Mechanical reliability analysis of a real network to support the design of Isolation Valve System

Luigi Berardi[1], Daniele B. Laucelli[1], Antonietta Simone[1], Gema Raspati[2],
Rita Maria Ugarelli[3], Orazio Giustolisi[1]
[1]Technical University of Bari, Via E. Orabona 4, Bari, Italy
[2]SINTEF Building and Infrastructure, Richard Birkelands vei 3, Trondheim, Norway
[3]SINTEF Building and Infrastructure, Forskningsveien 3b, NO-0314, Oslo, Norway
[1]luigi.berardi@poliba.it

ABSTRACT

The Isolation Valve System (IVS) allows to detach some portions of water distribution networks (WDN) to perform planned (e.g. maintenance) or unplanned (e.g. failures) works. Isolating WDN segments causes pressure reduction and possible insufficient water supply conditions; the larger the number of valves (and segments) the larger the reliability of the system in face of segment isolation scenario. This contribution introduces some reliability indicators ranging from single node and time step up to the entire WDN, based on the explicit pressure-driven hydraulic simulation of the system under each segment isolation scenario over an operating cycle. Such mechanical reliability indicators are used to support the selection among optimal alternative IVS design solution obtained by minimizing the number of valves and the length of segments. The strategy is demonstrated on the real WDN serving the municipality of Oppegård (Norway).

Keywords: Water Distribution Network, Isolation valve system, Mechanical Reliability

1 INTRODUCTION

Water distribution Networks (WDNs) are large and pervasive infrastructures that are vital for all human activities and welfare in modern cities. Unfortunately, asset deterioration undermines the high economic and social value of such infrastructures, and the rising frequency of network interruptions due to accidental (i.e. repair) or planned (i.e. replacement) works exposes the population to increasing risk of insufficient water supply. In this context, preparedness to planned or unplanned works intends to mitigate service disruption during abnormal conditions due to accidental extreme natural events (e.g., landslides) or intentional disruptions (e.g., attacks) as well as for normal occurrence of a single system component failure [1]. Planning effective isolation valve systems (IVS) and assessing WDN reliability in face of isolation of network portions (i.e. by closing of isolation valves [2]) is of key importance to support maintenance/management decisions. In fact, closing gate valves causes the alterations of the water paths due to the change of original network topology. This, in turn, might cause insufficient pressure regime in the portions of the network that are still connected to water sources [3][4]. In addition, when a WDN element is detached from the rest of the network by closing a set of isolation gate valves, it might result also into possible unintended isolation of other network portions, which are connected to water source(s) through the detached elements. All such alterations might cause unexpected functioning of flow/pressure control valves. The technical relevance of the WDN reliability analysis is demonstrated by the number of works published on such topic. Tung [5] reported few techniques for analysing WDN reliability including minimum cut sets, tie set analysis, and event or fault tree analysis. Xu and Goulter [6] introduced the first-order-reliability-method (FORM) to estimate the probability of minimum allowable head at some nodes. Other contributions (e.g. [7][8][9])

exploited graph theory and statistical metrics to analyse WDN vulnerability, although without explicitly analysing the impacts on WDN hydraulics. Todini [10] introduced the resilience index to measure of WDN performance under failure conditions based on the power required at each node. The Todini's resilience index was modified [11] accounting for the uniformity in diameter of pipes joined at each node as a surrogate of the redundancy of water paths in case of pipe interruption. Torii and Lopez [12] proposed a different approach based on the response surface analysis assuming 1mm diameter to simulate interrupted pipes. Anyway, all abovementioned works accounted for limited alterations of WDN topology. Tanyimboh et al. [13] computed reliability indices using modified demand-driven simulations to emulate pressure-driven analysis (PDA). Actually, PDA was recognized [14] to provide more hydraulically consistent results than demand-driven analysis (DDA) in pressure deficient conditions. PDA was used [15] to compute the fraction of unsupplied demand and volume as reliability indicators for each node and for the whole network. Later on, Deuerlein et al. [16] presented a methodology based on graph decomposition of the network to reduce the number of calls of PDA for reliability analysis.

