Case Report

Application of rehabilitation and active pressure control strategies for leakage reduction in a case-study network

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Abstract: The paper discusses the results of a simulation analysis to evaluate the potential of rehabilitation measures and active pressure control strategies for leakage reduction in a water distribution network (WDN) in southern Italy. The analysis was carried out by using a simulation model developed under EPANET-MATLAB environment. The model was preliminary calibrated based on pressure and flow measurements acquired during a field monitoring campaign in two districts of the WDN. Three different scenarios of leakage reduction including *i*) pipe rehabilitation (scenario S1), *ii*) implementation of pressure local control (S2), and *iii*) introduction of remote real time pressure control (RTC) (S3) were simulated and compared with current scenario of network operation (S0). Results of the simulations revealed that combination of the used strategies can improve the network performance by a significantly reduction of water leakage. Specifically, 16.7%, 35.0%, and 37.5% leakage reductions (as compared to S0) can be obtained under scenarios S1, S2, and S3, respectively.

Keywords: water distribution systems; rehabilitation, pressure control; real time control; leakage reduction strategies.

1. Introduction

The level of service in water distribution networks (WDNs) is related to criticalities such as the frequency of breaks and the amount of background leakage in the network. Very often such criticalities are the cause of pressure drops in the network pipes, which eventually turn into the detriment of users water demand satisfaction [1].

Modeling of the network coupled with information gained through measurement of flows and pressures can significantly contribute to the identification of anomalies in the WDN, to the proper estimation of leakage levels, as well as to the selection of actions for network rehabilitation and technological renewal [2,3].

For instance, strategies include methods for identifying pipes with high rehabilitation priority [4], as well as methods to reduce pressure (and thus leakage) in the WDN [5,6]. Pipe rehabilitation/replacement programs require acquiring knowledge about the characteristics of the pipes (typically, material, diameter, age, current status, historical frequency of breaks [7]. Most pressure control methods are based on dividing the WDN into district metered areas (DMAs) and on installing pressure control valves (PCVs) at their entrance for limiting pressure values in the downstream conduits [5]. Normally, PCVs allows performing local pressure control (they allow controlling the pressure value locally at the valve outlet) with the aim to control pressure levels in the whole downstream district. Therefore, local control entrusts on the use of hydraulic models of the network to predict pressure levels in the downstream nodes of the district [8,9]. Hydraulic models are also embedded in procedures for the optimal placement of control valves for leakage reduction [10,11]. However, use of models does not assure proper control of pressure in all the circumstances. Indeed, because of the uncertainty in the estimation of the spatio-temporal distribution of nodal water demands and energy losses in the WDN, large network portions might exhibit pressure excess/deficit during the day as compared to set-point values.

In the recent years, adoption of remote real time control (RTC) strategies has shown to outperform local control strategies with increased potential for pressure control and leakage reduction in WDNs [12,13,14,15]. Remote RTC systems use (distributed) remote information about the current status of the WDN in order to improve the effectiveness of pressure (and thus leakage) control strategies. Typically, pressure sensors installed in the network (in nodes that are far from the control valve site) acquire pressure measurements in continuous. Such measurements are transmitted in real time (normally using GSM) to controllers that are programmed to adjust dynamically upstream PCVs [16,17], in order to drive the pressure at the remote monitoring node to the desired set-point.

Much of the available studies on adoption of strategies for active control of pressure in WDNs (e.g., [16,17,18,19,20]) have mainly invoked use of simulation approaches. However, in most of the cases, models have been applied to WDNs, without being preliminarily calibrated on the basis of measurements carried out in the network. In line of principle, such an approach cannot always assure accurate evaluation of the level of water leakage in the network due to the predictive error of the used model.

In this paper, a simulation analysis was carried out to evaluate the potential of rehabilitation measures and active pressure control strategies for leakage reduction in a WDN in southern Italy. The reliability of the obtained results is corroborated by the preliminary calibration of the model used for the simulations on the basis of measurements acquired in the WDN during a specific campaign of monitoring. The experimental campaign was carried out separately for two network districts and included monitoring of pressure and flows at different nodes of the network.

