Real-Time Control of Pressure for Leakage Reduction in Water Distribution Network: Field Experiments

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Abstract: Studies have shown that real-time control (RTC) of pressure in water distribution networks (WDNs) can be very effective for leakage reduction. The aim of RTC is to regulate the pressure level over the WDN by guaranteeing a pressure that is nearly constant and as low as possible at the critical node. To this end, a pressure reducing valve (PRV) at the network inlet can be remotely controlled to ensure the optimal service level, regardless of upstream pressure and inflow. Field experiments in a district of Benevento, Italy are carried out to assess the suitability of the proposed approach. Results show that the system guarantees the required pressure at the critical node at all times. The controller is effective in optimizing pressure levels over the entire WDN by also reducing excessive pressure in the other nodes. Experiments show that the pressure control is effective in reducing leakage, as confirmed by the minimum night flow (MNF) measurements.
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Introduction

Pressure control is a very effective approach for leakage reduction in water distribution networks (WDNs), especially for background leakage (Vicente et al. 2016), the component of the water losses that is the most difficult to reduce. As is well known, water losses depend on system pressure (Lambert 2001). A power law is often used to represent leakage (Germanopoulos 1985), with an exponent of approximately 0.5 for metallic pipes and greater than 1 for plastic pipes (Greyvenstein and van Zyl 2007; De Paola and Giugni 2012). As a consequence, pressure control over a WDN allows for reducing water losses. From a technical viewpoint, the pressure can be regulated by means of a pressure reducing valve (PRV) installed at the WDN inlet. In some cases, for accurate flow control, the network can be divided into district meter areas (DMAs) (Cheong 1993). A PRV can be installed at the DMA inlet in order to better control pressure over a smaller network. A turbine or pump as turbine (PAT) can be also coupled to the PRV to exploit energy otherwise dissipated by the valve (Carravetta et al. 2014; Giugni et al. 2014). Pressure management also decreases frequency of occurrence of new bursts and leakages, thus resulting in the extension of the working life of the water infrastructure (Thornton and Lambert 2007).

The pressure set by the PRV at the WDN (or district) upstream is assessed to guarantee adequate service everywhere within the network. Such a pressure depends on several factors, including elevation, topology, and building height. Usually, one or more critical nodes can be identified, at which minimum pressure is achieved. The pressure at the PRV outlet may be set according to the maximum head losses within the WDN and the minimum pressure required at any node. However, such regulation is rather ineffective because of the continuous variation of inflow discharge and, consequently, of head losses within the WDN. Because the pressure at the PRV outlet is set according to the maximum head loss, during most of the day the pressure at the critical node is greater than required, especially during nighttime hours, when inflow discharge (and consequently head loss) is minimum. In some cases, the value at the PRV outlet can be switched among two (or more) values based on the time of day; nevertheless the pressure level over the network often remains greater than necessary. For optimal pressure level over the network, the pressure downstream of the PRV should be changed according to the head loss within the WDN. To this end, real-time control (RTC) of the pressure should be developed, which regulates the pressure at the PRV outlet in such a way that the pressure at the critical node remains constant and equal to the minimum value to ensure adequate service level.

Pressure RTC requires the dynamic behavior of the PRV to be known. Prescott and Ulanicki (2003) developed phenomenological, behavioral, and linear models to represent dynamic and transient behavior of a PRV. The models varied in accuracy and complexity, and were validated through experiments, showing good agreement in all cases. Only the linear model was unsuitable for representing PRV dynamics, because its behavior was unaffected by the needle valve setting. In WDNs with PRV regulation, sudden changes in the system demand can produce transients with large and persistent pressure variations (Prescott and Ulanicki 2008). Large instabilities can also occur at low flows (Ulanicki and Skworcow 2014).

Although real-time monitoring (RTM) is used in the management of WDNs to improve operational efficiency, often coupled to supervisory control and data acquisition (SCADA) systems, RTC is a relatively recent development. Current applications are generally

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limited to pump scheduling, demand forecasting, and regulation of level and inflow into reservoirs and tanks (e.g., Cembrano et al. 2000; Jamieson et al. 2007; Shamir and Salomons 2008; Kang 2014). Optimization methods have been developed to identify the best settings of the driving parameters, although practical applications in real WDNs are quite limited. Dotsch et al. (2010) proposed a self-organizing emergent multiagent system approach for the decentralized RTC of WDNs. Experiments, both those reported in the literature and those carried out on real WDNs, showed the effectiveness of the approach not only in satisfying consumer demands but also in achieving a more cost-efficient control of the operations of the network.

The literature includes several research studies on RTC of pressure in a WDN. Demonstrating the benefits arising from the control of PRVs, Campisano et al. (2010) performed numerical investigations to assess the effectiveness of the RTC of valves in terms of leakage reduction in WDNs. They used a proportional (P) controller in simulations, showing significant leakage reductions while respecting the pressure constraint at the control nodes. Campisano et al. (2012) further proposed a general method to calibrate a P controller for the RTC of a PRV for leakage reduction. They researched the optimal gain factor of the controller through trial and error by minimizing the mean absolute deviation of the control node pressure head from the set point. They applied the calibration method to the WDN proposed by Jowitt and Xu (1990). Kumar and Kumar (2009) also discussed different approaches for the tuning of proportional integral derivative (PID) controllers for water networks. However, they analyzed the performance of a reservoir level control and a reservoir inflow control, not the pressure control at a network node. Creaco and Franchini (2013) proposed an improved algorithm for RTC of pressure in a WDN, showing that measurements of flow discharge reduced deviations from the set-point pressure, thus improving the performance of the control system.

Berardi et al. (2015) discussed the advantages of the remote control of a PRV compared with the conventional local control. Campisano et al. (2016) proposed a methodology for target node identification and selection of appropriate RTC strategies in the case of single-control and multiple-control architectures. Improved control was obtained using proportional integral (PI) controllers for all the simulations. They selected the municipality of Oppegård in which to analyze the potential for exploitation of RTC to improve pressure control in WDNs. They analyzed the potential effects of noise in the pressure signal by adding random fluctuations to water demands as a source of pressure fluctuation in the network. Random pulses were considered to occur every 3 min. Fontana et al. (2016a) discussed the operation of a prototype for both pressure control and hydropower generation in WDNs. Pumps as turbines were used for generating electric power instead of dissipating the excess head by means of PRVs. Laboratory experiments showed the capability of the algorithm to control pressure at a control node while ensuring the maximum produced power. Needle valves were used for regulation; needle valves are commanded with a digital input signal, i.e., an open/close/stop command can be sent to the motor coupled to the valve.

Fontana et al. (2017) discussed the RTC of a PRV for pressure regulation at a network node in a laboratory setting. A pure integral (I) controller, which guarantees no error at steady state, was used for regulation. Laboratory experiments showed the effectiveness of the controller. For a monitored node far from the PRV, experiments also showed the benefit of using a suitable predictor coupled to the controller.

Nevertheless, almost all of the aforementioned studies discussed the issues arising from the RTC of pressure in a WDN only from a theoretical standpoint. Numerical simulations were developed, however, without any practical implementation of the algorithm being performed to date. Although in a few cases laboratory experiments were carried out, real field operation can be quite different from a controlled environment. Consequently, this paper discusses a real field implementation of the RTC of pressure in a WDN. A pilot-operated PRV was installed at the inlet of a DMA, commanded by a programmable logic controller (PLC) to guarantee a constant pressure at the critical node. The following sections discuss the equipment and communication architecture, the controller and algorithms for RTC, and the benefits achieved in terms of pressure management and leakage reduction.

WDN and Control Architecture

The experiments were carried out on a district of the Benevento WDN, managed by the GE.SE.SA. water company. Benevento is a medium-sized city of Regione Campania (Campania Region) in southern Italy with a population of approximately 60,000 (Fig. 1). The municipal WDN is a rather complex system, because of the topography, with elevation ranging between 496 and 115 m above sea level (ASL), and the extent of the area to be served (approximately 130 km^2). The average inflow is 291 L/s, which corresponds to a daily consumption of approximately 410 L per capita (Fontana et al. 2016b). No significant seasonality in water demand is recorded. At the end of the 1990s the network was redesigned to reduce leakage and divided into 30 district meter areas. At the inlet of each DMA, a PRV and a flow meter were installed to ensure flow measurement and pressure control over the district. The PRVs were set at a constant value (i.e., a constant pressure set point is maintained at the valve outlet). In some cases, a time-based valve setting was considered, with higher pressure during daytime hours to take into account the greater head losses.