The present study combines the analysis of topological modifications induced by closing gate valves and PDA to assess the impact of the isolation valve system (IVS) on WDN mechanical reliability in the water distribution system serving the municipality of Oppegård (Norway). To this end, the results of Extended Period Simulation (EPS) PDA of each possible failure scenario subsequent to each WDN segment isolation are used to formulate WDN reliability indices that permit comparing alternative IVS identifying the most vulnerable areas and supporting planning decisions.

2 MECHANICAL RELIABILITY INDICATORS

The assessment of WDN mechanical reliability entails the analysis of system capacity to supply water to customer under segment isolation scenarios due to the closure of gate valves, as identified by the Isolation Valves System (IVS), which are needed to perform planned or unplanned works. As such, this study accounts for possible works on WDN components like pipes, pumps, valves, etc. that implies the isolation of the entire segment these elements belong to. Hydraulic devices (e.g. pumps, control valves, meters, etc.) represents single-pipe segments since they are usually equipped with isolation valves on both upstream and downstream ends.

Given an IVS, the strategy for mechanical reliability follows two steps for each event e representing the isolation of one out of n_e segments identified by the IVS:

1) Identification of the portions of the network that remain connected to water sources [17] when relevant gate valves are closed, accounting also for unintended isolations (i.e. disconnection of other segment(s) fed through the intentionally isolated segment);

2) EPS in PDA over a typical (e.g. daily or weekly) operating cycle of the connected WDN portions. PDA is mandatory in order to account for pressure-dependent customer demands and background leakages [4] [18] because the closure of segments might cause pressure-deficient conditions for customer demands in some nodes. The EPS allows accounting for the different impact of isolation over time (i.e. accounting for patterns of water requests). It has to remark that the hydraulic model should also integrate the automatic identification of current WDN topology in consequence of possible abnormal functioning of controlled devices (e.g. pressure/flow control

valves, controlled pumps) caused by changes in reachability and connectivity of control nodes due to segment isolation.

Based on the abovementioned two steps, two indicators are computed for each simulation time step *t* out of *T* time steps considered in the EPS and for each *i*th node of the WDN:

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

$UN_{i,e,t}$ is the fraction of unsupplied customer demand at *i*th node based on the ratio between $d^{act}{}_{i,e,t}$, the actual demand supplied to customers computed in PDA using the Wagner's model (1988), and $d^{requ}{}_{i,e,t}$, the required customer demand varying over time. Note that, for (both intended and unintended) isolated nodes $d^{act}{}_{i,e,t}=0$ and the fraction $UN_{i,e,t}$ is unitary. $PR_{i,e,t}$ is the fraction of nodal pressure reduction based on the ratio between $p^{act}{}_{i,e,t}$, the actual nodal pressure computed in PDA, and $p^{normal}{}_{i,e,t}$, the nodal pressure computed in PDA in normal conditions. n_n is the number of nodes; $e=0$ indicates normal condition.

Indicators in Eq. (1) actually reports the hydraulic impact of each isolation event for each single node and for each time step of the operating cycle based on accurate WDN hydraulic modelling. As such, they represent the base information to assess the hydraulic reliability of each single node or for the entire WDN accounting for all possible events, which equals the number of segments identified by the IVS.

