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Leakage management: planning remote real time controlled pressure reduction in Oppegård municipality

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Abstract

Pressure control entails the cheapest technical solution to achieve leakage reduction in water distribution networks in short-medium time horizon. This work reports the planning of remote real time controlled (RRTC) pressure reducing valves (PRV) for the Oppegård (Norway) hydraulic network. It was achieved by using an advanced hydraulic model which integrates the pressure-dependent background leakage model with the simulation of PRVs based on remote control nodes. Results demonstrate that RRTC PRVs instead of existing locally controlled ones permits the reduction of the background leakages of about 35%. This rate increases over 40% if few additional RRTC PCV are installed.

Keywords: Water distribution networks; WDN models; leakages; pressure reduction valves.

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1. Introduction

Reducing leakages from water distribution networks (WDN) is a major management issue that have many operational benefits including the improvement of system hydraulic capacity, the increase of asset longevity, saving of water resources and, ultimately, the reduction of carbon footprint for water abstraction, treatment and pumping. In technical literature, water losses are classified into *bursts leaks* and *background leakages* (e.g. [1]). Although *burst leaks* might cause large roads disruptions and third party damages, they are mainly considered as "accidents" whose

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impact on WDN functioning depends on actual system mechanical reliability (e.g. existing isolation valve system) and the promptness of detection and repair. Normally, *burst* leaks are suddenly reported and repaired since they cause sensible pressure drops, service disruption and, sometimes, evident outflows. Vice versa, *background leakages* represents a pervasive problem in all WDNs since they refer to diffuse water outflows that are less evident than pipe bursts and involve major trunks, distribution pipes and private connection pipes. Thus, they can run for very long time before repair, resulting into huge volume of lost water with consequences on system hydraulic performance, asset condition and system management.

From hydraulic perspective, the increase of *background leakages* results into gradual deterioration of hydraulic capacity, with risk of insufficient water supply in case of extreme conditions (e.g. seasonal fluctuation of demand, firefighting). From asset perspective, *background leakages* accelerate deterioration as a combination of different effects including the continuous leaching of backfill soil that undermine the stability of the pipe (e.g. [2][3]) and the corrosion in metallic pipes at water-pipe-soil interface. All these factors cause make existing holes and cracks evolving towards major leaks. From management perspective, the increasing volume of water lost represents loss of money spent for energy and chemicals (e.g. for water treatment) as well as increase of carbon footprint of the water supply service.

Background leakages result from the joint effect of asset deterioration and pressure thus their reduction requires, in the *medium-long* term, the effective planning of pipe rehabilitation/replacement and, in the *short* term, the optimal control of pressure. This work deals with the latter option and analyzes the reduction of *background leakages* achievable by planning pressure control strategies that exploit current ICT capabilities to modulate pressure control devices (i.e. pressure reduction valves – PRV) based on pressure readings at remote “critical” nodes.

Some previous works actually report strategies to simulate PRVs whose closing degree is modulated based on remote control nodes, accounting also for the transfer function of the programmable logic control (PLC) units that drive the valve shutter (e.g. [4]). Others report the effectiveness of real-time control strategies for operational purposes [5, 6, 7, 8, 9], mainly aimed at keeping pressure under control in face of daily (or seasonal) fluctuation of customers’ water demand. Nonetheless, scarce contributions explicitly analyze and report the impact of remotely controlled PRVs on *background leakages* control and, more important, the advantages achievable over classical PRVs modulated based on local pressure (i.e. at valve downstream nodes). The main reason for the lack of such analyses stems from two main limitations of many used WDN hydraulic models: (i) they do not account for background leakages as diffused pressure-dependent pipe outflows; (ii) they are not able to simulate PRVs functioning based on pressure readings at remote control nodes.

Nonetheless, these analyses are of key importance for planning pressure control strategies and are relevant in oversized WDNs where high-pressure regimes are slightly affected by demand variations over the operating cycle and effective pressure management would reduce significantly *background leakages* while ensuring acceptable level of water supply service. Assessing the potentialities of remote control schemes over classical local control of PRVs in terms of achievable leakage reduction would increase awareness of technicians to support decisions on investments for implementing ICT solutions for real water losses reduction, going beyond the current empirical/subjective approaches to modulate PRVs based on local pressure values.