The control system was installed at the Santa Colomba district in the southwest of the city (Fig. 1). The total length of main pipes within the district is approximately 8.4 km (Fig. 2), with nominal diameters (ND) ranging between 50 and 250 mm (Table 1). The pipes are mainly made of ductile iron, dating back to the early 1980s. Steel pipes and high-density polyethylene (HDPE) pipes have also been used in recent years both for replacement of broken pipes and for small extensions (Table 2). The network serves approximately 2,800 properties, with a total population of approximately 8,600. The area served is fairly even, with elevation ranging between 122 and 135 m ASL. In the southern part of the district, a few nodes have higher elevation, up to 155 m ASL. Preliminary field measurements and hydraulic analysis were developed to identify the critical node, at which a constant pressure (at the minimum value) has to be guaranteed. The critical node was identified in Node P4.

A pilot-operated PRV was located at the DMA inlet for pressure control. In the first phase, a fixed setting of the valve was considered in order to maintain a constant pressure (approximately 59 m) at the district upstream regardless of the inflow discharge. To characterize district operation, inflow discharge Q and upstream pressure h_d (the pressure at the PRV outlet) were measured at the DMA inlet. Pressure was also measured at four locations (P1–P4) within the network (Fig. 2). Table 3 gives the elevations of Nodes P1–P4. To assess time variability of the monitored variables, Fig. 3 plots the pressure at Node P4 and the inflow discharge recorded over a 2-h interval (from 07:00 to 09:00 on November 14). The measurements used a sampling time of 30 s. The data show the great variability of the variables because of the continuous change in network operation due to random pulses. High-frequency pulses occur due to user demands, thus affecting the daily (low-frequency)

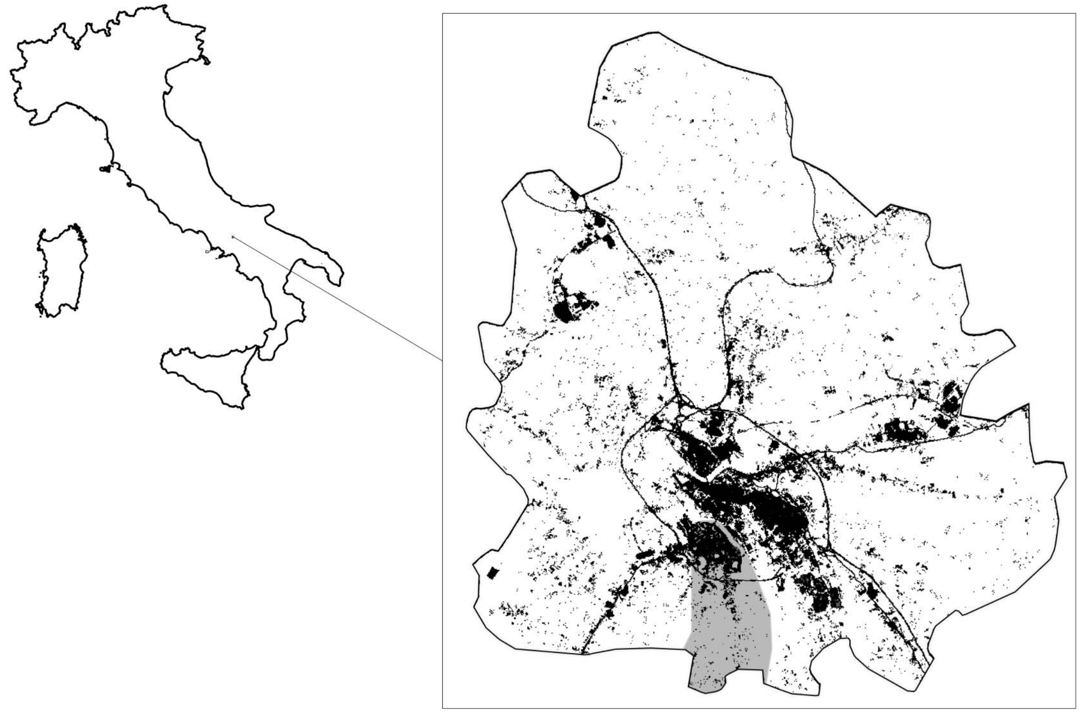

Fig. 1. Benevento municipality and the Santa Colomba district (shaded area)

pressure variability (Fig. 6). Such high-frequency pressure variability was much greater than that considered by Campisano et al. (2016) in their numerical experiments and could cause less-effective regulation of the PRV in the case of a purely P controller. Pressure and flow oscillations were also greater than those measured by Fontana et al. (2017) in laboratory experiments.

Fig. 4 plots the inflow discharge during the week of November 14–20, 2016. The data were collected every 30 s and further averaged over a 10-min interval to avoid spikes and pulses caused by instantaneous changes of network operation. Inflow discharge showed a very regular pattern during workdays, whereas differences on Saturday (dashed line) and Sunday (thick line) are seen for peak discharge and peak time. The pressure pattern was very regular as well, with generally small head losses. As an example, Fig. 5 plots the average pressure during the workdays of the week of November 14–20, 2016 for the Points P1–P3, showing head losses on the order of a few meters.

Hydraulic analysis enabled identification of the critical node (P4 in Fig. 2), which, being the farthest from the inlet as well as the highest of the network, is the most disadvantaged node. Pressure measurement at the node showed values between 18 and 23 m, with a very regular daily pattern (Fig. 6). Because of the low height of the buildings in the area, a pressure of approximately 18 m was estimated as the best trade-off between quality of service and leakage reduction. Such a value consequently drives the optimal pressure level over the district.

Equipment and Communication Architecture

Pressure was measured using WIKA S-11 pressure transducers (Klingenberg am Main, Germany), with a pressure range of 0–10 bar and accuracy 0.25%, which were installed at Node P4 and both upstream and downstream of the PRV. At the DMA inlet, a flow meter (G2 PMAG, Asti, Italy) was also installed. The pressure at the inlet was remotely regulated using a PRV with a motorized pilot.

The PRV was a pilot-operated Bermad (Porterville, California) EN 720 4SE-VI valve with nominal diameter 150 mm. The valve was hydraulically operated by means of a diaphragm actuator, which reduced the upstream pressure to a lower constant downstream pressure. Pressure regulation was independent of upstream pressure and flow discharge. Fig. 7 shows a schematic of the valve. The PRV was equipped with a motorized pilot with input voltage v ranging between 0 and 10 V. By varying v, an actuator compressed or stretched the pilot spring, thereby varying the outlet pressure h_d. An input voltage of 0 V corresponded to the maximum outlet pressure, whereas an input voltage of 10 V corresponded to the minimum outlet pressure (i.e., closed valve).

The steady-state operation of the PRV was characterized by means of laboratory experiments (Fontana et al. 2017). Fig. 8 plots the input voltage and the outlet pressure for various flow discharges Q_{fo}, i.e., the flow discharge at the fully open valve. The data show that the effective range of v varied between ~3 and ~7 V. For values less than ~3 V, no regulation was performed, and the pressure at the PRV outlet was the upstream pressure minus the head loss within the valve, on the order of 3–4 m. For v greater than ~7 V, the PRV closed, and a near-zero pressure was achieved. The data also show the linear relationship between h_d and v, regardless of the inflow discharge. Nevertheless, small deviations occurred because of the embedded hysteresis and the intrinsic nonlinear behavior of the PRV. The following equation was inferred between h_d (m) and v (V) and used in the controller:

$$h_d = -14.60v + 106.5 \quad (1)$$

Input voltage to the PRV was commanded by a CompactLogix L16ER-BB1B VLC (Allen Bradley, Rockwell Automation, Milwaukee, Wisconsin) which was installed in an electric panel at the DMA inlet. The PLC allowed acquisition of inflow discharge and the pressures upstream and downstream of the PRV as well. A Point I/O associated with the PLC was also installed at the critical node for pressure acquisition.

