WDSA CCWI 2022

2nd International Joint Conference on Water Distribution Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14775

DESIGNING ADVANCED ASSET MANAGEMENT FOR WATER DISTRIBUTION NETWORKS: APPLICATION TO A REAL CASE STUDY

Daniele B. Laucelli[1], Serena Spagnuolo[2], Antonio Rinaldi[3], Gianluca Perrone[4], Luigi Berardi[5], Orazio Giustolisi[6]

[1,6] Politecnico di Bari, Bari (Italy)
[2]Acquedotto Pugliese S.p.A., Bari (Italy)
[3]Studio AC3 Ingegneria S.r.l., Ferdinando di Puglia (Italy)
[4]IA.ING S.r.l., Lecce (Italy)
[5]University of Chieti-Pescara "G. D'Annunzio", Pescara (Italy)

[1] *danielebiagio.laucelli@poliba.it*, [2] *s.spagnuolo@aqp.it*, [3]*a.rinaldi@studioac3.com*, [4]*perrone@iaing.it*, [5] *luigi.berardi@unich.it*, [6] *orazio.giustolisi@poliba.it.*

Abstract

In recent years, water utility companies are facing several challenges in managing water distribution networks caused by the combined effect of aging, network complexity, changing water needs and availability. In this sense, the main trend to be countered is the increase in the deterioration of pipelines, therefore of water losses and finally the increasing probability of pipe failures. Leaks represent a significant challenge for water services in terms of technical, economic and safety damage, as well as reliability of service to users. Therefore, it is necessary to support technicians and water utilities in the effective management of water distribution networks in the short and long term, allowing them to gain a better understanding of network behaviour and to implement a more efficient use of water. To this end, optimal design solutions can be developed for asset management based on an integrated approach that incorporates advanced hydraulic modelling, network monitoring and technical-engineering knowledge of the network.

This work presents a complete methodology for water distribution network asset management, integrating optimal district metering areas design and pressure control with optimal pipe replacement. The case study presented concerns the city of Bari, the capital of the Puglia region, in southern Italy, a municipality of over 300,000 inhabitants, as part of a project tender for the improvement of the asset managed by Acquedotto Pugliese, the largest water company in Italy. Each designed activity in the methodology has been evaluated in terms of leakage reductions performances, under given economic constraints, to fully support technicians and water utilities in addressing water distribution network management plans.

Keywords
Asset management, pressure control, DMA design, optimal pipe replacement, real scale application.

1 INTRODUCTION

In the early twentieth century, the aim of Water Distribution Networks (WDN) was to support economic-industrial development and provide fire protection. The objective of the modelling studies was the development of hydraulic verification criteria of the WDN projects with respect to water requirements of the various types of users (civil, commercial, industrial, fire prevention). The WDN hydraulic simulation models had to calculate the operating pressures at the network nodes, given the pipe roughness and nodal demands. The design, therefore, became an assessment of nodal pressures with respect to the minimum pressures for a correct service to users and the minimum residual flow rates and pressures for the correct hydraulic performance of hydrants. On these assumptions, with the advent of automatic calculation, Todini [1] introduced the Global Gradient Algorithm (GGA), which a few years later became the hydraulic engine of EPANET, developed by Rossman [2]. Most current software packages are based on such a hydraulic engine or similar strategies. In general, all classic hydraulic simulators are born for hydraulic verification, and not for management purposes since they are based on the assumption of fixed demands at WDN nodes. This is called *Demand-Driven Analysis* (DDA).

Over the years, WDNs have become increasingly large, complex and aged, implying management needs with respect to volumetric losses, reliability, water quality, energy optimization, rehabilitation, etc. Todini [3] noted the need for a hydraulic simulation modelling that was able to evaluate the "effective" demand that can be supplied to users in pressure deficit conditions (i.e., pressure lower than the minimum required for correct service), therefore suitable for the new management tasks to be faced for a water company. Such hydraulic simulations are now called *Pressure-Driven Analyses* (PDAs). Several studies proposed the model of Wagner et al. [4], to represent the link between pressure at the network nodes and water demand actually supplied to users, such as Giustolisi et al. [5]. This model has proved consistent with the real hydraulic operation of the network where users statistically control the flow rates at the taps if the pressures are sufficient, while drawing the maximum flow rate from them (i.e., the maximum volume in a certain time interval), allowed by the pressure available when the network is in deficit conditions.

PDA analysis can represent different demand components in addition to the human one. In the last decade, researchers have investigated the possibility of making hydraulic simulation consistent with support for management decisions. From this perspective, representing water losses having a volumetric effect in the network would be useful for several management activities such as, for example, pressure control or rehabilitation planning. Such kind of losses are widely spread in the network and cannot be repaired individually since they are small (i.e., dripping). They produce significant volumes of water lost over time. Giustolisi and Walski [6] framed the representation of leakages, and other demand components, in the PDA simulation scheme, by developing the representation of the volumetric leakage component (*background leakages*) as a function of pressure at the single pipe level. Background leakages are an important indicator for asset management as they can define the state of deterioration of the network, albeit maintaining the information at the level of a single pipe. In fact, they are linked to the average pressures acting on the pipe; the advanced hydraulic simulation model from [3] based on that by Germanopoulos [7], assigns to each pipe a parameter (β) which can be considered a global indicator of deterioration and, therefore, of significant decision-making utility for any leakage management activity. It is important to clarify that representing the volumetric losses with hydrants concentrated in the network nodes, in addition to making the hydraulic calculation inaccurate from different points of view, causes the loss of information on deterioration at the individual pipe level (since it is concentrated a priori in the nodes), which is important for decision-making in rehabilitation. Furthermore, the classic hydraulic simulators (e.g., EPANET) are *demand-driven* while the volumetric leakages cannot be fixed in advance since they are a function of the average pressures on the pipes. Therefore, the WDN simulation for management purposes always requires PDA, both for the presence of volumetric losses and hydraulic verification of the users' water demands satisfaction.

Background leakages refer to small-flow leaks widespread in the hydraulic system, which should not be confused with those of higher flowrates (in technical-scientific literature called *burst leakages*). The generation and development of burst leakages, as known in international literature in these last fifty years, is closely related to the level of background leakages of which they are the natural evolution due to internal or external factors of the WDN, including: fatigue conditions due to traffic loads; operating pressure; thermic stress; laying conditions, etc.. Background leakages have a global influence on the WDN but generally do not affect the quality of the service in terms of minimum pressures, burst leakages are events that can have a local or global influence on the service depending on their position in the network and flow rate and in relation to the water capacity of the system. Therefore, the rationalization of asset management operations must be designed considering the reduction of background leakages as a relevant indicator of management control, which consequently has a positive effect on the generation and development of burst leakage. In this context, the replacement of old and deteriorated pipes must be done by optimizing the investment cost, but also with the aim of reducing background leakages. This objective cannot be achieved with a local vision, i.e., evaluating it with respect to the replaced pipes only, but globally, i.e., evaluating the extended hydraulic consequences of these replacements on the whole network. This is to avoid the effect of increased background leakages caused by the significant greater hydraulic conductance of the new pipes, which increases the operating pressures on the downstream portions of the WDN [8].