The present paper demonstrates that the advanced realistic hydraulic WDN modelling [10], overcoming previous limitations, permits to evaluate the benefits in terms of *background leakage* reduction, thus being effective to support pressure control strategies for leakage reduction.

This work is part of the *InnoWatING* project (Innovation in Water Infrastructure - new Generation, funded by the Norwegian Research Council) aimed at proposing an approach for smart operation and management of water distribution networks where real time control (RTC) techniques and ICT solutions will be integrated into advanced hydraulic modelling and tested on Oppegård WDN. The WDNetXL system [11] is adopted as the software platform where the hydraulic model of Oppegård WDN was implemented and strategies for optimal pressure control were integrated and demonstrated.

Next section recall and discusses the representation of *backgro*und leakages within the adopted WDN hydraulic model. Thereafter, remote and local control of PRVs are compared in the framework of planning support for pressure management. The case study of Oppegård WDN is introduced and different pressure management planning solutions are compared with the existing condition in terms of leakage reduction. Finally, conclusions and future recommendations are drawn.

2. Representing background leakages in WDN models

From hydraulic modelling perspective *background leakages* can be viewed as diffused outflows whose discharge depends on asset conditions and pressure along pipes. The model adopted herein [10, 12] assumes that background leakages outflow depends on the average pipe pressure, as the most immediate and technically sound assumption. Thus, the *background leakage* outflow from the *k*th pipe is computed as:

$$d_k^{leaks} = \begin{cases} \beta_k L_k P_{k,mean}^{\alpha_k} & P_{k,mean} > 0 \\ 0 & P_{k,mean} \leq 0 \end{cases} \tag{1}$$

where: k is the subscript of the *k*th pipe; d_k^{leaks} is the background leakage outflow along the *k*th pipe; β_k and α_k are model parameters [10, 13]; L_k is the length of the *k*th pipe. $P_{k,mean}$ is the model mean pressure along the *k*th pipe; assuming that the *k*th pipe is between nodes i and j, $P_{k,mean}$ is computed as $(P_i + P_j)/2$.

β_k and α_k are model parameters that should be estimated. In model (1) the exponent α_k actually entails the mechanical behavior of pipes in face of pressure changes, although it cannot be referred to a single orifice but rather has a statistical meaning that refer to the entire pipeline. For this reason, is was observed that, although its value should vary in the range [0.5; 2.5] based on physically-based considerations, values of about 1.0-1.2 were found to provide acceptable results for a wide range of material [14] (including those installed in Oppegård WDN). Vice versa, the coefficient β_k depends on pipe material, ageing, laying and service conditions and can be estimated for each pipe, similarly to pipe hydraulic resistance parameters (e.g. [15]), based on grouping of homogeneous cohorts of pipes and field pressure/flow measurements.

3. Planning pressure management by PRVs: remote vs. local control schemes

Pressure management is the first option for leakage reduction campaigns since it might result into significant reduction of water lost volumes before implementing expensive asset renewal/rehabilitation works. Effective pressure management in WDNs should pursue the correct service to customers while minimizing leakages. This means that, in absence of asset rehabilitation works, there is a minimum level of leakages that has to be tolerated because it is related to the minimum service pressure required.

In this technical framework, Pressure Reduction Valves (PRVs) permits to minimize the pressure surplus by modulating the opening degree of the shutter in order to determine a local head loss and achieve a desired pressure in the controlled area. Nonetheless, setting a pressure control scheme by PRVs actually asks for two types of problems to be solved by engineers: (i) select the most effective location(s) of the PRV(s); (ii) set control strategies to drive the shutter closure

Actually, problem (i) entail the identification of pressure control areas and relevant feeding pipes where the PRVs should be located. In practice, zones with high-pressure problems are already known to water utilities and pressure control areas are usually identified by using empirical approaches. It is worth to observe that effective control of pressure by PRVs might require closing gate valve(s) in order to bound the pressure control areas (i.e. thus avoiding “backdoors” for water). In addition, pressure management plans using PRVs should account for devices already installed through the network (i.e. gate valves and pressure control valves), since they entail past investments of the water utility which should be somehow preserved in the future plans.

