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Assessing mechanical vulnerability in water distribution networks under multiple failures

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Key Points:

- WDN vulnerability analysis using multiobjective optimization approach
- Soft ranking of solutions to get multiple WDN vulnerability scenarios
- The methodology is demonstrated on a real water distribution network

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Abstract Understanding mechanical vulnerability of water distribution networks (WDN) is of direct relevance for water utilities since it entails two different purposes. On the one hand, it might support the identification of severe failure scenarios due to external causes (e.g., natural or intentional events) which result into the most critical consequences on WDN supply capacity. On the other hand, it aims at figure out the WDN portions which are more prone to be affected by asset disruptions. The complexity of such analysis stems from the number of possible scenarios with single and multiple simultaneous shutdowns of asset elements leading to modifications of network topology and insufficient water supply to customers. In this work, the search for the most disruptive combinations of multiple asset failure events is formulated and solved as a multiobjective optimization problem. The higher vulnerability failure scenarios are detected as those causing the lower supplied demand due to the lower number of simultaneous failures. The automatic detection of WDN topology, subsequent to the detachments of failed elements, is combined with pressure-driven analysis. The methodology is demonstrated on a real water distribution network. Results show that, besides the failures causing the detachment of reservoirs, tanks, or pumps, there are other different topological modifications which may cause severe WDN service disruptions. Such information is of direct relevance to support planning asset enhancement works and improve the preparedness to extreme events.

1. Introduction

Water distribution networks (WDN) are vital infrastructures for all human activities, thus they are required to provide safe and reliable water supply service, even under abnormal functioning conditions [*Xu and Goulter*, 1999]. Nowadays, the threat for accidental or man-made disruptions motivates water utilities to plan risk mitigation works and to improve the preparedness for extreme events.

This work presents a methodology to figure out those scenarios involving multiple *mechanical* failures which result into abrupt modifications of WDN topology and water supply capacity. Solving such problem is actually an open research issue due to the large number of possible combinations of events in real systems, which makes computationally unfeasible the exhaustive enumeration. Such critical scenarios might be caused by extreme natural events (e.g., landslides or flooding) or intentional attacks (e.g., sabotages). Accordingly, the probability of each asset element to fail (e.g., based on statistical analyses) is unpredictable [e.g., *Matalas*, 2005]. Also in some contexts the most critical impact might be not caused by a single event but by a combination of events [*Tidwell et al.*, 2005]. Moreover, the time when the event starts and its duration are unpredictable as well as customers' water requests that may be quite different from normal conditions.

Identifying such failure scenarios is essential to support planning works aimed at improving system robustness and mitigate service disruption. It is worth noting that this is a different perspective from analysis of WDN reliability for management/operational purposes, which usually accounts for the probability of single failure events (e.g., accidental pipe bursts or planned interruptions) with a limited impact on WDN functioning under normal water requests.

When a WDN asset element fails, it is detached from the rest of the network by closing a set of isolation (gate) valves [e.g., *Walski*, 1993a, 1993b]. Actually, such maneuvers might result into possible unintended isolation of other network subportions (segments) which are connected to water source(s) through the detached elements. These alterations of the original network topology also cause change of water paths through the network and, eventually, insufficient pressure regime in the portions still connected to water sources [*Walski et al*., 2006]. Moreover, if pressure/flow control valves are installed, the alteration of normal working conditions might cause unexpected functioning of such valves, with possible unintended disconnection of other network subportions.

The WDN supply performances under failure events are simulated in this work by accounting for the hydraulically consistent demand-pressure relationship at WDN model nodes, in order to realistically simulate pressure deficient conditions. In addition, all changes of network topology due to closing valves (i.e., isolating network segments) are explicitly accounted before and during WDN analysis. All these peculiarities differentiate this work from most previous literature contributions that presented various strategies to quantify *mechanical* reliability, also in conjunction with the *hydraulic* reliability. For example, *Tung* [1985] reported six techniques for analyzing WDN reliability including minimum cut sets, tie set analysis, and event or fault tree analysis. *Xu and Goulter* [1999] first introduced the first-order-reliability-method (FORM) to estimate the probability of head at some node to be at or above the minimum allowable value, accounting for the uncertainty in WDN boundary conditions and component failures. Some approaches have also resorted to graph theoretic and statistical metrics to analyze vulnerability of WDN complex networks, without explicitly simulating the hydraulic impact of failed components [e.g., *Jacobs and Goulter*, 1988; *Yazdani and Jeffrey*, 2012a, 2012b].