The paper is structured in sections. First, the methods are presented, including the modalities of description of the water distribution network, the details of the monitoring campaign, the used simulation model, as well as the considered scenarios of simulation for leakage reduction. Secondly, results of the model calibration are presented, with emphasis on the obtained level of accuracy of the model. Third, simulation results are discussed in order to compare scenarios of application of strategies of rehabilitation and active pressure control for leakage reduction in the WDN.

2. Materials and Methods

2.1. Case-study network

A portion of the municipal WDN of the town of San Giovanni la Punta (Italy) was selected as case-study to evaluate benefits of some rehabilitation and active pressure control strategies.

The WDN (see Figure 1) consists of about 39 km of pipes and supplies about 6100 users (about 2400 households). Two main DMAs were identified in a conjunct work carried out with the water company that manages the water distribution in the network. The two districts supply the north-west area (district DMA1 in the following) and the south-east area (district DMA2) of the town, respectively.

The whole system is supplied by the reservoir "Alto", that is located in the northern part of the town at 422 m a.s.l. (maximum capacity approximately equal to 100 m3). The reservoir is supplied by well pumps operated through use of an inverter-based system that adjusts the inlet to maintain constant water level of 2 m in the reservoir during the 24 hours. A cast iron conduit conveys flow from the reservoir to the main branches and loops of the WDN including a 2 km long steel pipeline with the function of north-south backbone line (reported in orange in Figure 1). Most of the pipes larger than DN200 in the WDN are made of steel and cast iron, and date back to the years '80s and 2000s, respectively. Conversely, the small conduits are almost entirely in HDPE and were installed in the early 2000s. Various surveys carried out during the last decade by the water company have revealed the occurrence of leakages in several branches of the WDN. In this regard, important current criticalities concern the described backbone line. Indeed, such line is affected by high leakage levels that are cause of pressure problems (and inadequate water supply) for several households belonging to DMA1.

