Hydraulic reliability analysis of a real network with remotely real-time controlled pressure control valves

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ABSTRACT

The paper considers a real water distribution network, where current pressure control strategies exploit classical pressure control valves (PCVs). A previous study identified alternative pressure control strategies exploiting remote real time controlled pressure control valves (RRTC PCVs) together with existing classic ones, aimed at reducing background leakages. The proposed analysis relates to the hydraulic reliability of the system accounting for RRTC PCVs compared to the classic PCVs (already installed). The analysis also assumes fire protection requirements, statistical increase of customer demands and the increase of pipes deterioration (background leakages and pipe roughness). The hydraulic reliability analysis is part of the Management module of the WDNetXL system and is based on advanced hydraulic modelling, including pressure-dependent water demand components (e.g., background leakages), classic PCV and RRTC-PCVs as well as any hydraulic control device (pumps, directional valves) that might change WDN topology during the simulation.

Keywords: Water Distribution Network, Pressure control, Hydraulic Reliability

1 INTRODUCTION

The hydraulic reliability of water distribution networks (WDNs) is crucial for operational and management reasons; for WDNs, reliability can be defined as the capacity to deliver water to customers with adequate levels of service (flow and pressure) also under abnormal operating conditions [1]. When abnormal operating conditions are caused by changes of network topology due to the interruption of some network elements (e.g. pipes, valves, pumps, etc.) such analysis is referred as mechanical reliability assessment [2]. When abnormal operating conditions are caused by modifications of some factors affecting the hydraulic state of the WDN, for example due to statistical increase of customer demands, increase of pipes deterioration, etc., the analysis is referred as hydraulic reliability assessment [3]. From the WDN hydraulic reliability standpoint, the capacity to deliver water with adequate levels of service (i.e., WDN hydraulic capacity) is expected to decrease with time because of natural asset deterioration. Additionally, a number of random climate and socio-economic factors can affect the customers water consumptions, increasing the uncertainty surrounding the evaluation of future WDN functioning. From an engineering perspective, assessing actual WDN supply performances is of foremost importance for cost effective allocation of investments for planning enhancement works, even under uncertain scenarios [1]. All these issues motivated the adoption of a probabilistic approach for modeling increasing nodal demands and leakages/pipe resistances (due to hydraulic system deterioration) for assessing the hydraulic reliability of a WDN (e.g. [4][5][6]). In fact, overrating actual WDN reliability would lead to unexpected socio-economic emergency scenarios, service disruptions and, ultimately, waste of money. *Vice versa*, underestimating WDN reliability might motivate not necessary interventions, thus implying waste of money as well [3].

The hydraulic modelling of WDN behavior under uncertain demands and deterioration conditions is actually crucial to assess the WDN hydraulic capacity and plan possible upgrade/rehabilitation interventions. The most widely adopted approach to WDN hydraulic simulation was the demand-driven analysis (DDA) [7]. However, this approach proved reliable for normal operating conditions (i.e., when nodal pressure is sufficient for supplying the required water at nodes), showing some drawbacks for abnormal operating conditions (e.g., caused by changes in topology, peaking conditions, leakages, etc.) [8][9][10]. More recently, the pressure-driven analysis (PDA) approach [6][9] proved to be more consistent in simulating the hydraulic behavior of WDNs [11], allowing the simulation under different working conditions including unpredictable events (e.g., extraordinary scenarios of demands) or unavoidable changes of boundary conditions (e.g., asset deterioration). Many works investigated WDN capacity in terms of water supplied/unsupplied to customers (e.g. [11]) or from a risk-based perspective [3][4][12][13][14] using a DDA and sometimes a PDA strategy.

The proposed strategy for analyzing WDN hydraulic reliability accounts for possible modifications of hydraulic system boundary conditions and their uncertainty. The analysis reported herein is used to compare pressure reduction scenarios with RRTC PCVs compared to the classic/existing PCVs, considering one planning solution coming from a previous research on the same real network [15]. The analysis assumes fire protection pressure conditions, statistical increase of customer demands and the increase of pipes deterioration (i.e., the deterioration factor of the background leakage model and pipe roughness). The hydraulic performance of the WDN is assessed performing PDA in extended period simulation (EPS) over a 24 hours operating cycle for a number of possible scenarios. Result of uch simulations are used to assess detailed reliability indicators and an overall network reliability indicator (i.e. RI^{Net}) to compare the reliability of different pressure control solutions. The study is accomplished using the WDNetXL systems [16] that implements an advanced hydraulic simulation (PDA including pressure-dependent customer demands and background leakages [6][17]), the simulation of RRTC-PCVs, besides classic PCVs, as well as the simulation of any hydraulic control device (pumps, unidirectional valves, etc.). In particular, the hydraulic reliability analysis was implemented in the WDNetXL Management Module, see Figure 1.

