays.

Jain *et al*. (2001) compare three modelling techniques: 6 ANN (simple ANN models consisting of only one hidden layer, and 2) complex ANN models consisting of two hidden layers), 5 regressive models, and 2 time series models. The models use cumulative consumption volume, cumulative rainfall, and average weekly temperature to forecast the following week consumption.

Mouatadid and Adamowski (2017) evaluate the performance of one linear model (MLR) and three nonlinear self-learning models: ANN (feed-forward multi-layer perceptron architecture and were trained using a Levenberg-Marquardt (LM) backpropagation algorithm), SVR and an Elaboration Likelihood Model (ELM). The models forecast the consumption for 1/3 subsequent days, using the daily flow rate and some climatic variables (Maximum daily temperature, Total daily precipitation, Occurrences of precipitation).

Pacchin *et al*. (2017) present a bi-parametric hourly forecast model that is updated with each data entry. The model uses rolling 24 hour windows to forecast the next day hourly consumptions. The model does not use climatic variables are used but distinguishes weekdays and holidays.

Subsequently, Pacchin *et al*. (2019) present a comparison between different forecasting models. The models forecast hourly consumptions. The authors compare 6 models: ANN, a Pattern model based on the consumption seasonality, and two floating window models.

Seo *et al*. (2018) compare the performance of an extreme learning machine coupled with Variational Mode Decomposition (ELM-VMD) and a VMD-ANN. The models predict the daily consumption of the next 1, 3 and 5 days.

Tiwari *et al*. (2016) compare the performance of 3 ANN and 3 ELMs for the daily consumption forecast. The models use the observed daily consumption, the maximum temperature, and the intensity of rain.

Xu *et al*. (2019) present an hourly forecast hybrid architecture *model called CDBESN* (continuous deep belief network and an Echo State Network model)

Zhou *et al*. (2002) present a parametric model linked to seasonality. The model consists of an Hourly module and a Daily module. The model provides a 24 hour rolling window hourly forecast. In addition to the measured hourly flow, the model takes into account the forecasts of various climatic variables (i.e. Maximum Temperature, Precipitation, Evaporation, antecedent precipitation index). The Daily module models the weekly variability and differentiates between weekdays and holidays.

Zubaidi *et al*. (2016) evaluate the performance of three ANNs for forecasting daily consumption. The ANNs used are Backpropagation Neural Network (BP-NN), the Levenberg-Marquardt (LM), Backtracking Search Optimization Algorithm (BSA-ANN), and Gravitational Search Algorithm (GSA –ANN). The models use the observed daily consumption and some climatic variables (maximum average and minimum daily temperature, intensity of rain, evaporation, solar radiation, vapour pressure, maximum relative humidity).

Zubaidi *et al*. (2018) present models for the monthly consumption forecast. The authors use data pre-processing techniques to minimize prediction errors, to remove trends, seasonality and noise (Singular Spectrum Analysis). The authors use two ANNs: Hybrid Particle Swarm Optimization and Hybrid Backtracking Spiral Algorithm. The models use the observed monthly consumption and some climatic variables (Monthly volume, Maximum temperature, Average temperature, Minimum temperature, Precipitation intensity, Solar radiation, Vapor pressure).

In scientific literature, the water consumption short term forecast is a widely studied problem. Several authors have structured simple models or combinations of them. Others have developed advanced models (ANN or ELM). In defining a forecasting model, it is necessary to have a sufficiently large dataset available to guarantee enough data to train and verify the model. The characteristics of the available datasets affect the complexity and effectiveness of the models, Table 9.4.2 summarizes these characteristics. The analysis of the available modelling showed that the models often take into account sets of non-hydraulic variables. Water consumption is strongly bound to the population habits and activities. These activities are affected by climatic variations. Table 9.4.3 shows the amplitude of the forecast, the hydraulic and the climatic variables taken into account by the models. More than half of the models take into account one or more climatic variables. Short-term (weekly) variability is affected by the routine of work activities. Part of the models applies an explicit differentiation between weekdays and holidays. The consumption seasonality and the deviation from average conditions depend on a large number of interconnected factors:

- Climatic characteristics of the area of interest;
- Fluctuation of climatic variables:
    - Temperature;
    - Intensity and occurrence of rain;
    - Atmospheric pressure.
- Type of inhabited centre;
- Type of neighbourhood (e.g., residential district, commercial district);
- Type of buildings (houses, small condominiums, residential complexes) and their condition (historic building, new building);
- Rate (an adequate water rate can reduce waste and consumption);
- Water availability and presence of periods of resource lack;
- Social extraction and income of the inhabitants.

Authors	Dataset position	Served inhabitant	Data period
Alvisi *et al*. (2007)	Valencia, Spain	23000	1 year
Bakker *et al*. (2014)	Amsterdam, Rijnregi, Almere, Helden, Valkenburg, Hulsberg Netherlands	950000, 305000, 193000, 39000, 9200, 2400	2006-2011
Bougadis *et al*. (2005)	Ottawa, Canada	62228 (2001) 160175 (Forecasted for 2021)	May-semptember 1993-2002
Candelieri (2017)	Metropolitana milanese, Italy	1 million	october 2012 –september 2013
Candelieri and archetti (2014)	Metropolitana Milanese, Italy	1 million	march 2011 - march 2012
Felfelani and Kerachian (2016)	Mashhad city, Iran	3 million (20 million religious tourism)	4 years
Gato *et al*. (2007)	East Doncaster, Melbourne		April 1991 march 1994
Guo *et al*. (2018)	Changzhou, China	13000	February 2016 - January 2017
Herrera *et al*. (2010)	Southeast Spain	5000	January 2005 - April 2005
Jain *et al*. (2001)	Kanpur, India	12 000 plus gardens	1989-1998
Mouatadid and Adamowski (2017)	Montreal, Canada	1.65 million	february 1999 -august 2010
Pacchin *et al*. (2017)	Castelfranco Emilia, Italy	23000	1998-2000
Pacchin *et al*. (2019)	7 casi studio. Nord italy	120000, 20000, 9000, 7000, 7000, 2500 e 300 (3500 Tourism)	2 years
Seo *et al*. (2018)	Anseong-si, Hwaseong-si, Pyeongtaek-si, Osan-si, Suwon-si, and Yongin-si, South Korea.	3,840,907	2008-2017
Tiwari *et al*. (2016)	Calgary, Canada	1.1 million	March 2004 - December 2006
Xu *et al*. (2019)	Zhuzhou, China	600000 and factories	January 2016 -November 2016
Zhou *et al*. (2002)	Chelsea, Melbourne, Australia	35000	1 year
Zubaidi *et al*. (2018)	Melbourne, Australia	1.5 million	2006-2015
Zubaidi *et al*. (2018)	Melbourne, Australia	1.5 million	2010-2015

Table 9.4.2 Short term forecasting models dataset characteristics summary.

Authors	Forecast	Hydraulic observation	Climatic observation	Variability
Alvisi *et al*. (2007)	Hourly, Bi-hourly, floating window 24 hours	flow (hour)	-	-
Bakker *et al*. (2014)	Daily, Multy-daily	volume (day)	Average temperature (day)	weekdays and holidays
Bougadis *et al*. (2005)	Weekly	volume (week) Peak flow(week)	Average temperature (week) Rain volume (week)	-
Candelieri (2017)	Hourly, floating window 24 hours	flow (hour)	-	-
Candelieri and archetti (2014)	Acquisition of the first 6 hours of daily data, forecast of the remaining 18	flow (hour)	weather data (day)	weekdays and holidays
Felfelani and Kerachian (2016)	14 days	flow (hour)	Maximum temperature (day) Minimum temperature (day)	Weekday Religious holiday date
Gato *et al*. (2007)	Hourly	volume (day)	Rain volume (day) Maximum temperature (day) Days after rainfall	Weekday
Guo *et al*. (2018)	15 minutes, floating window 24 hours	flow (15 minutes)	-	-
Herrera *et al*. (2010)	Daily	flow (hour)	Average temperature (day) Rain volume (day) Atmospheric pressure (day) Wind speed (day)	weekdays and holidays
Jain *et al*. (2001)	Weekly	volume (week)	Average temperature (week) Rain volume (week)	-
Mouatadid and Adamowski (2017)	1-3 days	volume (day)	Rain volume (day) Maximum temperature (day) Rain occurrences (day)	-
Pacchin *et al*. (2017)	Hourly, floating window 24 hours	flow (hour)	-	weekdays and holidays
Pacchin *et al*. (2019)	Hourly	flow (hour)	-	-
Seo *et al*. (2018)	1-2-5 days	volume (day)	-	-
Tiwari *et al*. (2016)	daily	volume (day)	Maximum temperature (day) Rain intensity (day)	-
Xu *et al*. (2019)	Hourly	flow (hour)	-	-

Authors	Forecast	Hydraulic observation	Climatic observation	Variability
Zhou *et al*. (2002)	Hourly, floating window 24 hours	flow (hour)	Maximum temperature (day) Precipitation (day) Evaporation (day) API (antecedent precipitation index)	weekdays and holidays
Zubaidi *et al*. (2018)	monthly	Volume (month)	Maximum and average temperature (month) Minimum temperature (month)	-
Zubaidi *et al*. (2018)	Daily	volume (day)	Maximum average and minimum temperature (day) Rain intensity (day) Evaporation (day) Solar radiation (day) Vapour pressure (day) Maximum relative humidity (day)	-

Table 9.4.3 Short term forecasting models period and observations summary.

