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Integrated pressure control strategies for sustainable management of water distribution networks

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Abstract. Pressure control in urban Water Distribution Networks (WDNs) allows to reduce water losses, delays asset deterioration and makes effective replacement works. This contribution presents an integrated approach to control pressure for leakage reduction that combines a recent strategy for optimal design of district metered areas (DMAs) with optimal setting of pressure reduction valves. DMA design strategy encompasses the possibility of reconfiguring water flows by closing some gate valves at district boundaries, while the optimal setting of PRVs driven by local or remote real time controls improves leakage reduction and reliability of final solution. The integrated approach is implemented into the WDNetXL platform for advanced WDN analysis, planning and management and is demonstrated on a real urban WDN in Southern Italy. As such, this work proposes an innovative methodology while demonstrating its transfer to water utilities and practitioners to support decisions in real-world complex scenarios.

1 Introduction

The majority of urban Water Distribution Networks (WDNs) in Europe were built in the last century and, according to technical literature, they already surpassed their service life. The most evident effect of such infrastructure deterioration is represented by the water losses in terms of *volumetric real losses* and leakages from pipe *bursts*. Differently from leakages from pipe *bursts*, showing higher flow rate but reduced time for detection and repair, *volumetric real losses* encompasses both *background leakages* and *unreported bursts*, thus have major impact on water balance on annual scale [1]. Keeping water losses under control might have positive effects on WDNs, not only on saving of water resources by reducing the carbon footprint for water abstraction, treatment and pumping, but also on improving system hydraulic capacity and increasing asset longevity [2]. As water losses are due to the combined effect of asset deterioration and pressure, they can be reduced following two main strategies: (i) planning effective asset rehabilitation works and/or (ii) implementing optimal pressure management (e.g. [3]). Actually, although asset rehabilitation entails a *medium-long* term solution aiming at renewing the infrastructure, it is usually more expensive than pressure management and in many European areas, the investments needed are much higher than the available budget. In addition, filed experience demonstrates that pipe replacement not preceded by careful analysis of current and expected WDN hydraulic conditions, is likely to increase leakages. This is explained considering the combined effect of reduced hydraulic resistance and reduced leakages along new pipes, which result into higher pressure (and leakages) in downstream network sections. As such, pressure management represents the first step to approach WDN management also in conjunction with rehabilitation plans. Besides reducing *volumetric real losses*, it was reported [4] that pressure control strategies result into reduced rate of rising of *reported bursts*.

When pressure exceeds the value for sufficient water supply service to customers (i.e. service pressure) it is usually managed using pressure reduction valves (i.e. PRV). In the last two decades, a number of works investigated optimal strategies to operate PRVs based on *local* pressure reading (i.e. immediately downstream of the valve), (e.g. [5-7]), while Information and Communication Technologies (ICT) allowed the implementation of *Remote Real-Time Controlled* (*RRTC*) PRVs. A recent comparison [1] between *local* and *RRTC* PRVs demonstrated the increased efficiency in pressure control and leakage reduction of *RRTC* PRVs, besides the known advantages in terms of robustness of the control.

To implement effective leakage reduction strategies, the international literature (e.g. [3]) recommends WDN monitoring through district metering areas (DMAs). DMAs are WDN sub-portions usually designed for water balance purposes aimed at analysing water consumptions and, eventually, detect anomalies due to leakages or unauthorized consumptions. As such, pressure/flow monitoring based on DMAs can provide data to pre-localize new leakages and speed up detection and repair activities. In addition, monitoring flow and pressure is of primary importance to calibrate hydraulic models of

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WDNs to perform analysis and support planning and management decisions.

The design of DMA primarily follows WDN topology as it is based on the identification of those pipes that separate each DMA from the rest of the WDN, where flow meters should be installed. Previous works proposed various approaches for the optimal identification of DMAs such as: the maximization of reliability (e.g. [8-9]), the minimization of the number of open valves at DMA boundaries (e.g. [10]) or even accounting for resilience and minimum pressures [11]. Recently, the observation that DMA design requires the closure of gate valves aimed at reducing the number of flow meters, suggested the idea of driving DMA design by the achievable leakage reduction [12]. In fact, changing the original water paths through valve closures may reduce pressure and leakages. Laucelli et al. [13] proposed a structured approach for DMA design based on (i) topological subdivision of WDN into conceptual segments separated by *conceptual cuts* and (ii) the design of DMAs by identifying *conceptual cuts* where gate valves should be closed to minimize volumetric water losses. The solutions are obtained by solving a multi-objective optimization problem where the position of closed valves is driven by minimizing both the number of (expensive) flow meters and the volumetric water losses.

