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Review

Real time control of water distribution networks: A state-of-the-art review

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A B S T R A C T

This paper presents a review of the current state of the art of real time control (RTC) of water distribution networks (WDNs). After proving the basic concept and terms of RTC and presenting sensors, regulation devices and controllers typically used in WDNs, the paper goes on by describing the most frequent control objectives, which mainly include service pressure regulation, control of tank filling and energy production in each WDN district. Various control methodologies recently proposed in the scientific literature are presented and discussed, along with experimental and numerical results achieved. Also, aspects related to the cost-effectiveness of RTC are critically analyzed. The paper ends by giving an outlook into potential future developments in the area of RTC for WDNs.

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1. Introduction

Water distribution networks (WDNs) are complex systems made up of various interconnected nodes and pipes, which take water of suitable quality from sources to supply customers in the service area.

Based on the traditional design approach, WDNs are commonly expected to guarantee effectiveness and acceptable standards of service (i.e. pressure, flow, quality, reliability) in most operational scenarios. Recently, forms of real time control (RTC) of various levels of complexity have been successfully implemented in various case studies in the world, to achieve objectives of enhanced quantity/quality of the supplied water, and more in general, to improve the operation of WDNs. Real time control refers to a control time step of minutes or less. The control is not manual, intermittent or only at specific times.

In an age when WDN management issues are more and more considered by the managers of water utilities (Bello et al., 2019), a general analysis of the scientific and grey literature shows that at least three valid reasons exist for the implementation of RTC in WDNs: 1 – nowadays, Supervisory Control And Data Acquisition (SCADA) systems as well as Internet of Things technologies make it easier to monitor levels of applicability; 2 – results from numerous case studies have proven RTC to have significant potential for improving the operation of WDNs; 3 – RTC enables pursuing water and energy savings. The added value of RTC lies in the possibility to use current information about the real status of the system to improve its control, thus limiting inaccuracies due to assumptions and hypotheses on its operation.

About two decades after the publication of the first papers, the moment has come to take stock of the situation to highlight benefits and drawbacks of RTC in WDNs, since there is no literature review in this specific topic. Conversely, state-of-the-art papers were published in the research field of RTC of urban drainage systems (Schilling, 1989; Schutze et al., 2004; Campisano et al., 2015), where examples of field implementation are already available starting from the early 60s.

The aim of this paper is to survey and review the main endeavors of the two most recent decades on the topic of RTC in WDNs, with emphasis on hydraulics, control rationale and costs. The paper will offer researchers, academics and practitioners who are new to this topic an idea of the rationale for RTC and related technology, as well as of its successful implementation in a real case study.

In the remainder of the paper, first the fundamental concepts and terms of RTC and the devices typically used in WDNs are presented. Then, control objectives pertinent to WDNs are described, along with available numerical and experimental results and cost/benefit analyses. Potential for exploitation of such a technology, as well as existing technical and economic barriers to its large-scale application in real systems are discussed. The paper ends by reporting current and future trends of RTC in WDNs.

1.1. RTC concept and terminology

Typically, many operators of water supply systems use improperly the term "control" to indicate the result of the monitoring of system parameters (i.e., continuous acquisition of such properties as water levels in reservoirs, flows in pipes, and network pressure). However, acquisition of measurements is only one of the stages of the network control, which also includes the adjustment of actuators installed in the system (based on the collected measurements) to intervene in an active way on the distribution process. If active control of the system is performed with short time intervals occurring between two successive correction actions (i.e., from the order of some minutes downwards), the WDN is said to be controlled dynamically in real time (e.g., see Prescott and Ulanicki, 2008 and Campisano et al., 2010).

Therefore, the RTC of WDNs requires implementation of hardware elements in the network, such as various types of sensors and actuators, controllers, and data transmission systems. A sensor is a device that measures a physical property of the process to be controlled. An actuator is a device by which a control system acts upon the process. A controller is a device, recently in the form of a microprocessor or computer, that calculates the suitable corrections of the actuator setting for influencing the process, based on a preset rationale. Data transmission systems are physical and unphysical interconnections that enable the exchange of data between the various element of the control system.

Let us assume a process needs to be monitored and controlled in real time in a WDN. Furthermore, let us assume that at the initial time the process variable of interest (also called controlled variable) is at its desired set-point value. Due to the presence of disturbances, such as variations in source pressure-heads and/or in nodal demands, the variable of interest will tend to deviate from its set-point. A sensor is present to measure the controlled variable. Then, the measurement acquired through the sensor is signaled to the controller at prefixed temporal steps. Through data processing, the controller estimates how the actuator setting must be dynamically adjusted to minimize the current deviation of the controlled variable from the desired (set-point) value. Finally, the controller's correction is signaled to the actuator, which is adjusted accordingly at every control time step. Connections between sensor, actuator and controller are obtained through the data transmission system (based on leased/dedicated telephone lines, or on wireless communication systems, such as radio, cellular systems or satellite telecommunication devices, and so forth). The process control described above can usually be schematized by means of a control loop (Fig. 1).

Corrective actions can consist of discrete actions such as turning a pump on or off or fully opening or closing a valve. In other cases, they can consist of continuous adjustments in valve closure setting or pump speed. Set-point can be constant or time-dependent. The succession of set-points on time is called control strategy. Sometimes, a deadband is used around the set-point, to which no corrective actions correspond. This is done to prevent oscillation or repeated activation-deactivation cycles of the actuator.

The loop control outlined in Fig. 1 can be carried out in different modalities. Feedback control loops calculate actuator corrections based on the measured deviation of the controlled process from the

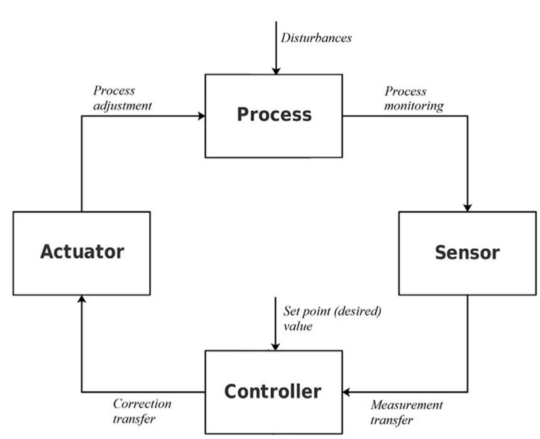

Fig. 1. Sketch of a control loop. Arrows indicate information flows, bold letters indicate hardware components, italic letters indicate sub-actions of the control loop.

set-point. In feedforward control, actuator corrections are calculated based on the deviation predicted for the near future, by means of a (simplified) model of the process. Feedback/feedforward control loops are combinations of the first two modalities.

1.2. RTC system architecture

The choice of the architecture of the RTC system (conceptually, the organization of its components) is an important step for obtaining a high performance of the system (Campisano et al., 2016).

There is no unique best choice of architecture that could be recommended to fit any RTC application to WDNs because implementation of control systems always faces different site-specific challenges (Stinson et al., 2006). However, in general, depending on the network topology and complexity, the RTC system architecture can be local or global. In the first case, process measurements are taken by a sensor probe directly (locally) at the actuator site, in which only one actuator is usually present. An example of this architecture is represented by the pump switch on/off based on the local water level measurement into the pump tank or a pressure control valve which hydraulically throttles the flow and attenuates downstream service pressure. In the second case (that is the most common for large networks), various sensors and actuators are typically present in the system. The measurements taken at all the sensor sites are signaled to a central control room, which globally operates the different actuators in a coordinated way. In most cases, the sensor and actuator can communicate directly but can be overridden by the control room. Typically, global RTC implies the implementation of remote control, thus requiring various levels of sophistication of the transmission system.