The problem (ii) of setting the most effective control strategy can be solved resorting to two different approaches:

- *local pressure control*
- *remote pressure control*

Local pressure control entails most of the PRVs currently operating in Europe and worldwide. It implies that the closing degree of the PRVs is modulated based on a set-point right downstream the valve. This means that the PRV start closing when the pressure exceeds the set-point at such node; while the valve opens when the pressure is below that value. The opposite happens for the so-called "pressure sustaining valves" where the control nodes is right upstream the valve.

Remote pressure control scheme is allowed by current ICT capabilities to collect pressure measurements from any (remote) node of the WDN, communicate it at distance (e.g. using radio or GSM protocols) and modulate the shutter opening degree by a Programmable Logical Control (PLC) unit to reach the set-point at remote node. The remote control node is usually designated as "critical", meaning that it is the first node where the pressure drop, even below the pressure required for a correct service. It is worth noting that such pressure value is actually a constant value over time depending on building height and residual pressure requirement to provide a correct water supply service.

From operational perspective, *remotely controlled* PRVs actually implies a number of advantages over classical *local control* that can be summarized in the following.

The classical *local control* requires to set a pressure which is actually varying over time according to the hydraulic system behavior and, in particular, the delivered water. Usually, this limitation asks for a time patter of pressure set values which depends on the "predicted" delivered water as well as on "expected" WDNs behavior, based on either empirical knowledge of the system or WDN hydraulic modeling. Vice versa, the *remote control strategy* permits to set the desired service pressure at "critical" nodes, which does not change over time (i.e. as it entail the desired water supply service conditions), making sure that, if the pressure at critical node is satisfied, all other nodes in the pressure control areas will have higher pressure (thus sufficient for correct service).

The *remote* pressure reading at "critical" node reflect the *true actual* behavior of the network, under both normal conditions (e.g. expected demands) and unpredictable variations of water outflows (e.g. firefighting). Differently, the time pattern of the set-point(s) at downstream node of *locally controlled* PRVs should be fixed a priori, requiring different control procedures to manage possible abnormal water requests scenarios.

The strategies entailing *remote pressure control* permits to implement the Remote Real Time Control (RRTC) of PRVs by installing and operating proper devices for data acquisition and transmission, data processing and mechanical actuators, equipped with long-life batteries or fed by electric power. Since such equipment represents an additional cost for the water utilities, if compared with *classical local control* strategies, it is necessary to assess the advantages of their implementation in terms of leakage reduction achievable, besides the other advantages in terms of WDN reliable operation in case of abnormal water requests.

The present paper demonstrates that using an advanced WDN hydraulic model [10] that integrates background leakage modelling and remotely controlled PRVs permits to support the optimal planning of remote real time controlled PRVs for leakage management purposes. In this framework, "planning" RRTC is intended to analyse the expected reduction of background leakages achievable by implementing different RRTC PRV plans assuming that the pressure set at "critical" control node is reached instantaneously. Thus, such analysis neglects the peculiar control of the valve status based on pressure measurement at control node.

4. Oppegård municipality

Oppegård municipality is located at south of Oslo and is served by a WDN (see Fig. 1) which extends for about 129 km, served area with substantial changes in elevation, ranging from 40 to 180 a.m.s.l. In order to cope with such topographic scenario, hydraulic operation combines pumping to feed areas with higher elevation (dark-red in Fig. 1) and pressure reduction by PRVs in areas with lower elevations (light green-blue in Fig. 1).