9.4.2 ORIGAMI PREDICTIVE MODELS

The drinking water demand can be considered as a time series. A time series is a collection of data obtained from sequential measurements over time (Esling and Agon 2012). Sequentiality implies a temporal relationship and data continuity.

The analysis of the time series allows identifying the recurring structures, the data dependencies and the mechanism that generated the examined data sequence. The analysis objective is the definition of synthetic statistics, the construction of models to interpret and forecast the evolution over time of the analyzed phenomenon.

The objective of origAMI modelling is the demand forecast and the operating anomalies identification. The project uses Data Mining techniques based on automated Deep Learning. The patterns (recurring behaviours or peaks) extraction and discovery from temporal data are known as time series analysis. Time series analysis is part of the complex of models and methodologies defined as temporal data mining (Roddick and Spiliopoulou, 1999).

Temporal Data Mining techniques

Some techniques commonly used for the analysis of time series data include linear or multivariate regressions, decomposition and classification based on Support Vector Machine. Such techniques require complete data sets. The relationship simplicity can affect the effectiveness of the model by ignoring complex nonlinear dependencies. Deep machine learning (DML) models can be more efficient in identifying and modelling intrinsic temporal dependencies in a time series (Gamboa 2017).

Artificial Neural Networks (ANNs) are a particular Machine Learning algorithm. The network consists of multiple artificial neurons or nodes, interconnected and organized in layers. An ANN uses an input and an output layer. Between these layers, there are one or more hidden layers. Each layer contains several neurons for processing data from previous layers. Deep Neural

Networks consist of numerous layers and have a greater ability to extract complex nonlinear dependencies from data, which makes them useful in predicting and detecting anomalies.

The most common approach used to model temporal dependencies using Deep Learning architectures are the Recurrent Neural Networks (RNN). In a non-recursive neural network, each input data is processed independently, thus losing any possible relationship. RNNs are more effective in analyzing data characterized by seasonality since they process them while retaining information relating to what has been observed up to that point (Sherstinsky, 2020).

origAMI uses an approach based on the use of RNN with Long-Short Term Memory (LSTM) and Gated Recurrent Unit network (GRU) recursive layers (Sherstinsky, 2020, Chung *et al*. 2014) for demand forecasting.

Anomaly detection is the process of identifying unexpected elements or events in a dataset. Such elements are referred to as outliers. Outlier detection algorithms also provide the degree of outlierness. The strategy proposed by origAMI is based on an unsupervised Deep Neural Network, trained on time series of data to recognize and predict the normal functioning patterns of the water network. The identification of anomalies takes place by estimating the error made by the prediction model. In the presence of an anomaly, the difference between the output of the neural network, trained to reproduce the normal water network operating regime, and the observed values is higher than in cases without anomalies. The error quantification allows assessing the "node risk". The node risk is an indicator of the probability that an anomaly has occurred, referring to an element of the network.

9.5 Prototyping and applications

The goal of the project is the creation of a WDN DSS framework. The collaboration of the research group with the company provided know-how on modelling and management of networks. The research activity supported the development of the platform prototype by collaborating in the implementation choices on modelling and user interface.

The following paragraphs provide information on DSS architecture and prototyping. The paragraph summarizes some specific technical aspects (Paragraph 9.5.1) such as programming languages, the operating environment and the database. Paragraph 9.5.2 presents some views and functionalities of the graphic interface and Paragraph 9.5.3 gives information on the meters used.

9.5.1 Implementation

The framework implementation mainly involved the capabilities of the company project partner. The implementation privileged choices aimed at guaranteeing high scalability, load balancing, redundancy and resilience (High Availability/Fault Tolerance/Disaster Recovery). The platform is designed as Cloud-Native, the cloud development environment is not tied to a particular Cloud Service Provider. The platform can be implemented on-premise (the software is installed and executed directly on a local machine).

Operating environment

The operating environment supports *DEVOPS* logic. The code is hosted on *GitLab*[1] and through the configuration of *GitLab* runners (on Linux machines), the pipelines are executed that carry out the steps of build, test, docs and proceed with the automatic deployment on *Kubernetes*[2] environments. The code development processes use a customized *GIT flow*[3]. Each microservice corresponds to a *GIT* project and is deployed in an independent Docker container. The development follows a DevSecOps logic in a CI/CD (Continuous Integration /Continuous Delivery) environment composed of *Sonarqube*[4], *Nexus artifactory*[5], *Gitlab, and Openshift*[6]. The development includes adequate Open Source governance that uses a Software Composition Analysis tool at the end of the developments, to prevent legal, operational and security risks associated with the use of Open Source.

Communication protocols

The framework supports LPWAN communication networks (NB-IoT, SigFox and Lora) and plans the integration with SCADA. In general, communication with external components is always possible thanks to the Wrapper mechanism.

[1] https://about.gitlab.com/
[2] https://kubernetes.io/it/docs/concepts/overview/what-is-kubernetes/
[3] https://git-scm.com/
[4] https://www.sonarqube.org/
[5] https://www.sonatype.com/products/repository-pro
[6] https://www.openshift.com/

Measurements from IoT devices have 2 entry points, Figure 9.2.1:

- If the device is connected directly to the core modules, the data is conveyed through the D*ata gathering/encoding module* to the *Message broker*.
- If the data is retrieved by the *wrappers*, they queue the raw data on the *Message broker* and are processed by the *Data gathering/encoding module* only if decoding is required.

Programming language

The main development language is *Java*, with support of *Spring Boot*[7] and *Quarkus*[8] frameworks. *Spring Boot* allows generating *Tomcat*[9] compatible packages. Angular JS[10] is the development framework for the web application. The AI algorithms of the *Idroanalytics* modules use *Python* language with the support of frameworks such as *Tensorflow*[11], *Keras*[12].

The need to use programming languages capable of supporting serverless/stateless applications is widely supported, thanks to the *Knative serving*[13] technology that provides serverless functions that have the particularity of not occupying resources if they do not carry out operations.

Database

There are two types of databases, based on the specific functionality to be implemented:

- **Relational** all the data that can be structured will be stored in relational databases, such as *Postgres*[14] and *Cloud SQL*[15].
- **Non-relational**, mainly for IoT data that uses no-*SQL such as Mongo-DB*[16].

The platform harmonizes data from all sources in an agnostic way and data storage is managed at the *Middleware* level, where data is collected, archived and historicized, Figure 9.2.1.

Data scheme

The data that characterize the WDN elements and *Users* served can be divided into two types:

- Static characteristics, that define entities characteristics statically:
    - Users (id, x, y, z, number of apartments, type of urban area, commercial activity, info, supplier hub);
    - Junction (id, x, y, z);
    - Connection (id, junction 1, junction 2, age, number of connections, material, diameter, replacement rate, average dynamic load, climate type);
    - Meter (id, junction, installation date, age, and measurement accuracy).
- Dynamic characteristics that define the entity based on its action:

[7] https://spring.io/projects/spring-boot
[8] https://quarkus.io/
[9] http://tomcat.apache.org/
[10] https://angularjs.org/
[11] https://www.tensorflow.org/
[12] https://keras.io/
[13] https://knative.dev/
[14] https://www.postgresql.org/
[15] https://cloud.google.com/sql
[16] https://www.mongodb.com/

- User history (user, timestamp, quantity);
- Network history (meter, timestamp, flow rate, pressure);
- Link failure (id, link, timestamp, type);
- Junction failure (id, junction, timestamp, type).

9.5.2 GRAPHICAL INTERFACE

To be effective, a DSS must ensure a complete and easy to use graphic interface. The proposed interface allows platform users accessing easily all information of their scope with a single login, Figure 9.5.1. The interface support near-real-time monitoring of the water network. Thanks to an integrated warning and notification system, users are informed of events or forecasts. Work orders are viewed from the same interface and are represented on the map. The framework allows integrating existing application components into the interface. The ability to integrate external systems aim of improving usability and reducing the number of tools with which the user must interact. The user takes advantage of the fast, responsive and intuitive WEB-CONSOLE and APP interfaces, designed to ensure a high user experience. The WEB-CONSOLE interacts with the rest of the platform to retrieve the information to display in sections that group different functions and show the data in the appropriate format. The prototype of the web application consists of a single web platform divided into pages related to specific features or groups of features:

- Login;
- Network;
- Simulation;
- Meters;
- Profiles;
- Notification;
- Rate Calculation;
- End Users.