The paper shows a full-scale application of the methodology developed by us for asset management based on the optimal planning of districtualization, pressure control, hydraulic monitoring [9] and rehabilitation which has as a core the advanced modelling of the hydraulic behaviour of WDNs, through a calibration of the project model with an innovative paradigm based on water balances, integrating in the hydraulic analyses the water volumetric losses as a function of pressures [10]. This modelling is an essential support for an integrated and efficient design, with the aim of achieving the quality of the investment by minimizing costs with respect to results, and effective, with respect to any technical-regulatory constraint, for example as outlined by ARERA [11] for Italy. The following sections illustrate in order: the methodological approach adopted; the case study and application of the methodology for an executive planning of asset management interventions for the city of Bari, the capital of Puglia, in southern Italy, a municipality of over 300,000 inhabitants, as part of a public tender for the improvement of the asset managed by Acquedotto Pugliese (AQP), the largest Italian water company.

2 METHODOLOGICAL APPROACH

The advanced phenomenological modelling of WDN behaviour plays the role of a methodological tool to support the various planning and design activities. In fact, the innovative hydraulic model overcomes the limits of classical modelling, of EPANET and of all commercial software packages, and allows to consider the volumetric water losses as a function of the average pressure at the individual pipes level. In general, it allows a more realistic simulation of the WDN functioning, for example, considering the different types of users (private tanks and pumping, real elevation of georeferenced users meters, etc.) or insufficient pressure conditions for a correct service [6].

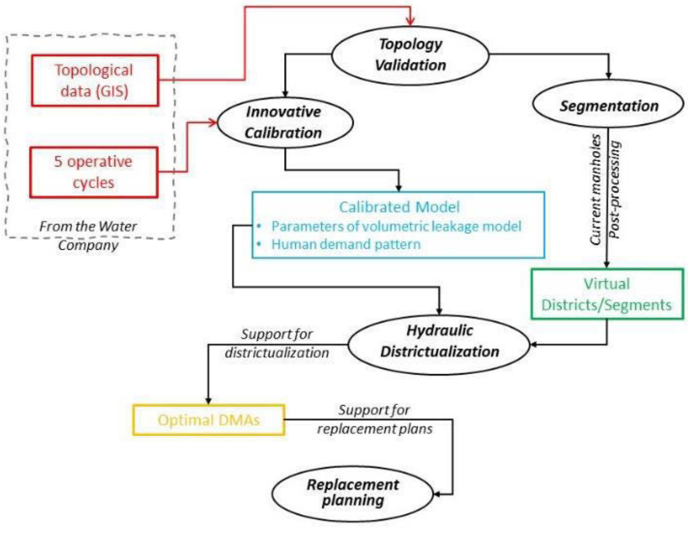

Figure 1. Flow-chart representing the adopted methodological approach.

Based on advanced hydraulic analyses, multi-objective optimization procedures, integrated with technical constraints, allows to obtain design solutions that are efficient (in the cost/benefit ratio) and effective (linked to each WDN features), supporting from a managerial perspective both to the current and future design choices. In fact, the design methodology adopted offers design alternatives defined in a paradigm of flexibility, through a structured approach to asset management aimed also at future opportunities of the water company.

Figure 1 shows the methodological process used to support the executive planning of the asset management of the city of Bari WDN, detailed in the following sections. In the following, the individual phases, as indicated in Figure 1, are described in greater detail.

2.1 Topology validation, enhancement of SIT data and integration of consumption data

The topology validation consisted in checking isolated nodes and/or pipes, disconnected network portions, verification of elevations through DEM, coherence of diameters, etc., and was performed, during the import of GIS data provided by AQP as ESRI® shapefile format. The GIS information data was acquired from (i) geodatabase extracted from the company GIS, containing data relating to pipes, devices (valves) installed along the pipelines and georeferencing of user meters, (ii) indication of the recently replaced pipelines, (iii) consumption database for each user and (iv) data recorded at the remote-controlled meters with reference to the year 2019. These checks made it possible to evaluate the AQP source database both with respect to the network topology and the actual functioning of the system reproduced by the advanced hydraulic model, functional to carry out all subsequent design phases.

2.2 Calibration of the model based on the concept of mass balance

The calibration of the advanced hydraulic model, which includes the volumetric losses at single pipe level as a function of pressure, was performed using the innovative approach presented by Berardi and Giustolisi [10], based on the concept of mass balance. The strategy adopted aims to identify (i) the parameters of the volumetric water loss model and (ii) the demand curve of the different districts. The strategy also allows the simultaneous calibration of the hydraulic resistances of the most hydraulically important pipes when useful. To calibrate the system, the measures of the hydraulic quantities made available by AQP for the year 2019 were used, as well as the information regarding the state of the system, i.e., the topology of the network, the presence of closed or partialized valves, in particular referring to the sectioning between the subnets, and the setting of the pressure control valves (PCV). To obtain a robust model to support management and planning activities, the calibration was carried out on the basis of five real daily operating cycles representative of different states of the system, as a combination of working days/holiday, winter/summer conditions. The calibration made it possible to define the model of volumetric losses and the characteristic demand patterns of the different operating conditions. More details about the calibration methodology adopted in the case study are provided by [12] presented at this conference. It should be noted that, in this methodological framework, it would be useful to carry out measurements of hydraulic quantities before carrying out the works designed to allow for the evaluation of the system condition variation with respect to the hydraulic model calibrated with the 2019 conditions.

2.3 Districtualization methodology

The districtualization is an operation of dividing the network structure of a WDN into districts to improve its management with respect to the monitoring of water or mass balances. For this reason, the technical tradition speaks of District Metering Areas (DMAs). Normally, DMA planning is a trial-and-error operation with which, empirically, the technician divides the network into homogeneous segments from the point of view of a certain characteristic (e.g., elevation, material and pipes age, diameter, etc.), also considering technical constraints such as: vulnerability of the system in relation to the main water transfer pipes, operating pressures in relation to the height of buildings, types of users. However, classic districtualization is not an optimized design process and does not produce design choices that can be replicated and scaled to other networks. Furthermore, the classic DMA design does not evaluate the opportunities for controlling the pressures in the network, through the reconfiguration of water flows following the closure of sectioning valves, which can reduce pressures and therefore stresses on pipes, thus reducing both the failure of the system components (burst leakages), that volumetric losses. Finally, the classic districtualization does not integrate the design of pressure control with PCV setting and location design.

To overcome all this, adopting a rational, efficient and effective strategy, also guided by the need to reduce volumetric losses, an advanced districtualization procedure was used, divided into two phases: (1) topological segmentation; (2) hydraulic districtualization [9]. Topological segmentation is formulated as a two-goal optimization which, on the one hand, maximizes the modularity index which measures the efficiency of the topological division into segments/modules and, on the other hand, minimizes the number of conceptual cuts that separate the segments/modules [13]. The hydraulic districtualization, or rather the real DMA design, aims at the optimal selection, in each of the conceptual cuts of the segmentation, of (i) closed sectioning valves, to reduce volumetric losses in compliance with the requirements of a correct service to individual users; (ii) flow meters, in the minimum number possible, to create measurement districts; (iii) the set points (also variable) of the PCV. The motivation of the division into two phases is connected to the hydraulic functioning of the WDN conditioned in a dominant way by the topological connective structure of the network. Therefore, segmentation is a cost/benefit optimization process for the virtual division of the topology with conceptual cuts near the nodes to obtain segments or modules that respect given objectives and constraints. Hydraulic districtualization is a cost/benefit hydraulic optimization process for installing sectioning valves or flow meters in conceptual cuts (that can be seen as manholes). The technical purpose is to reconfigure the water flows inside the network by reducing the volumetric losses as an effect of pressure reduction, with the constraint of respecting the operating pressures required for the different users during the operating cycle. Finally, advanced modelling allows the planning of PCVs both with local control (immediately downstream the device) and with Remote Real-Time Control (RRTC) through a "sentinel" node.