The analysis of WDN hydraulic behavior (see average pressure values in Fig. 2) revealed that pipe diameters are actually oversized with respect to the water request under normal functioning. This fact results into small (technically negligible) change of pressure regime over the operating cycle. In addition, the combination between the need of having at least 30 m of water pressure (for firefighting purposes only) and the change in elevation results into pressure that easily reach 70-80 m with maximum values over 130 m in the lowest elevation zones (i.e. North-West area circled in red in Fig.2). Such pressure regime currently results into a leakages level reported by the water utility is of about 24% of the total inlet water volume for the entire WDN. Actually, such figure increases in the high-pressure area like in the North-West area, despite 9 PRVs are installed and working based on classical *local* pressure control scheme.

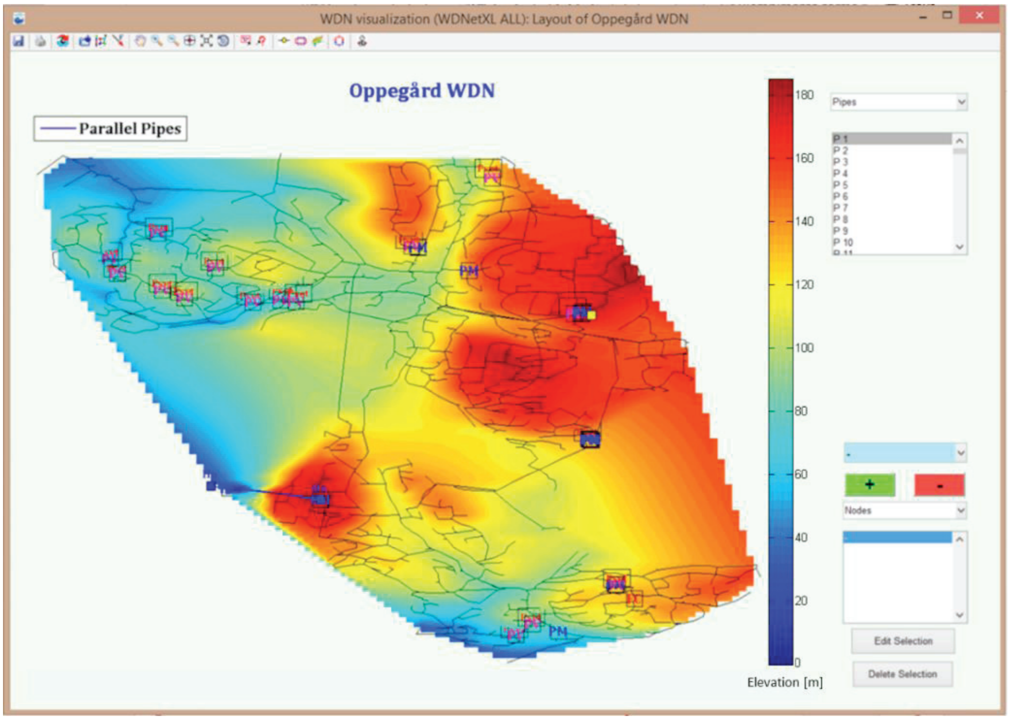

Fig. 1. Oppegård WDN elevations

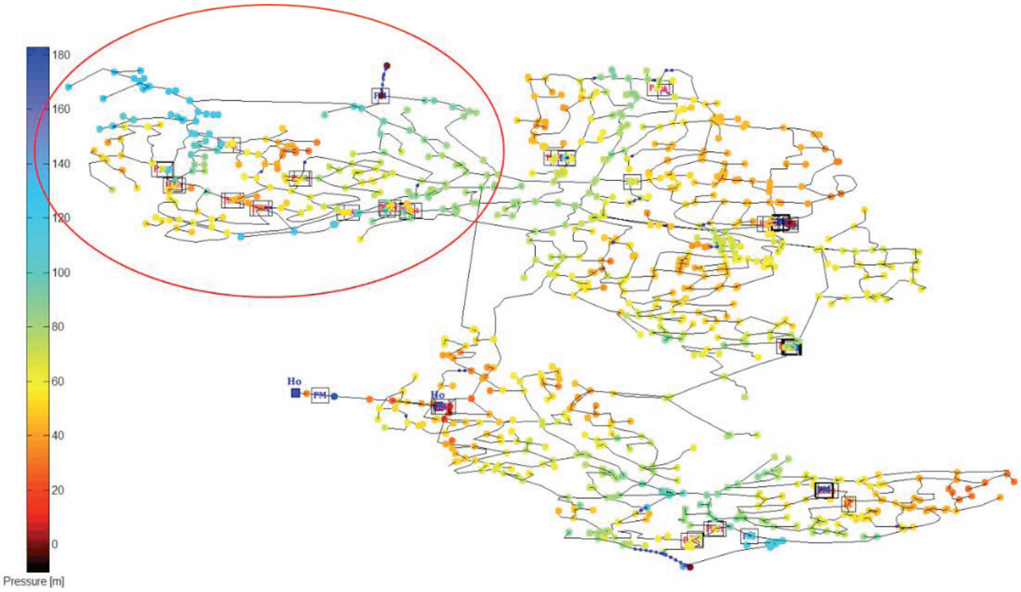

Fig. 2. Oppegård WDN model: average node pressures simulated over 24-hours extended period simulation.

5. Planning RRTC strategies for pressure management in Oppegård municipality