This work presents the integration of the two main pressure control approaches, i.e. operating PRVs and designing DMAs. Such integration was motivated by two main reasons. On the one hand, many WDNs already implement pressure control using PRVs, thus they should be considered while designing DMAs encompassing the change of water paths in the system to guarantee the pressure for correct water supply everywhere. On the other hand, the integration of the two pressure control strategies is expected to provide more effective management through the network and higher robustness in front of abnormal conditions (e.g. change of water demands).

The strategy has been proved on few real WDNs located in Southern Italy to support a consultant company (i.e. IA.ING s.r.l.) in designing DMAs aimed at system monitoring and leakage reductions, as required by the water utility managing the systems. Many of the analysed WDNs already implemented PRVs with *local* controls and show quite high leakage rate, even larger than 50% of total inlet water volume with more than 50 m^3/km of water lost per day.

The strategy was implemented in the WDNetXL system for advanced analysis, planning and management of WDN[14], since it already integrates customizable optimization components and, more important, consistent and robust hydraulic analysis module as a key requirement for supporting WDN leakage management by pressure control. In addition, making such advanced analysis on the WDNetXL platform working in Excel and GIS environment is intended to provide a pragmatic example of just-in-time transfer of research achievements to practitioners.

2 Pressure management through DMA design

In real WDN management context the design of DMAs mainly follows empirical approaches, resorting to the visual analysis of WDN topology and the expertise of technicians on the specific system. Unfortunately, this activity is rarely supported by WDN hydraulic analysis encompassing pressure-dependent modelling of leakages and does not take into account measurable indicators of the effectiveness of WDN division into districts. In addition, technicians and decision makers are usually sceptic in implementing "optimal" solutions that are not flexible and adaptable to local conditions and practical constrains (e.g. unfeasible installation of meters, precision of metering devices, etc.). The structured approach proposed in [13] is conceived to overcome such limitations, allowing technicians to follow and check the DMA design process at all phases, while allowing to drive and adapt final solutions to practical needs.

The first design phase entails the *topological segmentation*, where the WDN is divided into *conceptual modules*. Such phase solve a two-objectives optimization aiming at finding optimal trade-off solutions entailing the minimum number of *conceptual cuts* separating the *modules* and the maximum value of the *infrastructure modularity index* [15-16]. Such index comes from the reformulation of the modularity index developed in complex network theory, to account for the peculiarities of WDN as infrastructure systems. *Topological segmentation* returns a number of solutions that has the property of being nested into each other, meaning that *conceptual cuts* in segmentation solutions with lower number of segments are also in solutions with higher number of segments.

The second phase, *hydraulic DMA design*, identifies the *conceptual cuts* in one of the *topological segmentation* solutions where gate valves should be closed in order to reconfigure water paths and reduce pressure. This phase encompasses the solution of a multi-objective optimization aimed at minimizing the number of flow meters (i.e. *conceptual cuts* with no closed valves) and the expected *volumetric real losses*, while ensuring sufficient pressure to correctly supply water demands.

It is worth noting that such DMA design strategy represents a sort of redesign of existing WDNs. Indeed, it allows reconfiguring water paths as much as possible considering the constraints represented by existing pipes, current deterioration conditions and actual water requests.

3 Integrating PRV planning and DMA design

Pressure control via pressure reducing valves (PRVs) might resort to *classic* (*local*) or *remote real-time control* (*RRTC*) strategies. *Local* control consists of modulating the valve opening to keep a desired target pressure right downstream of the devices. This strategy usually employs hydro-mechanic valves where target pressure reading is integrated in the same devices. Since a *local* PRV modulates pressure from upstream of the controlled area, the change of customers' water demands over time causes a change of head losses through the WDN and requires defining a time-pattern of target pressure values in order to guaranteeing sufficient pressure conditions at peak demand and avoiding excess of pressure at low demand hours.