Intermediate architectures, all based on remote control, can be implemented for relatively large systems where measurements from a single remote sensor are used to adjust the settings of one (single-control) or more (multiple-control) actuators (Berardi et al., 2017). This is, for example, the case of one pressure gauge in the downstream network used to control one or more upstream pressure valves (e.g., see Campisano et al., 2016). Conversely, depending on the RTC objective, the system design can consider architectures characterized by a single actuator controlled based on measurements received from several remote sensors distributed in the network.

The control of the network can have different degrees of automation. It can be manual, supervisory or automatic. In the first case, actuators are adjusted based on decisions of human operators who compare controlled variables to set-points. In the second case, automatic controllers propose corrections to supervising operators, who can still modify them based on their expertise. In the last case, the control is fully automatized though manual override can be carried out in the case of an emergency.

1.3. Sensors, actuators and controllers for WDNs

Principal requirements for RTC sensors in WDNs are measurement accuracy and reliability, accompanied by the suitability for continuous recording and remote transmission. Although necessary for implementing robust RTC systems, sensor requirements are less stringent than those used for urban drainage systems where long-term sensor resistance to the harsh environment of sewer networks is also required (Schutze et al., 2004; Campisano et al., 2015). A certain degree of redundancy in the WDN is also required to increase the system's resilience to unexpected events determining sensors' malfunctioning with potential loss of data and subsequent deterioration of the control action on the actuators (Puig et al., 2016). Some concepts of fault detection in WDNs are provided in the following subsection. Main sensors used include:

- water level gauges such as floating hydrometers, bubblers, pressure inductive gauges and sonic gauges, to be typically installed in tanks to monitor water levels;
- pressure sensors, such as piezoresistive, capacitive, electromagnetic, piezoelectric and optical gauges, normally installed at demand nodes, control valve inlet/outlet, and pump suction/discharge to monitor pressure heads;
- flow meters, such as optical flow sensors, electromagnetic, or ultrasound flow meters, in addition to the pressure-based meters (e.g., Venturi-meter and Pitot-tube). Electromagnetic and ultrasound flow meters may also be able to correct for varying pressure and temperature (i.e. density) conditions, and for nonlinearities. Flow meters can be installed at WDN pipes and at users' connections, to monitor flows and consumption, respectively.
- traditional mechanical meters (e.g., Woltman and current meter) for volumetric measurements.

Usually, when used in the context of RTC, flow meters are installed to monitor flow at key pipes in the WDN, such as the feeding pipes of district metered areas (DMAs). In the case of flow meters, a very small sampling period (order of magnitude down to 1 s) is used for acquiring the reading. Volumetric meters are used, instead, at user connections with a higher sampling period (order of magnitude down to some minutes). While measurements can be taken locally at a high frequency, they may be communicated back to the control room at a “polling interval” which may be 15 min or an hour. In this case, they have “report on exception” which will call in at when a trigger level is hit. Actuators in WDNs include:

- pumps (axial or screw) with constant or variable speed, to be installed along WDN pipes to increase head;
- control valves that have a mechanical actuator, such as plunger, globe, piston and butterfly valves, to be installed along WDN pipes to modulate (control) flow;
- valves that have a spring-controlled actuator, such as the pressure reducing valves (PRVs), to be installed along WDN pipes to reduce the input upstream time-varying pressure head to a steady output downstream value;
- turbines or pumps as turbines (PATs), to be installed along WDN pipes to enable conversion of the surplus of total head into electrical energy.

If the range of flow in the valve-fitted pipe is large and the valve is sized to provide full demand when it is fully open, the valve may need to be substantially closed (almost fully closed) during low flow times (e.g. during night hours). Under such conditions, the potential occurrence of cavitation must be assessed in the system design-phase and anti-cavitation devices, such as anti-cavitation buckets, can be installed to prevent this phenomenon around the valve seat.

The control loop shown in Fig. 1 is the basic element of any RTC system, and specifically in WDNs. The manipulation of the actuators is entrusted to controllers (or control units). Digital control units such as Programmable Logic Controllers (PLCs) or Remote Terminal Units (RTUs) are used in the case of automatic control. Globally, RTUs and PLCs have similar potentialities, thus including data acquisition, pre-processing/filtering/validation, check for status, temporary storage of data, calculation power as well as high connectivity for data exchange with a central station (Campisano et al., 2015). In the control room, a SCADA system can manage all incoming and outgoing data. Alarms are generated here, and operators can monitor and control processes (e.g. change of setpoints). In addition, the SCADA system can enable additional information to be used for automatically executing the control, for example by incorporating additional validation steps beyond the basic controller logic. Some validation steps may use real-time dynamic hydraulic modelling of the WDN (Abu-Mahfouz et al., 2019).

Though the functionalities of PLCs and RTUs overlap with each other, an RTU is a microprocessor-controlled electronic device that interfaces objects in the physical world to a distributed control system or SCADA system by transmitting telemetry data to the system and/or altering the state of connected objects based on control messages received from the system. Instead, a PLC is basically a digital computer used for automation of electromechanical processes. In fact, RTUs tend to be used more for wide geographic telemetry, while PLCs are best suited for local area control.

PLCs and RTUs can be programmed according to a specific rationale in order to achieve the optimal control of the actuator. Rules/algorithms are implemented with the output correction signal being typically based on the current deviation between the measured value of the monitored variable and its setpoint (Schilling, 1989).

Two options are commonly preferred in WDNs. The first option is the discrete two-point or on/off-control, most frequently applied when only two settings are available for the actuator: on/off or open/closed. This is the case with a constant speed pump controlled to fill a tank. In the case of continuous control of the actuator, PID (proportional, integral, derivative) algorithms and related simplifications (e.g., P, PI, PD) can be adopted. A controller based on the PID logic calculates, at prefixed control time steps, deviation of the record from the set-point and provides proportional (P), integral (I), and derivative (D) corrective contributes to adjust the actuator.

Results from the literature have shown PID controllers to perform properly for accurate water level control in storage tanks (e.g., Kumar and Kumar, 2009) and for remote RTC of valves for pressure control in WDNs (e.g., Prescott and Ulanicki, 2008). PID controllers have been successfully used also for the real time control of water quality, including for example chlorine residual control in WDNs (Wang et al., 2006; Souza and Mohan Kumar, 2018).

Although PID algorithms have shown reliability and ease of implementation with use of industrial PLCs, calibration of such systems is needed to provide high performing control actions with sufficiently fast achievement of the set-point without risks of oscillations of the controlled variable (i.e. periodic oscillation of the controlled variable around the designed set-point to be achieved) (Ziegler–Nichols, 1942; Tyreus Luyben, 1992; Cohen–Coon, 1953; Åström-Hägglund, 1984).

In the context of pressure control in WDNs, controllers were also proposed starting from simple physical considerations on network behavior (e.g., Creaco and Franchini, 2013). Remarkably, forecast techniques can also be used with controllers to estimate the future state of the system, in order to obtain feedforward control (Page et al., 2017a, 2017b; Creaco, 2017; Page and Creaco, 2019). A significant aspect of a physically based controller, is that it often can be formulated to have no tunable parameter, i.e. is parameter-free. These controllers have been studied numerically by Creaco et al., (2017), Giustolisi et al., (2017), Berardi et al., (2017), Page et al., (2017a); 2017b; 2018, and Page and Creaco (2019). A parameter-free controller can often be used initially, and a related controller which has a tunable parameter can then be used by slowly changing the parameter away from its initial value to improve the control (Page et al., 2018).