Fig. 2. Main pipes of the Santa Colomba WDN; diameters and material of pipes are also given

Table 1. Distribution of Pipe Diameters within DMA

Diameter	%
≤80	35.1
80–100	13.6
150	45.2
250	6.1

Table 2. Distribution of Pipe Materials within DMA

Material	%
Ductile iron	85.0
Steel	12.8
HDPE	2.2

Table 3. Elevation of Nodes with Pressure Measurements within DMA

Node	Elevation (m ASL)
P1	125.7
P2	122.7
P3	130.9
P4	155.2

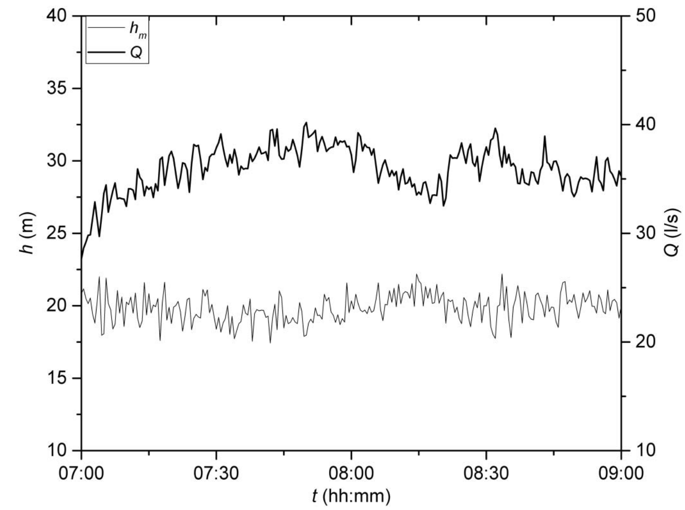

Fig. 3. Pressure at monitored node and inflow discharge from 07:00 to 09:00 on November 14, 2016 (fixed PRV regulation)

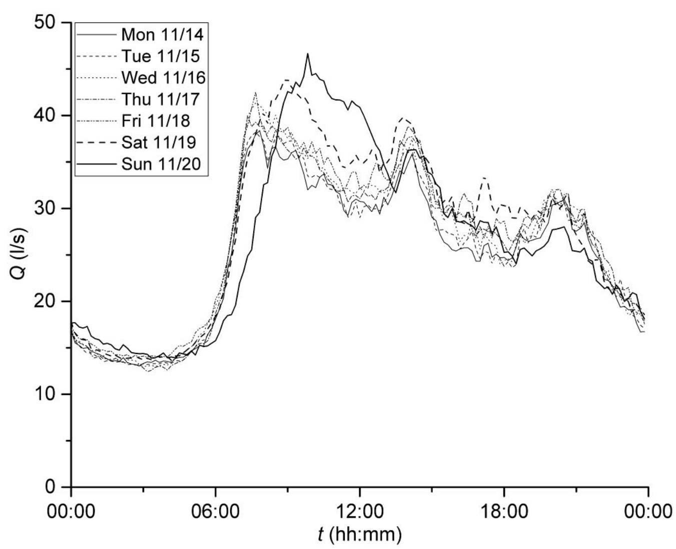

Fig. 4. Inflow discharge during the week November 14–20, 2016

The communication between the Point I/O and the PLC was a relevant issue because of the distance between them, which was on the order of 3.5 km, and because urbanization of the area, which caused a lack of visibility between the points. The Point I/O had to communicate with the PLC in order to transmit (in real time, with a sampling time of 750 ms) the acquired pressure, thus driving the regulation of the PRV. Among the investigated alternatives (e.g., Ethernet or Wi-Fi connection), only GSM/GPRS transmission guaranteed effective and reliable communication between

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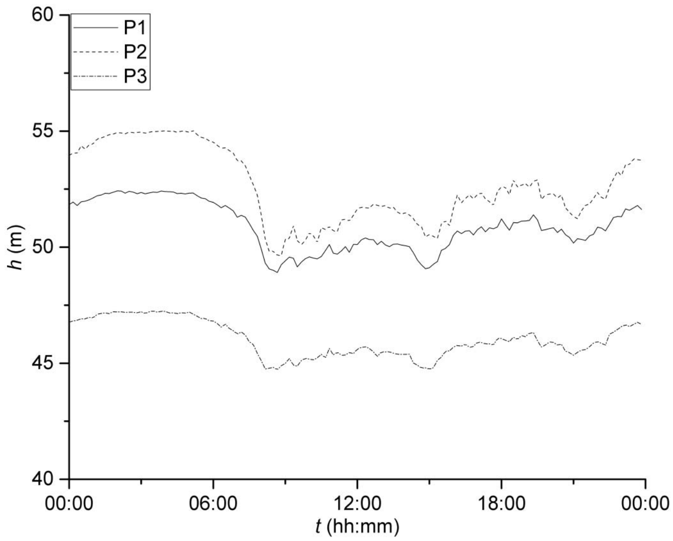

Fig. 5. Average pressure during workdays of the week November 14–20, 2016 at Points P1–P3

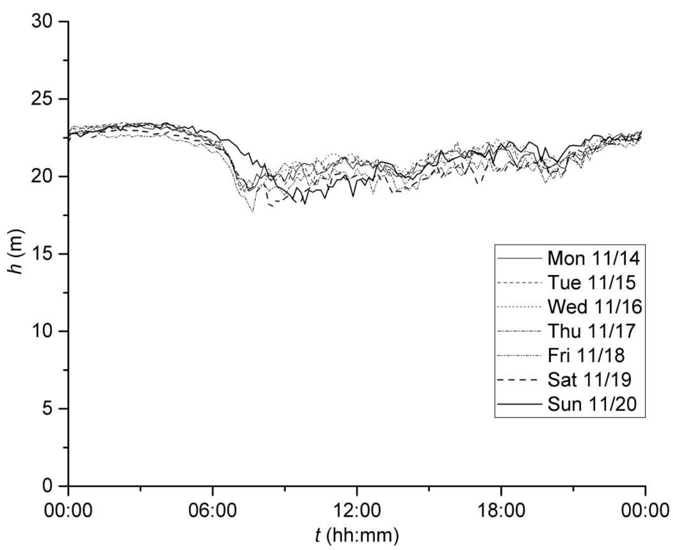

Fig. 6. Pressure at monitored node during the week November 14–20, 2016 (fixed PRV regulation)

the Point I/O and PLC. Thus modems (eWON 2005CD, HMS Industrial Networks AB, Halmstad, Sweden) were mounted at both the PLC and the Point I/O. The eWON modems, which used an Ethernet/IP communication standard to improve real-time performance, created a virtual private network (VPN), thus allowing secure traffic on a public TCP/IP network using authentication and cryptography protocols for coding and decoding data.

To allow data acquisition and process supervision, a triangle-based architecture was considered for communication, i.e., the modems did not establish a point-to-point connection. Such architecture is able to connect a supervisory control and data acquisition system for high-level process supervisory management (Fig. 9). A server (eWON eFive 25) was installed at the GE.SE.SA. offices, acting as an intermediary, receiving the data from the modems on site and sending the data to the PLC or to a device (e.g., the SCADA) in order to view the results. The server established a secured communication channel (VPN tunnel) between the modems

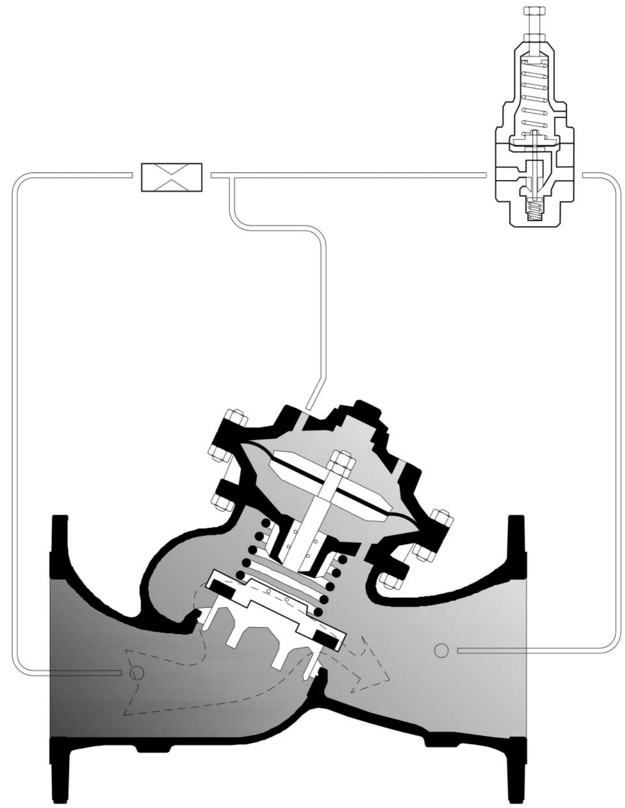

Fig. 7. Schematic of the PRV (adapted from Bermad 2017, with permission)

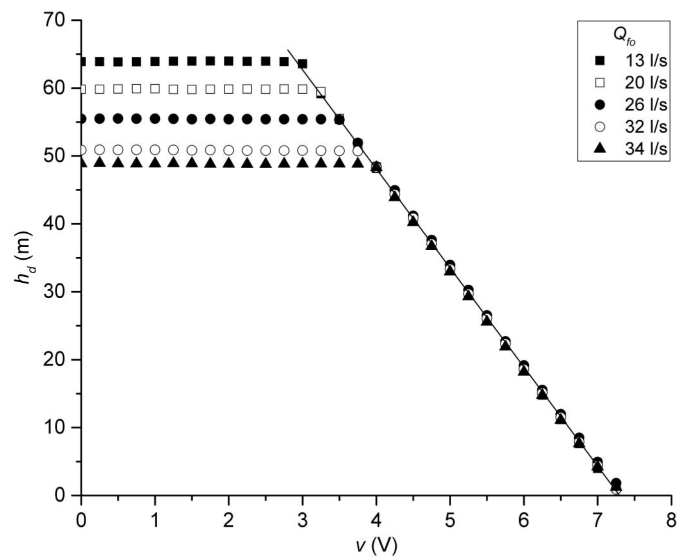

Fig. 8. Pressure at the valve outlet at varying input voltage and flow discharge

and the SCADA and protected the network with an integrated firewall.