Remote real-time control (*RRTC*) of PRVs consists of modulating the valve opening based on a target pressure at a *critical* node, which can be far positioned from the PRV. ICT solutions are available to transmit pressure readings from *critical* node to a programmable logic control (PLC) unit that modulates the opening of the valve using electric actuators. Differently from *local* PRVs, *RRTC* strategies requires to define a target pressure at the critical node that does not change over the operating cycle since it is usually close to the pressure required to supply water (e.g. depending on local elevation or the height of buildings). As such, planning *RRTC* controls strategies are much more robust than *local* ones, where the pattern of valve opening strictly relies on the demand scenario assumed during the simulations.

It was demonstrated that the comparison between *RRTC* and *local* PRVs pressure control strategies for leakage management requires the advanced hydraulic modelling of WDNs. Although the details of the model adopted in this work and implemented in the WDNetXL system can be found in few reference works (e.g. [17], [1]), it is worth to mention some key modelling requirements to support the planning of pressure control.

•The pressure-driven modelling of all water demand components is mandatory to provide a hydraulically consistent analysis of possible pressure-deficit conditions, while searching for optimal solutions [18].

•Model of volumetric leakages as pressure-dependent outflow distributed along pipes. The analyses in this work adopt the Germanopoulos' model [19], where leakage outflow from the *i*th pipe is computed as $q_i=\beta_i P_i^{\alpha i}$, with P_i average pressure in the *i*th pipe, α_i and β_i parameters depending on pipe deterioration and material.

•Advanced hydraulic modelling of *RRTC* PRVs assuming, for planning purposes, that pressure at *critical* node is reached instantaneously (i.e. without defining *a priori* the time-pattern of *local* control).

The strategy for DMA design mentioned above introduces a reconfiguration of the flow paths that result into changes of head losses within the network, thus locally modifying pressures from the original configuration. PRVs introduce a global control of pressure by modulating the hydraulic head (i.e. the energy) from upstream of the controlled area, aiming at minimizing the excess of pressure while matching the minimum pressure for correct supply.

It can be argued that high global reduction of pressure through PRVs means to reduce the hydraulic head (energy) available in the network, thus leaving less room for pressure reduction by reconfiguring water paths. This circumstance, in turn, would result into less closed gate valves and more flow meters to be installed on *conceptual cuts* at DMA boundaries. *Vice versa*, opening PRV leaves more chances to close gate valves, change water fluxes and increase head losses due to the increase of flows along the water paths that remain active. The latter conditions would result into lower number of flow meters, with reduced installation and maintenance costs as well as more reliable water balance.

Due to the redundancy of water paths in a WDN, there is not a unique optimal solution but many alternatives that minimize the number of flow meters and volumetric real losses, as a combined effect of PRVs and DMA configurations.

The procedure for integrating PRVs planning and DMA design follows two main steps.

1) Identification of the PRV control variables, i.e. the target pressure at critical node in *RRTC* strategies or multiple values of the time-pattern target pressure in *local* control strategies. Actually, *RRTC* PRVs represents the desired pressure condition at critical node that should be satisfied also by *local* control. As such, identifying the unique target pressure at critical node of *RRTC* PRVs would provide the time-pattern of target pressure to be implemented in *local* control. As mentioned before, the hydraulic model WDNetXL enables the simulation of *RRTC* PRVs.

2) Search for optimal pressure control solutions by solving the same multi-objective optimization problem as for the *hydraulic DMA design* (see section 4), including the PRVs control target value(s) identified in the first step as additional decision variables.

4 Case Study

The integrated strategy was used to support the optimal design of DMAs aimed at improving flow and pressure monitoring while reducing leakages in a real urban WDN. The system serves a population of about 12,000 inhabitants and the procedure was based on the preliminary implementation of the WDN hydraulic model in the WDNetXL platform (Figure 1).

The model included 987 nodes and 1105 pipes, with a pipeline length of about 38 km. The original WDN configuration already included a *local* PRV whose pressure settings are reported in Figure 2. Actually, such valve only modulated one line feeding the system, while a partially closed gate valve modulated the pressure along a second feeding line (black square in Figure 1). Based on annual water balance it was estimated that water losses are about 58% of total inlet volume, resulting into 59 m^3/km per day.

Before implementing the integrated procedure for optimal DMA design, the original feeding scheme was reconfigured by closing the second original feeding line in order to make pressure controllable through the PRV.