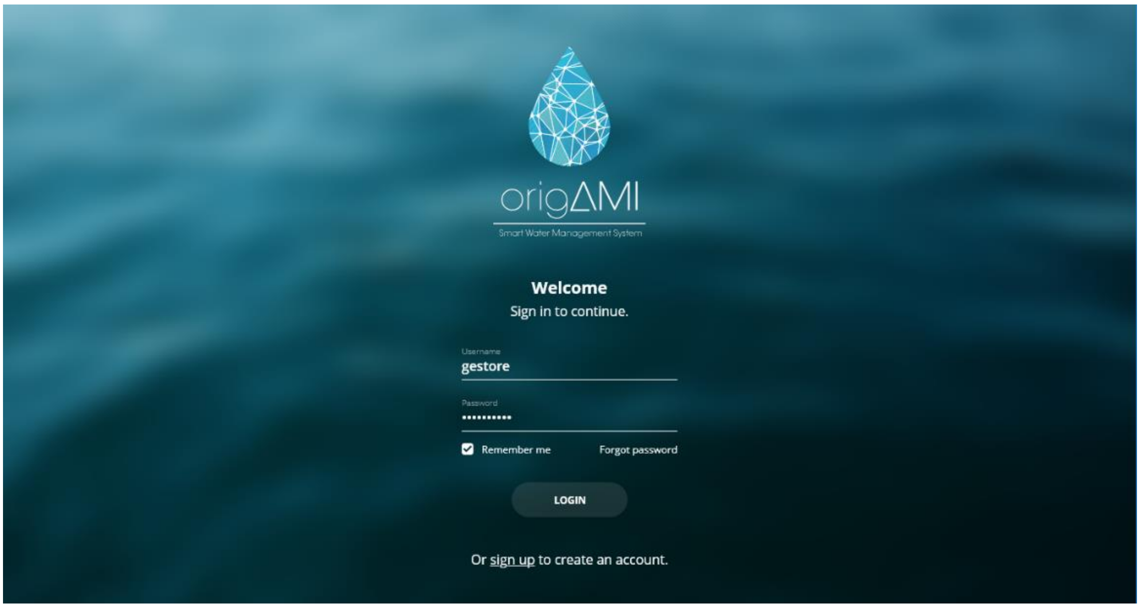

Figure 9.5.1 OrigAMI graphic interface: login.

Network and simulation

The origAMI main page shows the topological scheme of the WDN. The network is organized into districts, Figure 9.5.2a. This section is organized similarly to WEB-GIS in which the network elements, suitably georeferenced, are superimposed on base cartography.

This section shows the network districts and the connections between them. Each district is associated with a symbol that represents its status. The status represents summary information (e.g., presence of alerts, synthetic indices, etc.). In addition to the network map, the left section contains information on the district state (current and expected). In this section, it is possible to import or export BIM or EPENAET files and report malfunctions and breakages.

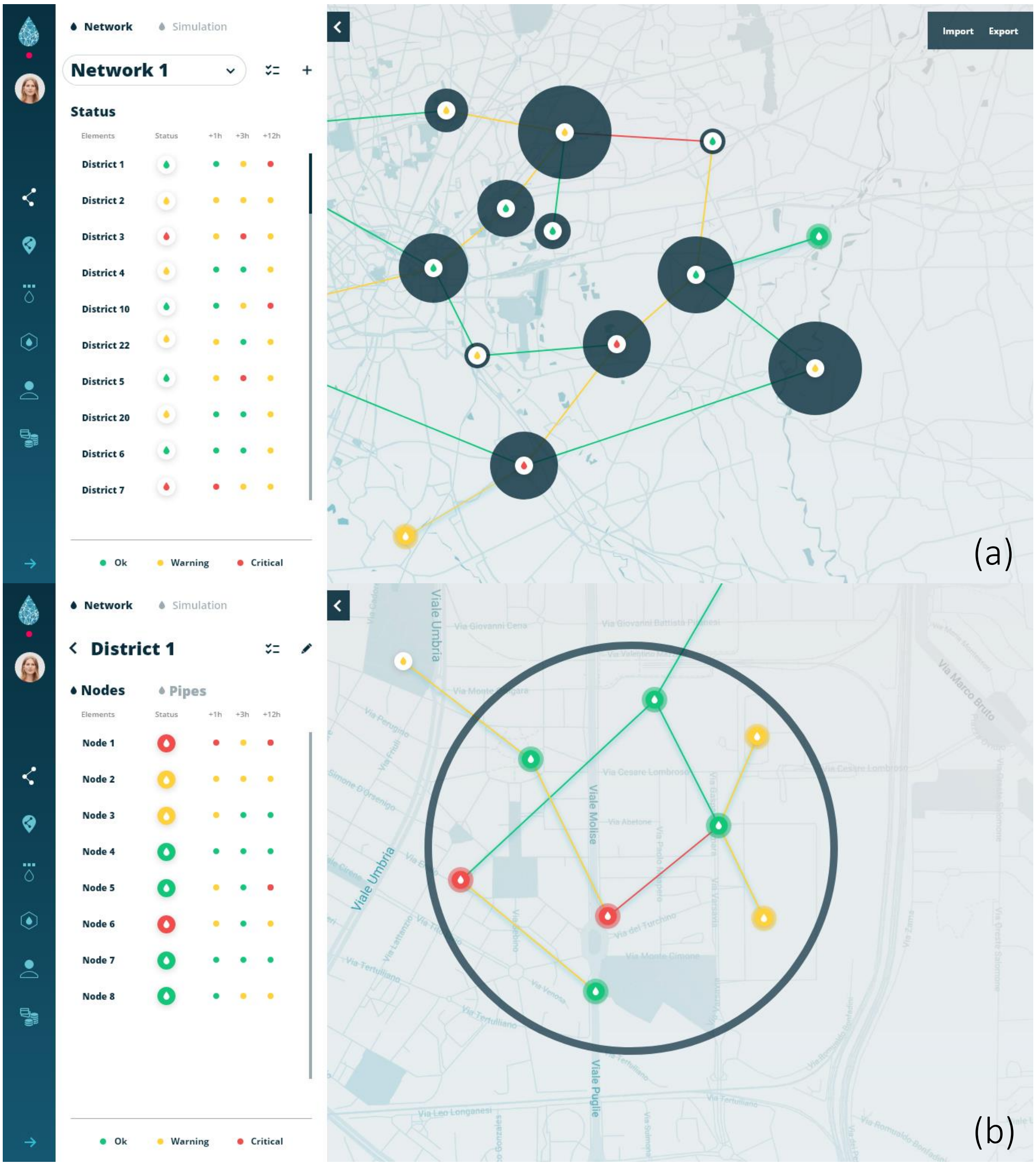

Figure 9.5.2 OrigAMI graphic interface: Network view (a) districts (b) full network.

From the districts view it is possible to switch to a detailed view of the portion of the network contained in the selected district, Figure 9.5.2b. In this tab, the platform shows specific indicators for the status of the pipes and nodes (element status, customized indicators). In the detail view, it is possible to query the network elements to know their status. The node details provide the list of meters and associated utilities.

The simulation tab is accessible from the network or district ones, Figure 9.5.2. This section allows starting a new hydraulic simulation and accessing the results of archived ones. The tab shows the overall demand curve of the selected network or district. The curve refers to the forecast for the next 24 hours. In the simulation tab, the colourimetric indication represents the hydraulic variables (nodal pressure, nodal demand, pipe flow, etc). In the district view, the colourimetric scale represents performance indicators or KPIs referring to the entire district. On the demand curve plot, a slider allows moving on the time axis, changing the displayed network operating regime.

Meters

As previously said, origAMI presupposes the implementation of an extensive network of smart meters. The Meter tab is dedicated to meter management, Figure 9.5.3. The meters are placed in the DMAs entry points and to the end-user service connections to the WDN. The model of a network rarely reaches such a high detail scale. In the platform, the meters are assigned to the network junctions according to a criterion defined by the manager. The tab lists the installed metering devices registered on the platform. The list includes information about the model, installation date, district to which it belongs, and associated junction. The tab allows adding, editing and deleting the meters.