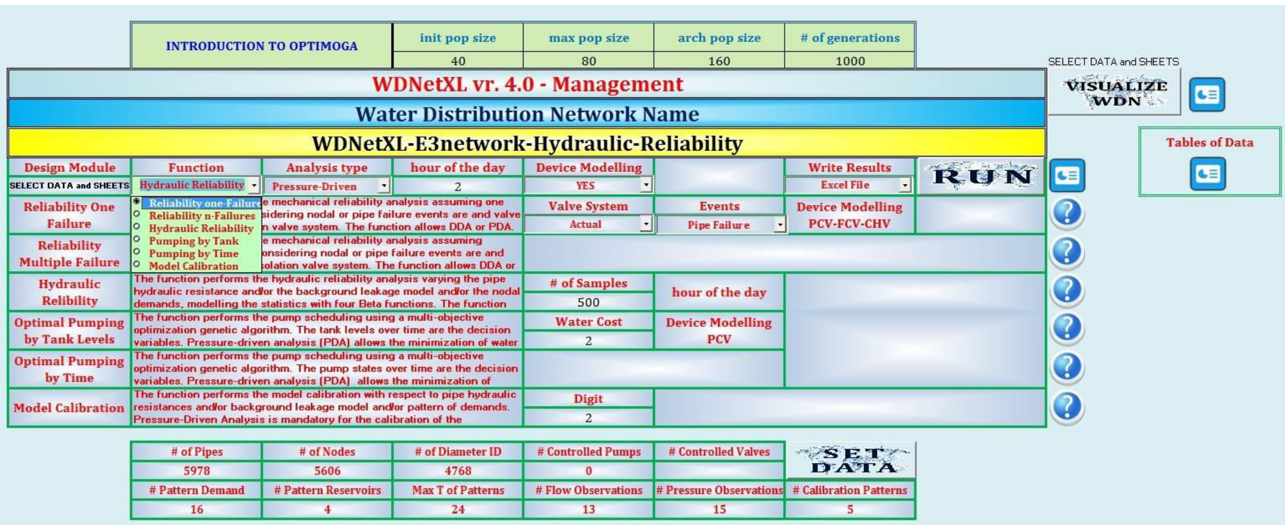

Figure 1. Snapshots of WDNetXL Management Module

2 HYDRAULIC RELIABILITY ANALYSIS

The proposed hydraulic reliability analysis can consider two different sets of uncertainty patterns, for pipe and node respectively, referred to four different parameters affecting WDN hydraulic behavior:

- Pipe uncertainty patterns: it contains indices of uncertainty patterns for pipe hydraulic resistance (R_k) and pipe deterioration coefficient of the Germanopoulos' background leakage model (β_k) (as in [6]. For those pipes where the value of these parameters is assumed as deterministic no uncertainty pattern is defined.
- Node uncertainty patterns: it contains indices of uncertainty patterns for customer (human) demand lumped at nodes (d_s) and outflow coefficient of the uncontrolled orifice (free) demand ($C_{s\text{-}unc}$). For those nodes where the value of these parameters is assumed as deterministic, no uncertainty pattern is defined.

The reliability analysis can be performed considering uncertainty patterns for each single parameter in different analyses or uncertainty on multiple parameters in the same analysis. It is worth noting that hydraulic failures entail insufficient WDN capacity to provide adequate water supply service. Such conditions usually happen because of increased water requests, severe asset deterioration or both. Indeed, increasing customer water requests (e.g. due to socio and/or climatic changes) implies more water flowing through the network and, then, the increase of the head losses along water paths. Asset deterioration may result into increased pipe hydraulic resistance and increased water leakages from pipes, joints and fittings. As a component of the WDN water demand, leakages may further increase head losses up to unacceptable pressure at delivery points.