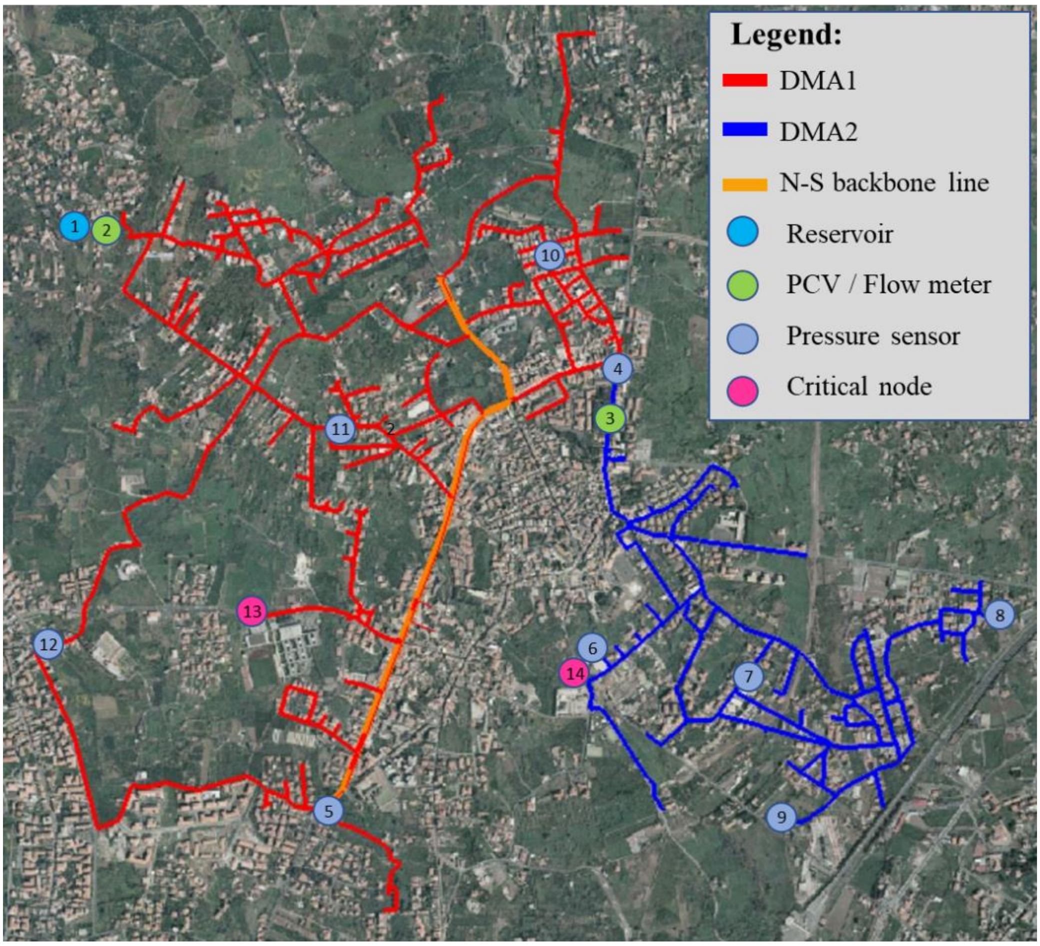


Figure 1. Sketch of the WDN with identification of the two DMAs (in red DMA1, in blue DMA2).

2.2. Monitoring campaign

A campaign of monitoring was carried out during the research work to explore the behaviour of the network in terms of water consumption and pressure in the two districts.

Specific objective of the experimental monitoring was to identify criticalities in the current operation of the WDN (e.g., identify areas of leakage, hydraulic malfunctioning, etc.). Further objective was to setup a dataset of measurements to be used for the calibration of the simulation model adopted for the analysis of the WDN.

The experimental campaign was carried out separately for the two districts (in the months of October 2018 and April 2019 for DMA2 and DMA1, respectively). A flow meter (at the inlet of the district) and five pressure sensors were installed in nodes of each DMA (see Figure 1) for two consecutive weeks. During such periods, flows and pressures were monitored at intervals of 1 min and 10 min, respectively. Used flow meters allowed flows to be measured with accuracy of 0.5%, while pressure sensors provided pressure measurements with 0.1% accuracy. All the data were stored locally and downloaded at the end of the monitoring period for the successive analyses. In particular, recorded measurements enabled determining the daily pattern of the pressure in the two districts, thus identifying areas at low or high pressure (thus more or less prone to leakage) in the network during the 24 hours. Also, the analysis of the data allowed determining the daily pattern of flows supplied to the two DMAs, thus enabling a measure of the total sum of household consumptions and of water leakages in the two districts.

Moreover, the comparison of the data of flow with quarterly data of grouped billed consumptions (provided by the water company for each household of the WDN) allowed to unbundle leakage contribution by the total measured flow.

2.3. Model of the network

A hydraulic model of the network was setup to assess benefits determined by implementation of scenarios of rehabilitation and active pressure control in order to reduce leakage levels in the WDN.

The EPANET-MATLAB environment [21] was used to model the network. The extended period simulation (EPS) of the WDN was performed, i.e., the simulation was run assuming successive conditions of steady state for the 24 hours of the day.

Overall, the network was skeletonized using 921 links and 869 nodes. Preliminarily, pipe roughness was estimated based on the available information from surveys concerning pipe material and level of pipe corrosion. On this background, values of Hazen-Williams roughness coefficients were set equal to 140, 95, and 75 for pipes in HDPE, cast iron, and old steel, respectively.

Network leakage was evaluated using a pressure-driven approach, based on the equation proposed by [22]:

$$Q_k = \beta P_k^{\alpha} \sum_{J=1}^{n_{j,k}} \frac{L_{j,k}}{2} \tag{1}$$

where Q_k [L/s] and P_k [m] are the k-node leak and pressure, respectively; $n_{j,k}$ is the total number of *j*-pipes converging to node *k*; $L_{j,k}$ [m] is the length of pipe *j* converging to node *k*; and α and β are leakage coefficients to be calibrated.