Todini [2000] introduced the resilience index as a measure of WDN performance under failure conditions based on the power required at each node. *Prasad and Park* [2004] modified the original Todini's resilience index by accounting for the uniformity in diameter of pipes connected at each node as a surrogate measure of the redundancy of water paths in the system in case of *mechanical* failure. The resilience index was also used by *Farmani et al*. [2005] to achieve optimal robust design solutions; the reliability of solutions was also evaluated in terms of the number of pipe failures (i.e., closures) leading to pressure deficit in at least one node. All these works considered the alteration of water supply service with respect to normal working conditions in face of limited alteration of network topology (e.g., due to accidental/planned single pipe outage). A recent approach based on approximating the reliability analysis with analytical response surface has been proposed by *Torii and Lopez* [2012]; in their work authors assumed 1 mm diameter to simulate interrupted pipes instead of explicitly modifying network topology in consequence of pipe interruptions.

Some other contributions [e.g., *Tanyimboh et al*., 2001] computed reliability indices based on a variant of classical demand-driven simulations which emulates the pressure-driven analysis. Indeed, pressure-driven analysis was recognized to provide more realistic results than demand-driven analysis in pressure deficient conditions [e.g., *Todini*, 2003]. *Filion et al*. [2007] evaluated WDN reliability considering damages due to mismatching of sufficient pressure under firefighting scenarios and pipe bursts due to excess of pressure. Also in that work WDN performances were evaluated with respect to normal working conditions.

Giustolisi et al. [2008a] proposed the fraction of unsupplied demand and volume as reliability indicators for each node and for the whole network; unsupplied water was estimated by pressure-driven extended period simulation assuming normal functioning demand patters. *Deuerlein et al*. [2009] also presented a methodology for analyzing system reliability where a graph decomposition of the network [*Deuerlein et al*., 2008] was exploited to reduce the number of calls of pressure-driven simulation.

Finally, a recent work by *Zhuang et al*. [2012] considered also the reliability/availability analysis aimed at quantifying the adaptive operation as a response to WDN failure. In their work, authors resorted to graph theory procedures to identify the topological changes (both intentional and unintended) due to closing gate valves. Thus, the analysis was aimed at supporting operational decision and not planning asset enhancement works.

In section 2, the WDN modeling background used herein is briefly described first. Afterward, the proposed strategy for analyzing WDN vulnerability is detailed considering the failure of multiple elements requiring the isolation of one or more segments. The procedure returns a set of disruption scenarios, all technically meaningful for planning purposes, and entailing very different topological and hydraulic states of the system. Such scenarios are not necessary limited to reservoirs, tanks, pumps, or control valves as would be expected based on technical insight. The procedure is proved on a real network.

2. WDN Modeling Background

Reproducing the impact of *mechanical* failures on WDN water supplying capacity requires the automatic detection of WDN portions still connected to water sources and the hydraulically consistent analysis of the system

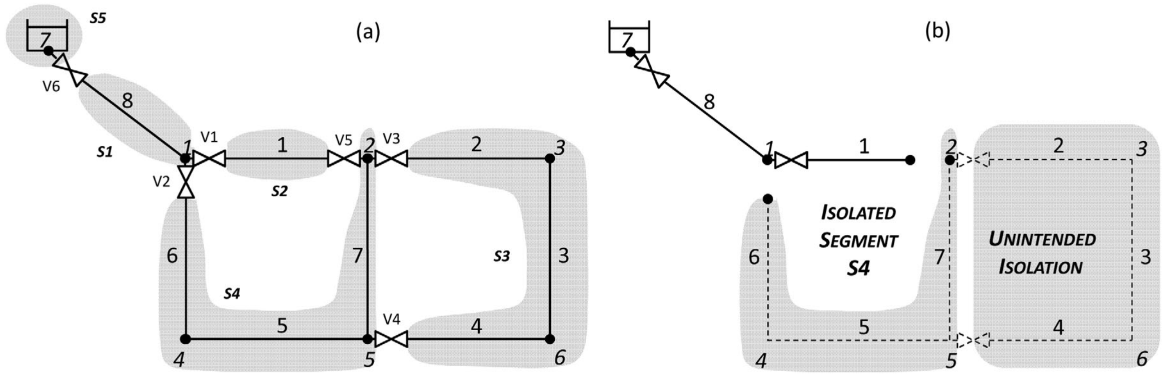

Figure 1. (a) Example of network segments isolated by closing gate valves and (b) unintended isolation due to detaching segment S4.

under pressure deficient conditions. The detection of current network topology has to be performed before model run (i.e., to detect intended and unintended segment isolations due to closing gate valves) and during the hydraulic simulation (i.e., to reproduce the effects of automatic closing of control/directional devices).