The analysis can be accomplished using PDA or DDA varying the selected boundary conditions according to a specific Beta probability density functions (βPDFs) (see Eq. (1)) in order to model uncertainty. The use of βPDFs is justified by the fact that they are bounded by definition [3]. For each WDN model boundary condition (i.e. uncertain parameter), the procedure allows to assume various ranges of variation and specific βPDF reflecting possible technical prior information.

$$f\left(x|a,b\right)=\frac{1}{B\left(a,b\right)}x^{a-1}\left(1-x\right)^{b-1} \quad \text{with} \quad B\left(a,b\right)=\int_0^1 x^{a-1}\left(1-x\right)^{b-1}dx \tag{1}$$

The WDNetXL Management module allows analyzing four different βPDF functions that are plotted in Figure 2 along with the Normal (Gaussian) PDF:

- the beta-decreasing with a=1 and b=4.0554. The function shows an exponential decreasing shape bounded in the range [0; 1] and a mean value equal to 0.1977. This βPDF function could be useful for simulating trends related, for example, to system deterioration, assuming lower probabilities for higher values of the parameters in the within the range of variation.
- the beta-extreme with a=4.6216, b=1.5405. The function shows a shape that distributes more probability to values above the mean, with a mean value equal to 0.75. This βPDF function could be useful because, within the fixed range of variability, further peak conditions for the uncertain variable can be assumed (e.g. for design purposes with higher probability for values higher than the mean in the range of variation).

- the beta-uniform with a=1, b=1. The function shows a uniform shape bounded in the range [0.2198; 0.7802] in order to have standard deviation equal to 0.1618 and a mean value equal to 0.5. This βPDF function could be useful when there is no reliable statistical information, i.e. no prior on the expected values of uncertain parameters.
- the beta-symmetric with a=b=4.2748. The function shows a bell shape similar to the Normal PDF, assuming an average value equal to 0.5. This βPDF function could be useful because, unlike the normal PDF, it has the advantage of being bounded within a certain range, thus overcoming troubles related to the sampling of the spurious negative values on PDF tails.

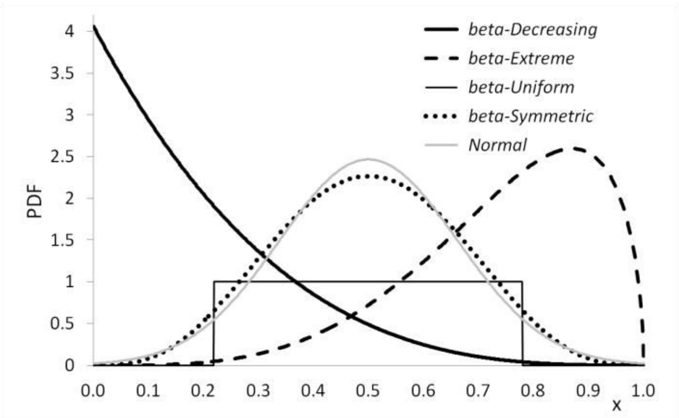

Figure 2. βPDF and Normal PDF (βPDF constrained to a standard deviation equal to 0.1618).

The procedure computes for each event in EPS two indicators, respectively related to the customers demand ($UN_{i,e,t}$) and to the nodal pressure ($PR_{i,e,t}$):

$$
\begin{aligned}
UN_{i,e,t} &= 1 - \frac{d_{i,e,t}^{act}}{d_{i,0,t}^{requ}} \quad \forall i \in n_n \quad \forall e \in n_e \quad \forall t \in [1,T] \\
PR_{i,e,t} &= 1 - \frac{p_{i,e,t}^{act}}{p_{i,0,t}^{normal}} \quad \forall i \in n_n \quad \forall e \in n_e \quad \forall t \in [1,T]
\end{aligned}
\tag{2}
$$

where $UN_{i,e,t}$ is the fraction of unsupplied customer demand; $d^{act}{}_{i,e,t}$ is the actual customer demand computed in PDA using the Wagner's model [18]. Note that $d^{act}{}_{i,e,t}$ is null and the fraction $UN_{i,e,t}$ is unitary for unsupplied nodes; $d^{requ}{}_{i,0,t}$ is the required customer demand varying over time; $PR_{i,e,t}$ is the fraction of nodal pressure reduction with respect to normal conditions; $p^{act}{}_{i,e,t}$ is the actual nodal pressure computed in PDA or DDA. Note that p^{act} is set null and the fraction PR is unitary for negative pressures; $p^{normal}{}_{i,0,t}$ is the nodal pressure in normal conditions; i and t are subscripts indicating the i-th node and the time t of the EPS during T; e *is* a subscript indicating the e-th sampled event; n_n and n_e are the number of nodes and events, respectively; e=0 stays for normal condition.