Controller for RTC

As mentioned previously, several studies have investigated the use of controllers for RTC of pressure. Although an open-loop

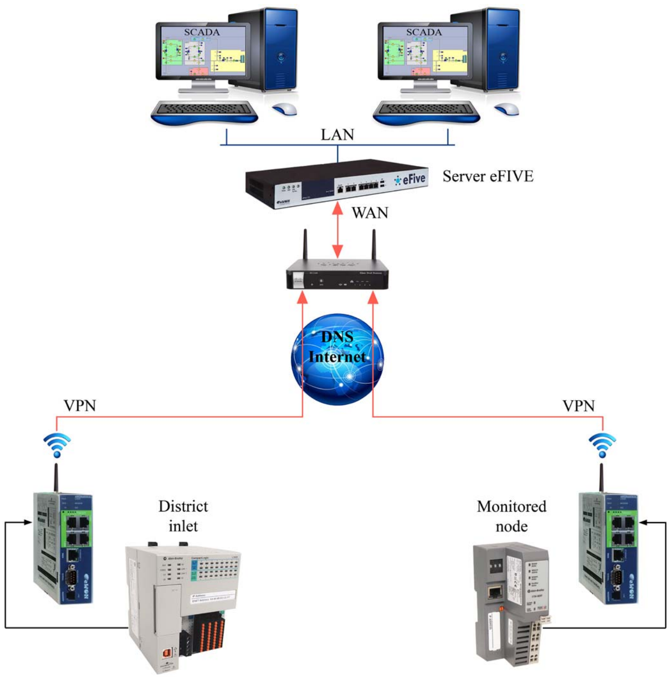

Fig. 9. Communication architecture between monitored node and DMA inlet

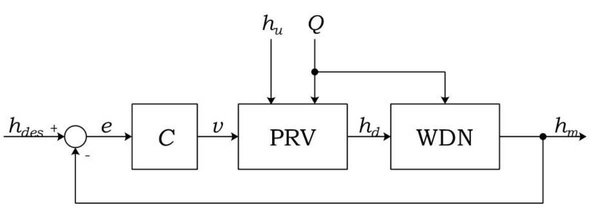

Fig. 10. Block scheme of a feedback controller for real-time pressure regulation

(or feedforward) controller is very simple, it cannot account for the hysteresis embedded in the valve, and the head losses within the network are of uncertain determination because of the unpredictable flow distribution within the WDN.

As an alternative, a closed-loop (or feedback) controller can be used for effective pressure control. The issue was carefully discussed by Fontana et al. (2017), whose results were used in the present study and supported several decisions concerning the controller and the equipment. Fig. 10 represents a closed-loop controller for pressure RTC in a WDN using the typical block scheme language of control engineering.

In such a scheme, the arrows indicate flow of information. The output arrows are related to physical quantities (the output), whose dynamic behavior is affected by other quantities (the input), indicated by the input arrows. The plus and minus signs respectively indicate whether the corresponding variables are added or subtracted. The PRV's (information) output is the pressure head h_d downstream of the valve, and the input is the voltage controlling the pilot. The PRV behavior is also affected by the upstream pressure h_u and the flow Q running the PRV. Unlike the input voltage, such variables are noncontrollable inputs and are called, in control engineering, disturbance inputs.

The pressure measured at the monitored node h_m is transmitted to a PLC located at the network inlet and compared with the desired pressure h_{des} (i.e., the set-point value). The resulting error $e = h_{\text{des}} - h_m$ drives the controller C commanding the opening and closing of the valve. If $e < 0$, then the actual pressure at the node is greater than required and the PRV is thus commanded to reduce the outlet pressure set point. Conversely, for $e > 0$ the pressure at the monitored node is lower than the set point value, and the controller thus commands the PRV to increase the output pressure set point. Such an error is the input to the controller, whose output is the voltage input v to the PRV.

In principle, a PID controller can be used (e.g., Aström and Murray 2008)

$$v_{\text{ref}}(t) = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt} \tag{2}$$

where K_P, K_I, K_D = proportional, integral, and derivative gains, respectively, to be tuned according to the system characteristics. Because of the slow variation over time of pressure and discharge in a WDN, a purely integral controller (i.e., $K_P = 0$, $K_D = 0$) was considered. This choice was based on priority being given to static performance (i.e., keeping the monitored pressure close to the set point) over dynamic performance (i.e., quickly recovering from the consequences of abrupt changes of conditions, such as rapid flow-discharge variations). A purely integral controller introduces a filtering action on the pressure measurements which cancels the effects of the high frequency pressure variations due to user demand. Without such filtering action, the system would react to those variations, causing the PRV to continuously adjust its set point with little practical effect on the WDN. A prompter system could be obtained through a PI controller, but in that case some low-pass filtering of the measurements should be introduced as well.

Unlike a proportional controller, an integral controller also takes into account the duration of the error, because the controller response is the accumulated error multiplied by the constant K_I: the larger the accumulated error, the larger is the output response of the controller. A relatively small gain was used because large gains may cause overshooting of the system, in which the output variable surpasses the desired value and then decreases until undershooting, and so on with oscillations. Nevertheless, such a behavior can be accepted in the case of a limited number of oscillations and a relatively small extent of both overshooting and undershooting. The integral controller also showed good performance in laboratory experiments (Fontana et al. 2017) in the case of abrupt variation of the set point pressure at the monitored node.

A relevant issue in the design of a feedback pressure controller for WDNs is the delay between the time at which a pressure is modified upstream (i.e., when a command signal is sent to the PRV) and the time at which the effects of such a variation are measured downstream (i.e., the pressure variation returns to the PLC). When the monitored node is far from the inlet at which the PRV is installed, such a delay can amount to many seconds. The delay depends on many factors, the most relevant generally being the finite propagation velocity of pressure waves in the conduits—the pressure variation induced by the PRV is felt after a certain time at the monitored node, mainly depending on the distance between the nodes and on the pipe material. Other minor factors also affect the delay, e.g., the time required for actuation of the valve and transmission delay. When the delay amounts to many seconds (i.e., much larger than the typical time constant of the system), oscillations and even instabilities can occur (e.g., Franklin et al. 2015), especially for larger values of the gain.

One solution to this problem is to slow the reactions of the system, i.e., by reducing the gain, although at the cost of reducing the dynamics performance of the controller. As an alternative,

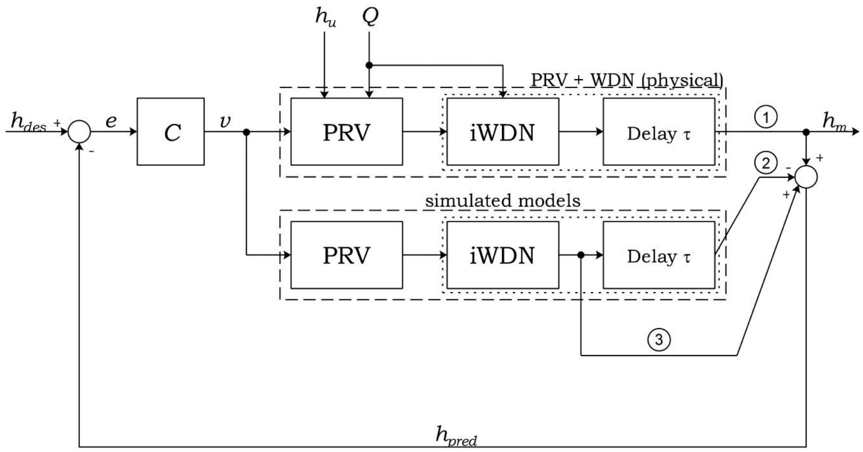

Fig. 11. Block scheme of the controller with Smith predictor

Fontana et al. (2017) discussed the implementation of the Smith predictor (Fig. 11) to improve the performance of the controller. The authors assumed that the real WDN can be described by the (information) cascade of an ideal WDN (iWDN) and a finite delay block, which delays the signal by τ seconds. The iWDN models the pressure decrease between the PRV outlet and the monitored node as a function of flow discharge. The blocks in the dashed box on Line 1 of Fig. 11 represent the physical system (PRV + WDN) affected by the delay. Its output can be cancelled out by subtracting the value predicted by the simulated models (dashed box on Line 2). The final outcome is the predicted value h_{pred} by the iWDN simulated model which does not include the delay (Line 3). In other words, the fed-back quantity h_{pred} is the prediction of the output of the WDN after τ seconds, i.e., if there is no delay.