1.4. Quality of measurements and fault detection

The good quality of sensor measurements is an essential prerequisite for the success of RTC. Therefore, fault detection must be implemented to guarantee the reliability of RTC systems (Puig, 2009). Nowadays, numerous Statistical Process Control (SPC) methods are available for the detection of faulty measurements (Venkatasubramanian et al., 2003a; b; c), including univariate methods, like control charts (Schraa et al., 2006), and multivariate methods, e.g. based on Principal Component Analysis (PCA) (Rosen and Lennox, 2001; Yoo et al., 2006). The main difference between univariate and multivariate methods lies in the fact that the former process the measurements obtained from a single sensor, checking the acceptability of their measurement noise. The latter, instead, check this acceptability based on the interrelation with other measured signals. If the same variable is measured by multiple sensors at the same time, a confidence interval can be created to diagnose faulty measurements in the generic sensor.

Off-line measurements can be used as reference to validate online measurements. In this context, non-zero residuals are allowed, as long as they are small and normally distributed. If a reference measurement is available, Shewhart control charts (checking measurements falling beyond a three-sigma limit) can be used to detect drift-, shift-, and outlier effects (Thomann et al., 2002).

Alternatively, residuals can be analyzed under the assumption of errors being represented like random variables with zero mean and constant variance (homoscedasticity). Standard statistical tests (searching for serial dependency or autocorrelation) can be used to evaluate this property and detect potential sensor faults (Dochain and Vanrolleghem, 2001).

In the case of measurements available from multiple (e.g., three) sensors for a generic controlled variable, the operation of the RTC system may be as follows. An alert message is given in the presence of an outlier in the controlled variable at a certain time of the day. If the actuator setting at that time of the day is close to those in the previous days at the same time and if the outlier is present only in one of the sensors installed for monitoring the controlled variable, the outlier is associated with poor quality data. Therefore, the operation of the RTC system may go on ignoring this outlier and relying on the measurements from the other sensors. Otherwise, if the actuator setting is different from those in the previous days at the same time and the multiple sensors agree on the measurement of the controlled variable, this may be classified as an anomalous event in the system controlled in real time. Indeed, this may happen when the forcing conditions of the system are significantly different from those expected at that time of the day, like when the overall demand of the WDN suddenly increases due to the opening of one or more hydrants for firefighting or to a pipe burst.

2. Control objectives

2.1. Service pressure control

Service pressure in WDN must be high enough to enable users' full demand satisfaction. When it falls below a desired threshold, which may be a function of building height, the WDN cannot supply all users with requested flows. Therefore, at nodes experiencing pressure deficits, the distributed flow becomes lower than the demand (Ciaponi et al., 2015). Conversely, excessive service pressure has various negative impacts, such as the increase in leakage and pipe bursts and the reduction in infrastructure life (Vicente et al., 2016). Hence comes the advisability of regulating (controlling) service pressure in real time, to reduce it and keep it close to the desired pressure threshold, which is assumed to be the set-point value in the regulation process. RTC can be conveniently performed independently at each District Metered Area (DMA), if the WDN is divided into DMAs. Specifically, if the district has lower ground elevations compared to the feeding source, regulation can be performed via control valves to dissipate pressure surpluses. Conversely, if it has higher ground elevations, it can be performed via variable speed pumps (VSPs). This is the case with closed distribution systems, with no storage capacity (Walski and Creaco, 2016; Page et al., 2018). In both the cases of control valves and VSPs, device settings are adjusted in real time to lead the controlled pressure head to the set-point value, under various operating conditions of the district. The use of RTC can reduce leakage while fully satisfying demand.

2.2. RTC of control valves in the presence of pressure surplus

A large scientific literature exists concerning the dynamic regulation of service pressure in water distribution systems. In this framework, research efforts were dedicated to proving its better performance, in comparison with the use of static PRVs and of control valves actuated with no feedback from the WDN. In fact, AbdelMeguid et al. (2011) and Creaco and Walski (2018) showed the benefits obtained by using, instead of the static PRV, a PRV locally controlled in real time as a function of the flowing water discharge. These authors proved that a locally controlled PRV enables larger service pressure abatements in the WDN, with beneficial effects in terms of leakage reduction. These benefits increase when remote control as a function of the pressure-head at the critical node in the DMA is implemented instead of local control (e.g., Berardi et al., 2017; Creaco and Walski, 2018). Furthermore, Campisano et al. (2010) proved that, compared to valve regulation based on the results obtained by applying optimization algorithms to the average daily pattern of demands (Araujo et al., 2006) with no feedback from the current WDN status, control valve regulation in real time has better flexibility under time varying water demand conditions.

Furthermore, other efforts were spent mainly on the development of increasingly efficient algorithms for RTC of service pressure through control valves. While in most situations the pursuit of very high performance in the control may be unjustified considering the slow demand variations occurring in WDNs, the rapid response of the controller is needed to react to large and rapid changes in flow. In fact, the combination of transients and slow response can lead to undesirable pressure fluctuations. Large and rapid changes in flow may take place in the following cases:

- A large industry needs a lot of water quickly and then goes back to low use. For example, filling of a batch mixing tank for some process.
- Fire fighters quickly open/close hydrants (even though they are trained not to).
- Operators quickly open/close valves/hydrants for flushing/flow testing/shutdowns (even though they should know not to even better than fire fighters).
- A pump to a higher-pressure zone/wholesale customer is turned on/off without a slow-closing operating control valve or soft start/VFD.

A summary of the key features of the works dedicated to algorithm development is available in Table 1, which also reports if each work has dealt with the issue of stability analysis (i.e., the analysis of occurrence of permanent oscillations in actuator setting and controlled variable, due to the overreactive response of the actuator).

An early example of local RTC comes from Prescott and Ulanicki (2008), who analyzed numerically the feedback control of pressure reducing valves at very small-time steps, order of magnitude of milliseconds. The objective of the study was to investigate the interaction between mechanically actuated PRVs and water network transients. Unsteady flow network models incorporating random pulsed demands were combined with a behavioral PRV model to demonstrate how the response of the system to changes in demand can produce large or persistent pressure variations, similar to those seen in practical experiments. A PID control system, to replace the existing PRV hydraulic controller, was proposed and this alternative controller was shown to significantly improve the network response in numerical and field applications. As a development of the work of Prescott and Ulanicki (2008), AbdelMeguid et al. (2011) developed the AQUAI-MOD® controller, which aims to modulate the PRV outlet pressure according to the valve flow. In their work, the Authors constructed a numerical model of the PRV and controller and validated it through experiments in a laboratory rig.

The first attempt to explore benefits of introducing remote feedback RTC for pressure control valves in WDNs is provided in Campisano et al. (2010). The objective of the described RTC system was to reduce pressure surplus (and leakage) in the network. To achieve such an objective, the authors suggested assuming, as controlled node, the node with the lowest pressure head in the WDN district or some critical customer. In this node, the pressure head is assumed to be monitored in continuous and the average value of the pressure is transmitted to the valve site at prefixed control time steps (minutes). P controllers were assumed to calculate the valve settings as a function of the deviation of actual pressure value from the set-point. The WDN behavior was analyzed through the extended period simulation, in which transients are neglected. The results of the simulations proved the RTC system to enable proper pressure control with leakage reduction while meeting the conditions for full demand satisfaction in the daily operation of the WDN.

While sticking to the same simulation framework as Campisano et al. (2010), Campisano et al. (2012) developed, through the dimensionless approach, a method for the calibration of P controllers in WDNs. The numerical applications proved that P controllers calibrated through this method have a fast response with no occurrence of permanent oscillations around the set-point, which are the sign of instability in the control. This method can be used by practitioners as an alternative option to other well-established techniques (Ziegler–Nichols, 1942; Tyreus Luyben, 1992; Cohen and Coon, 1953; Åström and Hägglund, 1984) from industrial control engineering.

Using a similar numerical model to Campisano et al. (2010), Creaco and Franchini (2013) showed better controller performances (including attenuated pressure head oscillations around the set-point) can be obtained if the proportional control logic is replaced with a new logic, which makes use of measurements concerning both the pressure head at the controlled node and the water discharge in the pipe fitted with the control valve. This new physically-based logic evaluates the valve setting adjustment starting from the pressure head deviation based on physical considerations on steady states in the WDN. In fact, it aims to correct the valve head loss coefficient as a function of measured water discharge and pressure head deviation. The adjusted valve setting is obtained starting from the adjusted head loss coefficient by using the relationship between head loss coefficient and valve setting provided by the manufacturer.