2.4 Support for districtualization

The methodological scheme adopted supports the DMA design allowing the water company, once the sectioning valves are fixed, to choose the number of DMAs to monitor in an optimal way (costs/benefits), leaving the possibility of integrating the flow monitoring, activating the districts nested within the current DMAs. These districts are, in fact, already prepared in a "topologically" efficient way with respect to the sectioning valves determined with the hydraulic districtualization [9]. In particular, the strategy allows adopting various selection criteria that can be integrated with each other and are not exclusive, such as the “expert” choice, based on the judgment of the technicians based on the knowledge of the system as well as evaluations of the technical feasibility of the installations; or the "metrological" choice, based on the preliminary analysis of flow rates/speeds expected in the positions where the flow meters will be installed, with respect to their technical characteristics and the aim of reducing uncertainties on the district's water balances.

2.5 Support for the rehabilitation and replacement of old and deteriorated pipes

Rehabilitation is not a management option for a "massive" reduction of volumetric losses since replacement interventions affect, for economic reasons, a small percentage of the WDN. On the other hand, WDNs are commonly characterized by widespread deterioration in relation to the average age of the pipelines. In this context, the replacement of old and deteriorated pipes must be done by optimizing the investment cost, but also with the aim of reducing volumetric losses, as a management indicator of the overall effects of the rehabilitation on the network. This objective cannot be achieved with a local vision, evaluating it only with respect to the replaced pipes, but globally, evaluating the extensive hydraulic consequences of these replacements, on the whole network. This has led to the awareness, in the technical-scientific field, that rehabilitation based on a local methodological approach can become a negative element globally for the hydraulic system even if locally positive for the replaced pipelines.

In the proposed methodology, support for pipes replacement comes after the choice of DMA and setting of PCVs. In fact, the choice of pipes to be replaced with the best cost/benefit ratio, i.e., investments/reduction of volumetric losses, depends on the new hydraulic structure obtained following the reconfiguration of the flows. Therefore, once the hydraulic districtualization solution has been assigned, the rehabilitation support tool allows to identify the pipes which, for a given budget limit, maximize an efficiency index given by the ratio between the reduction in expected loss following the replacement and the intervention cost.

This decision support system for asset management, as well as being implemented in the WDNetXL-WDNetGIS platform, is provided by IDEA-RT through Digital Water services developed to allow the analysis and immediate comparison of design alternatives aimed at helping the water company understanding of solutions, and for the following needs to support the execution of works [14].

3 CASE STUDY: THE TOWN OF BARI – PUGLIA - ITALY

The methodological approach illustrated in the previous section was adopted as part of a public tender that AQP launched in relation to the new regulatory framework for the sector defined in Italy by ARERA, an agency that controls the water companies like OFWAT in the UK. In particular, the requested design operation is aimed at reducing losses and optimizing WDN management. Parameter M1a, introduced by ARERA, defined as the volume of water loss per km of network per day, is the indicator on which the reduction of losses is measured [11]. The results of the design described below, therefore, will refer to this indicator.

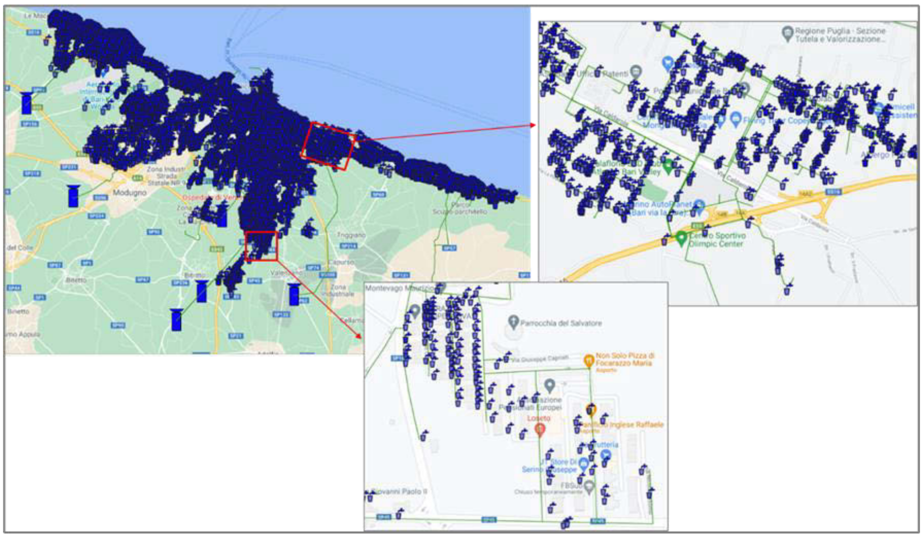

Figure 2. Model of the Bari network in QGis with georeferenced users.

The hydraulic model of the Bari network is made up of 9057 trunks and 7762 nodes. It was built starting from the acquisition of data provided by AQP in ESRI® shapefile format, with WDNetGIS [14]. The information on GIS data was acquired from (i) geodatabase extracted from the company GIS, containing data relating to pipes, devices (valves) installed along the pipelines and georeferencing of user meters, (ii) indication of the recently replaced pipelines, (iii) consumption database for each user and (iv) data recorded at the remotely controlled meters with reference to the year 2019. The model used considers the single georeferenced users as single points of consumption, and not aggregated in nodes as for the most of commercial software. This allows to better evaluate the effectiveness of management design with respect to the users. Figure 2 shows the Bari WDN in QGis with details on the representation of individual private users.

The Bari WDN is fed by eight reservoirs: (1) Palese-Santo-Spirito; (2) Bari-Modugno; (3) Nuovo di Bari-Bitritto; (4) Ceglie-Carbonara; (5) Bari-Ceglie del Campo; (6) Valenzano; (7) Torre a Mare; (8) Loseto. Figure 3 shows the altimetry of the Bari network with the aid of the 3D visualization of WDNetXL and indication of the flow meters at reservoirs.

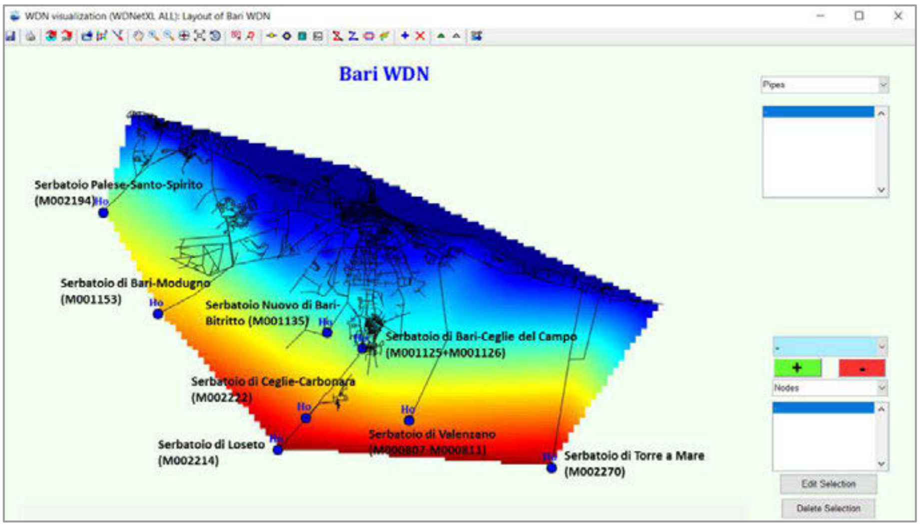

Figure 3. Altimetry of the Bari WDN by WDNetXL 3D visualization.