A pressure control module was developed in MATLAB. The module was coupled to the hydraulic model to allow simulation of potential benefits deriving from adoption of active control of pressure in the WDN based on remote RTC [12]. The control module allows implementing architectures of RTC systems and to use various types of PCVs (e.g., screw-based valves; plunger valves, etc.) for pressure control in the WDN. A control strategy derived from the literature [16] was implemented in the module. The strategy assumes that pressure at each of the two DMAs is controlled on the basis of the pressure value in one node (critical node) of the district. Specifically, pressure measurements acquired at the critical node are remotely transmitted in real-time to the controller that operates the adjustment of the PCV.

The control algorithm implemented in the pressure control module provides (at each control time step) the valve shutter displacement Δa [-] based on the deviation e_t [m] at time *t* between the current pressure value and the related set-point value at the critical node:

$$\Delta a = a_{t+\Delta t_c} - a_t = -K\, e_t \tag{2}$$

where a_t and $a_{t+\Delta t_c}$ are valve opening degrees at time *t* and $t + \Delta t_c$, respectively; Δt_c is the control time step, and K [m^{-1}] is the controller gain.

Eq. 2 shows that Δa is proportional to e_t through K. Therefore, with respect to the shutter position a, the adopted algorithm shows the characteristics of an integral-type controller. Moreover, the negative sign in Eq. (2) allows considering the negative proportionality between Δa and e_t, if gain K is assumed intrinsically positive.

Finally, valve regulation is constrained by the limits 0 and 1 (saturation), corresponding to valve fully closed and fully open, respectively. The control module allows also including limits (of the valve manufacturer) to the mechanical velocity of the shutter of the valve, to prevent risks of unwanted transients in the network [12].

2.4. Model calibration

The availability of measurements in the network allowed the calibration of the simulation model, thus increasing the reliability of the simulation results concerning the potential benefits due to implementation of leakage control strategies in the WDN.

Calibration was carried out using the Genetic Algorithm Toolbox available in MATLAB environment. The adopted procedure is based on the recent application by [23] and consists in calibrating simultaneously the optimal values of the hourly multipliers of the daily curve of consumptions, and the optimal values of coefficients α and β of Eq. 1 for leakage evaluation. The value of the two coefficients was assumed equal for all the pipes of the network, except for coefficient β related to the backbone line in steel that was evaluated separately, to improve model results.

Average hourly measured values of flow and pressure at each DMA were provided as model input with the aim of minimizing the following objective function:

$$OF = \sum_{h=1}^{n_h} \sum_{i=1}^{n_i} \left(\frac{P_{C_{i,h}} - P_{M_{i,h}}}{P_{M_{i,h}}} \right)^2 \quad (3)$$

being P_C [m] and P_M [m], computed and measured pressure values, respectively; n_i the total number of installed pressure sensors; n_h the number of hourly values considered.

Use of Eq. 3 was subject to the constraint that total inflow to each DMA is always equal to the sum of household consumption and leakage in the district, at any time step of the simulation.

2.5. Scenarios of simulation

Three main scenarios were considered for the simulations that include options of rehabilitation/active pressure control of the WDN.

The first scenario (S1) concerns the rehabilitation of the described backbone line in steel in order to eliminate leakages identified during the field surveys. Such scenario includes improvement of water supply to users of DMA1 as determined by of the re-arrangement of circulation of flows in the conduits.

The second scenario (S2) adds up to S1 the installation of two PCVs to allow local control of the pressure in the network. The two PCVs are assumed to be conventional screw-based valves and to be installed at the inlet of each DMA (PCV1 at node 2 of the DMA1 and PCV2 at node 3 of the DMA2, as shown in Fig.1). In this scenario, each valve is set with the objective of reducing as much as possible pressure levels in the respective DMA, while ensuring the full demand satisfaction to all the users of the district. This is obtained by identifying preliminary the critical node of each DMA, that is the node with the lowest value of pressure in the district during the 24 hours (nodes 13 and 14 for DMA1 and DMA2, respectively). Then, the scenario considers that pressure at the critical nodes can never drop down below the minimum value of 30 m. Accordingly, local pressure setpoint at PCV1 and PCV2 outlet is set to 7.5 m and 33 m for DMA1 and DMA2, respectively.