A number of methods to analyze the Isolation Valve System (IVS) and generated network configurations have been recently proposed [e.g., *Jun and Loganathan*, 2007; *Alvisi et al*., 2011]. In this work, the topological representation of the IVS reported in *Giustolisi and Savic* [2010] is adopted using graph theory tools to detect network components generated by valve shutdowns. Based on the existing IVS, this methodology identifies also the portions of the network which are still connected to water sources when one or more segments are detached by closing their gate valves (while all other valves remain open). This in turn might cause the unintended disconnection of other subportions. For example, Figure 1a shows a schematic of the IVS which determines valves and segments reported in Table 1. Figure 1b shows the unintended isolation of segment S3 due to the isolation of S4 by closing valves V2 and V5.

The unintended disconnection of network subportions might also happen due to the automatic closure of hydraulic devices like directional devices (e.g., check valves) or pressure control valves. In order to account for such devices, some WDN simulation models (e.g., EPANET2 by *Rossman* [2000]) do not detect topological changes and use, instead, heuristic procedures. Nonetheless, such numerical expedients were observed to result into incorrect solutions or lack of convergence of the solving algorithm [*Piller and Bremond*, 2001; *Deuerlein et al*., 2008]. A mathematically consistent approach to model the behavior of these devices was proposed by *Deuerlein et al*. [2009] based on content and cocontent model theory. The algorithm reported in *Giustolisi et al*. [2012a] is used herein which entails a pragmatic approach based on adjustment of energy balance equations and on the automatic detection of network topology inside the WDN hydraulic simulation run, without using heuristic expedients.

The WDN hydraulic model used here entails pressure-driven analysis and permits defining all components of water demands (i.e., including customers' requests, outflows from uncontrolled orifices and background leakages) [e.g., *Giustolisi et al*., 2008b; *Giustolisi and Walski*, 2012] as pressure-dependent functions.

Giustolisi and Walski [2012] also showed that, under pressure deficient conditions, the leakage demand component is usually much lower than its human-controlled counterpart. Thus, neglecting water leakages does not impair the results of WDN vulnerability analysis where pressure deficient scenario are mainly considered.

Table 1. Valves and Segments (Pipes and/or Nodes) of the IVS in Figure 1

Segment ID	Pipes	Nodes	Valves
S1	8	1	V1-V2-V6
S2	1		V1-V5
S3	2–3-4	3–6	V3-V4
S4	5–6-7	2–4–5	V2-V3-V4-V5
S5		7	V6

2.1. Some Remarks on WDN Modeling for Mechanical Vulnerability Assessment

The analysis reported herein refers to multiple simultaneous asset failures which cause abrupt modifications of network topology

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(see section 3) due to unpredictable extreme events (e.g., landslides caused by flood events, sabotages). The scope of this analysis is to point out the most vulnerable scenarios to support planning of infrastructure enhancement works.

In such circumstances, the change of problem domain (i.e., topology) is dominant over the variation of model boundary conditions (i.e., initial level(s) of tank(s), customers' demands). This means that the worst configurations (i.e., those causing the worst water supply scenarios) do not change if the demands assumed for simulation changes (i.e., the problem is scalable with respect to demands).

In addition, it is not reasonable under extreme events to expect that customer normal water requirements are fully satisfied. Also the duration of service disruption and the time when it starts are not predictable. All these technical considerations make the boundary conditions for WDN hydraulic simulation highly uncertain.

Accordingly, the simulated supplied demand should be assumed just as an indicator of WDN residual supply capacity to drive the search for most disruptive topological alterations.

Performing the classical Extended Period Simulation (EPS), with demand patterns of normal functioning scenarios, would be actually ineffective for this analysis since it would increase the computational burden without actually improving the accuracy of results due to the uncertainty of boundary conditions.

Having said this, each failure scenario is simulated herein as a steady-state snapshot using the Generalized WDN modeling [*Giustolisi et al*., 2012c] assuming a time step equal to 150 min and an average value of water demand. In fact, the Generalized WDN model allows to couple emptying/filling of tanks within classical WDN simulation (considering demand-driven or pressure-driven analysis). This way the hydraulically consistent simulation of water level in tanks (i.e., local reliability) is preserved, without requiring classical EPS.