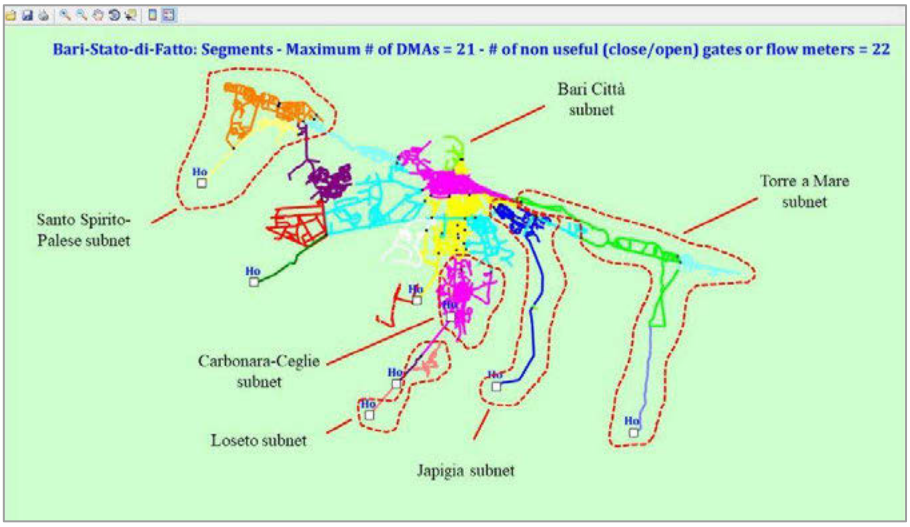

Figure 4. Pseudo-districts and subnets of the Bari network.

Based on the data provided, it emerged that the Bari WDN is divided into six sub-networks, each hydraulically independent, called: Santo Spirito-Palese, Bari city, Carbonara-Ceglie, Loseto, Japigia and Torre a Mare. Furthermore, the presence of many closed sectioning valves in the network leads to the identification of pseudo-districts, so defined because, as there is no presence of flow meters, these districts cannot provide information on monitoring for management purposes. It follows that most of the closed valves do not identify actual DMAs but only attempts to control the pressures (by means of closed or partialized valves), which alter the water paths in the network on a heuristic basis. Figure 4 shows the existing pseudo-districtualization for the network of Bari (with the different colours) and the 6 subnets.

The modelling of the Bari WDN was performed by assuming the existing subdivision of the global network into the six subnets in Figure 4. Two possible optimal segmentation scenarios for the allocation of district wells were considered according to the complexity of each subnet: (i) based on the positions of existing devices, in order to reduce the number of new manholes; (ii) not assuming the aforementioned constraint but involving the selection of the largest number of manholes in the current positions on the basis of the engineering judgment. Typically, the second scenario resulted in fewer flow measurements and isolation valves at the edge of the districts.

For the sake of brevity, the following section shows the application of the procedure for the Bari-City subnet only, and a general picture of results for all 6 subnets.

4 RESULTS AND DISCUSSION

The Bari city subnet is the only one to be fed by three reservoirs (Bari-Modugno; Bari-Bitritto; Bari-Ceglie del Campo). The hydraulic model of the Bari city subnet has 148 closed/partialized valves. These devices do not create real DMAs but aim to produce a local pressure control on a heuristic basis. The closed valves shown in the model are generally isolation (gates) valves used improperly as sectioning valves used to modify the water flows in the network in order to locally reduce the pressures. The throttled valves, on the other hand, produce a greater effect of pressure reduction in the hours of maximum consumption and have a minimum impact during the night hours in which, however, the pressures and losses are higher, thus resulting ineffective for losses reduction. These valves represent an inherent element of uncertainty linked to their real shutter degree.

For the Bari city subnet, some throttled valves act on main feeding pipelines, conditioning the water flow distribution in the network in the current scheme, while others allow for local pressure reduction. The remaining throttled valves produce local pressure control effects, generally superimposed on the control carried out by the PCVs in operation, which in the Bari city subnet are 4. Figure 5 shows the Bari city subnet with closed valves (red X), throttled ("Km" black) and the PCV ("PV" purple).

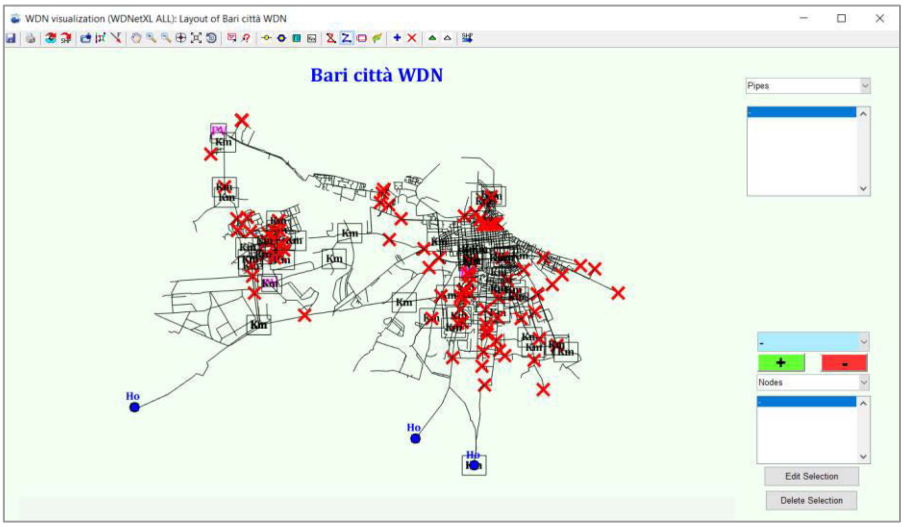

Figure 5. Bari city subnet with closed/throttled valves and PCV.

The subnet of Bari city has areas, in the neighbourhoods built between 1800 and 1900, with a widespread presence of doubling of pipes for final users' water distribution, determined by the stratification of different interventions over time. This configuration represents an anomaly in the topological structure and causes a greater risk of failure, or less reliability of the service, as well as producing greater volumetric losses due to the increase in the length of the pipelines and the number of joints. The study reported here, before proceeding with the DMA design, considered the removal of the double pipes (indicated in Figure 6 with the blue crosses) and the replacement of the remaining small diameters (40-80mm) to be replaced with a minimum diameter of 100mm.

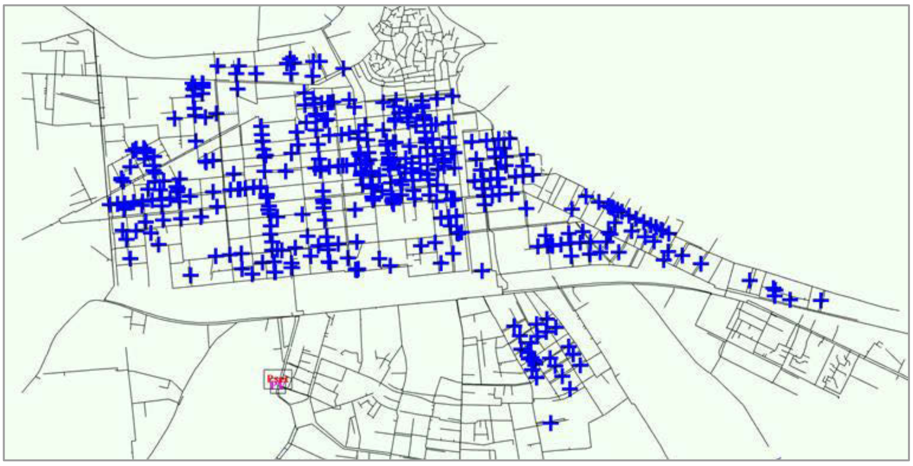

Figure 6. Double pipes removed in the Bari city subnet.