The third scenario (S3) considers adoption of remote RTC for pressure control in the WDN. Two plunger valves (DN300 for DMA1 and DN80 for DMA2) are assumed to be installed at the same sites as in scenario S2. Recent laboratory experiments have shown this type of valves to provide potential for accurate RTC in WDNs [24]. The scenario assumes the same pressure setpoint (30 m) at the two critical nodes as for scenario S2 (nodes 13 and 14). However, in comparison to scenario S2 the valves are directly controlled on the basis of the remote pressure measurements acquired in real time at the critical nodes. Simulation of scenario S3 included preliminary identification of a suitable value of the controller gain K to perform effective pressure control in the two districts without the occurrence of permanent pressure oscillations [25]. In agreement with previous literature results (e.g., [19,26], the simulations under RTC were carried out using control time Δt_c=5 min.

Scenarios S1, S2, and S3 were compared to scenario zero (S0), the current reference scenario in which no actions are taken to reduce leakage levels in the network.

3. Results

3.1. Results of the monitoring campaign and leakage level estimation

On the one hand, results of the analysis of the data of the monitoring campaign with specific reference to flow measurements at node 2 show that average daily flow to the whole WDN is equal to 56.5 L/s. Moreover, flow measurements at the inlet of DMA2 reveal that average daily inflow to this district is 11.8 L/s. By difference, nodes of DMA1 are supplied with total average daily flow of 44.7 L/s.

On the other hand, the analysis of the billed consumptions (from the database of the households) points out consumptions for the whole WDN corresponding to an average value of the flow of 14.9 L/s. The same analysis at the scale of DMA, provides 9.9 L/s and 5.0 L/s for DMA1 and DMA2, respectively. This last result is consistent with the spatial distribution of population, since about 2/3 of the total population served by the WDN belongs to DMA1.

Based on above, comparison of the results of the monitoring campaign and of the billed consumption would confirm a huge level of leakage in the WDN (about 73.6% of the total inflow, i.e. about 92.2 m3/d/km). The same comparison at the scale of DMA shows that leakage levels for DMA1 and DMA2 are equal to 78% (107.4 $m^3/d/km$) and 58% (53.4 $m^3/d/km$), respectively.

3.2. Results of model calibration

Figure 2 reports optimal values of the hourly demand multipliers M_h for consumptions at both DMA1 and DMA2 as result of the model calibration in the scenario of simulation S0.

The figure shows that the two patterns are rather similar with the occurrence of three main peaks of consumption (the first at early morning, the second at lunch time, and the third at dinner time) as well as with the minimum flow value occurring during the night. Slight differences are shown between the two DMAs with first peak being larger and in advance for DMA1 as compared to DMA2 due to the widespread presence of commercial activities in DMA1.