It was assumed that a *RRTC* PRV can be installed and the control node was set as reported with "P_{set}" in Figure 3. Consistently with local rules of the water supply service and with the presence of private water storages, the minimum pressure to be guaranteed at customers was set to 6 m of water column (mWC).

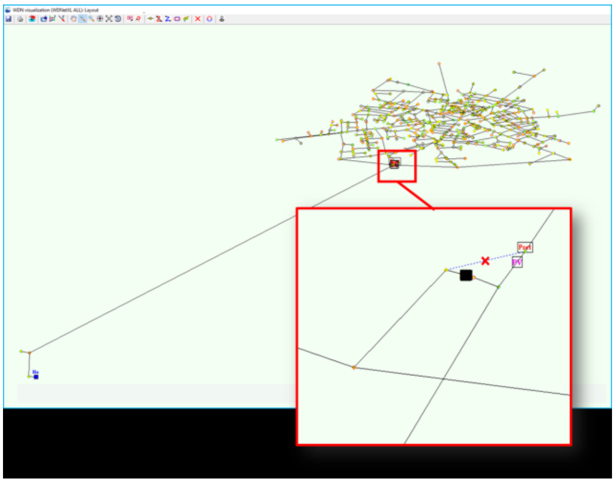

Fig. 1. WDN layout and details on feeding lines.

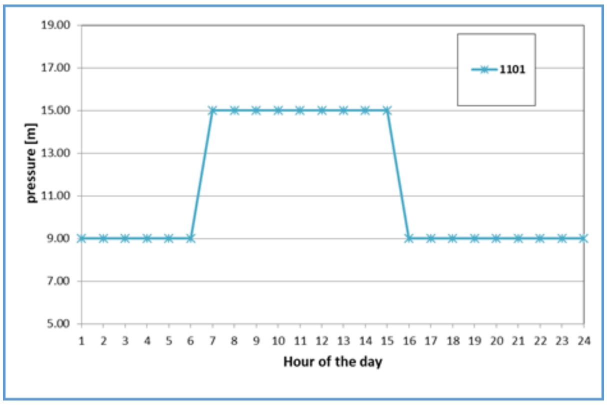

Fig. 2. Original pressure settings of the *local* PRV.

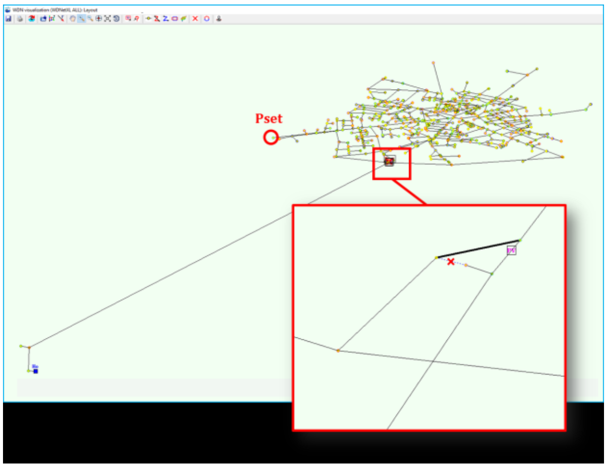

Fig. 3. New feeding configuration and location of critical node controlling *RRTC* PRV.

The first phase identified 25 solution of *topological segmentation* with a maximum number of 56 conceptual cuts separating 25 *segments/module*. Figure 4 reports the topological segmentation, with the maximum number of segments, which was assumed for the second step searching for *optimal hydraulic DMA design* while simultaneously optimizing the pressure settings at critical node of the *RRTC* PRV.

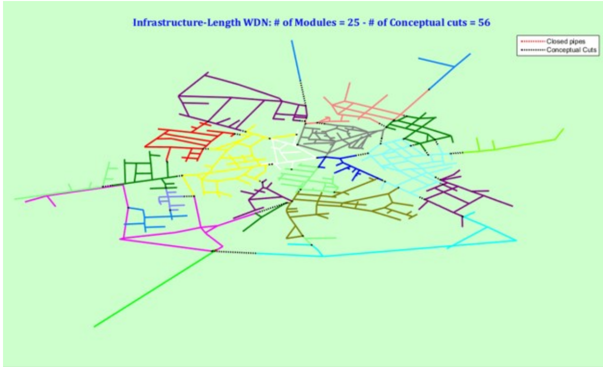

Fig. 4. Network *topological segmentation*.