Eq. (2) reports the reliability indicators of unsupplied demand RI^{UN} and pressure deficit RI^{PR} for the *i*th node at time step *t*. It is obtained by averaging $UN_{i,e,t}$ and $PR_{i,e,t}$ over the n_e isolation scenarios, weighted by the length of the isolated segment. The assumption of length of the isolated segment as the weight for each isolation event *e* follows the observation that pipe failure probability increases with pipe length, besides other covariates (e.g. pipe age, material, soil, external loads, etc.). Thus, indicators in Eq. (2) represent the reliability of each single node at time *t* in consequence of interruptions caused by possible failure events, where the interruption of longer segments are assumed to be more likely that shorter ones.

$$
\begin{aligned}
RI_{i,t}^{UN} &= avg_e\left(UN_{i,e,t}\right) \quad \forall i \in n_n \quad \forall t \in [1,T] \\
RI_{i,t}^{PR} &= avg_e\left(PR_{i,e,t}\right) \quad \forall i \in n_n \quad \forall t \in [1,T]
\end{aligned}
\tag{2}
$$

Eq. (3) reports the reliability indicators of the entire network for each time step *t* ($RI^{Net}{}_t$) and over the entire operating cycle (RI^{Net}):

$$
RI_t^{Net} = 1 - \frac{\sum_i avg_e\left(d_{i,0,t}^{requ} - d_{i,e,t}^{act}\right)}{\sum_i d_{i,0,t}^{requ}} \quad \forall t \in [1,T]; \quad RI^{Net} = \sum_t \left[\frac{D_t}{D}\right] RI_t^{Net}; \quad D_t = \sum_i d_{i,0,t}^{requ}
\tag{3}
$$

$RI^{Net}{}_t$ depends on the ratio between the total mismatching of water demand averaged over all events and the total water requests in normal conditions. In addition, in this case, the average over n_e events is weighted by segment length. As such, the lower the total average mismatching of demands the higher the network reliability indicator at time t. As such, network reliability indicator at time t increases as the water demand that can be actually supplied, based on Wagner's model and averaged over the n_e events, approach the normal conditions at time t.

RI^{Net} is the average of RI^{Net}_t weighted by the total required demand at time t in normal conditions (D_t); D is the total required demand of the network over the entire operating cycle. Indeed, similar values of RI^{Net}_t result into larger impact at peak demand hours.

Differently from previously adopted reliability analyses based on surrogate indicators of the actual WDN behaviour under isolation scenarios, those reported in Eqs. (1-3) combine the analysis of WDN topological alterations due to each failure event with the pressure-driven simulation over an operating cycle. As such the effect of pressure reduction caused by topological changes are explicitly accounted for in terms of reduction of background leakages and, in case of pressure deficient conditions, as reduction of water supplied to customers which affect the hydraulic behaviour of the system as a whole.

3 MECHANICAL RELIABILITY ANALYSIS TO SUPPORT ISOLATION VALVE SYSTEM DESIGN

The main technical purpose of the Isolation Valve System (IVS) in a WDN is to enable the isolation of one or multiple portions of the system, while permitting water supply in the parts of the systems still connected to water sources. In recent years, a number of strategies has been proposed to drive the most effective location of the isolation valves (e.g. [17]). The main criteria proposed so far to drive the design of the IVS mainly relate to minimizing the number of gate valves while pursuing similar segments in terms of number of elements (e.g. pipes and nodes), pipeline length or customer water requests. Although such criteria intend to minimize the impact of segment isolation the water supply service, it can be argued that minimizing the number (i.e. cost) of gate valves is conflictual with all other objectives. As such, the IVS design problem has been formalized (e.g. [17]) as a multi-objective optimization problem in automatic optimization algorithms where each objective functions is quite fast to compute for each candidate solutions, since they are based on fast network topological analyses and base WDN model data. Irrespectively on the optimization strategy adopted, results of such multi-objective optimization problem belong to a Pareto front representing the best technical alternatives for decision makes.

Actually, considering the current need of water utilities for assessing the reliability of WDNs under unpredictable and increasingly frequent failure events, mechanical reliability is a technically consistent driver for supporting the design of IVS. From WDN mechanical reliability perspective, the *N-valve rule* [17] allowing the isolation of each single pipe, would be the best since it would introduce the minimum alteration of WDN topology and hydraulic paths in face of pipe isolations. Nonetheless, the *N-valve rule* is not a viable IVS solution for real WDNs because it would require a huge number of valves with unreasonable costs for installation and maintenance. As such, WDN mechanical reliability is conflictual with the number (cost) of gate valves to be installed.