As one major objective of the *InnoWatING* project, planning effective pressure management is meant to provide a *short-medium* term solution to reduce water leakages in Oppegård WDN. To accomplish such task the Oppegård WDN hydraulic model was implemented in the WDNetXL system, whose hydraulic modelling features permits the simulation of both remote controlled PRVs and the estimation of background leakages, based on model in (1).

For the sake of the demonstration, the analysis reported herein refers to the North-West area only (circled in Fig. 2) and considers the following technical alternatives: (i) the elimination of existing valves; (ii) the installation of new valves controlled from remote nodes; (iii) possible closure/opening of gate valve to bound the controlled areas.

Starting from current network condition (i.e. 9 PRVs in North-West area, with no RRTC), the present analysis reports six alternative plans for PRVs installation, entailing both *classical* and RRTC schemes.

Fig. 3 reports the analysis area with the position of currently installed PRVs (i.e. designated as “PV”); labels “Set” indicate the control nodes, which are all right downstream the PRVs in the current condition. The simulated water volume lost from the analyzed area is about 911 m^3/day. Fig.3 also shows in more details the elevation pattern of the analyzed area, ranging from about 55 m (blue) to 120 m a.s.l. (yellow).

Fig. 4 shows three alternative pressure management plans, describer in the following.

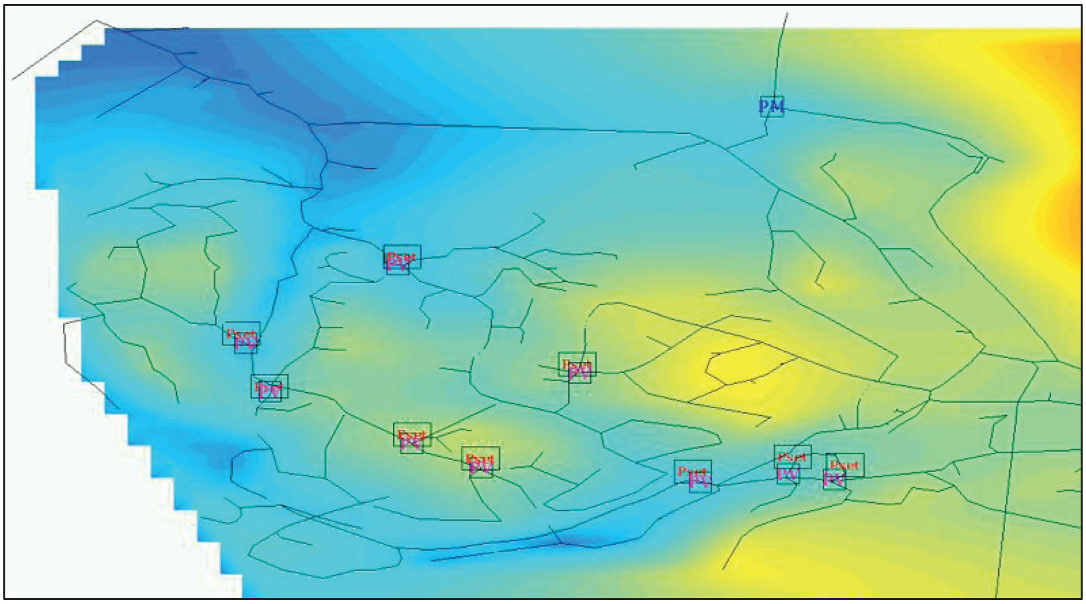

Fig. 3. Oppegård WDN: location of existing PRVs and elevation pattern in the analysed area.