Field Experiments

Preliminary analysis was carried out to identify the iWDN model and the finite time delay τ between the controller output and the return of h_m at the PLC (Fig. 11). As mentioned previously, the iWDN model schematizes the ideal behavior of the network at varying inflow discharges, assuming that the pressure variation at the inlet due to PRV regulation propagates instantaneously. The model returns the decrease between the PRV outlet pressure h_d and the monitored node pressure h_m, i.e., $\Delta h = h_d - h_m$. The head loss at any point of the WDN can be, in principle, calculated using the well-known (nonlinear) equations for the heads and flows. Actually, it is not possible to obtain an exact model of the iWDN, because of the continuous variation of demand at network nodes. Indeed, for the same inflow discharge, different flow distributions may occur within the network and, consequently, different head losses.

According to a different approach, the iWDN model can be inferred from the field measurements averaged over a significant time interval. To this end, a constant input voltage was sent to the valve, thus ensuring a constant pressure set point at the PRV outlet. Values were recorded every 30 s during the period August 5–31, 2016. Because of the high-frequency random pulses occurring in the network (Fig. 3), values of flow and pressure drop were averaged over a 10-min interval (Fig. 12). A quadratic interpolating relationship was also inferred in order to identify a (simplified) model of the ideal WDN. This model was used as the iWDN in the Smith predictor. The intercept of the curve is the elevation difference Δz between the PRV z_{PRV} and the monitored node z_m; the result was totally consistent with the actual elevations.

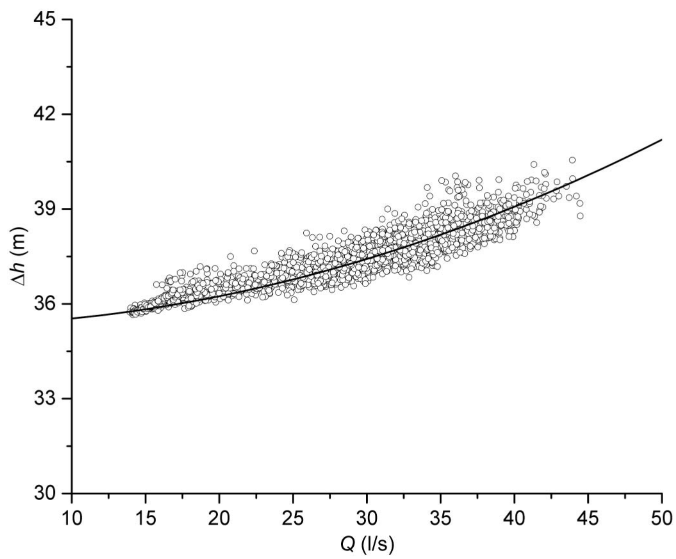

Fig. 12. (Averaged) Pressure difference between PRV outlet and monitored node at varying flow discharge

Experiments were further carried out to estimate the time delay. A pressure decrease was generated at the PRV outlet and compared with the resulting pressure transient measured at the monitored node (Fig. 13). Input voltage was varied between 2.8 and 3.5 V, corresponding to a pressure decrease of approximately 15 m. Data were collected over a 750-ms interval for greater time resolution. The plotted data show the delay occurring between the operation of the PRV and the monitored node. The narrow vertical lines in Fig. 13 represent the time at which pressure began to be regulated by the PRV and the time at which the pressure variation was felt at the monitored node. Analysis was carried out to estimate such delay by maximizing the correlation coefficient between the two pressure patterns. A delay of $\tau = 9$ s was estimated.

To compare the benefits deriving from a RTC of the pressure against a fixed regulation of the PRV, the pressure patterns at the monitored node h_m (Fig. 14) and the valve outlet h_d (Fig. 15) were plotted. The input voltage commanded by the PLC to the PRV was also plotted (Fig. 16). Measurements covered a 3-day interval from 12:00 p.m. Friday to 12:00 p.m. Monday, so as to analyze the operation of the network in different conditions (Table 4). Again, values were averaged over a 10-min interval.

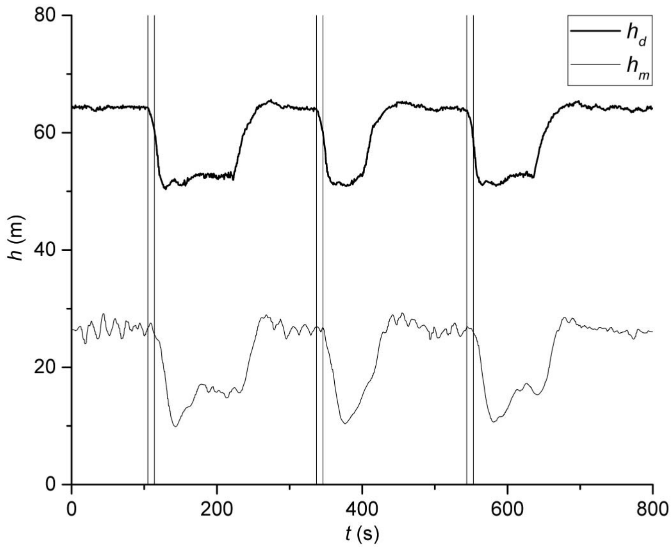

Fig. 13. Time delay between PRV outlet and monitored node

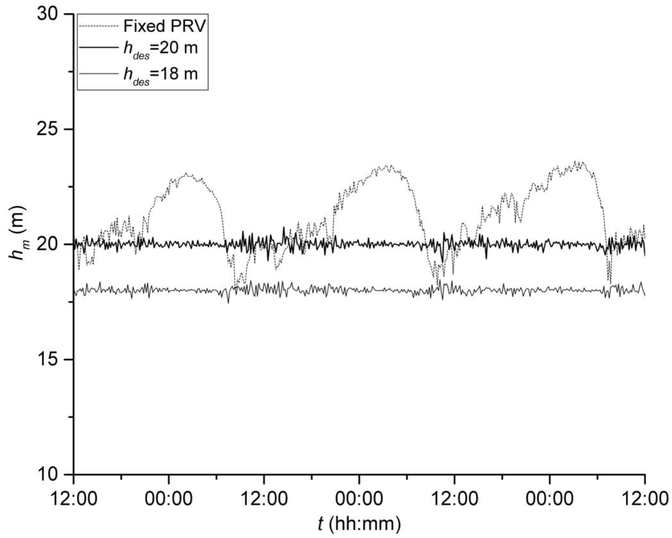

Fig. 14. Pressure at Node P4 (fixed PRV and RTC)

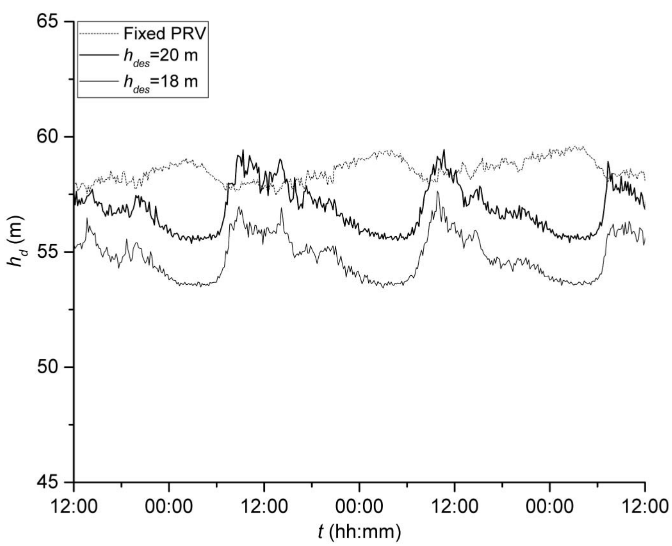

Fig. 15. Pressure at DMA inlet (fixed PRV and RTC)