Nonetheless, including the calculation of indicators in Eqs. (1-3) within optimal IVS design procedures, would require the EPS in PDA of each candidate IVS solution including all possible segment isolation events. This, in turn, would require quite long computational runtime, especially for those solutions involving a large number of segments (and valves) in real WDN including thousands of nodes and pipes.

Based on such observations, this study aims at demonstrating how network mechanical reliability indicators can be used to effectively support the selection among different IVS design solutions as obtained by applying design strategies. In more details, the strategy adopted herein assumes that some optimization criteria, like those discussed above, were previously applied to get a set of optimal IVS design solution. Thereafter, for each candidate IVS, indicators in Eqs. (1-3) are computed to support the selection of the most effective solution from mechanical reliability perspective.

4 CASE STUDY

The WDN serving the municipality of Oppegård (Norway) is used to demonstrate the abovementioned strategy. Due to the peculiar elevation conditions, the original Oppegård WDN includes pumping stations, tanks and pressure reduction valves aimed to providing adequate pressure everywhere in the system (for additional details see e.g. [19]). For the sake of demonstration, the present study neglects all pressure control valves, while pumps and tanks are the same as in the original network. It is worth remarking here that the strategy allows accounting for all pressure control devices, but they are not reported herein order to facilitate the discussion of results.

4.1 Isolation Valve System Design

No information were available on the IVS in the original Oppegård WDN, and the only gate valves were assumed at both ends of devices and at tank inlet and outlet pipes. The design of the IVS was accomplished by performing a multi-objective optimization simultaneously minimizing the number of valves and the maximum length of segments. Figure 1 (left) shows eighty optimal IVS solutions. The less expensive solution includes 43 valves (i.e. the originally assumed gate valves only) and 25 segments including both single device pipes and very large segments. The most expensive solution includes 541 valves and 426 segments, whose maximum length is lower than 2km and coincides with the longest pipe in the network.

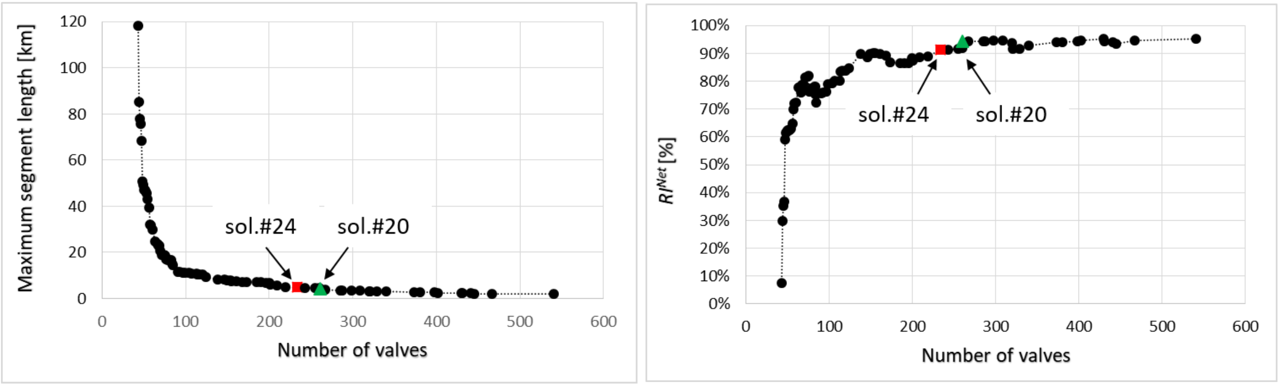

Figure 1. (Left) Isolation Valve System (IVS) design solutions in Oppegård WDN; (right) Network Reliability Indicator RI^{Net} [%] for each IVS solution in Oppegård WDN

Fig. 1 (left) clearly shows that the largest reduction of maximum length of the segments can be achieved increasing the number of valves up to about 250. For more than 250 valves, the marginal reduction of segment lengths is quite lower. Although the length of segments can be assumed as a surrogate of the impact of isolations on WDN behaviour, it is hard for decision maker to be confident about the best choice for a given available budget.