By making use of the software WDNetXL, Giustolisi et al. (2017) presented the numerical comparison of three kinds of controllers for pressure RTC, specifically the P controllers of Campisano et al. (2010), the physically-based controller of Creaco and Franchini (2013) operating on valve resistance and a novel physically-based controller operating on the head loss across the control valve. The results of their work proved the superiority of the physically based controllers with a slight predominance of their novel controller.

Table 1
Summary of the key features of the various works in the framework of RTC for the regulation of service pressure through control valves.

Work	Kind of approach	Level of RTC complexity	Kind of control	Control logic	Control time step	Actuator	Analysis of stability
Prescott and Ulanicki (2008)	numerical (unsteady flow)/ experimental (field)	local	feedback	PID	milliseconds	pressure reducing valve	no
Campisano et al. (2010)	numerical (EPS)	remote	feedback	P	minutes	generic control valve	no
AbdelMeguid et al. (2011)	numerical (unsteady flow)/ experimental (laboratory)	local	feedback	physically based	milliseconds	pressure reducing valve	no
Campisano et al. (2012)	numerical (EPS)	remote	feedback	P	minutes	generic control valve	yes
Creaco and Franchini (2013)	numerical (EPS)	remote	feedback	physically based	minutes	generic control valve	no
Giustolisi et al. (2017)	numerical (EPS)	remote	feedback	physically based	minutes	generic control valve	no
Page et al. (2017a)	numerical (EPS)	remote	feedback/ feedforward	physically based	minutes	generic control valve	no
Creaco et al. (2017)	numerical (unsteady flow)	remote	feedback	physically based	minutes	generic control valve	no
Creaco et al. (2018)	numerical (unsteady flow)	remote	feedback	physically based	minutes	generic control valve	yes
Creaco (2017)	numerical (EPS)	remote	feedforward	physically based	minutes	generic control valve	no
Fontana et al. (2018a)	theoretical/experimental (laboratory)	remote	feedback	I	milliseconds	pressure reducing valve	yes
Fontana et al. (2018b)	experimental (field)	remote	feedback	I	milliseconds	pressure reducing valve	no
Janus and Ulanicki (2018)	Numerical	local	feedback	PID with gain compensator	milliseconds	pressure reducing valve	yes
Galuppini et al. (2019a)	Numerical	remote	feedback	PI, PI with Smith predictor and Linear Quadratic Gaussian	seconds	generic control valve	yes
Galuppini et al. (2019b)	Numerical	remote	feedback	PI and PI with Smith Predictor	seconds	generic control valve	yes
Page and Creaco (2019)	numerical (unsteady flow)	remote	feedback/ feedforward	physically based	minutes	generic control valve	no

However, for the novel controller the authors did not provide any closed form expressions for estimating the suitable setting correction for the control valve at the generic control time step.

Page et al. (2017a) implemented water discharge prediction through a linear relationship inside the physically based controller of Creaco and Franchini (2013). The resulting controller is parameter-free and of feedback/feedforward kind. In fact, the suitable actuator setting correction at the generic time step is estimated based on variables at the old time, pressure head deviation at the controlled node and water discharge in the valve-fitted pipe, and on the forecasted water discharge at the new time. The results of the numerical work of Page et al. (2017a) proved the controller to be stable and responsive under smooth demand conditions in the WDN.

A field-oriented methodology to evaluate benefits of pressure RTC to reduce leakage by pressure control valves in WDN was tested by Campisano et al. (2016). The paper introduced modalities for addressing the selection of the proper RTC system architecture based on the network connectivity at the valve sites. Criteria for target node identification and RTC strategy selection in case of single-control (one valve-one target node) and multiple-control (multiple valve-one target node) architectures were developed. The impact on the control performance of controller calibration and on communication protocol selection procedures was also explored. The methodology was applied to a Norwegian WDN in which the installation of a field-pilot RTC system is in progress.

In order to overcome the limitations of results obtained using EPS, Creaco et al. (2017) investigated the potential of unsteady flow modelling for the simulation of remote feedback RTC of pressure in WDNs, performed through the algorithm of Creaco and Franchini (2013). The applications concerned a skeletonized WDN in which random pulsed nodal demands had been generated though a stochastic model for pulsed demand. Compared to EPS, the unsteady flow model proved to provide sounder description of the amplitude of the pressure head variations at the controlled node. Furthermore, it facilitates identification of the suitable control time step to be adopted for obtaining a prompt and effective regulation. Nevertheless, EPS-based models are enough to provide quite accurate estimates of daily leakage and of valve setting patterns, at a much smaller computational cost.

A similar unsteady flow model was used by Creaco et al. (2018) to analyze numerically the behavior of remotely controlled valves, in comparison with PRV, during hydrant activation scenarios for firefighting. In fact, these scenarios deserve attention due to the inherent high-flow conditions, which are very different from usual operational scenarios. The model was applied to a skeletonized WDN model, in which a PRV and an RTC valve were alternatively been assumed to be installed at the pipe connecting the source node to the remainder of the WDN. The results highlighted the better capability of RTC of controlling service pressure at the critical node and, therefore, in the whole WDN. Pressure deficits occur in the presence of the PRV, which is not able to sense the pressure signal from the remote critical node. The larger service pressure occurring with RTC results in beneficially larger outflows from the hydrants operated in the WDN. Creaco et al. (2018) also investigated numerically the issue of RTC stability, showing that the parameter of the control logic of Creaco and Franchini (2013) must not overcome a threshold to prevent control instability.

By working numerically with EPS, Creaco (2017) developed a generalization of the control logic of Creaco and Franchini (2013) for the remote RTC of control valves. Compared to the work of Page et al. (2017a), the author developed a fully feedforward controller, in which the suitable actuator setting correction at the generic time step is estimated only as a function of forecasted variables at the new time, namely pressure head deviation at the controlled node and water discharge in the valve-fitted pipe. The author applied his controller to the EPS of a skeletonized WDN with random pulsed nodal demands averaged over the control time step. This marks an important difference from the work of Page et al. (2017a), bringing numerical simulation closer to the real behavior of WDNs. A related study to that of Creaco (2017) not only discussed the derivation of the various physically based controllers in one place (Page and Creaco, 2019), but also showed how the water discharge prediction in Page et al. (2017a) can be improved in the presence of random pulsed nodal demands. The results of the applications highlighted that the new logic yields advantages, in terms of closeness of controlled variable to set point and of total variation of the device setting, above all when the water discharge pattern features contained random fluctuations and large hourly variations.

Fontana et al. (2018a) discussed the theoretical framework of RTC of a PRV for pressure regulation in a WDN. The authors identified a simplified dynamic model of a hydraulically operated PRV and developed a controller for closed loop regulation of the pressure at any given monitored node. Basically, the regulation of pressure at any node is obtained by dynamically modifying the outlet pressure of the PRV. This marks a difference from the remote RTC described above, where the remote control is obtained by operating on valve closure setting. Fontana et al. (2018a) showed that a pure P controller is unable to control pressure at any node with a PRV, because an error between set-point pressure and controlled pressure head should be present in order to generate the control signal to set the downstream pressure. A zero error would imply zero input signal, regardless of the desired downstream pressure, whereas an integral controller block can have a nonzero constant output with a zero error (i.e., at steady state). The integral term can cause overshooting of the system, but it may be accepted if the relative extent thereof with respect to the desired step does not exceed some value and the set-point value is rapidly achieved. They also discussed the issues (e.g., stability) arising from RTC of the pressure at a monitored node. A finite delay may generate oscillations and even instability. Therefore, smaller values of gains should be chosen, or the Smith's predictor should be added to the controller.