The calibration of the Bari city subnet model was carried out using the monitoring data provided by AQP for the year 2019, with reference to five days (operating cycles) representative of different operating conditions: weekdays and holidays in winter, weekdays and holidays in summer and New Year's Day (given the atypical functioning with respect to the remaining days of the year). Such a model calibration is more robust than any alternative based on data relating to a single specific day or representative of the "average" behaviour of the system, therefore more effective in supporting the DMA planning rehabilitation interventions aimed at reducing volumetric losses [10]. Figure 7 shows the hourly average flow rates measured at the three reservoirs of the subnet for the five days chosen (120 hours).

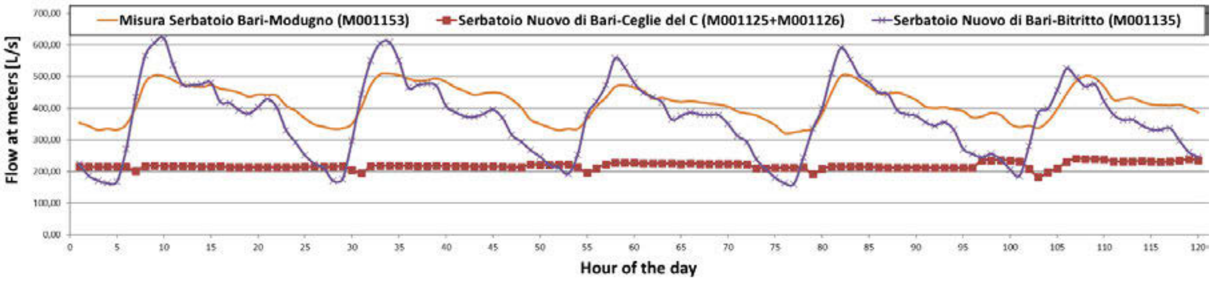

Figure 7. Hourly average flow rate measured at the three reservoir of Bari City subnet.

The calibration results return, for each calibration solution, the statistics relating to the average and maximum error at the flow meters, the average and maximum error of the mass balances at DMA level and the total real losses estimated as the ARERA M1a indicator.

Figure 8 shows the input, demand and leakages values for each of the five days considered in the calibration phase. It can be observed that day by day the calibration allows to identify a variable demand and the real losses as a function of pressure and deterioration. It is possible to note that the change in input is mainly associated with demand, while the losses remain almost constant, as expected for oversized networks such as the Bari WDN, further highlighting the robustness of the calibration strategy [10].

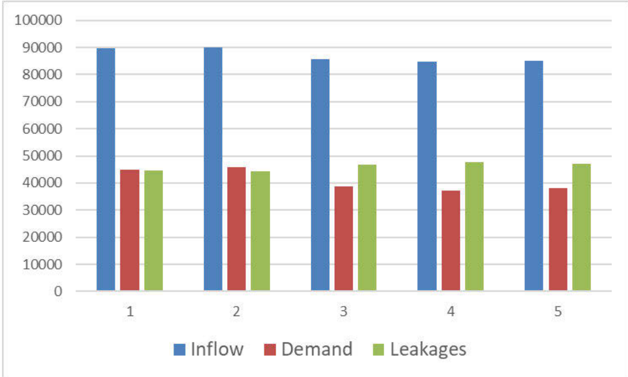

Figure 8. Input, demand and leakages for the five network operating conditions.

Figures 9-11 report the main results of the hydraulic analysis of the Bari City subnet following the model calibration procedure. Figure 9 shows the temporal trend of the input water volumes of the network, highlighting the trend of leakages as a function of the pressure and volumes feeding the private tanks, a particular element of the analysed network; Figure 10 shows the trend of the average pressures inside the network; and Figure 11 shows the spatial distribution of the linear leakages index (m^3/ km/day) equivalent to the M1a index for each pipe of the network.

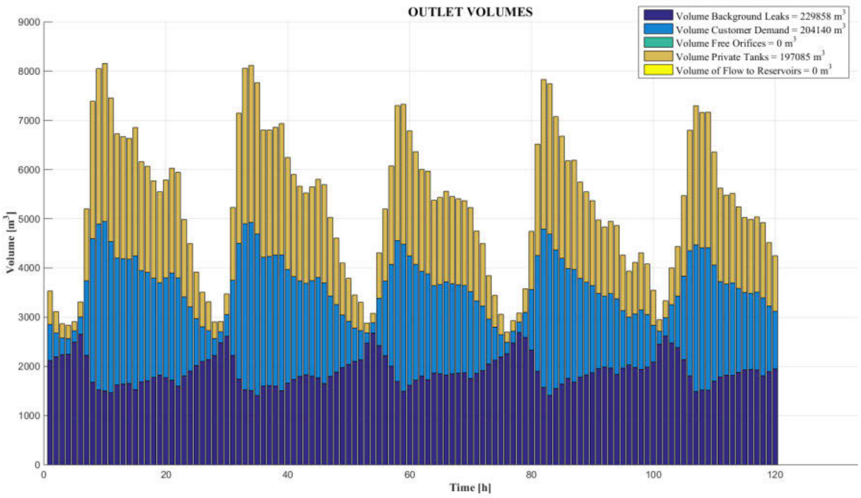

Figure 9. Volumes of demand components of the Bari city subnet during the five chosen operating cycles.

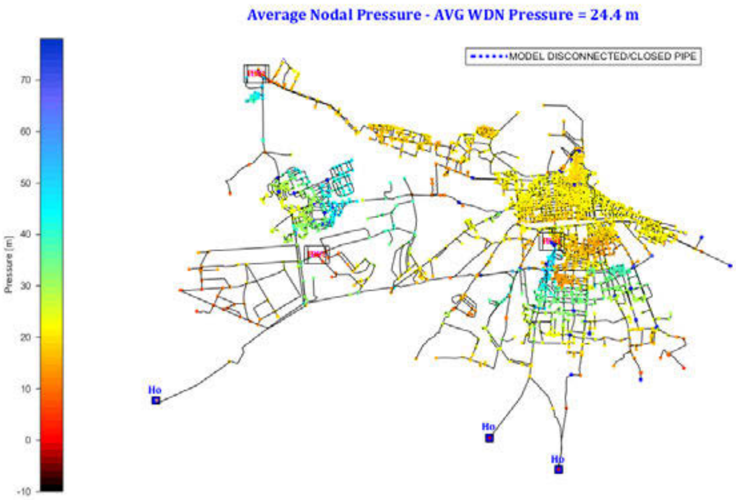

Figure 10. Trend of average pressures within the subnet.