4.2 Supporting IVS design with mechanical reliability analysis

Each IVS design solution reported in previous section was considered to compute the mechanical reliability indicators in Eqs. (1-3). The EPS (PDA) was carried on considering 24 hourly time steps and accounting for patterns of water requests provided by Oppegård municipality, with a pressure for correct service equal to 25m. For the sake of the example, the Germanopoulos' model [20] was used for modelling background leakages as estimated in [19].

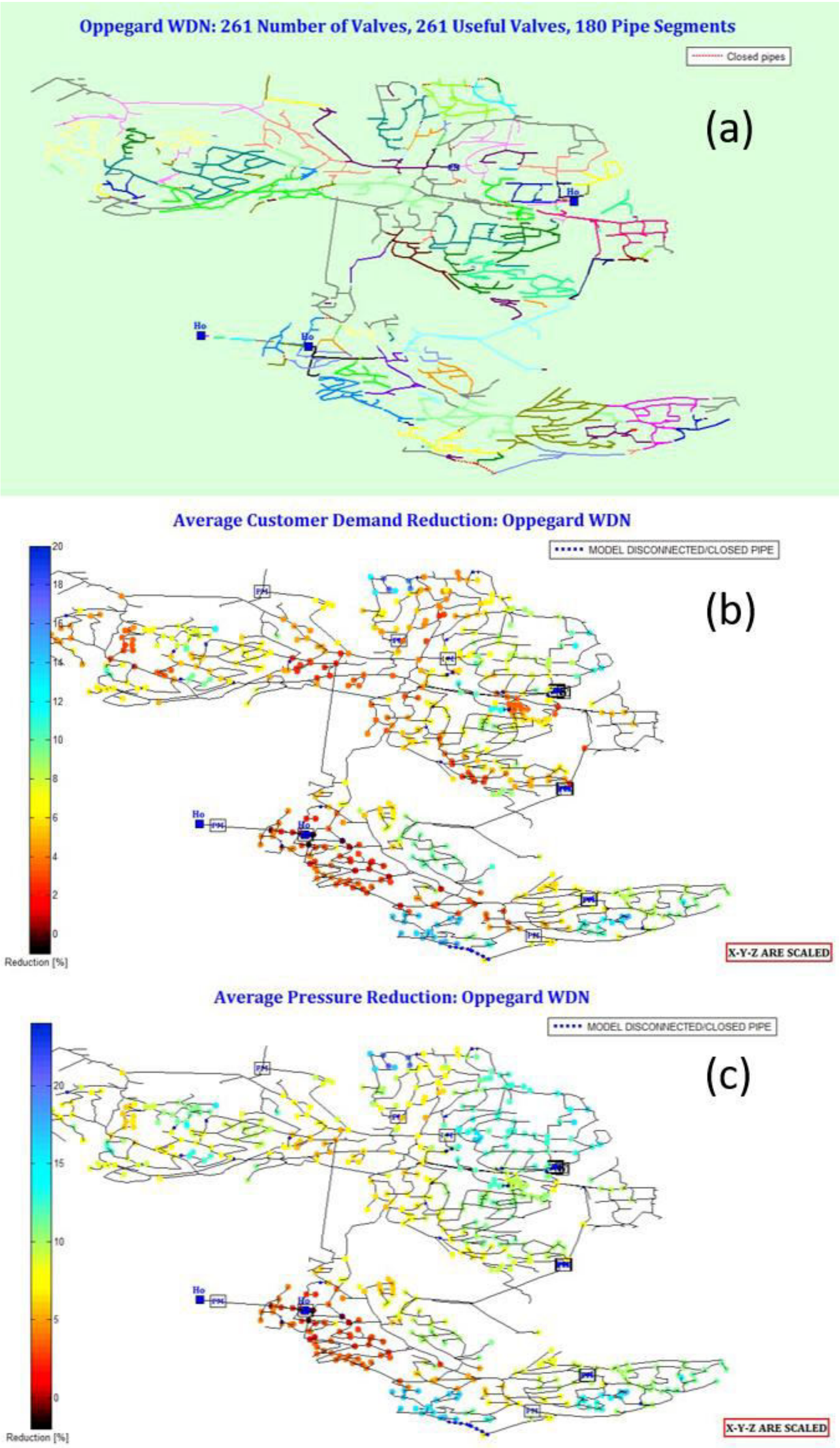

Figure 3. Mechanical Reliability of Oppegård WDN: (a) IVS solution #20; (b) Average reduction of customers' demand; (c) Average reduction of pressure with respect to normal conditions.

Fig. 1 (right) reports the network mechanical reliability indicator (RI^{Net}) as computed in Eq.(3) for each IVS. As expected, from the discussion above, increasing the number of valves and minimizing the length of segment result into a general increase of network reliability. In particular, RI^{Net} for the solution with 43 valves is about 7%, while adding only 4 valves (47) RI^{Net} increases up to 59%. The maximum value of RI^{Net} is about 95%, which means that none of the IVS is able to have no impact on WDN hydraulic behaviour but, rather, there are some nodes that are affected by pressure deficit as consequence of some segment isolation in some hours of the day.

Nonetheless, the increasing trend of RI^{Net} with the number of gate valves is not monotone and there are some subsets of solutions (e.g. from 63 to 85 valves and from 173 to 219) where the trend is opposite. There are two main causes for this to happen: (i) the problem is not linear and the WDN hydraulic behaviour is strongly affected by changes in topology due to different IVS; (ii) any strategy/constraint was adopted to have nested segments while designing the IVS. Actually, neglecting the latter constraint mirrors the most commonly adopted approach for optimal IVS design where solutions are not "contiguous", meaning that the segments in a given IVS solution are not necessarily included in the segments of the cheaper IVS solutions on the Pareto front.