Fontana et al. (2018a;b) also discussed laboratory and field experiments to show the reliability of algorithms and equipment for RTC of pressure in a WDN. Laboratory experiments demonstrated the controller's ability to regulate pressure at the monitored node. The integrator gain was varied to identify the best trade-off between transient duration and stability of regulation and issues related to transport delays were analyzed, showing that oscillations and instabilities may arise in real environment for large gain values. Field experiments showed the effectiveness of the equipment, communication architecture and algorithm for pressure control in real environment. An integral controller was used to account for the high variability of pressure at the monitored node, coupled to the Smith's predictor because of the distance between PRV and controlled node. The controller resulted quite effective, guaranteeing very stable regulation without oscillations and instabilities.

Compared to the previous works, the main merit of Janus and Ulanicki (2018) was to propose a solution to tackle the occurrence of instabilities in the RTC of PRVs through PID units. The authors took inspiration from an instability event recorded in a large-scale pressure control scheme in one of the major cities in the United Kingdom. In fact, if the valve controller is tuned at medium valve openings, characteristic of normal operating conditions, the increased gain at low valve openings can cause the control system to be too reactive in its valve position adjustments, leading to oscillations. As a remedy, they carried out a numerical investigation to show that instabilities can be prevented by implementing gain compensation inside the PID control. A more formal and comprehensive analysis of instability was performed by Galuppini et al. (2019b), who applied tools and methodologies of control system theory to analyze both nominal and robust stability of RTC algorithms. The authors showed that, due to the nonlinearity of the gain of the process under control, it is advisable to base the regulator design on high order models, which better describe the dynamics of the process around the working point. Otherwise, wide robustness margins must be provided in the design of the feedback system. For this purpose, it is shown that the introduction of a low-pass filter and a Smith Predictor can significantly improve the robustness of the control scheme, while, at the same time, helping to reduce the cost of control.

Galuppini et al. (2019a) investigated numerically the benefits of considering the dynamic behavior of the WDN in the set-up of RTC algorithms, in comparison with the algorithm developed by Creaco and Franchini (2013) based on physical considerations on the steady state behavior of the system. Specifically, the authors applied a PI controller, a filtered PI controller and a Linear Quadratic Gaussian controller in two WDNs. Though increasing the number and size of actuator setting adjustments, all control algorithms improve the state of the art in terms of regulation error in presence of pulsed nodal demand. On average, the reduction in the regulation error added up to about 40%. Therefore, the adoption of these algorithms is advisable in all cases when the more rapid wearing of the control valve is not a limiting factor.

2.3. RTC of variable speed pumps in the presence of pressure deficits

Compared to control valves, the applications to VSPs supplying water to closed distribution systems are less numerous.

In this context, some research efforts (e.g., Walski and Creaco, 2016) showed that the installation of VSPs at DMA inlets may be beneficial in terms of long run operational costs. In fact, besides the same kind of pressure-reduction benefits as that obtained with control valves, the use of VSPs in lieu of fixed-speed pumps enables reduction in the consumption of electric energy, and as a result in the water utility's expenses.

This has been tested in small-scale experimental test-beds which perform RTC to control the pressure remotely with VSPs. These studies found the following deceases in the electrical energy used by the VSPs relative to a fixed speed pump:

- 35.03% (Bezerra et al., 2012);
- 19.23% (Silva et al., 2015);
- 66.2% (Filho et al., 2018).

Other contributions concern the set-up of controllers (see Table 2). Using a similar approach to Page et al. (2017a), Page et al. (2017b) developed a physically-based controller for VSPs. This controller is parameter-free and of feedback/feedforward kind. In fact, the suitable correction in pump speed at the generic time step is estimated based on variables at the old time, pressure head deviation at the controlled node and water discharge in the VSP-fitted pipe, and on the forecasted water discharge at the new time. Like the controller of Page et al. (2017a) for control valves, the controller of Page et al. (2017b) for VSPs proved stable and responsive under smooth demand conditions in the WDN.

Using the same approach as for the control valve, Creaco (2017) also developed a feedforward controller for VSPs, which evaluates pump speed correction as a function of the forecasted water discharge in the VSP-fitted pipe and of the forecasted pressure deviation at the controlled node. As mentioned above, a merit of the work of Creaco (2017) lies in accounting for random pulsed nodal demands. The Author remarked that, in the case of the VSP, the oscillations of the controlled variable caused by the pulsed nature of demands are smaller, especially under low demand conditions, compared to the control valve. This is because the pump tends to dampen the effects of water discharge variations better than the valve, especially under low-demand conditions (which require high valve closures and low pump speeds).

Simplified physically-based controllers, which do not use a forecasted water discharge, have also been formulated by Page et al. (2017b). The tendency of oscillations of the controlled variable to be small due to pulsed demand variation was also observed for these controllers (Page et al., 2018).

Several studies reported experimental remote RTC investigations using a small laboratory testbed that models a WDN. These studies do not use physically based controllers but provide valuable insight into the experimental performance and stability of controllers on a time scale of seconds or milliseconds. Various studies were done for a single VSP. First, a controller using fuzzy logic was studied (Bezerra et al., 2012). Fuzzy logic is an attempt at the formalization and mechanization of the human capability to make rational decisions. Second, both PID and an enhancement, called active disturbance rejection control (ADRC), was compared (Madonski et al., 2014). ADRC improves the performance of a classical feedback controller, for example PID, by adding a disturbance observer that reconstructs and rejects the unwanted perturbation in the system in each control cycle.

Another related approach was used by Filho et al. (2018) and De Araújo Moura et al. (2018), who proposed a feedback controller based on Artificial Neural Networks (ANN). The actuator was either two identical VSPs in parallel (Filho et al., 2018) or a single VSP (De Araújo Moura et al., 2018). Training was done based on laboratory experiments through the Descending Gradient (Filho et al., 2018) or Levenberg–Marquardt (De Araújo Moura et al., 2018) backpropagation algorithms. For both studies, the controllers proved stable and robust in the testing phase.

The controller in Filho et al., (2018) incorporates the minimization of the measured electrical power use of the two VSPs. For low demand it is found that only one of the two identical VSPs needs to operate. However, as the demand increases, both VSPs start to operate with each at the same pump speed. This work also shows that the controller is robust under disturbances which occur when the pumps switch.

The various studies that do not use physically based controllers have almost entirely been carried out by related authors. A gap in the literature is that these Authors need to provide clarity on which of the many controllers they proposed performs the best. Furthermore, comparison to a state-of-the-art physically based controller would be invaluable.

2.4. Water level control

If the WDN is gravity fed by tanks (open distribution systems), pumps are typically used to re-fill the tanks by pumping water from source(s). Unlike closed distribution systems, in this case pumps are required to fill tanks in a reasonable time period, with no need to regulate pump speed. Indeed, pump on/off switches need to be optimized to minimize the daily cost of electricity and the wear of the pumps and motors, which depends on various variables such the number of pump switches.

In the context of tank filling, the traditional approach considered in the scientific literature for the optimization of pump on/off switches is Pump Scheduling (PS), for which an extensive literature review was carried out by Mala-Jetmarova et al. (2018). This approach lies in considering a historical pattern of outflows from the tank, e.g. the daily average pattern, and in applying optimization techniques to optimize pump statuses at each time step of operation. However, PS features a high number of decisional variables, equal to the number of pumps present in the station times the number of time steps for the optimization (Alvisi and Franchini, 2017). Furthermore, the implementation of the results of PS yields largely suboptimal solutions, resulting in spilling from the tank and high cost of electricity, when the generic day of WDN operation differs from that considered in the optimization framework. To partly correct the issue of suboptimality, at the end of the generic day of system operation, forecast techniques could be used to predict outflows in the following day, to be used as input for PS. However, it must be noted that the results of forecast techniques always feature some degree of uncertainty, which results once more in problems of suboptimality (Quintiliani and Creaco, 2019).