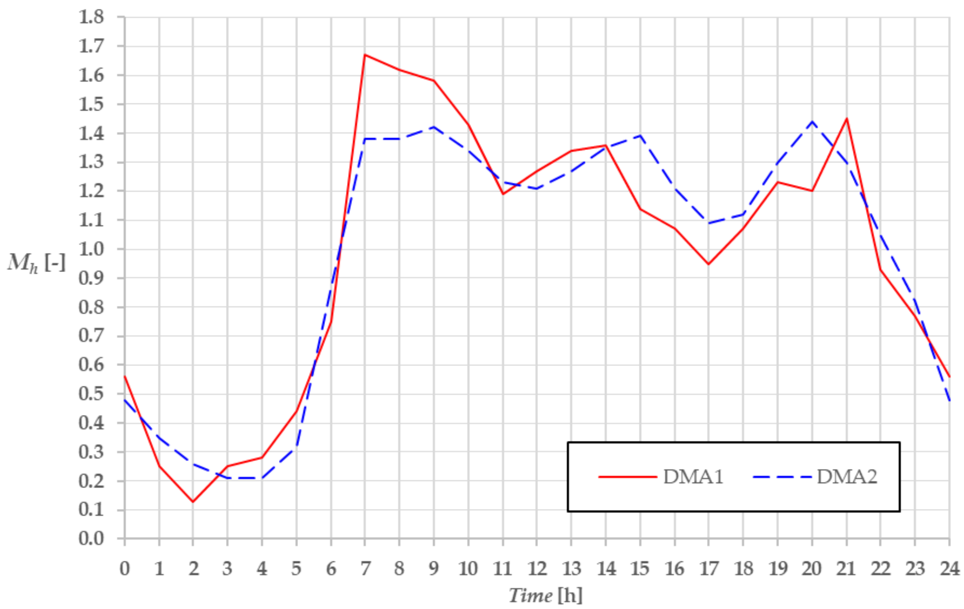


Figure 2. Results of model calibration. Hourly demand multipliers for the two DMAs.

Also, the calibration returned the optimal values of leakage coefficients of Eq. 1. Specifically, the calibration procedure returned α=0.87 and β=2.85×10^{-5}. Such values were attributed to both types of pipes in stainless steel and in HDPE. It was not considered the opportunity to differentiate the coefficients for the two types of pipe material given the very modest incidence of pipes in stainless steel as compared to that of pipes in HDPE. As expected, according to the results of the optimization, a larger value of the coefficient was obtained (β =4.77×10^{-4}) for the backbone line in steel.

Values of the absolute mean percent error (MAPE), and of the root mean squared percent error (RMSPE) as obtained by the optimization process for flow and pressure values at the various nodes of installation are shown in Table 1 for DMA1 and DMA2, respectively. Remarkably, the table shows maximum value of MAPE for pressure values to be 4% and 2% for DMA1 and DMA2, respectively, while the largest value for the flow is 1.7% as obtained for DMA1. Consistently, maximum RMSPE values obtained for the two DMA are 5.1% and 2.5% at nodes 11 and 8, respectively.

Table 1. Results of model calibration. Values of MAPE and RMSPE for flow and pressure.

	DMA1						DMA2				
	Flow	Pressure					Flow	Pressure			
Node	**2**	**10**	**11**	**12**	**4**	**5**	**3**	**6**	**7**	**8**	**9**
MAPE	0.017	0.037	0.040	0.032	0.031	0.022	0.006	0.016	0.014	0.020	0.014
RMSPE	0.020	0.045	0.051	0.038	0.039	0.026	0.008	0.020	0.017	0.025	0.018

3.3. Results of simulation scenarios

Scenarios of intervention described at previous section 2.5 were simulated in order to evaluate the potential for leakage reduction. The simulations were run with reference to water demands of a "average" day as obtained based on the measured flow discharges during the monitoring campaign. Results of the simulations are summarized in Figure 3.

The figure shows that scenario S1 of rehabilitation of the leaking segments of the backbone line allows to reduce total daily leakage volume from about 3600 m^3/d to about 3000 m^3/d (about 2082 m^3/d and 918 m^3/d for DMA1 and DMA2, respectively). Globally, this would mean recovering about 16.7% (about 6.95 L/s) of the current network leakage. In addition, the rehabilitation of the pipeline leads to improved pressure levels in the WDN, that is reflected into an improved satisfaction of the nodal water demands with specific reference to nodes od DMA1 that were characterized by supply deficit.

As scenario S2 is considered, Figure 3 shows that the total leakage volume in the WDN drops down to 2330 m^3/d (1726 m^3/d in DMA1) and 604 m^3/d in DMA2), that is 35% leakage reduction with respect to the current scenario S0 (about 14.7 L/s recovered). The figure shows also that replacement of the two PCVs with valves controlled by remote RTC (scenario S3) has further potential to improve the pressure control action with respect to scenario S2. The total leakage volume in the WDN drops down to about 2252 m^3/d, that is 37.5% leakage reduction as compared to S0 (about 15.6 L/s recovered).