Moreover, Fig. 2 (right) shows that, for a number of valves larger than 234 (solution #24) the value of RI^{Net} is almost constant with values ranging from 91.18 to 95.15. Such observation suggests looking at those IVS solutions that allows getting reliability close to the maximum with the minimum number of valves. In particular, solutions #20 and #24 on the Pareto front were compared in terms of RI^{Net}, maximum length of segments, number of valves and average pressure reduction.

It was observed that solution #20, requiring 27 valves more than solution #24, results into RI^{Net} =94.13% (about 3% larger than solution #24) with maximum segment length equal to 3.8km (1 km shorter than solution #24). Both solutions #20 and #24 show average pressure over the operating cycle larger than the minimum for a correct service, although areas with pressure reduction for solution #24 area larger than solution #20. Fig. 3 shows (a) the IVS in solution #20, (b) the average reduction of water supplied to customers and (c) the average reduction of pressure at each node considering 180 possible segment isolation scenarios.

5 CONCLUSIONS

The proposed strategy for assessing the mechanical reliability of WDNs is based on the advanced hydraulic modelling accounting for pressure dependent demand components including both demand supplied to customers and background leakages. This approach enables the analysis of average supply capacity of the network as a whole and for each node accounting for pressure reduction caused by water paths alteration due to segment isolations. Network reliability indicator RI^{Net} is proved to effectively support the selection among a set of optimal alternative IVS design solutions. Detailed analyses of hydraulic performances in terms of pressure reduction and customer's demand mismatching provide also indications about areas that are more susceptible to possible segment isolation due to failure events. All the analyses presented in this study were formed using the Management and Analysis modules of the WDNetXL systems [21].

References

[1] L. Berardi, R. Ugarelli, J. Rostum and O. Giustolisi, "Assessing mechanical vulnerability in water distribution networks under multiple failures", Water Resour. Res., vol. 50, pp. 2586–2599, 2014.