As an alternative option to PS, remote feedback RTC can be used to regulate tank filling. This consists of switching on and off the pumps present in a pumping station, as a function of the water level in the tank. The two-point control is applied in this context. Numerical optimizations are used to optimize on/off trigger levels for each pump, to minimize the daily pumping cost and other variables, such as the number of pump switches or the time lag between two successive switches. If a system of pumps in parallel feeds a tank, pump on/off trigger levels must be optimized in such a way that the tank level always lies between a minimum and a maximum level. The on-trigger level is a suitably low level in the tank, in correspondence to when the generic pump is set on. Conversely, the off-trigger level is a suitably high level in correspondence to when the pump is set off.

The key features of the main contributions in the context of RTC of fixed speed pumps for tank filling are summarized in Table 3.

The simplest method (Fixed Trigger Levels, FTLs) for the RTC of pumps lies in setting, for each pump, the on and off trigger levels as constant values in the whole day (Paschke et al., 2001). As an improvement of the FTLs method, various authors used the Reduced Fixed Trigger Levels (RFTLs) (e.g. Creaco et al., 2016a,

Table 2
Summary of the key features of the various works in the framework of RTC for the regulation of service pressure through variable speed pumps.

Work	Kind of approach	Level of RTC complexity	Kind of control	Control logic	Control time step	Analysis of stability
Bezerra et al. (2012)	experimental (laboratory)	remote	feedback	fuzzy logic	seconds	no
Madonski et al. (2014)	experimental (laboratory)	remote	feedback	PID ADRC	milliseconds	yes
Page et al. (2017b) Page et al. (2018)	numerical (EPS)	remote	feedback /feedforward	physically based	minutes	no
Creaco (2017)	numerical (EPS)	remote	feedforward	physically based	minutes	no
Filho et al. (2018) De Araújo Moura et al. (2018)	experimental (laboratory)	remote	feedback	ANN	seconds	yes

2016b; Marchi et al., 2016). In the RFTLs method, the day is assumed to be divided into two or more energy-tariff periods (peak and off-peak periods), as regulated by the energy utility, in each of which the on and off trigger levels are defined for each pump. Ultimately, the RFTLs method was conceived to reduce the use of pumps when energy costs more. This is accomplished by running the pump(s), such that the water level in the tank is close to the highest point at the end of the low tariff period, i.e. at the beginning of the peak period, and near the minimum desired level at the end of the peak period.

Though being beneficial in terms of pumping costs, the RFTLs method may increase the wear of pumps. In fact, the pursuit of the beneficial condition described above may require the on/off trigger levels for the generic pump to be too close, thus overly increasing the number of pump switches. To make up for this unpleasant effect, Alvisi and Franchini (2017) proposed Variable Trigger Levels (VTLs), later also used by Housh and Salomons (2019). In VTLs the off-trigger level in the off-peak period and the on-trigger level in the peak period are set constant and equal to the maximum and the minimum acceptable tank water level, respectively. The two other trigger levels, instead, are assumed variable in time with a power law.

To correct the drawbacks of RFTLs, Quintiliani and Creaco (2019) proposed the RFLATS methodology, where RFLATS stands for Reduced Fixed Trigger Levels with Additional Time Slots. In this kind of control, additional time slots where trigger levels must be optimized are added immediately before tariff change instants. This enables the beneficial condition mentioned above to be obtained without changing trigger levels continuously (as in Alvisi and Franchini, 2017 and Housh and Salomons, 2019) and without overly increasing the number of pump switches (as in RFTLs).

2.5. Service pressure control, and energy production maximization using flow control

When a WDN district has lower ground elevation than its source node, turbines can be used to dissipate pressure surpluses. Compared to the simple use of PRVs, this causes larger installation costs, which may be paid back in the long run by the production of electrical energy. Instead of turbines, Pump as turbines (PATs), i.e. pumps running in reverse mode (Carravetta et al., 2014), can be used, resulting in many advantages including lower cost, shorter delivery time, easier installation and service availability (Williams, 1996; Isbasoiu et al., 2007). As some works have shown (e.g., McNabola et al., 2011; Samora et al., 2016), the combination of pressure control and hydropower generation offers large potential revenues and attractive capital payback periods.

Besides the PAT itself, a by-pass pipe must be installed to convey the flow that is unsuitable for power generation (because either it is too small, or it exceeds the PAT capacity). For flow modulation, control valves can be installed at both the PAT and by-pass pipes. However, if no real time regulation is performed in these control valves, the power generation and pressure reduction effects are sub-optimal at each time step of the system operation.

Therefore, the operation of the PAT and control valves can be dynamically improved through RTC, to pursue maximization of produced electrical energy while guaranteeing a sufficiently high service pressure downstream.

In this context, Fontana et al. (2016) developed theoretical and experimental analyses for the operation of a prototype for hydropower generation in WDNs. The prototype is composed of two parallel lines: the generation pipe equipped with a needle valve (PRV) and a PAT, and the by-pass line equipped with a needle valve. RTC was implemented to both maximize the power generated by the PAT at varying upstream pressure and inflow discharge and ensuring the required pressure at the critical node. Because the impeller has a constant rotational speed, the optimization problem was simply solved by convoying the maximum possible flow through generation pipe while respecting the minimum pressure level at the critical node. To this end, a two-level control strategy was implemented: the high-level controller which determines pressure drop and flow between the lines; and the low-level controllers, which operate the PRVs to obtain the desired set points of pressure and flow.

A switching control (also called bang-bang control) was used, because the needle valves are controlled through a digital signal switching among the three possible inputs (open/stop/close). The open command starts the rotation of the motor at a fixed speed in the opening direction, the close command starts the rotation in the closing direction, and the stop command stops the motor rotation. In the experiments, the control time step and signal input to the valves were set to be of the order of milliseconds in order to reduce the valve velocity.

Fontana et al. (2018c) further improved the prototype RTC by maximizing power generation by also varying the rotational speed of the impeller. To this end, an inverter was added to the prototype. The algorithm maintains the two-level control strategy, but a non-trivial optimization problem arises because of two decisional variables, namely the maximum possible flow through generation pipe and the rotational speed of the impeller. Two approaches were proposed to solve in real time the optimization problem. In the first, the generated power was maximized using a Matlab optimization toolbox Yalmip, which calculates the rotational speed and the discharge in the PAT. To allow communication between Matlab and the PLC which operates the PRVs and inverter, an Open Platform Communication (OPC) standard solution was used. The second approach does not require an external optimization module but uses relationships to represent the operation of the PAT by means of dimensionless parameters (flow number, head number and power number).

Numerical and laboratory experiments were also carried out to assess the operation and reliability of the proposed control algorithms. Preliminary results developed by Fontana et al. (2018c) showed that the control algorithm operates properly under certain operating conditions. Fontana et al. (2019) further validated the effectiveness of the control algorithm carrying out extensive laboratory experiments under different operating conditions. In all cases, experiments revealed that the prototype's operation showed robust behavior without instabilities also when abrupt flow discharge and set point pressure variation occurred.

Table 3
Summary of the key features of the various works in the framework of RTC of fixed speed pumps used for tank filling.