Leakage reduction obtained in both scenarios S2 and S3 is strictly depending on the decreasing of the pressure level in the network during the 24 hours of the day. The results of local control of the pressure as obtained by using the two PCVs are shown in Figure 4. The figure shows pressure to decrease at the two critical nodes 13 and 14 for DMA1 and DMA2, respectively. However, the desired set-point of 30 m is achieved only in some hours, while the pressure remains higher than the set-point for the rest of the day (on average 31.5 m and 31.3 m for the two critical nodes). Figure 4 also reports the results of the simulation of scenario S3 with the adoption of remote RTC. The simulation was performed using K=0.005 m^{-1} (as obtained by preliminary runs aimed at the tuning of the controller). The figure shows that the used value of the gain allows driving the pressure (at both critical nodes) to the set-point without incurring in the generation of oscillations of the pressure during the day. Remarkably, the RTC system is able to maintain pressure set-points in an accurate way during the 24 hours. Specifically, the figure highlights that maximum pressure deviation from the set-point is smaller than 1 m at both DMAs (against 3-4 m in case of local control of S2). Figure 4 also reports the curve of the valve opening settings *aDMA1* and *aDMA2* in the two districts. As shown, openings/closures of the valve shutter are consistent with the daily water demand pattern at the two DMAs. In fact, the two plunger valves are adjusted by the control algorithm in order to close majorly during night hours (when pressure levels are normally higher) and to open during the peaks of the water demand.

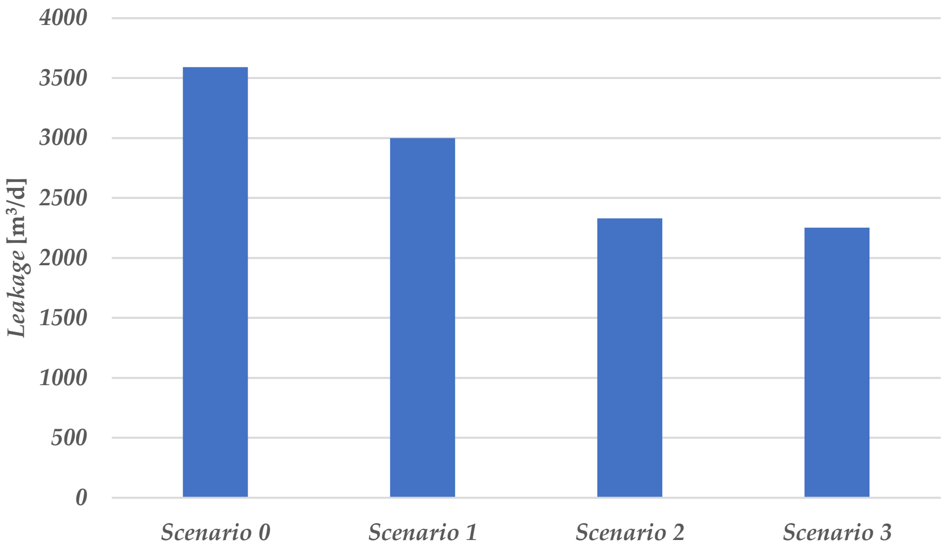
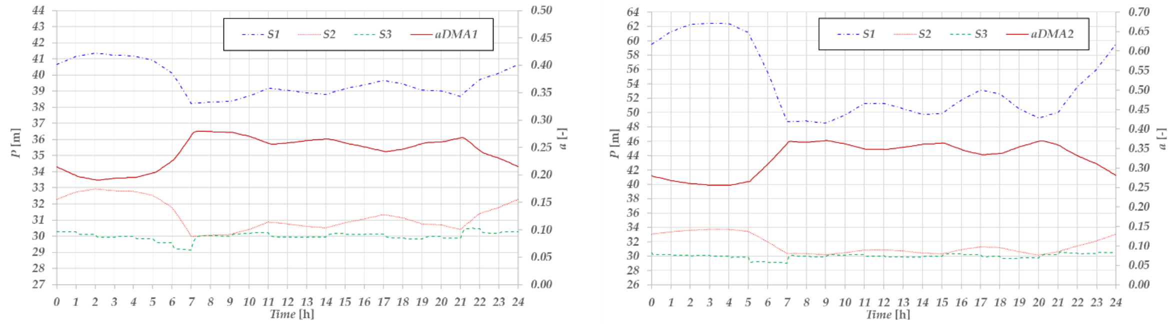