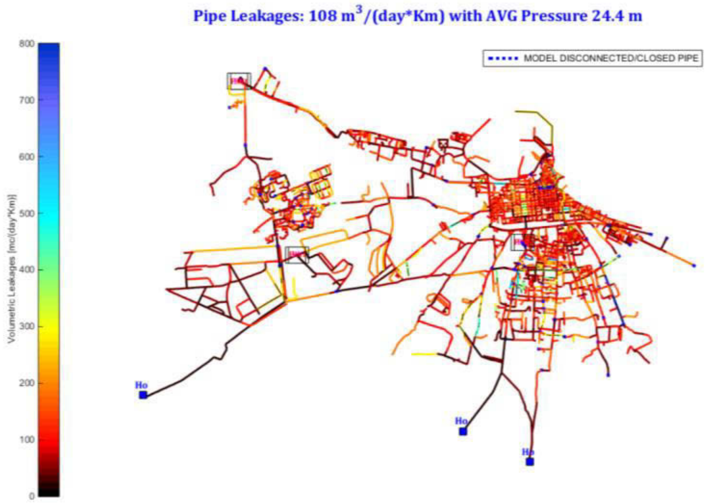

Figure 11. Linear losses for each pipe of the subnet that define the M1a indicator.

Based on the hydraulic analysis using the calibrated model, the DMA design had the main objective of rationalizing the subdivision of the network for future management purposes, pursuing the goal of containing the areas subject to pressure fluctuations and lowering of the pressure regime in the network. To support efficient design solutions, the design process took as reference two network conditions (i) the current condition, as per the calibrated model; (ii) the project condition following the removal of the double pipes described above. In addition, the design considered the need to preserve the operational continuity expressed by AQP, promptly evaluating the overlap between the existing hydraulic scheme and the optimal district configurations designed independently of the current scheme. As mentioned above, districtualization is a two-stage process: (i) the segmentation of the topological network structure of the WDN; (ii) and the real hydraulic districtualization in relation to the decision on the installation of sectioning valves and flow measurements.

For the Bari city subnet, this optimal districtualization process was not used to produce design solutions ex-novo, but to support engineering judgment and system knowledge in the allocation of sectioning valves or flow meters. The design process integrated information on the position of sectioning valves and optimized flow meters with evaluations on the engineering judgment also related to the position and setting of the PCV. The evaluation of each alternative was checked in detail in terms of impact on the hydraulic functioning of the entire subnet of Bari city. As a result, this objective has minimized the number of throttled valves currently present. This process reconfigured the water flows in a topologically and hydraulically optimal way while maintaining the current supply schemes and the existing PCVs. The hydraulic districtualization solution chosen (Figure 12) to support the subsequent engineering assessments represents the best compromise between the maximum leakage reduction and the minimum number of flow meters in the network.

It should be noted that the results of the districtualization procedure also allows metrological evaluations of the flow meters planned. For example, for each flow meter it is possible to carry out a survey on the expected speeds and flows, thus being able to select the most important meters that make the monitoring and water balance activity more reliable associated with the future management of the network, based on the planned districtualization (i.e., avoiding situations in which the operating conditions cause the flow in the meter to reverse). Figure 13 shows the general picture of the DMAs identified for the Bari city subnet, also considering the PCVs within the system. In fact, the DMA planning is integrated with the evaluation of the PCV set point that feed the system. Figure 14 shows the consequent trend of leakages and the average pressure of the network. The proposed solution allows to reduce the volumetric losses as a function of pressure, i.e., to reduce the values of the index of linear losses M1a for each pipe and for the entire network.

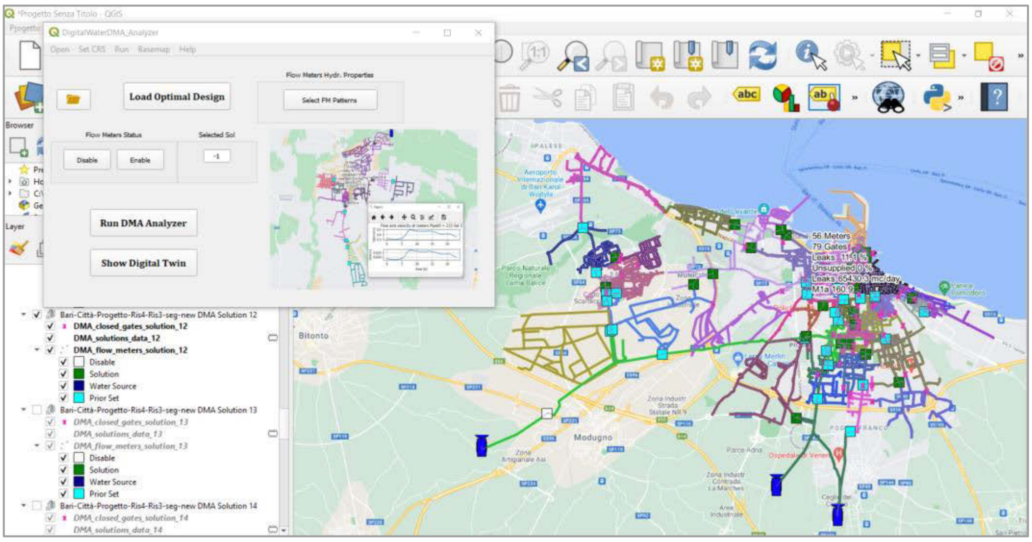

Figure 12. Districtualization solution chosen for the Bari city subnet (solution 12).

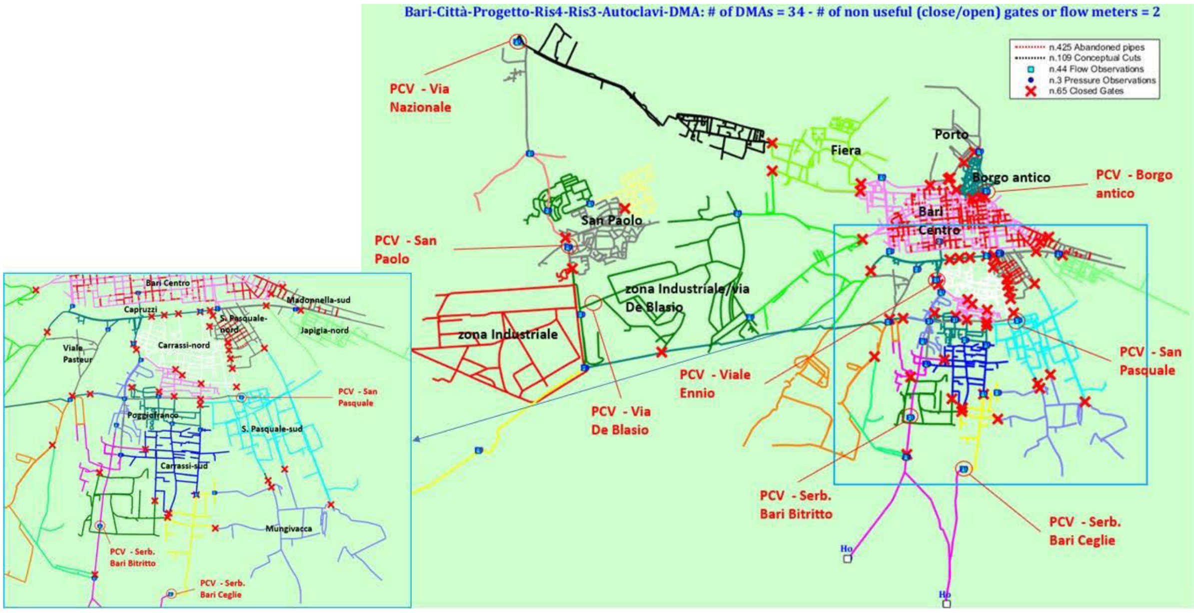

Figure 13. DMAs identified for the Bari City subnet, with indication of the project PCVs.