Work	Kind of approach	Level of RTC complexity	Kind of control	Control logic	Control time step	Kind of trigger levels
Paschke et al. (2001)	numerical (EPS)	remote	feedback	two point control	minutes	fixed
Creaco et al. (2016a; 2016b)	numerical (EPS)	remote	feedback	two point control	minutes	reduced fixed
Alvisi and Franchini (2017)	numerical (EPS)	remote	feedback	two point control	minutes	variable
Housh and Salomons (2019)	numerical (EPS)	remote	feedback	two point control	minutes	variable
Quintiliani and Creaco (2019)	numerical (EPS)	remote	feedback	two point control	minutes	fixed

3. A real case study

This case study is taken from the work of Fontana et al. (2018b), which describes the application of RTC in Benevento, a medium size city of Regione Campania (Campania Region), in southern Italy, with a population of around 60,000 inhabitants (Fig. 2). The WDN, managed by the GE.SE.SA. water company, is divided into 30 District Meters Areas (DMAs) for improved leakage control. At the inlet of each DMA, a PRV and a flow meter are installed, to ensure flow measurement and pressure control over the district. A control system for pressure RTC was installed in one district of the network.

The control system was installed in the "Santa Colomba" district and has been operating since September 2016. The total length of main pipes within the district is around 8.4 km (Fig. 3), with Nominal Diameters (ND) ranging between 50 mm and 250 mm.

The network serves around 2800 properties, with a total population of about 8600 inhabitants. The area served is fairly even, with elevation ranging between 122 m above sea level (asl) 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 identified the critical node (see Fig. 3), where a minimum pressure has to be guaranteed.

3.1. Equipment and communication system

Pressure transducers are installed at the monitored node and both upstream and downstream of the PRV. At the DMA inlet, an electromagnetic flow meter (Mod. G2 PMAG) was also installed. The pressure at the inlet was remotely regulated using a PRV with motorized pilot.

The PRV is a pilot-operated Bermad valve, Mod. EN 720 4SE - VI, Nominal Diameter 150 mm. The valve is hydraulically operated by means of a diaphragm actuator, which reduces the upstream pressure to a lower constant downstream pressure. Pressure regulation is independent of upstream pressure and flow discharge. The PRV is equipped with a motorized pilot, with input voltage v ranging between 0 V and 10 V. By varying v, an actuator compresses or stretches the pilot spring, thus varying the outlet pressure h_d.

An input voltage of 0 V corresponds to the maximum outlet pressure, whereas an input voltage of 10 V corresponds to the minimum outlet pressure (i.e, closed valve). Input voltage to the PRV is commanded by a PLC, which is 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 is also installed at the critical node for pressure acquisition. During the installation stage, the communication between the Point I/O and the PLC was a relevant issue because of the distance in between, being in the order of 3.5 km, and with urbanization of the area causing a lack of "visibility" between the points. The Point I/O has to communicate with the PLC to transmit (in Real Time) the acquired pressure, thus driving the regulation of the PRV. GSM (Global System for Mobile communications)/GPRS (General Packet Radio Service) transmission is used to assume effective and reliable communication between Point I/O and PLC, thus a modem was mounted at both the PLC and the Point I/O.

A triangle-based scheme was considered for communication, i.e. the modems do not establish a point-to-point connection. Such a scheme can connect a SCADA system for high-level process supervisory management (Fig. 4). A server was installed at GE.SE.SA. offices, receiving the data from the modems on site, i.e. the modem close to the monitored node and the modem close to the district inlet, which signal data on measured critical pressure head and entering water discharge in the DMA, respectively. The server then sends the data to the PLC, which process them to evaluate actuator setting corrections.

3.2. Controller for RTC

A pure integral controller was used for the regulation of the PRV as proposed by Fontana et al. (2018a; b). Unlike a proportional action, the integral controller introduces a filtering action on pressure measurement, thus eliminating the effects of high frequency pressure variations due to user demand. As a result, the PRV

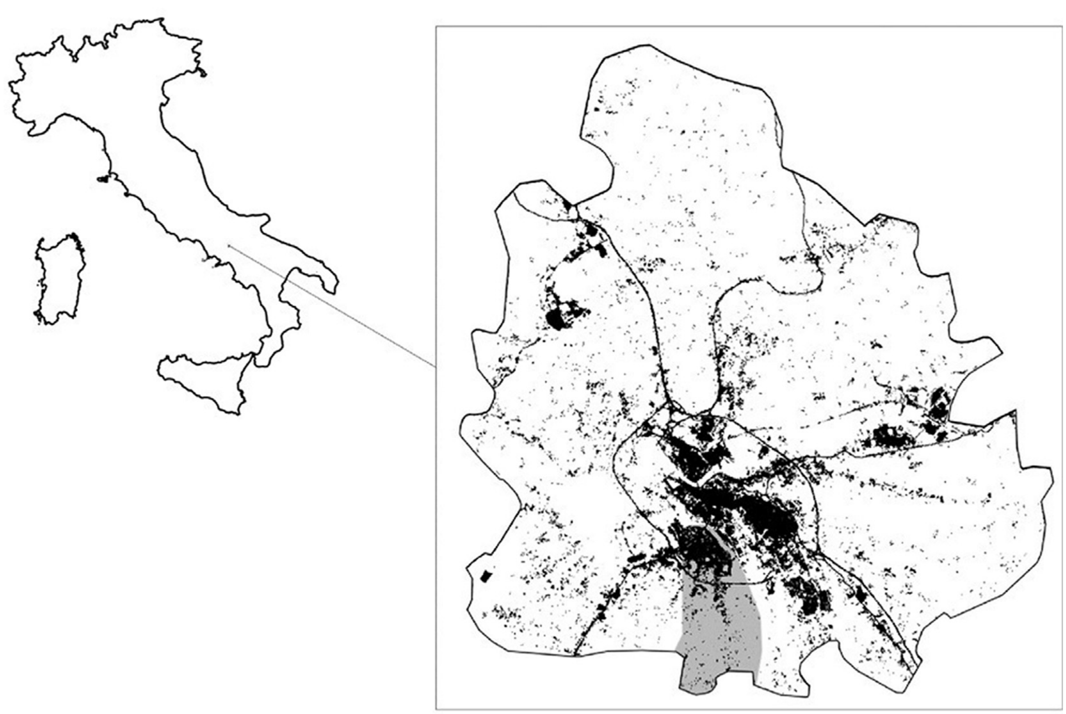

Fig. 2. Benevento city and Santa Colomba district.

Fig. 3. WDN of Santa Colomba district with position of the monitored node.

reacts more slowly (in the order of minutes) to pressure variations at the critical node but is totally consistent with the operation of a WDN. The finite delay between the time at which the signal is sent to the PRV and the time at which the effects of such a regulation are measured downstream at the critical node was also considered in the controller's design. Such a delay may cause oscillations and even instabilities in pressure control, especially for larger values of the gain. To this end, the Smith's predictor was implemented, thus improving the performance of the controller. Preliminary laboratory experiments confirmed the effectiveness of the adopted solution (Fontana et al., 2018a).

3.3. Measurements from the field

Some measurements were carried out in the field to assess the effectiveness of the pressure RTC and compare the benefits against a traditional pressure control in a WDN. Fig. 5 shows the experimental pattern at the critical node during a 3-day interval considering: a) traditional pressure regulation, by setting a constant input signal to the PRV, so as to guarantee a minimum pressure close to 18 m; b) RTC with a set point pressure of 20 m at the critical node; and c) RTC with a set point pressure of 18 m at the critical node. Results show, in case of RTC, a quite regular pressure pattern, with negligible deviations from the set point value (Fig. 5). The benefits of such a control are evident especially during night hours, because a significant pressure regulation can be performed against a fixed PRV, thus reducing pressure over the network. RTC also ensures a lower and more regular pressure pattern within the whole WDN. Experiments showed a reduction in both fluctuation amplitude and standard deviation, indicating a lower variability of pressure over time. The effectiveness of the RTC was also assessed in terms of leakage reduction within the WDN. Minimum Night Flow (MNF) was measured at the network inlet, showing a decrement by approximately 1 L/s when RTC was applied, in comparison with the case of PRV regulation in the absence of RTC.