After computing the indicators of Eq. (2), the results are averaged, considering the n_e sampled events, obtaining:

$$
\begin{aligned}
RI_{i,t}^{UN} &= avg_e\left(UN_{i,e,t}\right) \quad \forall i \in n_n \quad \forall t \in [1,T] \\
RI_{i,t}^{PR} &= avg_e\left(PR_{i,e,t}\right) \quad \forall i \in n_n \quad \forall t \in [1,T]
\end{aligned}
\tag{3}
$$

where $RI^{UN}{}_{i,t}$ is the reliability indicator for the fraction of unsupplied customer demand for each i-th node and over time t; $RI^{PR}{}_{i,t}$ is the reliability indicator for nodal pressure reduction for each i-th node and over time t; avg_e indicates the average over all sampled events.

The overall reliability indicator of the network are:

$$RI_t^{Net} = 1 - \frac{\sum_i avg_e\left(d_{i,0,t}^{requ} - d_{i,e,t}^{act}\right)}{\sum_i d_{i,0,t}^{requ}} \quad \forall t \in [1,T]$$
$$RI^{Net} = \sum_t \left[\frac{D_t}{D}\right] RI_t^{Net} \qquad D_t = \sum_i d_{i,t}^{requ} \tag{4}$$

where D is the total required demand of the network, D_t is the total required demand at time t. The terms in square brackets are weighs over time to consider the pattern variation of the demand.

3 CASE STUDY

The hydraulic reliability analysis, based on the abovementioned indicators, is performed on the real WDN of Oppegård (Norway), following the study reported in Berardi et al. [15], which planned different scenarios of the location of classical and RRTC PCVs in Oppegård WDN in order to control pressures and thus reduce leakages.

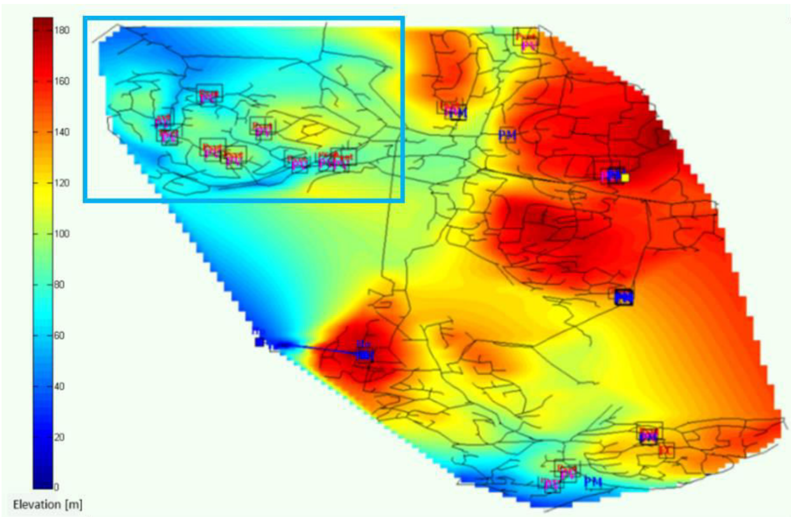

Figure 3. Oppegård WDN elevations

The municipal network of Oppegård (see Fig. 3), a town located at south of Oslo (Norway), extended for about 129 km of pipelines and suppling an area with significant changes in elevation, ranging from 40 to 180 a.s.l.. A minimum pressure of 25 m has to be guaranteed everywhere in the system for firefighting and, for the same reason, diameters are oversized with respect to normal water requests. Therefore, the pressure regime is roughly invariant over the day, irrespectively on water demand pattern. Pumping stations guarantee sufficient pressure in high elevation areas (dark-red in Fig. 3). Classic PCVs (i.e. controlled from valve downstream node) are installed to limit pressure in lower zones (light green-blue in Fig. 3). This work considers also one of the pressure control planning solution reported in details in [15] and in Fig. 4 in the North-West portion of the city (blue rectangle in Fig. 3). Such solution results into estimated background leakage reduction of about 41% lower than in the original configuration in North-West Oppegård, as obtained by using five RRTC-PRVs and four original PRVs, and closing some different pipes as indicated with red crosses in the two scenarios in Fig. 4, in order to border the pressure control areas.