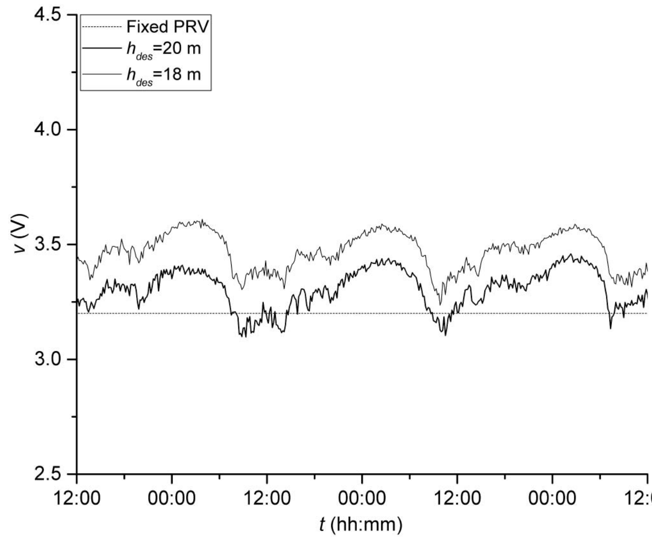

Fig. 16. Input voltage commanded to PLC (fixed PRV and RTC)

Table 4. Time Intervals of PRV Operation

PRV control	Start day	End day
No RTC	November 18	November 21
$h_{\mathrm{des}} = 18$ m	December 2	December 5
$h_{\mathrm{des}} = 20$ m	October 21	October 24

In the case of fixed regulation, input voltage to the PRV was set so as to guarantee a minimum pressure of approximately 18–19 m at the monitored node. An input voltage of 3.2 V resulted, which corresponded (Fig. 8) to an output pressure h_d of approximately 59 m. The valve was not able to guarantee a constant pressure at its outlet. Slight variations, on the order of 1–2 m, occurred during the day (Fig. 15), mainly because of variations in flow discharge. The larger the flow discharge, the smaller was the pressure at the PRV outlet. The pressure at the monitored node (Fig. 14) was consistent with flow discharge, because of the head losses within the WDN. Without RTC, the maximum values of h_m were achieved during nighttime hours, when the inflow discharge was minimum. Pressure at the monitored node ranged between 23 m (during nighttime hours) and 18 m (during peak hours).

In the case of RTC, the set-point pressures $h_{\mathrm{des}} = 20$ m and $h_{\mathrm{des}} = 18$ m were considered in the experiments. The integrator gain was set to $K_I = -0.002$, which was negative because of the negative slope of the PRV model given by Eq. (1), and it was relatively small in order to filter out fast variations of flow and pressure. For both $h_{\mathrm{des}} = 20$ m and $h_{\mathrm{des}} = 18$ m, the values of h_m showed a quite regular pattern, with very small deviations from the set-point pressure (Fig. 14). The benefit of RTC was evident especially during nighttime hours, with a reduction in pressure of approximately 3 m and 5 m for $h_{\mathrm{des}} = 20$ m and $h_{\mathrm{des}} = 18$ m, respectively. In the case of RTC, data also showed the greater variability of pressure at the monitored node during peak hours due to the pressure pulses associated with the (random) user demands, whereas lower variability occurred during nighttime hours. The pressure at the valve outlet was consistent with the aforementioned considerations. Values of h_d were greater during peak hours because of the greater head losses, whereas they achieve smaller values during nighttime hours (Fig. 15). When passing from $h_{\mathrm{des}} =$ 20 m to $h_{\mathrm{des}} = 18$ m, the outlet pressure decreased by approximately 2 m, as expected.

Table 5. Pressure Variability with and without RTC

PRV control	h_m (m) Average	h_m (m) Standard deviation	h_m (m) Range	h_d (m) Average	h_d (m) Standard deviation	h_d (m) Range	Q (L/s) Average
No RTC	21.2	1.4	5.5	58.5	0.5	2.1	26.9
$h_{\mathrm{des}} = 20$ m	20.0	0.2	1.6	56.9	1.0	4.1	25.7
$h_{\mathrm{des}} = 18$ m	18.0	0.1	1.0	54.8	1.0	4.2	25.3

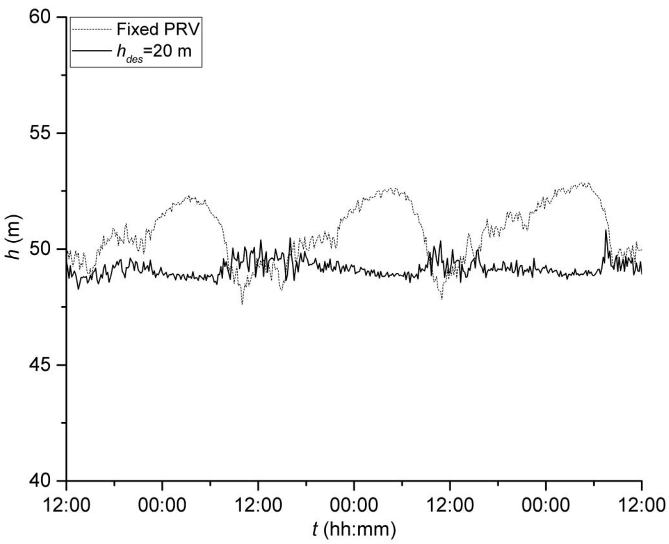

Fig. 17. Pressure pattern at Node P1 (via Bonazzi)

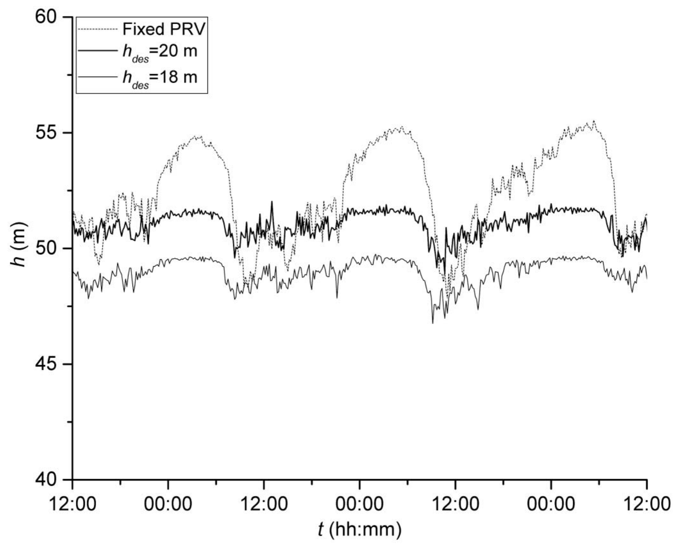

Fig. 18. Pressure pattern at Node P2 (via Rivellini)

Table 5 presents a detailed analysis of pressure variability consequent to the RTC, with average pressure, standard deviation, and range of values given at both the monitored node and downstream of the PRV for fixed PRV regulation, $h_{\mathrm{des}} = 20$ m, $h_{\mathrm{des}} = 18$ m. The data show a reduction of the average pressure at the monitored node when passing to a RTC, as well as reduced standard deviation and range of values. In such a case, pressure was far more stable, with standard deviations of approximately 0.1–0.2 m, with beneficial effects also in terms of amplitude of pressure fluctuation, thus reducing the occurrence of new breaks and leakages. Conversely, pressure at the PRV outlet showed greater variability with RTC due to variability of head losses during the day, which were compensated by the valve to guarantee a constant pressure at the monitored node. Flow discharge also decreased passing from no RTC to $h_{\mathrm{des}} = 20$ m to $h_{\mathrm{des}} = 18$ m. Nevertheless, flow reduction was less significant than pressure reduction, because data were measured in different periods of the year, as discussed subsequently.

The pattern of the input voltage commanded by the PLC to the PRV (Fig. 16) was consistent with the output pressure. Data show that v increased during nighttime hours (when a lower pressure at the PRV outlet was required) and decreased for greater inflow discharges. Also in this case, the curves for $h_{\mathrm{des}} = 20$ m and $h_{\mathrm{des}} = 18$ m were shifted by an almost constant quantity.