Figure 3. Potential leakage reduction under implementation of the different scenarios.



(a) **(b)**

Figure 4. Pressure levels at the critical nodes of (a) DMA1, and (b) DMA2 under scenarios S1, S2, S3.

As already discussed, the simulations under EPS were performed considering a day with average characteristics among the days of the monitoring campaign. However, it should be stressed that benefits of remote RTC as compared to local control of pressure are normally emphasized under conditions of high spatio-temporal variability of water demands in the WDN. In fact, while local control remains affected by uncertainty in water demands, in principle remote RTC systems are able to assure appropriate pressure control in real time in all the circumstances.

An important aspect that deserves discussion concerns the concurrent use of the two PCVs installed at the two DMAs. In fact, PCV2 reduces significantly pressure levels at DMA2 while determining pressure sustain in the upstream DMA1, thus reducing beneficial effects of pressure reduction as determined by PCV1. In this regard, the results of a further simulation (not presented here) of the WDN that includes implementation of PCV1 only, allowed quantifying that pressure value at node 4 (upstream of PCV2) would be about 4 m less than pressure value determined at the same node in scenario S2.

The accuracy (thus the transferability into practice) of the simulation results obtained deserves specific discussion. The availability of measurements from the monitoring campaign allowed appropriate calibration of the simulation model, with average MAPE (Table 1) corresponding to absolute error in pressure in the order of 0.5 m (for a 30 m set-point). Based on the results of the simulations, such an error is generally smaller than pressure differences as obtained by the comparison of the different scenarios, thus confirming the reliability of the results of leakage reduction.

4. Conclusions

A simulation analysis was carried out to evaluate the potential of rehabilitation measures and active pressure control strategies for leakage reduction in a WDN in southern Italy.

Three main scenarios were considered for the simulations. The first scenario (S1) concerned the rehabilitation of a steel backbone line of the WDN in order to eliminate leakages that were identified during the survey of the network. The second scenario (S2) added up to S1 the installation of two PCVs to allow local control of the pressure in the network. The third scenario (S3) considered adoption of remote RTC for pressure control in the WDN by means of two plunger valves in place of the PCVs adopted in S2. The three scenarios were compared to scenario zero (S0), i.e. the current reference scenario in which no actions are taken to reduce leakage levels in the network.

The analysis has shown that combination of the used strategies can significantly improve the network performance. Specifically, rehabilitation of the backbone line (scenario S1) would provide a significant reduction of the current leakage level of the WDN. Addition of local pressure control (scenario S2) would add further benefits. The adoption of remote RTC (scenario S3) in comparison with local pressure control increases leakage reduction. Additional benefits of remote RTC as compared to local control of PCVs would be observed under conditions of high spatio-temporal variability of water demands in the WDN.

Two main aspects played an important role on corroborating the reliability of the results of the analysis. Firstly, simulations were based on the results of accurate calibration of model parameters on the basis of a program of measurements carried out during the monitoring campaign. Secondly, the modeling of the pressure control processes by using local control of PCVs and remote RTC was carried out based on the literature results of consolidated experimental investigations.

Evidently, the results of this analysis must be considered as preliminary and open to further research work. In real cases, the choice of measures of intervention to adopt would require the evaluation of the benefit in terms of leakage reduction, but can not prescind also on a comprehensive analysis of the costs (including economic, environmental, and social costs) of each scenario of implementation.

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