The second phase resulted into six solutions encompassing various leakage reduction as percentage of the original leakage volume and linear water losses, as reported in Table 1.

Table 1. DMA design solution accounting for *RRTC* PRV.

Solution	**1**	**2**	**3**	**4**	**5**	**6**
# DMA	25	25	25	25	25	25
# Closed gate Valves	31	30	29	28	27	26
# Flow meters	25	26	27	28	29	30
RRTC PRV P_{set} [mWC]	16	12	10	10	10	10
Leakage reduction [%]	0	15.2	21.2	21.5	22.5	22.8
Linear losses [m^3/km/day]	59.3	50.0	46.5	46.3	45.7	45.5
Average pressure [mWC]	19.5	16.7	15.3	15.3	15.2	15.2

Each solution identifies a different set of closed gate valves and pressure meters to be installed in the *conceptual cuts*. In fact, the number of flow meters and closed gate valves sums up to 56 in all solution. In addition, each solution reports the optimal pressure set value at control node of the *RRTC* PCV. It is worth noting that different solutions represent different trade-offs between the number of flow meters and the leakage reduction. For example, solution 1 shows the minimum number of flow meters although it does not reduce the original leakages. Such solution also shows the maximum value of P_{set} at *RRTC* PRV control node.

Solutions from 2 to 6 encompass more flow meters and less gate valves, although they are located on different sets of *conceptual cuts*. The different reconfiguration of flow results into various scenarios of alteration of flow paths, leading to different local pressure configurations. In fact, although solutions from

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3 to 6 show the same P_{set} value controlling *RRTC* PCV, they show a progressively increasing leakage reduction.

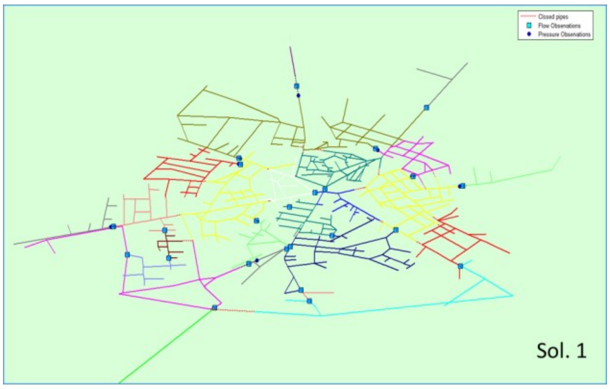

Fig. 5. DMA design solution 1.

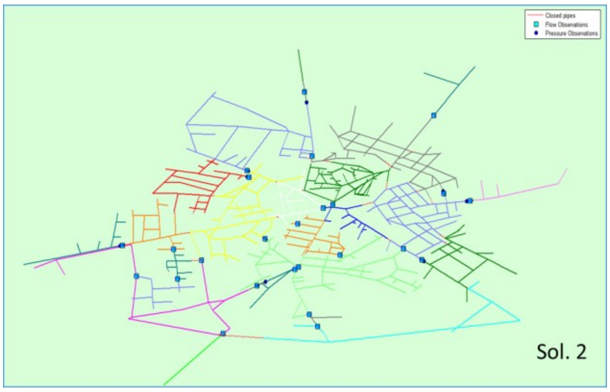

Fig. 6. DMA design solution 2.

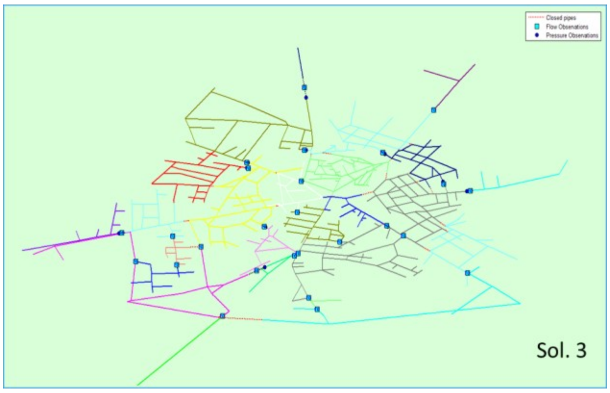

Fig. 7. DMA design solution 3.