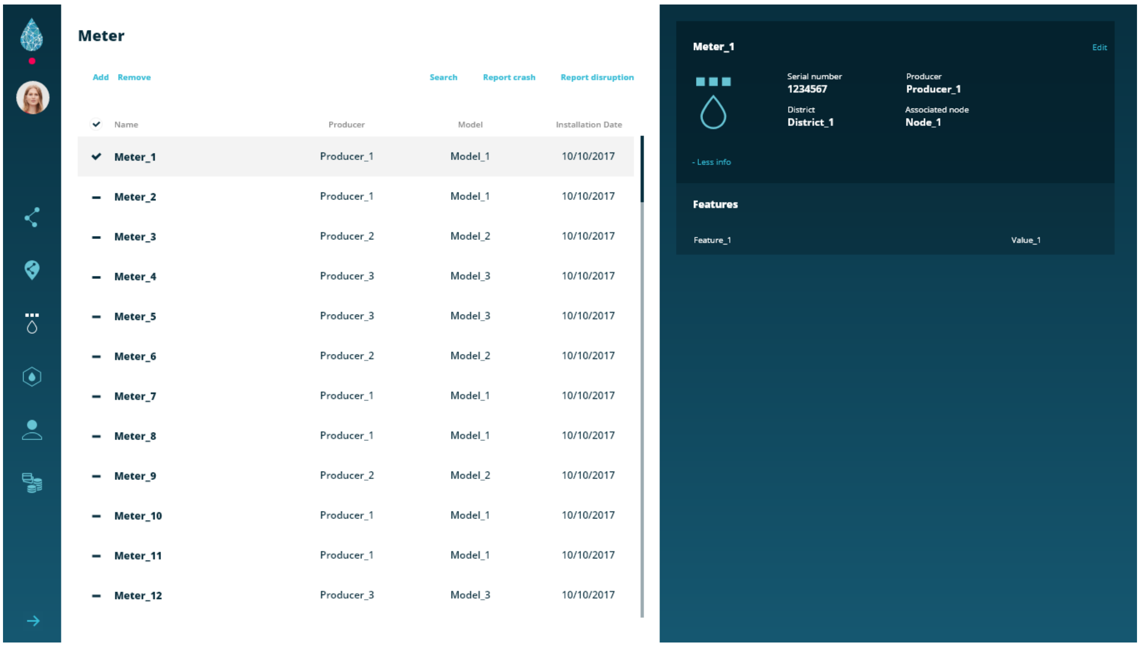

Figure 9.5.3 OrigAMI graphic interface: Meter.

Profiles and users

The *Profiles* and *Utilities* tabs, Figure 9.5.4 a) and b), respectively, allow consulting the registered *Profiles* and *Users*. The Profiles tab, Figure 9.5.4a, shows a table containing the information on the various registered *Profiles* that contains a summary (user code, payment status, service status and meter status). For each *Profile*, a detail section shows complete information (associated users, personal data, payment status, etc.). In this section, it is possible to retrieve the payments and bills history. The *Utilities* tab, Figure 9.5.4b, shows the registered *Users* table. It contains information on the water supplied, the meter installation date, the last maintenance interventions date. The *User* detail section shows the information on the associated *Profile*, the next payment due date, the water consumption.

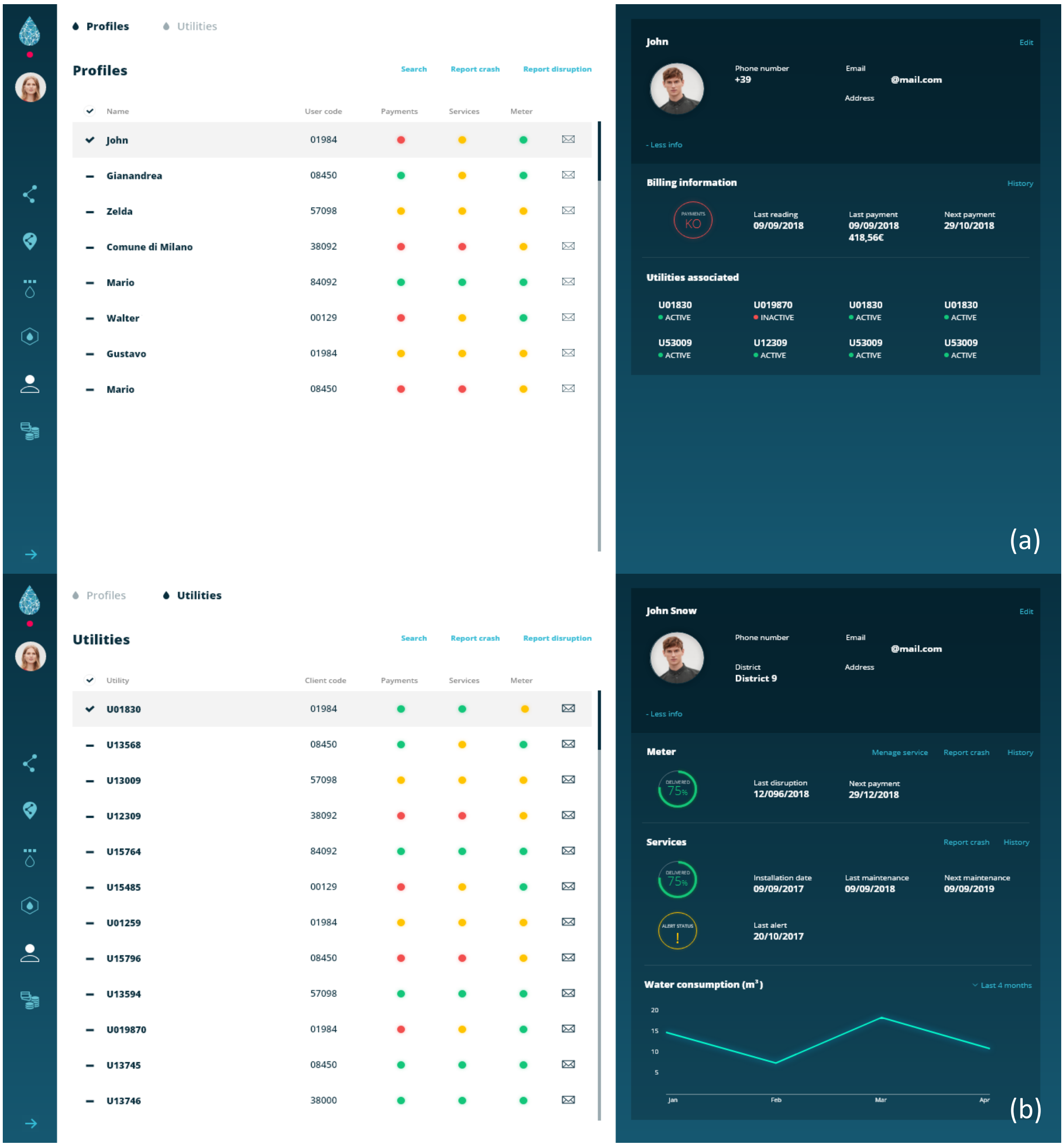

Figure 9.5.4 OrigAMI graphic interface: (a) *Profiles* (b) *Utilities.*

Notification and events

origAMI is designed to send and receive different types of notifications. It is possible to exchange notifications between users or to receive self-generated notifications following the detection of certain events or series of events (see Event Manager). The Notifications tab allows managing notifications, Figure 9.4.5. The tab lists all the notifications, which can be sorted by date or filtered by status (read/unread). An additional tab allows defining permissions and rules for generating notifications.

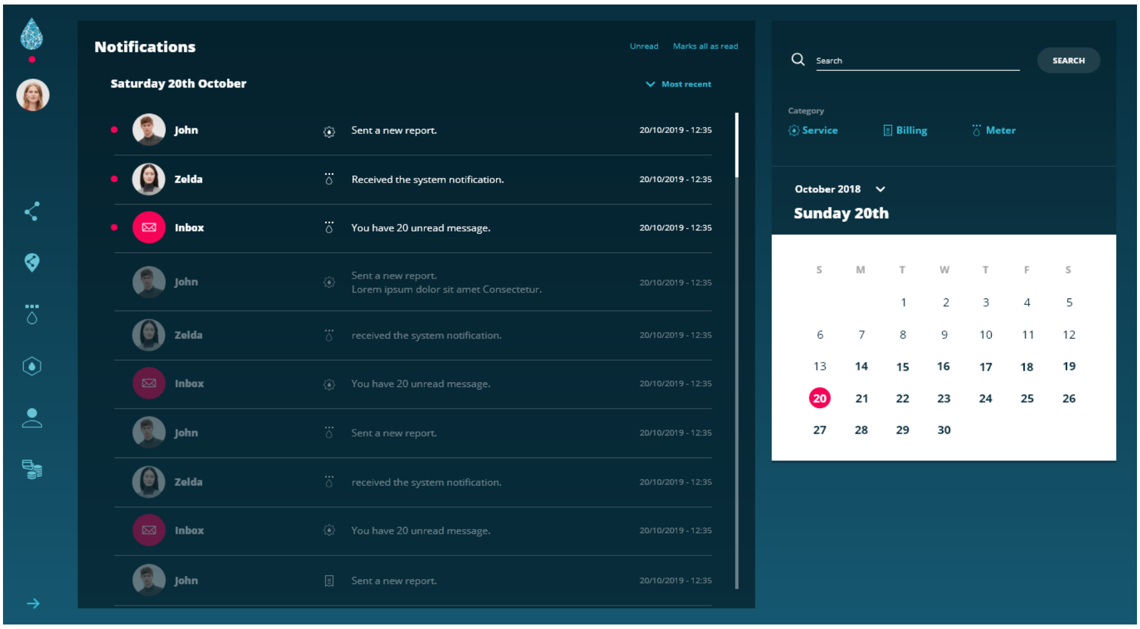

Figure 9.5.5 OrigAMI graphic interface: Notifications.