Scenario (a) preserves 4 existing PRVs, while 3 RRTC PRVs are installed to control remote “critical” nodes in relevant pressure control areas. Arrows indicates the relationship between each PCV and relevant remote control nodes. The location of new PRVs was selected manually considering the changes in elevation and the need to reach the desired service pressure (i.e. 30 m) at “critical” nodes, while reducing pressure as much as possible along the pipeline in order to curtail water losses. The leakage reduction achievable with scenario (a) permits to save about 122 m^3/day (i.e. about 13% of reduced background leakages with respect to current configuration), although with a lower number of PRVs than those currently installed (i.e. 7 instead of 9) 3 of which entail RRTC. The assessment of background leakages resulted from the extended period simulation (EPS) of the Oppegård WDN hydraulic model over 24 hours of typical operating cycle provided by the water utility.

Scenario (b) is similar to (a) except for the pressure control of the long trunk running in the northern part of the area though the lowest elevation zone (from green to dark blue). Controlling pressure from upstream of such trunk permits to double the water saving, up to 244 m^3/day (i.e. about 27% reduction of current leakages in the area). Also in this case such water saving is expected to be achieved with two PRVs less than current configuration.

Scenario (c) is the same as (b) with the addition of one more RRTC PRVs (i.e. red arrow) that permits to control pressure also in the trunk feeding the area from the South, which also serves low elevation zones. Adding such valve results into an estimated background leakage reduction of about 35% of current value, although the number of planned valves is still lower than the current one (8 instead of 9).