Table 1. Summary of devices and DMA after and before DMA design

	N. DMA	N. Closed valves	N. Partially closed valves	N. Flow meters	M1a index	Average pressure** [m]
Current condition	27*	95	56	3	108.65	24.40
Design condition	34	65	8	43	92.9	24.20

** Non-metered pseudo-districts; ** Assessed on 5 different operating cycles (120 hours)*

Table 1 shows a summary/comparison between the devices and the districts present in the current status and in the project condition of the districtualization in the Bari city subnet, without any rehabilitation intervention.

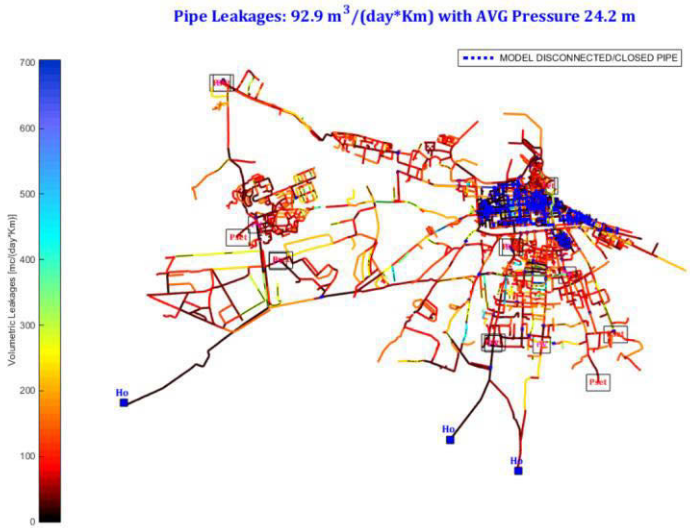

Figure 14. Distribution of volumetric leakages in the subnet of Bari city following the districtualization.

The rehabilitation support strategy was developed coherently with the integrated DMA design. Therefore, the rehabilitation interventions were planned with reference to the districtualization solution chosen (Figure 13).

For the Bari city subnet, different investment levels have been identified corresponding to a value up to 20% of the replacement cost of the entire system, considering the pipes with the maximum efficiency index, calculated as the ratio between the intervention cost and the expected leakage reduction. The rehabilitation support procedure determines the pipes to be replaced in a multi-objective scheme, looking at the best cost/benefit ratio, i.e., investments (cost of replacement compared to the cost of replacing the entire system)/reduction of volumetric losses (assessable through the advanced model starting from the new hydraulic structure obtained following the districtualization).

Table 2 – Rehabilitation plans for the subnet of Bari city as districtualized.

Cost [%]	Cost [€]	# Pipes	Replaced pipes length [m]	Volumetric leakages reduction [m³/days]	Efficiency [-]
15.00%	19528731	238	62609	14161	2.50
15.98%	20801895	263	66968	14912	2.47
17.01%	22142303	286	70995	15633	2.43
18.03%	23472519	312	75344	16295	2.39
19.05%	24795509	334	79973	17051	2.37
20.00%	26037678	360	84145	17659	2.34

Table 2 shows 6 intervention plans among the 20 developed by the procedure. For each of the plans obtained, the number of pipes replaced, the total length of the same, the efficiency index and the expected reduction of losses on a daily basis are reported. Figures 15 and 16 show the rehabilitation plan corresponding to a cost of pipes replacing of 15% (displayed in the QGIS environment, indicating the ranges of the M1a value within the network and the position of the devices) and the relative results obtained in terms of volumes supplied in the 5 operating cycles considered.

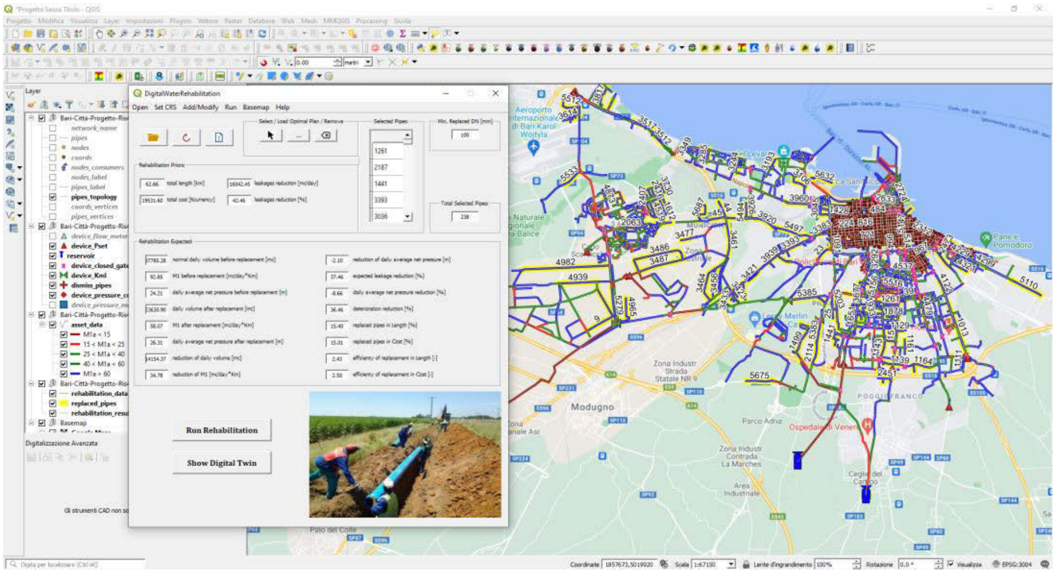

Figure 15. Rehabilitation plan corresponding to a replacement cost of 15%.

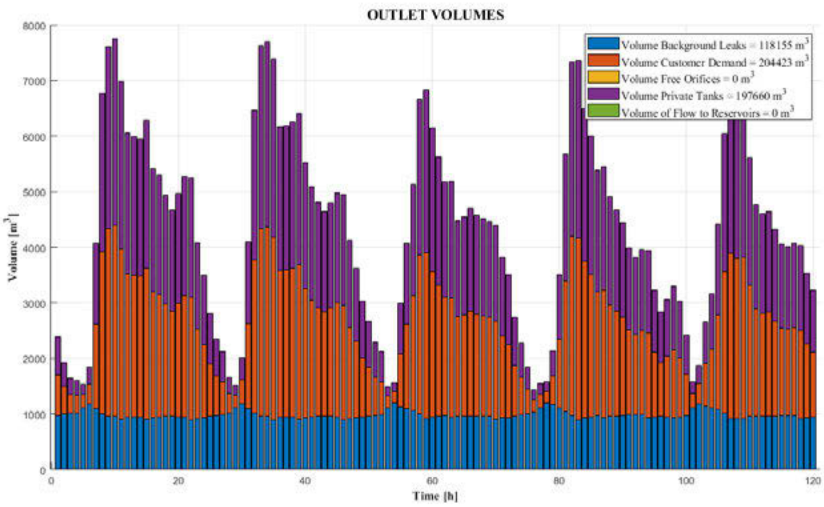

Figure 16. Volumes of the demand components of the Bari city subnet following rehabilitation.

In conclusion, the overall results should be reported. Table 3 shows the results relating to the districtualization phase. Figure 17 shows the complex of 68 DMAs identified for the entire city of Bari. Finally, Table 4 shows the expected reduction of annual leakages that can be achieved with a pipe replacement (optimal in a hydraulic/topological sense) approximately of 20% for each subnet.