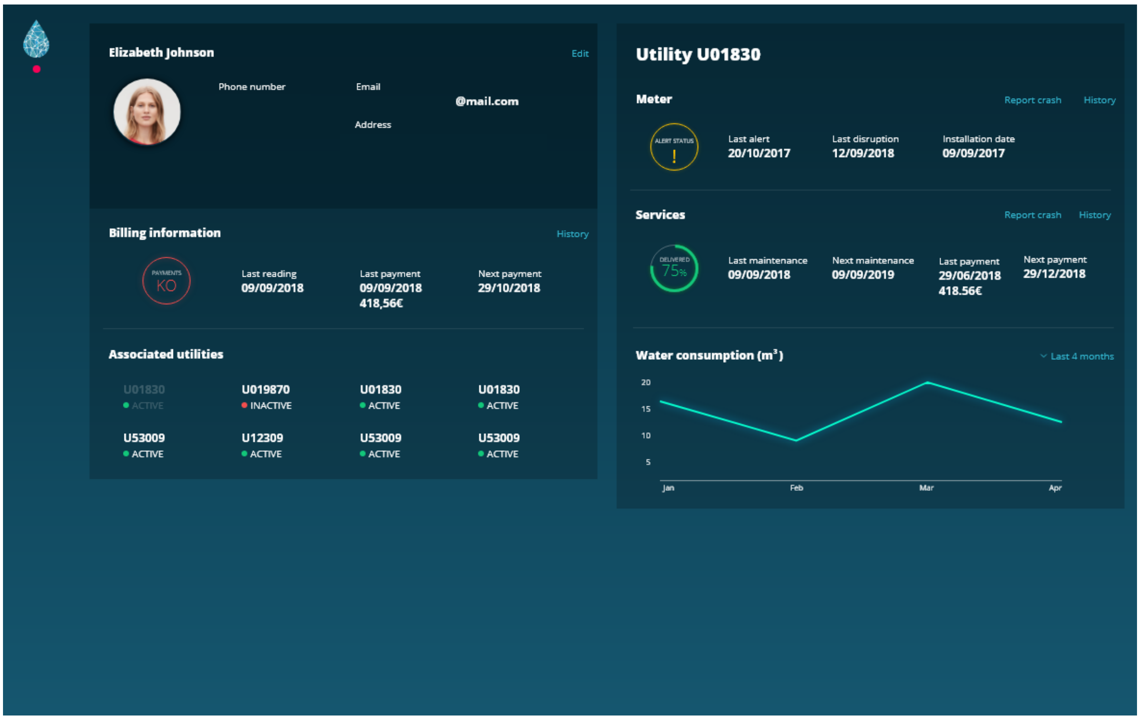

Figure 9.5.6 OrigAMI graphic interface: End-users interface.

End Users

The water service end-users can access the platform. Customers cannot access sensitive information on the WDN and its operating status. Figure 9.5.6 shows the tab dedicated to customers, it contains information on payments, the Profile data, and the associated *Users*. The tab also shows the information on the associated meter such as the model, the last problems dates, and the installation date. By accessing the platform, the customer can report malfunctions.

Rate Calculation

The platform supports rate calculation and application. The rate, depending on the country, is strictly regulated and standardized. OrigAMI contains a tab to track revenue based on the applied rate. This tab allows calculating and checking the rate, and analyze consumption and revenues using the values measured by the meters. The Rate Calculation tab contains a panel for analyzing the consumption and revenue history. The *Users* are classified (private users, commercial users, public services, network maintenance) and for each category, the tab provides overall information on billed volumes, revenues, etc.

9.5.3 Metering devices

To ensure the network correct management operations, it is necessary to equip wells, tanks and particular pipes with suitable instrumentation. The real-time detection of the operating regime of a network, through the adoption of advanced infrastructures, such as the AMI, allows the manager to disengage from procedures that require the use of walk-by or drive-by metering recovery mechanisms (Maiolo *et al.* 2019). The platform is based on a network of smart meters and an Internet of Things (IoT) paradigm. An AMI allows integrating the acquisition and pre-processing of consumption data into frameworks or digital media.

Structuring the prototype requires the identification of the communication protocol and sensors with characteristics compatible with their extensive use over time and space. The sensors must be equipped (or integrated) with a data transmission module. OrigAMI uses a Low Power Wide Area Network (LPWAN) data transmission protocol. LPWAN is a class of protocols for connecting devices and meters that allows long-range communications and low energy consumption with low operating costs (Maiolo *et al.* 2019). The LPWAN protocols low energy consumption is suitable for battery-powered meters.

Transmission modules to be adapted to private meters require high penetration radio technology; water meters are often located in basements or under the road surface. It is also necessary that the transmission have extensive territory coverage; a WDN reaches sparsely populated and rural areas. A suitable device must be battery powered and have very low energy consumption. Devices with high autonomy guarantees reduced maintenance costs.

LoRaWan, SigFox and NB-IoT are LPWAN protocols. As detailed in Mekki *et al.* (2019) the NB-IoT protocol has a good performance on range, coverage and battery life, but guarantees excellent scalability, low latency and excellent quality of service (QoS) compared to the other ones evaluated.

The tested meters are mechanical and use an external transmission module. The transmission module is equipped with a battery that guarantees operation for approximately 10 years (1 data transmission per day). The transmission module is compatible with the NB-IoT protocol and relies on the 4G network (5G coverage is not yet available on the trial site). The meter-communication module tests evaluate that:

- The NB-IoT network connection module does not affect the meter operation;
- An unauthorized user cannot disable the meter or the communication module unless causing physical damage to the device and triggering a warning;
- The collaboration with the manufacturer allowed possible to implement remote monitoring of the battery charge level;
- The connection modules can be configured on-site (e.g. messages frequency and the number of attempts to re-send messages);
- The devices are stably connected in case of good coverage of the network connectivity.

OrigAMI prototype connects to transmission modules with an NB-IoT protocol but also enable the SigFox or LoRa ones. The WDN supplying the city of Rende (**Chapter 3**) acted as a prototype area. Three meters were set up in the network area, Figure 9.5.7 and Figure 9.5.8. The device meters private users consumption, and are placed in an underground car park, located under the served building. OrigAMI received and stored the data sent by the meters.

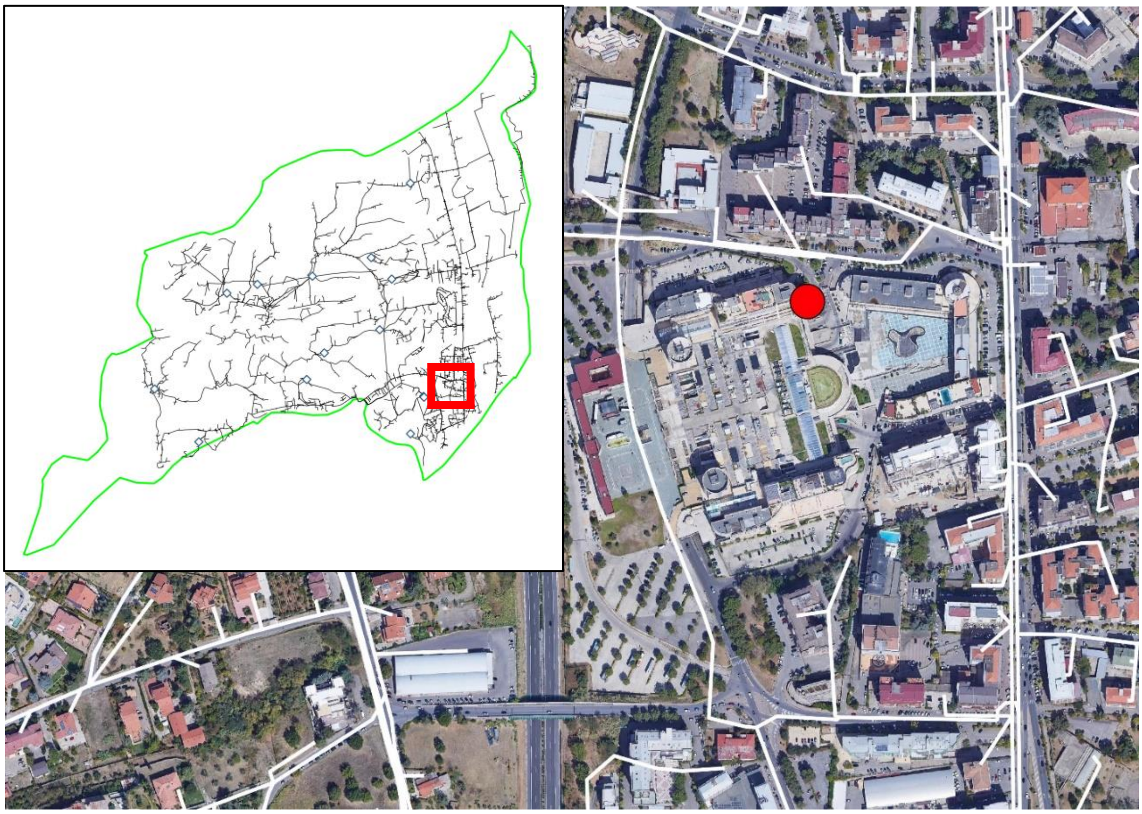

Figure 9.5.7 NB-IoT meter positioning. Google Satellite background.