[2] T. M. Walski, "Water distribution valve topology for reliability analysis", Reliab. Eng. Syst. Safety, 42(1), pp. 21–27, 1993

[3] T. M. Walski, J. S. Weiler, and T. Culver, "Using criticality analysis to identify the impact of valve location", Proc. 8th Annual Water Distribution Systems Analysis Symposium, 2006

[4] O. Giustolisi and T. M. Walski, "Demand components in water distribution network analysis", J. Water Resour. Plann. Manage., 138(4), 356–367, 2012

[5] Y. K. Tung, "Evaluation of water distribution network reliability", Hydraulics and Hydrology in the Small Computer Age, vol. 1, pp. 359–364, Am. Soc. of Civ. Eng., New York, 1985

[6] C. Xu and I. C. Goulter, "Reliability-based optimal design of water distribution network", J. Water Resour. Plann. Manage., vol. 125, pp. 352–362, 1999.

[7] P. Jacobs and I. C. Goulter, "Evaluation of methods for decomposition of water distribution networks for reliability analysis", Civ. Eng. Syst., 5(2), 58–64, 1988.

[8] A. Yazdani and P. Jeffrey, "Water distribution system vulnerability analysis using weighted and directed network models", Water Resour. Res., 48, W06517, 2012.

[9] A. Yazdani and P. Jeffrey, "Applying network theory to quantify the redundancy and structural robustness of water distribution systems", J. Water Resour. Plann. Manage., 138(2), 153–161, 2012-

[10] E. Todini, "Looped water distribution networks design using a resilience index based heuristic approach", Urban Water, 2(2), 115–122, 2000.

[11] T. D. Prasad and N.-S. Park, "Multiobjective genetic algorithms for design of water distribution networks", J. Water Resour. Plann. Manage., 130(1), 73–82, 2004

[12] A. J. Torii and R. H. Lopez, Reliability analysis of water distribution networks using the adaptive response surface approach, J. Hydraul. Eng., 137(3), 227–236, 2012.

[13] T. T. Tanyimboh, M. Tabesh, and R. Burrows, "Appraisal of source head methods for calculating reliability of water distribution networks", J. Water Resour. Plann. Manage., 127(4), 206–213, 2001.

[14] E. Todini, "A more realistic approach to the ‘‘extended period simulation’’ of water distribution networks", Proc. of the CCWI'03 Conference, Advances in Water Supply Management, pp. 173–184, Taylor and Francis, Netherlands, 2003.

[15] O. Giustolisi, Z. Kapelan, and D. A. Savic, "Extended period simulation analysis considering valve shutdowns", J. Water Resour. Plann. Manage., 134(6), 527–537, 2008.

[16] J. W. Deuerlein, A. R. Simpson and S. Dempe, "Modeling the behavior of flow regulating devices in water distribution systems using constrained nonlinear programming", J. Hydraul. Eng., 135(11), 970–982, 2009.

[17] O. Giustolisi and D. A. Savic, "Identification of segments and optimal isolation valve system design in water distribution networks", Urban Water J., 7(1), 1–15, 2010.

[18] O. Giustolisi, Z. Kapelan, and D. A. Savic, "Extended period simulation analysis considering valve shutdowns", J. Water Resour. Plann. Manage., 134(6), 527–537, 2008

[19] L. Berardi, D. Laucelli, R. Ugarelli, and O. Giustolisi, "Hydraulic System Modelling: Background Leakage Model Calibration in Oppegård Municipality", Proc. Eng., 119, 633-642, 2015.

[20] G. Germanopoulos, "A technical note on the inclusion of pressure-dependent demand and leakage terms in water supply network models", Civ. Eng. Syst., 2, 171–179, 1985.

[21] O. Giustolisi, D.A. Savic, L. Berardi and D. Laucelli, "An excel-based solution to bring water distribution network analysis closer to users", in: Proc. of Computer and Control in Water Industry (CCWI), Exeter, UK, 2011, vol. 3, 805–810.