Pressure regulation at Node P4 was beneficial for the other nodes within the WDN, resulting in both a lower pressure and a more regular pressure pattern. Figs. 17–19 plot the pressure patterns for the same time intervals as in Table 4 at Nodes P1–P3, respectively. For Node P1 and $h_{\mathrm{des}} = 18$ m, data were not available because of a technical issue in the sampling device. For example, the average pressure at Node P2 in the considered interval was 52.4 m, whereas it decreased to 51.0 m when RTC was considered with $h_{\mathrm{des}} = 20$ m. Both fluctuation amplitude and standard deviation decreased as well, indicating lower variability of pressure over time at the node. In particular, the fluctuation amplitude decreased from 7.7 to 3.1 m, and the standard deviation decreased from 2.0 to 0.6 m. For $h_{\mathrm{des}} = 18$ m, the average pressure decreased to 49.0 m, whereas the amplitude of pressure fluctuation and standard deviation remained essentially the same. Similar considerations also applied to the other nodes, showing in all cases a

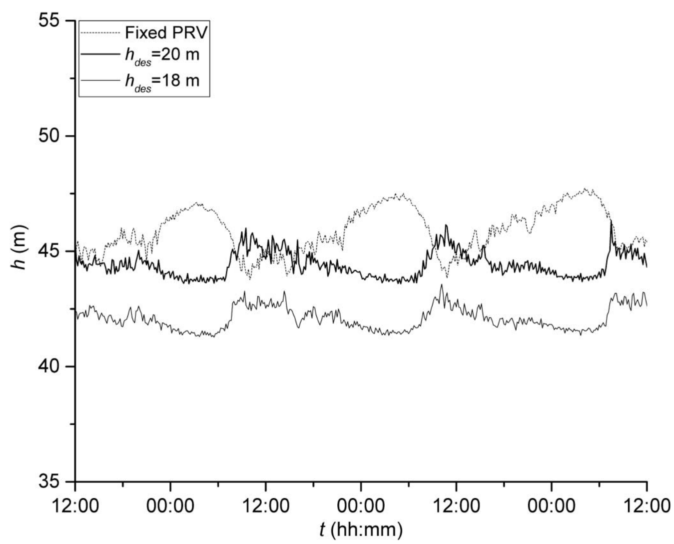

Fig. 19. Pressure pattern at Node P3 (via Pellico)

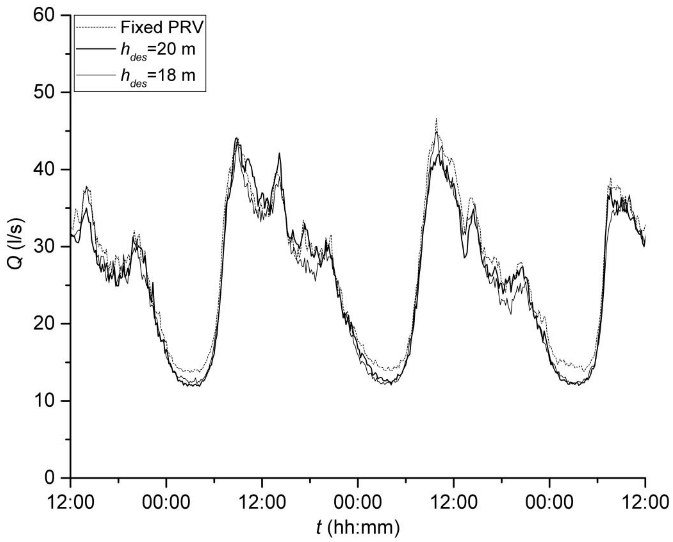

Fig. 20. Inflow discharge (fixed PRV and RTC)

more uniform pressure distribution (over time) and consequently a reduced stress on pipes, fittings, and valves.

Finally, Fig. 20 plots the inflow discharge. The benefit from the RTC was evident during nighttime hours, when water demands were minimum and inflow was mainly represented by water losses. The plotted data show a significant reduction of the night flow when the RTC was operating (approximately 10%). Instead, no significant reduction was recorded in the night flows passing from $h_{\mathrm{des}} = 20$ m to $h_{\mathrm{des}} = 18$ m, because of the greater nighttime consumption usually recorded in the district in the weeks before the Christmas holidays.

To assess the effectiveness of the control for reduction of water losses, the minimum night flow (MNF) was compared for different PRV regulations, where MNF was calculated as the average inflow discharge between 2:00 a.m. and 4:00 a.m. from October 10, 2016 to December 10, 2016 (Fig. 21). In spite of the day-by-day MNF variations, the benefits of RTC-aided pressure management were clear. The plotted data showed a decrement of approximately 1 L/s in the MNF when RTC was applied with respect to the case in which a fixed pressure set point was imposed downstream the PRV. The MNF generally increased during weekend nights, moreover showing an increasing trend from the end of November, due to the increased nighttime consumption in the weeks before the Christmas holidays. As mentioned previously, that explains the similar values in MNF with $h_{\mathrm{des}} = 20$ m and $h_{\mathrm{des}} = 18$ m.

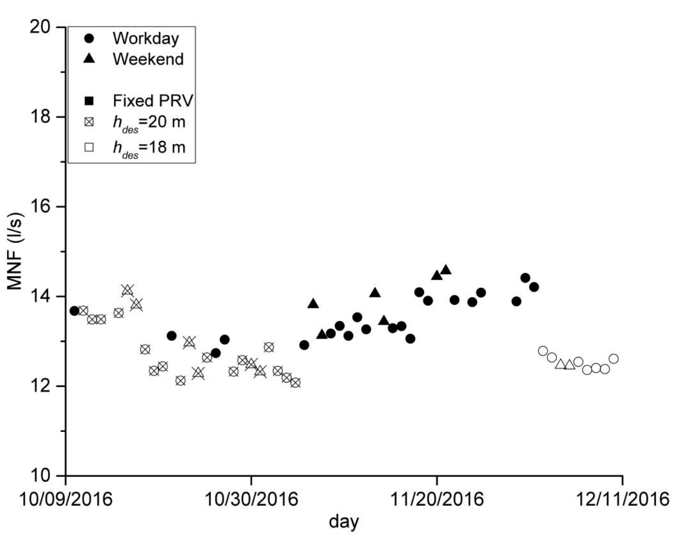

Fig. 21. MNF recorded from October 2016 to December 2016 (fixed PRV and RTC)

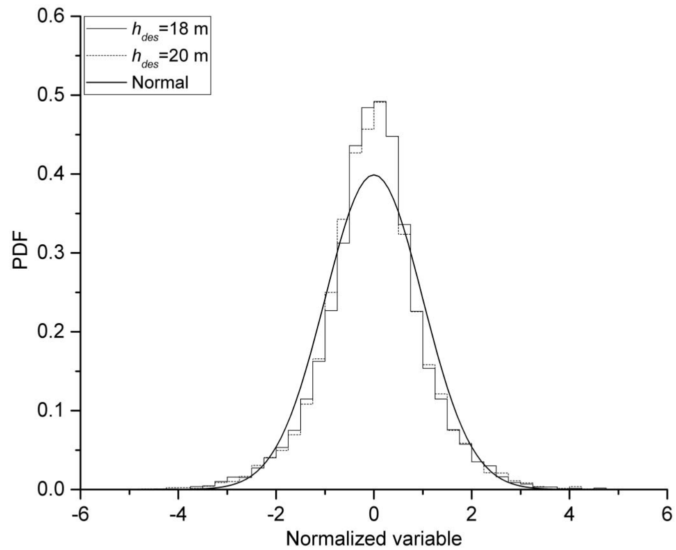

Fig. 22. PDF of normalized pressures at Node P4 and standard normal distribution

Further analysis was carried out to assess how RTC affects pressure variability at Node P4. As mentioned previously (Fig. 3), pressure showed high variability at the node. Furthermore, in the case of RTC, pressure was not constant, although the average value coincided with the set-point pressure. Pressure values were normalized and the probability distribution functions (PDFs) estimated (Fig. 22). These PDFs were also compared with the normal probability distribution. The data show that the PDFs were quite similar for both $h_{\mathrm{des}} = 20$ m and $h_{\mathrm{des}} = 18$ m, although with a slight difference with respect to the normal distribution. The measured values were narrower than the normal PDF. The normality hypothesis was rejected by normality tests carried out on the populations. The tests outlined by Shapiro and Wilk (1965), Anderson and Darling (1954), Martinez and Iglewicz (1981), Chakravarti et al. (1967), D'Agostino (1970), D'Agostino et al. (1990), and D'Agostino and Pearson (1973) were performed, showing in all cases (except the D'Agostino Skewness test) that the normality hypothesis was to be rejected. This seems to suggest that the linearity assumption, which one would expect to hold for small signals and which would maintain normality of signals all around the feedback loop, actually does not apply. In turn, this may depend on the hysteretic behavior of the PRV. The problem deserves further investigation, but its technicalities put it outside the scope of the present work.