Figure 9.5.8 NB-IoT meter positioning, 3D Google terrain model.

Since their installation, the NB-IoT sent messages with consumption at sub-hourly intervals, with no delays. The network stability and the error tolerance were sufficient for the use case, ensuring no information loss during transmissions. The meters recorded for about a year. Readings were taken at irregular intervals and it was found that

- ID01 meter recorded 7683.32 h (320 days) of readings, with an average of 1.5 hours between readings 4924 readings.
- ID02 meter recorded for 1320.88 h (553 days), with an average of 13 hours between readings 1018 readings.
- ID03 meter showed anomalies that did not allow the correct use of the transmitted data.

Figure 9.5.9 and Figure 9.5.10 show the data retrieved from the origami platform via the NB-IoT network for the ID01 and ID02 meters.

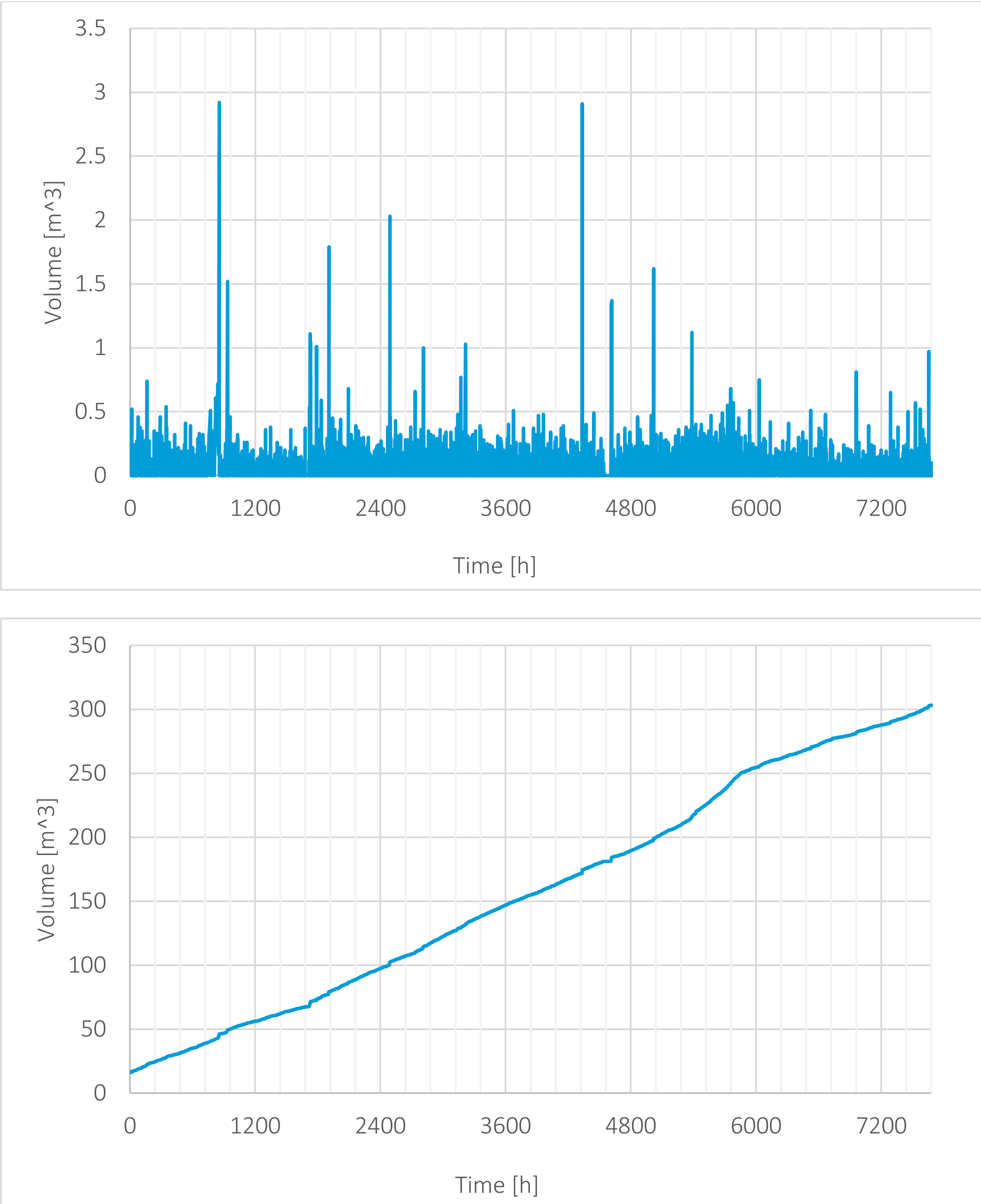

Figure 9.5.9 Smart meter ID01 reading (a) meter reading (b) cumulative reading.

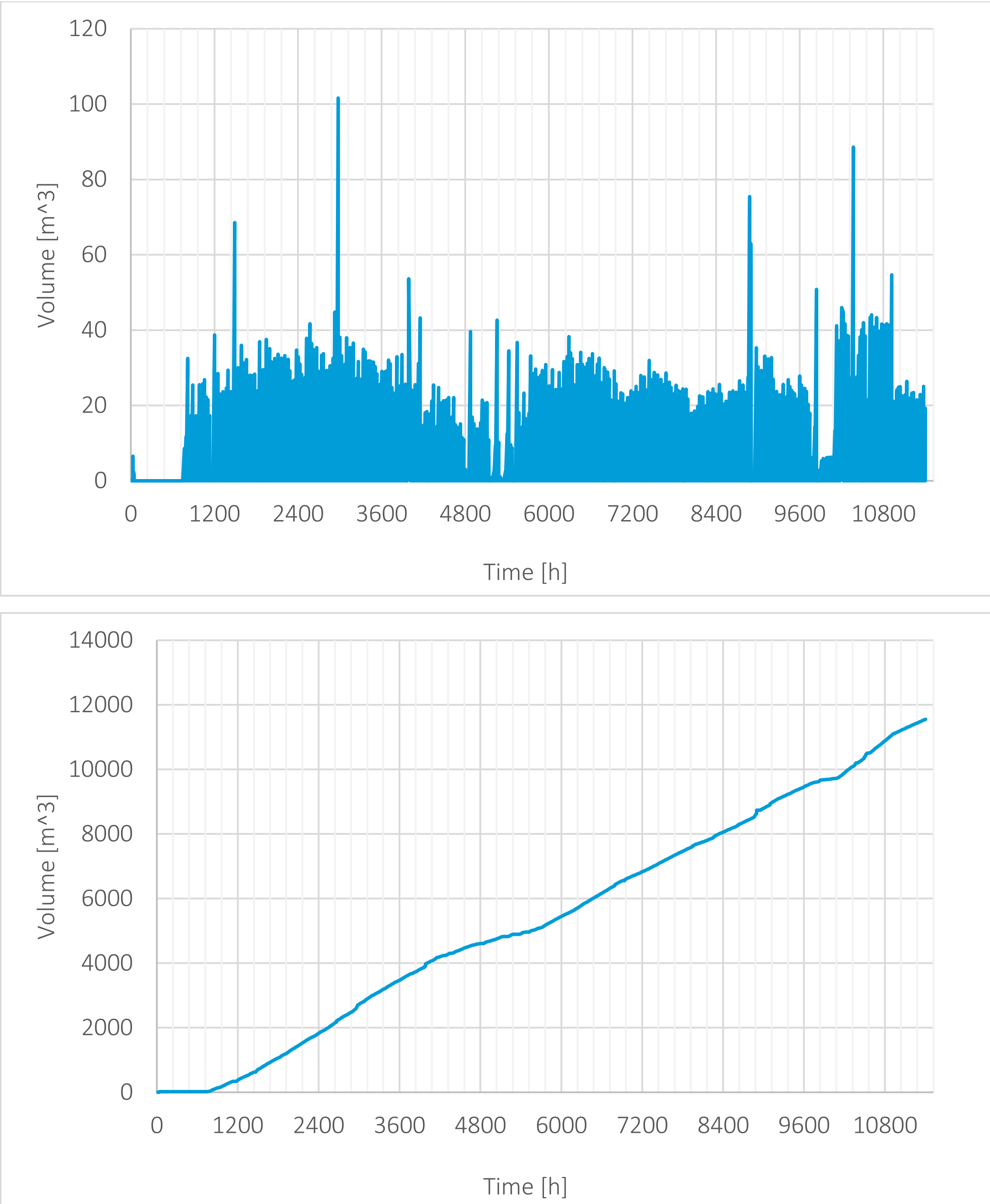

Figure 9.5.10 Smart meter ID02 reading (a) meter reading (b) cumulative reading.