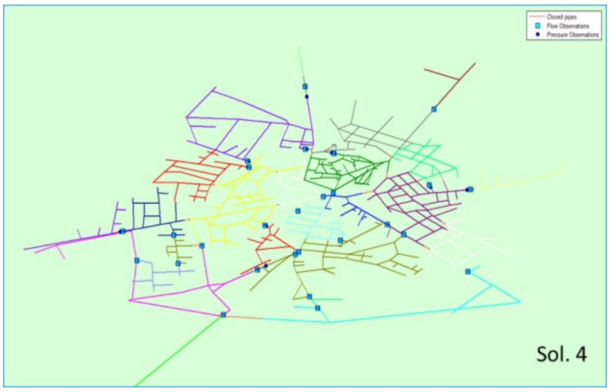

Fig. 8. DMA design solution 4.

Figures from 5 to 10 show the DMA configuration of the six solutions in Table 1 reporting the locations of flow meters separating the DMAs as cyan squares. For the sake of clarity, the same figure reports only the pressure meters that might be installed in the same manholes of flow meters.

It is worth noting that the different leakage reduction rates also relate to the average pipe pressure. In more details, Table 1 reports that solutions 1 and 2, entailing the minimum leakage reductions, show the highest average pipe pressure (over 16mWC). *Vice versa*, average pressure does not change moving from solution 3 to 6, consistently with the similar reduction in leakages in these solutions.

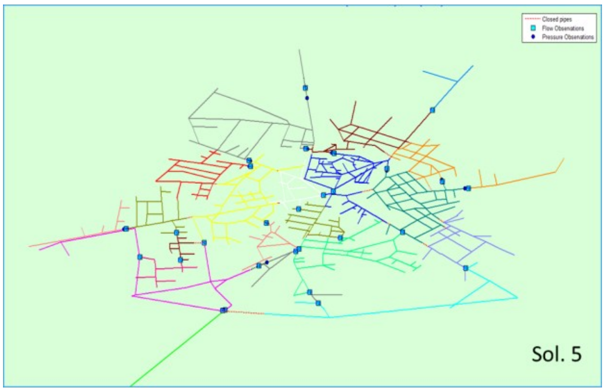

Fig. 9. DMA design solution 5.

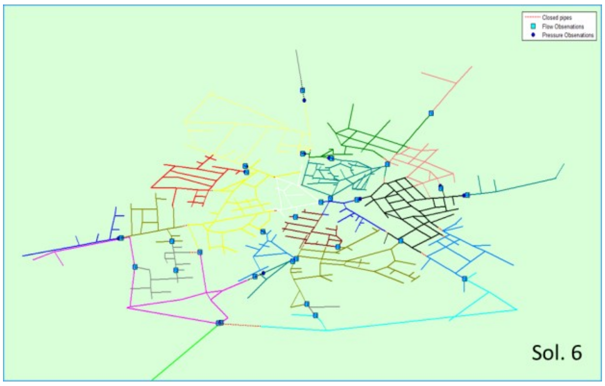

Fig. 10. DMA design solution 6.

The analysis of data reported in Table 1 in conjunction with DMA layout for each solution in Figures 5 to 10 provided a decision support to technicians to select the most effective configuration to be implemented in executive design. In more details, solution 3, the hydraulic DMA configuration resulting into the highest leakage reduction with the minimum number of flow meters (27), was selected. Indeed, the increase of number of flow meters in solution 4 to 6 is not justified by technically relevant reduction in volumetric real losses.

Figure 11 reports the location of closed gate valves in solution 3, which determine the reconfiguration of water paths in the network. Figures from 12 to 16 report the most relevant result of hydraulic simulation of the network under DMA design solution 3.

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Figure 13 shows the volume of water delivered to customers and lost from volumetric real losses during each hour of the typical daily operating cycle. It is worth noting that, in face of the pressure control through *RRTC* PRV, pressure-dependent leakages vary over the day, as results of head-losses along the modified water paths.

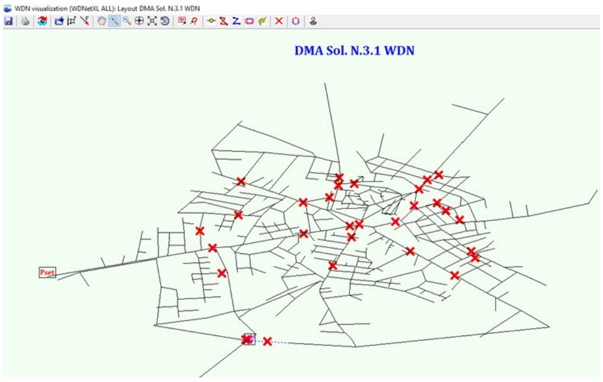

Fig. 11. Closed gate valves in DMA design solution 3.