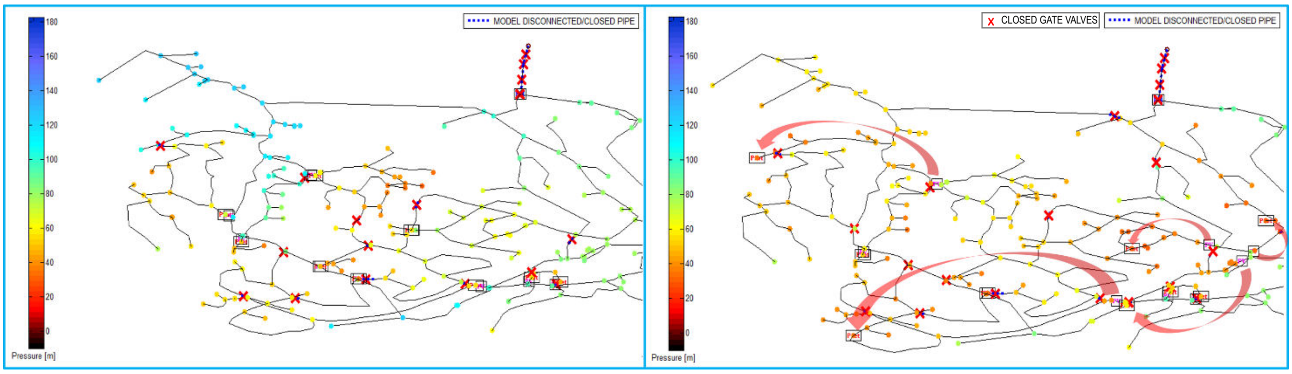

Figure 4. North-West Oppegård WDN: (left) original configuration with 9 PRVs; (right) Pressure control planning scenario with 5 RRTC-PRVs and 4 original PRVs

The hydraulic reliability analysis was accomplished considering the uncertainty on: (i) pipe hydraulic resistance (R_k); (ii) pipe deterioration coefficient of the Germanopoulos' background leakage model (β_k) and (iii) customers' nodal water requests (d_s). Such uncertainties were considered independently and simultaneously and the value for each parameter was selected from the beta-decreasing PDF. For the sake of the example and due to the oversized pipes which makes the system reliable in face of small changes in the boundary conditions, it is assumed herein that the maximum increases of each current WDN model parameters with respect to the original values (i.e., used in [15]) are: four times for pipe hydraulic resistance (R_k), eight times for pipe deterioration coefficient (β_k) and eight times for customers' water requests (d_s). For each hydraulic reliability analysis run, 500 uncertain scenarios were samples through a Latin Hypercube sampling strategy (e.g. as in [3]). The unsupplied customers demand ($UN_{i,e,t}$) and the nodal pressure ($PR_{i,e,t}$) reported in Eqs. (2) have been computed for each scenario as well as the indicators $RI^{UN}{}_{i,t}$ (fraction of unsupplied customer demand for each ith node at time t) and $RI^{PR}{}_{i,t}$ (nodal pressure reduction for each ith node at time t), reported in Eqs. (3). Finally, the overall network reliability indicator (RI^{net}) reported in Eqs. (4) was computed for each scenario considering existing PRVs and assuming planned RRTC-PRV, as summarized in Table 1.

Table 1. RI^{Net} for each hydraulic reliability analysis scenario.

RRTC PRVs				*PRVs*			
β_k	d_s	R_k	β_k, d_s, R_k	β_k	d_s	R_k	β_k, d_s, R_k
99.97%	*80.70%*	*99.98%*	*46.85%*	*99.95%*	*84.20%*	*99.82%*	*51.00%*

It can be observed that increasing the pipe deterioration parameters (i.e. β_k up to eight times the values in [15]) and pipe hydraulic resistance (i.e., R_k up to four times the original values) independently results into similar network hydraulic reliability, due to pipe oversizing which guarantee high WDN hydraulic capacity, even in face of high leakage rates. *Vice versa,* assuming a maximum variation of customers demand (d_s) up to eight times of the original value result into RI^{net} of about 80% and 84% for RRTC-PRV and classic PRV configurations respectively, with a reduced hydraulic capacity for the RRTC-PRV scenario, due to the closure of some pipes that were aimed at ensuring controllability of RRTC-PRVs and reduce background leakages.