4. Discussions

Compared to static control, in which actuator settings are not dynamically modified in time, RTC has undisputed beneficial effects but features larger installation and operational costs. While investigating the economics of RTC to control pressure, Creaco and Walski (2017, 2018) found that the benefits of RTC where greatest in large pressure zones, where the variable operating and maintenance costs (energy, chemicals) of lost water is very high, the number of continuously running leaks is large, and the demand showed significant variations over the course of the day. Local RTC was generally more economical than remote RTC because only one vault was required, and no communication cost was involved, but remote RTC was the best technology for responding to unusual events (fire, shutdowns) in the system. Sensors for remote RTC could be located at critical customers (e.g. hospitals, key factories) instead of at the inflow to the zone.

In most of the research papers on RTC, providing minimum acceptable pressure is an objective in order to reduce leakage and pipe breaks, as well as to contribute to extending infrastructure life. However, providing a target pressure above the minimal has benefits in terms of customer satisfaction, less need to pump in taller buildings, better performance by fire and irrigation sprinklers, better fire flow through hydrants, and greater margin of safety to prevent intrusion during emergencies. In many cases, the expected benefits pay back the larger installation costs in a sustainable time frame.

A survey has revealed that RTC is now employed in many real world WDNs. In most cases, the configuration described in the section entitled “A real case study”, featuring a PRV with setting regulated in real time to guarantee desired pressure-head values at the remotely controlled node(s), is the favorite one. The installation of RTC typically follows WDN partitioning into DMAs, with the objective to monitor WDN consumption and leakage and to regulate service pressure. As an additional example well-documented in the scientific literature, there is the city of Denizli (e.g., see Güngör et al., 2019) in western Turkey, in which the PRV-based RTC configuration is effectively operating in one of the DMAs of the WDN. Like the real RTC application described above, the transfer of data is carried out through the GSM/GPRS transmission, and a SCADA system is used for high-level process supervisory management. Conversely, the setting of the PRV is regulated locally as a function of the water discharge.

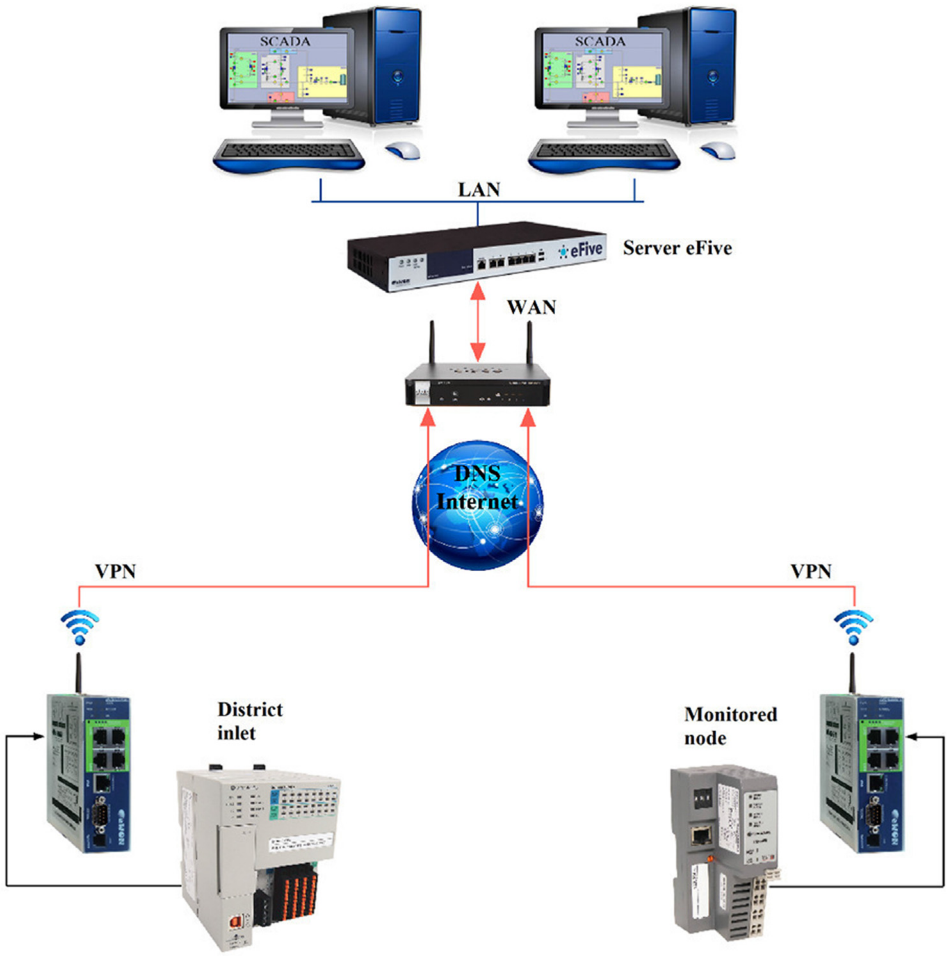

Fig. 4. Sketch of the used triangle-based communication scheme between the GE.SE.SA. server and the modems installed at district inlet and monitored node.

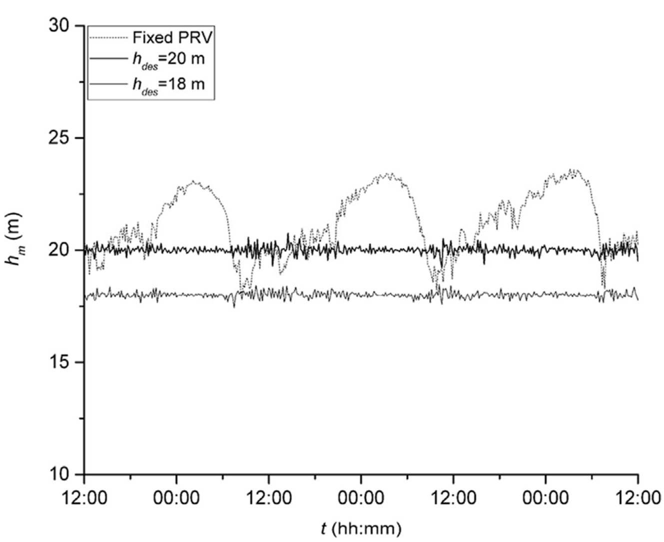

Fig. 5. Pressure pattern at the monitored node (fixed PRV and RTC).

5. Conclusions

The literature review of the works on RTC in WDNs has highlighted the following aspects:

1 – all works have proven that RTC is highly beneficial in many contexts, such as service-pressure control, tank level regulation and optimization of hydroelectric energy production
2 – service-pressure control through valves is, by far, the most investigated topic
3 – regrettably, the number of numerical works largely exceeds that of experimental works. In most cases, the prediction capability of numerical models of RTC has not been corroborated through comparisons with experimental data.
4 – the number of works reporting about experimental results in real WDNs is very small (in this review only the papers of Fontana et al., 2018b; Janus and Ulanicki, 2018; Güngör et al., 2019 which use a PRV as an actuator).

The issues related to points 3 and 4 should drive the future endeavors of the scientific community. In fact, only by comparison of numerical and experimental results can the marginal benefits of more and more sophisticated RTC algorithms be suitably assessed. Furthermore, the performance of RTC in real case studies need to be analyzed and compared in depth, to have better insight into real benefits and limits of this control solution. Since various water utilities (e.g., in the UK and in Northern Italy) claim that they have been adopting RTC in their WDNs, researchers ought to get in contact with them to receive useful hints and feedbacks. Another prospect for RTC could be the extension to aspects of water quality. In fact, while the RTC of disinfectant residuals has been considered in a few studies (e.g., Wang et al., 2006; Souza and Mohan Kumar, 2018), important issues such as the use of RTC for maneuvering isolation valves to isolate DMAs in the case of contamination events have been totally overlooked.

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