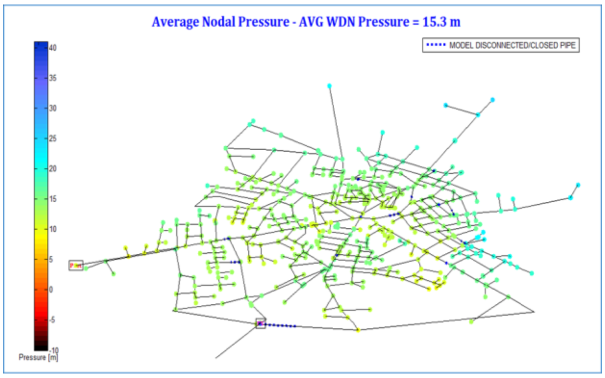

Fig. 12. Nodal pressure in DMA solution 3.

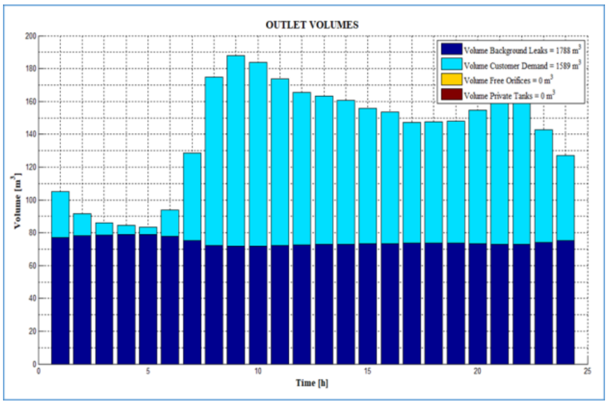

Fig. 13. Customers' demand (cyan) and volumetric real losses (blue) volumes in DMA design solution 3.

Figure 14 also reports the expected linear losses, as cubic meter per km and per day, for each pipe. The highest values (dark blue) are mainly located in the old city centre, because of the high pipe deterioration parameter assumed due to small diameters, and in the suburban areas showing high pressure. Such kind of information provide a reliable indication about the candidate pipes for future replacement works, although careful hydraulic analyse need to be performed.

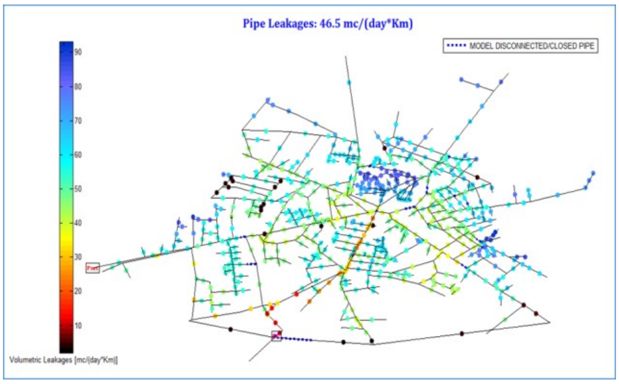

Fig. 14. Linear leakages in DMA design solution 3.

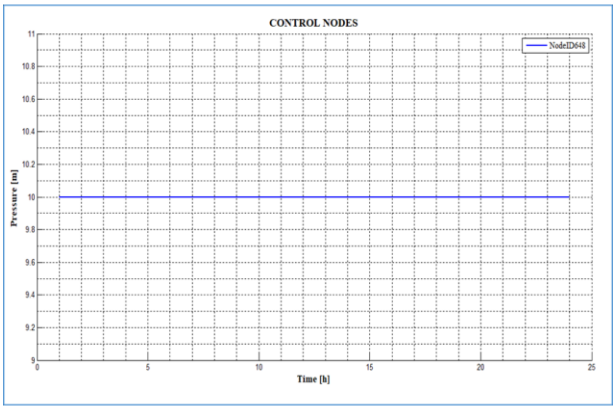

Fig. 15. Pressure at *RRTC* PRV control node in DMA design solution 3.