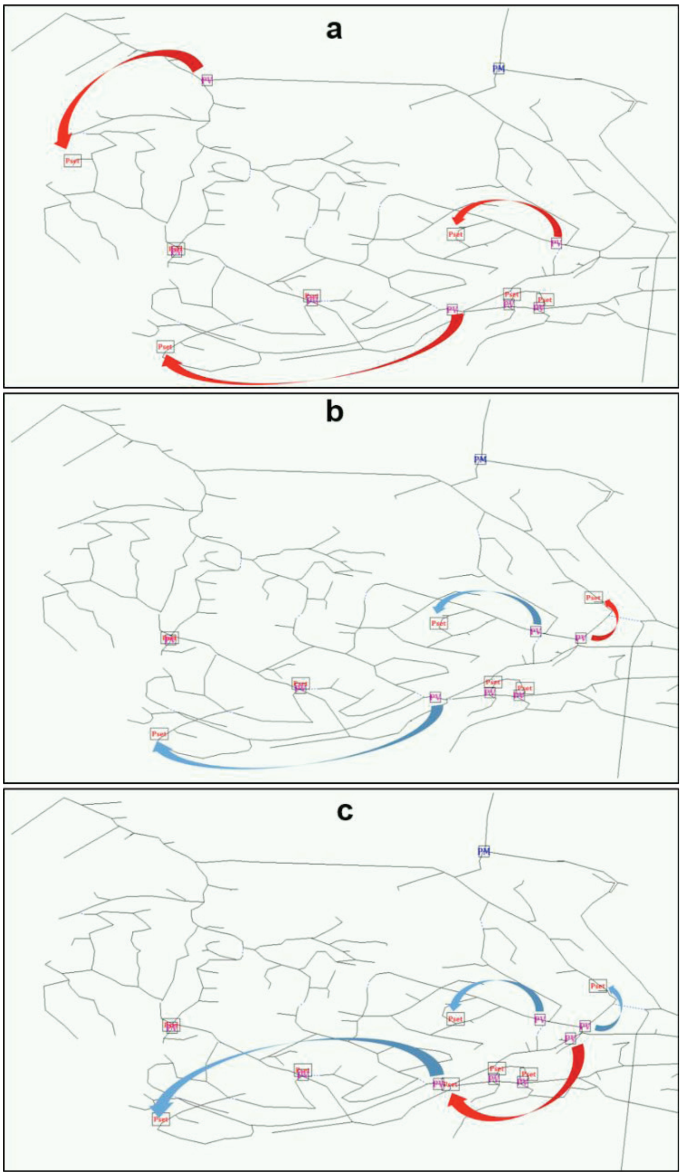

Fig. 4. Pressure management plans with less than 9 PRVs installed.

The analysis of scenarios (a), (b) and (c) demonstrates that the advanced hydraulic modeling permits to simulate possible RRTC pressure management alternatives in terms of both actual effectiveness of valve-node association (i.e. controllability of the "critical" node from valve location) and the assessment of possible background leakages reduction. Results shows that, in the analyzed area, even a limited application of RRTC PRVs might result into a considerable reduction in water losses, although with a lower number of installed valves.

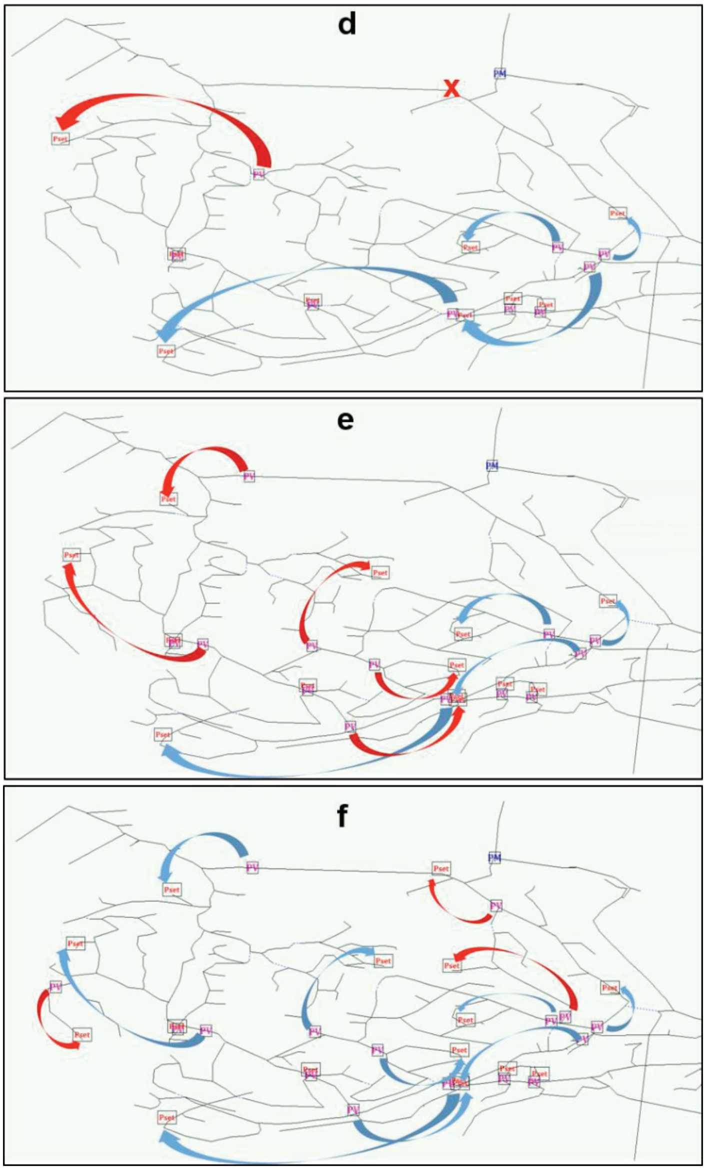

Fig. 5. Pressure management plans with at least 9 PRVs installed.