5 CONCLUSIONS

The complexity of the Bari network, albeit divided into six separate subnets, suggested using districtualization as a strategic tool for all subsequent asset management activities. Therefore, with reference to each subnet, in addition to reducing water losses, the primary objective of the districtualization was the rationalization of the system in terms of enhancement of the network operating, with the possibility of its monitoring and control. This has allowed a drastic reduction in the use of empirical expedients aimed at local pressure control, such as gate valves currently partialized or closed, in favour of the reconfiguration of water flows in the network by means of sectioning valves with the minimum number of flow measurements at the edge of the designed DMAs and use of PCVs. The strategic value of the design support here reported is demonstrated in every aspect by the advanced hydraulic analysis and operational-managerial assessments.

Table 3 – Design solutions based on system conditions during the year 2019.

	Torre a Mare	Japigia	Bari Città	Carbonara-Ceglie	Loseto	Santo Spirito-Palese	Total
#DMA	5	5	34	12	1	11	68
#Closed Valves	3	4	65	18	-	10	123
#Flow meters	5	5	44	12	1	11	78
# PCV	2	2	8	2	-	2	16
Leakage Reduction [%]	36,31	11,31	18,14	17,29	-	25,36	19.95
M1a [m³/km/day]	44,20	123	92,90	40,70	-	45,10	77.2
Leakage Reduction [m³/year]	402.660	247.650	3.052.870	235.510	-	484.350	4.780.360

Table 4 – Reduction of volumetric losses following rehabilitation.

	Torre a Mare	Japigia	Bari Città	Carbonara Ceglie	Loseto	Santo Spirito-Palese	Total
Leakage Reduction [m³/year]	434.815	1.269.567	6.445.684	438.202	-	636.631	9.224.899

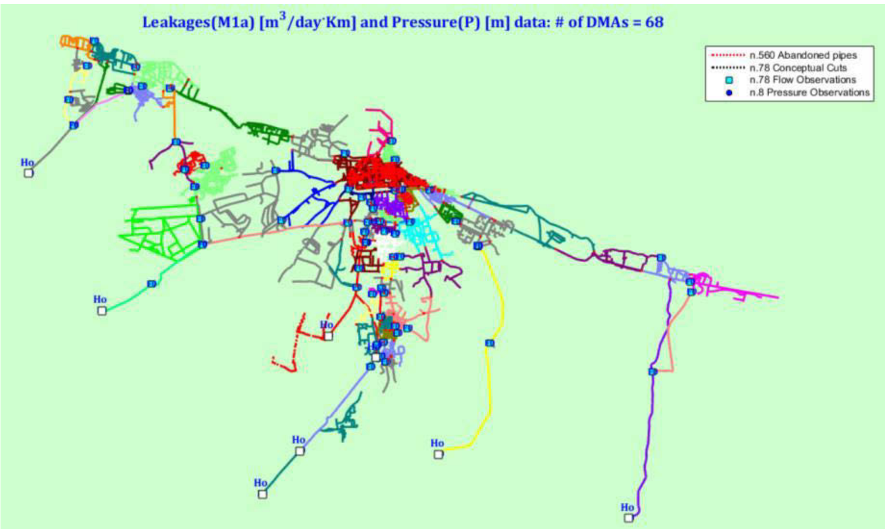

Figure 17. DMA designed for the Bari network.

The decision support system for districtualization, using dedicated Digital Water services, allowed to select, among all the optimal positions for flow meters, the most effective with respect to management budget constraints (i.e., limiting the maximum number of meters to be installed), to the expert knowledge of the network about possible technical constraints, as well as metrological evaluations with reference to the expected flow rates at the measurement points. Therefore, the innovative scheme to support districtualization allows to choose the number of DMAs to be activated with flow meters, at the same time indicating perspective measurement stations nested in the chosen DMAs. These perspective meters are useful for planning future investments and preparing the system for the Internet of Things (IoT) framework of the near future. Furthermore, they can be used for mobile meters and/or to organize active leakage control activities even for long time, because they are not invasive for the system as they are based on sections already prepared in the project.

6 ACKNOWLEDGEMENTS

This paper was financed by European Union - PON Ricerca e Innovazione 2014-2020 E FSC, call D.D. 13 July 2017 n. 1735, Project "*Energidrica - Efficienza energetica nella gestione delle reti idriche*" (code ARS01_00625). Authors want to thank the academic spin-off company IDEA-RT s.r.l. (www.idea-rt.com) for providing WDNetXL software and digital services and related pictures.

7 REFERENCES

[1] Todini, E., and Pilati, S., "A gradient method for the solution of looped pipe networks", Computer Applications in Water Supply, vol.1, 1988, pp. 1-20.

[2] Rossman, L.A., EPANET 2.0 User Manual. Water Supply and Water Resources Division, National Risk management Laboratory, USEPA, Cincinnati, OH, 2000.

[3] Todini, E., "A more realistic approach to the extended period simulation of water distribution networks", in Proc. CCWI 2003 Conference, London, UK: Taylor&Francis, 2003, pp. 173-184.

[4] Wagner, J.M., Shamir, U., and Marks, D.H., "Water distribution reliability: simulation methods", Journal of Water Resources Planning & Management, vol. 114, no. 3, 1988, pp. 276-294.

[5] Giustolisi, O., Savic, D.A., and Kapelan, Z., "Pressure-driven demand and leakage simulation for water distribution networks", Journal of Hydraulic Engineering, vol. 134, no. 5, 2008, pp. 626-635.

[6] Giustolisi, O., and Walski, T.M., "A Demand Components in Water Distribution Network Analysis", Journal of Water Resources Planning & Management, vol. 138, no. 4, 2012, pp. 356 -367.

[7] Germanopoulos, G., "A technical note on the inclusion of pressure-dependent demand and leakage terms in water supply network models", Civil Engineering Systems, vol. 2, no. 3, 1985, pp. 171-179.

[8] Pelletier, G., Mailhot, A. and Villeneuve, J.P., "Modeling Water Pipe Breaks. Three Case Studies", Journal of Water Resources Planning & Management, vol. 129, no. 2, pp. 115-123.

[9] Laucelli, D., Simone, A., Berardi, L., and Giustolisi, O. "Optimal Design of District Metering Areas for the Reduction of Leakages", Journal of Water Resources Planning & Management, vol. 143, no. 6, 2017, pp. 04017017-1-12.

[10] Berardi, L., and Giustolisi, O. "Calibration of Design Models for Leakage Management of Water Distribution Networks", Water Resources Management, vol. 35, 2021, pp. 2537–2551.

[11] ARERA, Deliberazione 27 Dicembre 2017 917/2017/R/IDR - Regolazione della Qualità Tecnica del Servizio Idrico Integrato ovvero di ciascuno dei singoli servizi che lo compongono (RQTI), 2017 (in Italian).

[12] Giustolisi, O., Ciliberti, F., Laucelli, D., and Berardi, L., "Mass Balance Calibration of Water Distribution Networks: application to a real case study", in Proc. WDSA-CCWI 2022, Valencia, Spain 2022.

[13] Giustolisi, O., and Ridolfi, L. "A novel infrastructure modularity index for the segmentation of water distribution networks", Water Resources Research, vol. 50, no. 10, 2014, pp. 7648–766.

[14] Idea-RT, "WDNetXL-WDNetGIS", http://www.idea-rt.com/products-our-job/, June 2022.