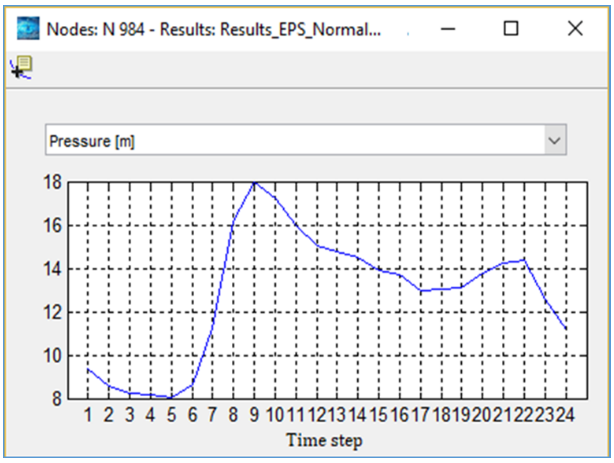

Fig. 16. Time pattern of target pressure for *local* PRV control node in DMA design solution 3.

Figure 15 shows that the *RRTC* PCV is verified to keep the target pressure constant at control node. Actually, if a *RRTC* PRV could not be installed, the same simulation provides the time-pattern of pressure target for *local* PCV control (i.e. in the same control node of the original configuration in Fig. 1); it's reported in Fig. 16 whose trend mirrors the customers' demand.

4.1. Adaptable selection of DMAs

As mentioned above, the DMA design solution 3 identifies the gate valves that should be closed in order to minimize volumetric real losses. Nonetheless, the location of flow meters to be implemented in real contexts should match constraints due, for example, to budget limitations or practical feasibility of installation. The nesting of *topological segments* allows to eliminate some flow meters, thus merging contiguous DMAs.

The adopted DMA design strategy allows to implement some criteria based on expert judgement, segment nesting or effective metering to drive the reduction of flow meters, as reported in [20]. For the sake of completeness, Figure 17 reports an example of reduction of flow meters from 27 (solution 3) to 9. This results into 7 DMAs for water balance. The same figure reports the location of 61 pressure meters including those at DMA boundaries (on both side of closed gate valves), in the manholes of the original 27 flow meters as well as on locations decided by the technician about the centre of the DMAs.

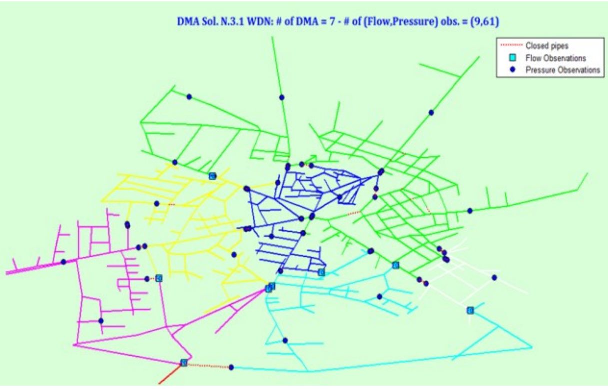

Fig. 17. Example of DMAs selected based on solution 3.

5 Conclusions

Pressure control in WDN is of preeminent importance to control and reduce water losses even before planning asset rehabilitation. Monitoring of flow and pressure is also a crucial task for supporting management, operation and planning activities in such urban infrastructures. This work presents a strategy for pressure control that integrates an innovative DMA design approach with the simultaneous optimization of pressure reduction valves (PRVs). It provides the optimal location of closed gate valves separating DMAs and the candidate locations of flow meters while allowing to set the target values for PRVs accounting for both *RRTC* and *local* control. Indeed, closed valves introduce a local control of pressure by reconfiguring flow paths, while PRV upstream of the controlled area enables a global pressure control.

It is worth to remark that devising and setting a PRV upstream of the WDN, besides enabling leakage reduction, results into improved reliability of the DMA design solutions in face of possible variation of hydraulic conditions after DMA implementation.

The demonstration on a real water distribution system proved the effectiveness and adaptability of the strategy to practical constraints that usually hamper the implementation of "optimized" district design.

The strategy as a whole was implemented in the WDNetXL platform, working on both GIS and Excel environments.

Data and pictures from WDNetXL provided by IDEA-RT s.r.l. (www.idea-rt.com). Work partially funded by the "Development and Cohesion Fund 2007-2013 - APQ Research Apulia Region" Regional program FutureInResearch".

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