9.6 General considerations and future development

The national and European regulation aims to a more sustainable and optimized water resources use. These regulation and the avalaibility of advanced computational tools make necessary to use advanced management tools.

Decision support tools Systems allow making integrated management of the water service more effective and efficient. The DWSMAMI PhD project supported the development of the origAMI platform. The platform is a prototype of an advanced and multidisciplinary WDN management system. It is structured as a support tool for managerial, economic and hydraulic decisions. The flow of data from the extensive use of smart meters enables the platform to use forecasting and anomalies identification models.

To date, origAMI is still in development. The main future developments of the prototype include the integration of hydraulic-mathematical modelling to enable the districtization and optimization phases in terms of correct resource allocation, development of the tool for the prediction of network malfunctions, development of web apps for facilitating smart management for different levels of users.

9.7 Bibliography

- Aiello, G., Giovino, I., Vallone, M., Catania, P., & Argento, A. (2018). "A decision support system based on multisensor data fusion for sustainable greenhouse management." Journal of Cleaner Production, 172, 4057-4065.
- Alvisi, S., Franchini, M., & Marinelli, A. (2007). A short-term, pattern-based model for water-demand forecasting. Journal of hydroinformatics, 9(1), 39-50.
- Bakker, M., Van Duist, H., Van Schagen, K., Vreeburg, J., & Rietveld, L. (2014). Improving the performance of water demand forecasting models by using weather input. Procedia Engineering, 70, 93-102
- Boelee, L., Bahrom, R., Amer, H., Zamri Sondor, N., Brown, E., Ahmad, F., & Wilson, G. (2017). "Operational decision support system for sustainable water resource management for Sungai Selangor." E-proceedings of the 37th IAHR World Congress, August 13 – 18, 2017, Kuala Lumpur, Malaysia
- Bougadis, J., Adamowski, K., & Diduch, R. (2005). Short-term municipal water demand forecasting. Hydrological Processes: An International Journal, 19(1), 137-148.
- Candelieri, A. (2017). Clustering and support vector regression for water demand forecasting and anomaly detection. Water, 9(3), 224.
- Candelieri, A., & Archetti, F. (2014). Identifying typical urban water demand patterns for a reliable short-term forecasting–the icewater project approach. Procedia Engineering, 89, 1004-1012.
- Capano, G., Carini, M., Chiaravalloti, F., Pantusa, D., & Maiolo, M., (2016). Modellizzazione matematica a supporto di infrastrutture avanzate di misura e controllo delle grandezze caratteristiche della gestione dei sistemi acquedottistici. XXXVII Corso di Aggiornamento in "Tecniche per la difesa dall'inquinamento", 15-18 giugno 2016, Guardia Piemontese (CS), EdiBios (conference proceedings)
- Chung, J., Gulcehre, C., Cho, K., & Bengio, Y. (2014). Empirical evaluation of gated recurrent neural networks on sequence modelling. arXiv preprint arXiv:1412.3555.
- Delpla, I., Monteith, D. T., Freeman, C., Haftka, J., Hermens, J., Jones, T. G., ... & Thomas, O. (2014). "A decision support system for drinking water production integrating health risks assessment." International journal of environmental research and public health, 11(7), 7354-7375.
- Esling, P., & Agon, C. (2012). Time-series data mining. ACM Computing Surveys (CSUR), 45(1), 1-34.
- Felfelani, F., & Kerachian, R. (2016). Municipal water demand forecasting under peculiar fluctuations in population: a case study of Mashhad, a tourist city. Hydrological Sciences Journal, 61(8), 1524-1534.
- Fischer, A., Ter Laak, T., Bronders, J., Desmet, N., Christoffels, E., van Wezel, A., & van der Hoek, J. P. (2017). "Decision support for water quality management of contaminants of emerging concern". Journal of Environmental Management, 193, 360-372.
- Gamboa, J. C. B. (2017). Deep learning for time-series analysis. arXiv preprint arXiv:1701.01887.
- Gato, S., Jayasuriya, N., & Roberts, P. (2007). Temperature and rainfall thresholds for base use urban water demand modelling. Journal of hydrology, 337(3-4), 364-376.
- Grimaldi, M., Sebillo, M., Vitiello, G., & Pellecchia, V. (2020). "Planning and Managing the Integrated Water System: A Spatial Decision Support System to Analyze the Infrastructure Performances." Sustainability, 12(16), 6432.
- Guo, G., Liu, S., Wu, Y., Li, J., Zhou, R., & Zhu, X. (2018). Short-term water demand forecast based on deep learning method. Journal of Water Resources Planning and Management, 144(12), 04018076
- Herrera, M., Torgo, L., Izquierdo, J., & Pérez-García, R. (2010). Predictive models for forecasting hourly urban water demand. Journal of hydrology, 387(1-2), 141-150.
- Islam, M. S., Sadiq, R., Rodriguez, M. J., Najjaran, H., & Hoorfar, M. (2016). "Integrated decision support system for prognostic and diagnostic analyses of water distribution system failures." Water Resources Management, 30(8), 2831-2850
- Jain, A., Varshney, A. K., & Joshi, U. C. (2001). Short-term water demand forecast modelling at IIT Kanpur using artificial neural networks. Water resources management, 15(5), 299-321.
- Karavokiros, G., Nikolopoulos, D., Manouri, S., Efstratiadis, A., Makropoulos, C., Mamassis, N., & Koutsoyiannis, D. (2020). "Hydronomeas 2020: Open-source decision support system for water resources management." In EGU General Assembly Conference Abstracts (p. 20022).