Conclusions

This paper deals with the RTC of pressure in a WDN. Field experiments were carried out to assess the effectiveness of equipment and communication architecture and the algorithm for pressure control. An integral controller was used to account for the high variability of pressure at the monitored node. Moreover, the distance between the PRV and the monitored node necessitated use of the Smith predictor, which, coupled with a suitable value of the integrator gain, guarantees very stable regulation without oscillations and instabilities.

The controller proved to be quite effective, with a pressure at the monitored node very close to the set-point value regardless of the inflow discharge. No significant difference was noticed at varying set-point pressures.

Finally, a preliminary analysis of the benefits arising from the RTC of pressure was performed. The data show that RTC of pressure guarantees reduced MNF on the order of 1 L/s or more with respect to the case in which a fixed pressure was imposed downstream of the PRV. The daily saving was slightly lower because of the lower pressure during peak hours in case of fixed PRV regulation. The control was also effective in optimizing pressure levels over the entire WDN, by reducing the amplitude of pressure fluctuation also in the other nodes. Nevertheless, a deeper analysis should be developed, e.g., analyzing the effects of the integrator gain on the control and the possibility considering different pressure settings during nighttime and daytime slots.

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Notation

The following symbols are used in this paper:

e = pressure error (i.e., difference between the set-point pressure and the measured pressure);
h = pressure;
h_d = pressure downstream of the PRV;
h_{des} = pressure set point (i.e., desired pressure);
h_m = pressure at the monitored node;
h_{pred} = pressure predicted by the Smith predictor;
h_u = pressure upstream of the PRV;
K = gain of the controller (with subscript P, I, or D, depending on the controller);
Q = flow discharge;
Q_{fo} = flow discharge at fully open valve;
v = input voltage to the PRV;
z = node elevation;
Δh = pressure difference between the PRV outlet and the monitored node;
Δz = elevation difference; and
τ = time delay.

References

Anderson, T. W., and Darling, D. A. (1954). "A test of goodness-of-fit." *J. Am. Stat. Assoc.*, 49(268), 765–769.

Aström, K. J., and Murray, R. M. (2008). *Feedback systems: An introduction for scientists and engineers*, Princeton University Press, Princeton, NJ.

Berardi, L., Laucelli, D., Ugarelli, R., and Giustolisi, O. (2015). "Leakage management: Planning remote real time controlled pressure reduction in Oppegård municipality." *Procedia Eng.*, 119, 72–81.

Bermad. (2017). "Bermad waterworks. Hydraulic control valves 700–800 series." Porterville, CA.

Campisano, A., Creaco, E., and Modica, C. (2010). "RTC of valves for leakage reduction in water supply networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2010)136:1(138), 138–141.

Campisano, A., Modica, C., Reitano, S., Ugarelli, R., and Bagherian, S. (2016). "Field-oriented methodology for real-time pressure control to reduce leakage in water distribution networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000697, 04016057.

Campisano, A., Modica, C., and Vetrano, L. (2012). "Calibration of proportional controllers for the RTC of pressures to reduce leakage in water distribution networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000197, 377–384.

Carravetta, A., Fecarotta, O., Sinagra, M., and Tucciarelli, T. (2014). "Cost-benefit analysis for hydropower production in water distribution by a pump as turbine." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000384, 04014002.

Cembrano, G., Wells, G., Quevedo, J., Pérez, R., and Argelaguet, R. (2000). "Optimal control of a water distribution network in a supervisory control system." *Control Eng. Pract.*, 8(10), 1177–1188.

Chakravarti, I. M., Laha, R. G., and Roy, J. (1967). *Handbook of methods of applied statistics*, Vol. 1, Wiley, New York.

Cheong, L. C. (1993). "International report on unaccounted for water and economics of leak detection." *Proc., IWA World Conf.*, IWA Publishing, London.

Creaco, E., and Franchini, M. (2013). "A new algorithm for real-time pressure control in water distribution networks." *Water Sci. Technol.*, 13(4), 875–882.

D'Agostino, R. B. (1970). "Transformation to normality of the null distribution of g1." *Biometrika*, 57(3), 679–681.

D'Agostino, R. B., Belanger, A. J., and D'Agostino, R. B., Jr. (1990). "A suggestion for using powerful and informative tests of normality." *Am. Statistician*, 44(4), 316–321.

D'Agostino, R. B., and Pearson, E. S. (1973). "Tests for departure from normality. Empirical results for the distributions of b2 and $\sqrt{b1}$." *Biometrika*, 60(3), 613–622.

De Paola, F., and Giugni, M. (2012). "Leakages and pressure relation: An experimental research." *Drinking Water Eng. Sci.*, 5(1), 59–65.

Dotsch, F., Denzinger, J., Kasinger, H., and Bauer, B. (2010). "Decentralized real-time control of water distribution networks using self-organizing multi-agent systems." *4th IEEE Int. Conf. on Self-Adaptive and Self-Organizing Systems*, Budapest, Hungary, 223–232.

Fontana, N., Giugni, M., Glielmo, L., and Marini, G. (2016a). "Real time control of a prototype for pressure regulation and energy production in water distribution networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000651, 04016015.

Fontana, N., Giugni, M., Glielmo, L., Marini, G., and Verrilli, F. (2017). "Real time control of a PRV in water distribution networks for pressure regulation: Theoretical framework and laboratory experiments." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000855, 04017075.

Fontana, N., Giugni, M., and Marini, G. (2016b). "Experimental assessment of pressure-leakage relationship in a water distribution network." *Water Sci. Technol. Water Supply*, 17(3), 726–732.

Franklin, G. F., Powell, D. J., and Emami-Naeini, A. (2015). *Feedback control of dynamic systems*, 7th Ed., Pearson Higher Education, Inc., Upper Saddle River, NJ.

Germanopoulos, G. (1985). "A technical note on the inclusion of pressure dependent demand and leakage terms in water supply network models." *Civil Eng. Environ. Syst.*, 2, 171–179.

Giugni, M., Fontana, N., and Ranucci, A. (2014). "Optimal location of PRVs and turbines in water distribution systems." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000418, 06014004.

Greyvenstein, B., and van Zyl, J. E. (2007). "An experimental investigation into the pressure-leakage relationship of some failed water pipes." *J. Water Supply Res. Technol. AQUA*, 56(2), 117–124.

Jamieson, D. G., Shamir, U., Martinez, F., and Franchini, M. (2007). "Conceptual design of a generic, real-time, near-optimal control system for water-distribution networks." *J. Hydroinf.*, 9(1), 3–14.

Jowitt, P. W., and Xu, X. (1990). "Optimal valve control in water distribution networks." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(1990)116:4(455), 455–472.

Kang, D. (2014). "Real-time optimal control of water distribution systems." *Procedia Eng.*, 70, 917–923.

Kumar, M. P., and Kumar, M. S. M. (2009). “Tuning of PID controllers for water networks: Different approaches.” *J. Am. Water Works Assn.*, 101(7), 95–107.

Lambert, A. O. (2001). “What do we know about pressure–leakage relationships in distribution systems?” *IWA Conf. on System Approach to Leakage Control and Water Distribution Systems Management*, Brno Univ. of Technology, Brno, Czech Republic.

Martinez, J., and Iglewicz, B. (1981). “A test for departure from normality based on a biweight estimator of scale.” *Biometrika*, 68(1), 331–333.

Prescott, S. L., and Ulanicki, B. (2003). “Dynamic modeling of pressure reducing valves.” *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2003)129:10(804), 804–812.

Prescott, S. L., and Ulanicki, B. (2008). “Improved control of pressure reducing valves in water distribution networks.” *J. Hydraul. Eng.*, 134(1), 56–65.

Shamir, U., and Salomons, E. (2008). “Optimal real-time operation of urban water distribution systems using reduced models.” *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2008)134:2(181), 181–185.

Shapiro, S. S., and Wilk, M. B. (1965). “An analysis of variance test for normality (complete samples).” *Biometrika*, 52(3–4), 591–611.

Thornton, J., and Lambert, A. O. (2007). “Pressure management extends infrastructure life and reduces unnecessary energy costs.” *IWA Int. Specialised Conf. “Water Loss 2007*,” IWA Publishing, London.

Ulanicki, B., and Skworcow, P. (2014). “Why PRVs tends to oscillate at low flows.” *Procedia Eng.*, 89, 378–385.

Vicente, D., Garrote, L., Sánchez, R., and Santillán, D. (2016). “Pressure management in water distribution systems: Current status, proposals, and future trends.” *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)WR.1943-5452.0000589, 04015061.