The peculiar elevation pattern of this Oppegård area motivated also the extension of such analysis including three more scenarios where the number of RRTC PRVs is progressively increased in order to achieve lower background leakage volumes. The scenario in Fig. 5(d) is obtained from that in Fig. 4(c) by adding one RRTC PRV (red arrow) to control pressure in the lowest elevation area. This scenario actually requires to bound the controlled area by closing the pipe indicated with the red "x", which actually change the water paths in that area. The resulting background leakages are reduced by more than 41% with respect to the current real configuration.

Finally, scenarios (e) and (f) are obtained by further subdividing the network into pressure zones controlled by 13 PRVs (8 RRTC) and 16 PRVs (10 RRTC), respectively. These scenarios permit to achieve more than 43% and 47% of water losses reduction in the analyzed area.

The diagram in Fig. 6 summarizes residual water losses and savings achievable in terms of yearly volumes by increasing the number of PRVs and, in particular, RRTC PRVs. All analyzed scenarios result into lower water leakages than current configuration.

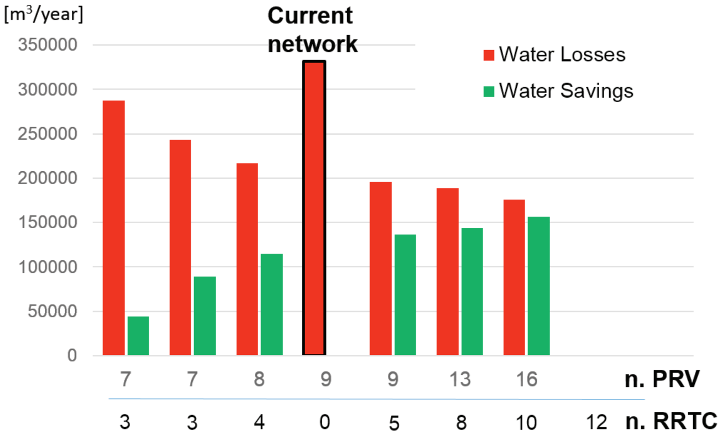

Fig. 6. Water leakages achievable under different PRVs planning alternatives.

6. Discussion and conclusions

Planning effective pressure management strategies represents the *short-medium* term countermeasure to reduce real water losses in WDNs. Pressure reduction valves (PRVs) entails the technical expedient to provide water with sufficient pressure to users, while avoiding pressure surplus resulting into background leakages. Nowadays ICT solutions permits to move from *classical local control* of PRVs, to *remote real time control* (RRTC) strategies where valves area modulated based on pressure readings ant remote "critical" nodes.

As for other asset upgrades of the WDN infrastructure, possible alternative configuration of RRTC PRVs need to be preliminary evaluated in terms of efficacy (i.e. actual controllability of the "critical" node from candidate valve location), effectiveness (i.e. background leakage reduction achievable) and related costs for installation. This paper demonstrate that an advanced WDN hydraulic model that permits to simulate remote control of PRVs, while assessing pressure-dependent background leakages along pipes over an operating cycle, is essential to support the planning of RRTC solutions.

The analysis refers to a sub-portion of Oppegård WDN, which is prone to experience background leakages due to severe changes in elevation and current high pressure regimes.

On the one hand, results show that using remotely controlled PRVs permits to achieve higher water leakage reduction than classical local controlled ones (currently installed in the network). This confirms that, even for Oppegård WDN, RRTC solutions represent a viable and effective solution for pressure control.

On the other hand, the analysis itself demonstrate how it can be useful to support such planning activity. In fact the estimation of background leakages integrated with the realistic simulation of pressure control devices based on any remote nodal pressure reading permits to verify the actual efficacy of the candidate solutions and to compare different solutions with each other. From such perspective, Fig. 6 represents by itself a decision support tool where technicians can quantify the benefit (e.g. water volume saving over one year) in face of increasing investment.

It is worth to remark that the present analysis does not encompass any optimized strategy for WDN segmentation and PRVs location, which is by itself an emerging issue in technical research. Nonetheless, the integration of the advanced model adopted here with possible optimization strategies for supporting RRTC planning is part of ongoing and future research.

Acknowledgements

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