- Lamberti, P.; Maiolo, M.; Mazzola, R.; Veltri, P. (1994) Rapporto sui consumi idropotabili sul finire degli anni ’80. In I Quaderno del Gruppo Nazionale “Consumi idropotabili”; Taglialatela, L., Bertola, P., Eds.; CUEN Editrice: Napoli, Italy. (In Italian)
- Liemberger, R., & Farley, M. (2004, September). Developing a nonrevenue water reduction strategy Part 1: Investigating and assessing water losses. In Paper to IWA Congress.
- Lo, H. W., Liou, J. J., Huang, C. N., Chuang, Y. C., & Tzeng, G. H. (2020). “A new soft computing approach for analyzing the influential relationships of critical infrastructures.” International Journal of Critical Infrastructure Protection, 28, 100336.
- Maiolo, M., Carini, M., Capano, G., Pantusa, D., & Iusi, M. (2019). Trends in metering potable water. Water Practice and Technology, 14(1), 1-9.
- Mekki, K., Bajic, E., Chaxel, F., & Meyer, F. (2019). A comparative study of LPWAN technologies for large-scale IoT deployment. ICT express, 5(1), 1-7.
- Monstadt, J., & Schmidt, M. (2019). “Urban resilience in the making? The governance of critical infrastructures in German cities.” Urban Studies, 56(11), 2353-2371.
- Mouatadid, S., & Adamowski, J. (2017). Using extreme learning machines for short-term urban water demand forecasting. Urban water journal, 14(6), 630-638.
- Pacchin, E., Alvisi, S., & Franchini, M. (2017). A short-term water demand forecasting model using a moving window on previously observed data. Water, 9(3), 172.
- Pacchin, E., Gagliardi, F., Alvisi, S., & Franchini, M. (2019). A comparison of short-term water demand forecasting models. Water resources management, 33(4), 1481-1497
- Power D.J., Sharda R. (2009) Decision Support Systems. In: Nof S. (eds) Springer Handbook of Automation. Springer Handbooks. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-78831-7_87
- Ribeiro, R., Loureiro, D., Barateiro, J., Smith, J. R., Rebelo, M., Kossieris, P., ... & Mansfield, L. (2015). Framework for technical evaluation of decision support systems based on water smart metering: the iWIDGET case. Procedia Engineering, 119, 1348-1355.
- Roddick, J. F., & Spiliopoulou, M. (1999). A bibliography of temporal, spatial and spatio-temporal data mining research. ACM SIGKDD Explorations Newsletter, 1(1), 34-38.
- Rossman, L.A. (2000) EPANET 2: Users Manualus Environmental Protection Agency; Water Supply and Water Resources Division, National Risk Management Research Laboratory: Cincinnati, OH, USA.
- Sechi, G. M., & Sulis, A. N. D. R. E. A. (2007). “Mixed simulation-optimization technique for complex water resource system analysis under drought conditions.” In Methods and tools for drought analysis and management, Springer, Dordrecht, pp. 217-237.
- Seo, Y., Kwon, S., & Choi, Y. (2018). Short-term water demand forecasting model combining variational mode decomposition and extreme learning machine. Hydrology, 5(4), 54.
- Sherstinsky, A. (2020). Fundamentals of recurrent neural network (RNN) and long short-term memory (LSTM) network. Physica D: Nonlinear Phenomena, 404, 132306.
- Sherstinsky, A. (2020). Fundamentals of recurrent neural network (RNN) and long short-term memory (LSTM) network. Physica D: Nonlinear Phenomena, 404, 132306.
- Shuang, Q., Zhang, M., & Yuan, Y. (2014). “Node vulnerability of water distribution networks under cascading failures.” Reliability Engineering & System Safety, 124, 132-14Z.
- Tiwari, M., Adamowski, J., & Adamowski, K. (2016). Water demand forecasting using extreme learning machines. Journal of Water and Land Development.
- Westphal, K. S., Vogel, R. M., Kirshen, P., & Chapra, S. C. (2003). “Decision support system for adaptive water supply management.” Journal of Water Resources Planning and Management, 129(3), 165-177.
- Xu, Y., Zhang, J., Long, Z., Tang, H., & Zhang, X. (2019). Hourly urban water demand forecasting using the continuous deep belief echo state network. Water, 11(2), 351.
- Zhou, S. L., McMahon, T. A., Walton, A., & Lewis, J. (2002). Forecasting operational demand for an urban water supply zone. Journal of hydrology, 259(1-4), 189-202.
- Zubaidi, S. L., Dooley, J., Alkhaddar, R. M., Abdellatif, M., Al-Bugharbee, H., & Ortega-Martorell, S. (2018). A Novel approach for predicting monthly water demand by combining singular spectrum analysis with neural networks. Journal of hydrology, 561, 136-145.
- Zubaidi, S. L., Gharghan, S. K., Dooley, J., Alkhaddar, R. M., & Abdellatif, M. (2018). Short-term urban water demand prediction considering weather factors. Water resources management, 32(14), 4527-4542.

10. Conclusion

Human society is facing great challenges to ensure sustainable development, which does not compromise biodiversity and the available resources to future generations. Climate change and unsustainable consumption strategies are progressively reducing the overall freshwater availability. The European community and its member states are promoting numerous actions aimed at reducing waste, optimizing consumption and promoting reuse. The DWSMAMI research project is part of the set of programmatic actions promoted by Europe to support research and development activities to promote sustainable development, improve health and quality of life and supporting the development of Smart Communities.

The DWSMAMI project supported the origAMI R&D project. The projects aim to improve the management processes of drinking water distribution infrastructures by developing a decision support tool based on advanced metering infrastructures. The integration within the DSS of mathematical hydraulic modelling and advanced management tools has made it possible to define an advanced framework that exploits Information and Communications Technology (ICT) tools from an Internet of Things (IoT) and Big Data perspective.

OrigAMI is a technical-managerial framework for designers, managers and citizens that provides tools to manage the near-real-time metering. The framework Integrates remote consumption measurement with EPANET's hydraulic modelling capabilities. The integration of hydraulic modelling and the characteristics of the graphical interface make the DSS suitable for controlling the infrastructure. The management of operational maneuver tools is associated with economic management interfaces (rate calculation, utility bills generation and management) and maintenance management utilities (reactive maintenance, prioritization of interventions, automatic notifications and warnings). The use of data from the AMIs required the definition of management logic and big data analysis. The platform integrates a model for the consumption forecast and one for the anomaly identification. The first allows improving management and optimize operational maneuvers, the second supports workflow management and the critical issues reaction by quickly identifying anomalous operating scenarios. The modular structure of the platform guarantees high scalability and adaptability of the solution. Modules can integrate additional specific analytical tools or models. The WEB-GIS graphical interface guarantees ease of reading and organize the database in a format compatible with BIM software.

The use of ICT tools for complex infrastructure management requires the construction of the network digital model that contains sufficient information for the hydraulic simulation, the assets operational management, and the construction of the BIM database. The European Union has presented the INSPIRE to support the development of policies related to environmental impacts through legislation that guarantees easy access to complete and good quality territorial data.

Despite the regulatory requirements, the current state of digitalization of the networks is uneven and characterized by various criticalities. The digitization process is strongly influenced by the available data (Maiolo *et al*. 2020). This work defines the quantity and quality of the information necessary for the digital model construction for the hydraulic simulation. The application to different cases allowed characterizing a strategy for the digital model production and its use for simulations and processing. Among the networks analyzed, the one serving the Portuguese city of Santarém is also used in the study of performance indices. A DSS for the management of drinking water networks requires synthetic and quick tools for performance assessment.

The research focused on the definition of concepts related to the reliability of the network in water stress or component failure scenarios. The reliability of a network is in many cases an ambiguous and difficult to define concept. Many authors define it as the ability of a network to meet the end-user demand in all operating scenarios. Others use surrogate assessment methods that rely on entropy or resilience indices. The study of the resilience indices has made it possible to produce different elaborations on the characteristics of these indices, and how the hydraulic modelling influences their assessment. The performance indices, despite being presented in different formulations, have recurring features. The use of an analytical framework, consisting of indices with a very simple structure (Caldarola and Maiolo 2019) allow remodelling of these indices with simple analytical structures and identifying shared constructs. The study made it possible to evaluate the applicability of these indices and to characterize them as local synthetic indices (Bonora *et al.*, 2019, 2020a, 2020b).

The need for optimized and sustainable management of existing infrastructures implies an improvement in management practices and, at the same time, a series of actions to improve and recover the physical components. The study of accessory models for WDNs includes optimal resource allocation models. These models, typical of operations research, allow identifying optimal configurations of connections for resource transportation. The simplifications necessary for the application of these models may compromise the validity of the optimal solutions identified. The developed methodology makes it possible to identify the optimal routes for the construction or renovation of pipe networks. The methodology makes it possible to identify paths linked to the real orography of the territories while being able to take into account hydraulic and use of the territory constraints.

The collaboration between the research group and the company allowed deepening the business logic that guides the development and release processes of a complex architecture such as origAMI, introducing research related functionality and models. OrigAMI is the prototype of a structured management framework to connect operational, managerial and economic needs, using an innovative approach based on IoT, Smart Cities and integration with tools and approaches typical of scientific research.

10.1 Bibliography

- Bonora, M. A., Caldarola, F., & Maiolo, M. (2020a). A new set of local indices applied to a water network through Demand and Pressure Driven Analysis (DDA and PDA). Water, 12(8), 2210.
- Bonora, M. A., Caldarola, F., Maiolo, M., Muranho, J., & Sousa, J. (2020b). The New Set Up of Local Performance Indices into WaterNetGen and Application to Santarém's Network. In Environmental Sciences Proceedings (Vol. 2, No. 1, p. 18). Multidisciplinary Digital Publishing Institute.
- Bonora, M. A., Caldarola, F., Muranho, J., Sousa, J., & Maiolo, M. (2019). Numerical experimentations for a new set of local indices of a water network. In International Conference on Numerical
- Caldarola, F., & Maiolo, M. (2019). Local indices within a mathematical framework for urban water distribution systems. Cogent Engineering, 6(1), 1643057.
- Maiolo M., Carini M., Pantusa D. Bonora M. A., Capano G., Mel R., Sinopoli S. (2020) INGEGNERIZZAZIONE E INTEROPERABILITA' DEI DATI PER LA GESTIONE INTEGRATA DELLE RETI IDRICHE URBANE XXXVII Convegno Nazionale di Idraulica e Costruzioni Idrauliche Reggio Calabria, 7-9 Settembre 2020
- Maiolo, M., Sousa, J., Carini, M., Chiaravalloti, F., Bonora, M. A., Capano, G., & Pantusa, D. (2019, June). Optimization Model for Water Distribution Network Planning in a Realistic Orographic Framework. In International Conference on Numerical Computations: Theory and Algorithms (pp. 545-556). Springer, Cham.

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