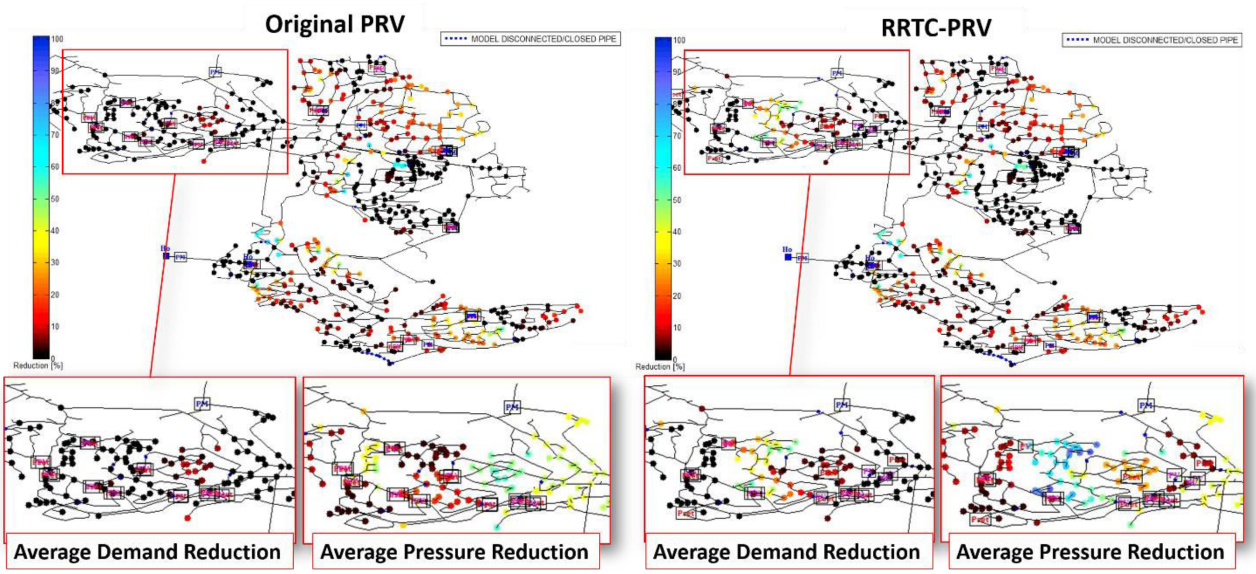

Figure 5. Hydraulic reliability analysis assuming uncertain increase of customers' demands (ds): (left) original configuration with 9 PRVs, (right) Pressure control scenario with 5 RRTC-PRVs and 4 original PRVs in North-West Oppegård

Fig. 5 compares the results of the hydraulic reliability analyses for the two pressure control scenario described above, assuming the increase of water demand only. Looking at the entire WDN, it is evident that in both cases high elevation areas (se Fig. 3) are those more exposed to insufficient water supply under abnormal scenarios. Nonetheless, as expected, in both scenarios the hydraulic reliability is exactly the same except for the North-West area, where different pressure control strategies are adopted. In the bottom Fig. 5 the North-West area is magnified and demand and pressure reduction are reported as averaged over 500 sampled scenarios. The higher pressure reductions for the scenario with RRTC-PRV are due to the combination of demand increase and different configurations of closed pipes (see Fig. 4). Consequently, the rate of possible unsupplied demand in the same areas (i.e. average demand reduction) is higher than in current PRV configuration. From WDN management perspective, such analysis hints that closed pipes should be actually equipped with gate valves, (e.g. remotely controlled) in order guarantee sufficient pressure under exceptionally higher water demand scenarios, while allowing saving large volume of water under normal conditions.

Finally, looking at Table 1, assuming the simultaneous increase of all uncertain parameters (β_k, d_s, R_k) dramatically changes the hydraulic reliability of the systems in both configurations, confirming also the reduced hydraulic capacity of the RRTC-PRV scenario.

4 CONCLUSIONS

This contribution reports the hydraulic reliability analysis strategy based on advanced WDN hydraulic modelling and relevant use to compare various pressure reduction scenarios. The analysis is currently implemented in the WDNetXL Management module and is intended to support various planning activities and enable comparison among alternative solutions. In the case of Oppegård municipality, the WDN is oversized because of firefighting requirements and quite high uncertain variations of pipe hydraulic resistance, pipe deterioration coefficient and customers' nodal water requests are assumed. In this case, two alternative pressure control scenarios, using existing classic PRV or a combination with some RRTC-PRVs are analyzed. The hydraulic reliability analysis is also proved to return useful information to drive efficient and reliable pressure management actions, suggesting the areas that would be more susceptible to abnormal conditions.

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