It is worth to note that classical EPS would be advisable for WDN reliability assessment in face of accidental/planned *single* events (e.g., pipe bursts/replacement), which is not the case here. In fact, the impact on the WDN functioning in that context is assumed to be very limited and is supposed to happen under normal functioning conditions.

3. Segment Failures Versus Nodal Failures

As reported by *Walski* [1993a, 1993b], system reliability strictly depends on the existing IVS. An IVS entailing the so-called *N-valve rule* implies the lowest possible impact on network topology since it permits to detach each single pipe from the system by closing two isolation valves put at its ends (e.g., pipe 1 in Figure 1a). Unfortunately, the IVS in real WDNs is far from entailing the *N-valve rule* and isolating a pipe usually requires the detachment of all elements falling into the same segment.

In real systems (like for the case study reported here), some nodes are not simply pipe junctions but coincides with physical elements (i.e., valve vaults/manholes). Assuming that failures occur in these nodes means that relevant valves cannot be longer operated. This could happen because the accidental/intentional disruptions make valves inaccessible or because of malfunctioning of gate valves (e.g., seized up). In both circumstances, all segments joined at that node should be isolated.

Based on such observations, two types of scenarios are considered for the assessment of WDN mechanical vulnerability, namely *segment failures* and *nodal failures*.

Segment failure scenarios imply that the failed element belongs to one segment only which is detached by closing the isolation valves at its boundaries. For example, in Figure 1, segment S3 must be disconnected by closing V3 and V4 if a failure occurs on pipes 2, 3, 4 or on nodes 3 and 6. The number of single *segment failure* scenarios equals the number of segments identified by the IVS.

Nodal failure scenarios are supposed to require the detachment of all pipes (and relevant segments) adjacent to the failed node. For example, in Figure 1, if node 2 fails, pipes 1, 2, and 7 should be isolated detaching segments S2, S3, and S4. Thus, *nodal failures* are expected to have a higher impact on WDN functioning than *segment failures*. The number of single *nodal failures* depends on the existing IVS, although it is usually lower than the number of single *segment failures*.

The computational resources today available and the effectiveness of WDN model adopted here permit the exhaustive simulation of all *single-failure* scenarios, in reasonable computational time even on laptop computers and for large real WDNs with a near *N-valve rule* IVS. Nonetheless, this work focuses on a more complex problem pertaining the identification of those combinations of simultaneous failure events which are likely to result into highly disruptive impact on WDN functioning.

4. Assessment of WDN Vulnerability Under Multiple Mechanical Failures

The number of possible combinations of k simultaneous failures out of n_e possible events can be computed as $n_e!/[k!(n_e-k)!]$, which is dramatically higher than the number of *single-failure* events, even for small real networks. This makes infeasible the exhaustive analysis of all possible scenarios and motivates this work.

The analysis of WDN vulnerability should explore the space of such combinations that cause topological modifications and severely affect WDN supply capacity. Nonetheless, in real WDN, there are various combinations of k simultaneous failures reflecting very different topological alterations, hydraulic states, and impact on various WDN portions. Discerning the failure events that simultaneously might result into very disruptive conditions is of technical interest in order to allocate resources for risk mitigation works.

Accordingly, the technical problem is not only to find the "worst" combination of k failures in terms of WDN performance but, rather, to unveil a set of different k failures scenarios resulting into severe WDN malfunctioning, for $k \geq 1$.

It is worth noting that, achieving more than one of k failures scenarios (for any number k) makes the procedure more technically robust in face of the uncertainties surrounding the boundary conditions of the WDN model (e.g., human water requests, initial level of tanks, duration and starting time of the event).

4.1. Methodology

It is assumed here that the higher vulnerability scenarios result into the lower total supplied demand (as an indicator of WDN supply capacity) in consequence of the lower number k of simultaneous failures. Thus, the search is formulated as a multiobjective optimization problem although it permits to achieve multiple solutions for each number k of simultaneous failures.

The objective functions to be simultaneously minimized are: (i) the number of simultaneous events (i.e., leading to segment(s) detachment); (ii) the total water demand supplied to customers, as predicted by the WDN simulation model.

Such objectives are actually conflicting since it can be reasonably assumed that WDN supply capacity worsen as the number of simultaneous failures increase. In fact, the more segments are detached by closing valves, the less water paths feed the connected nodes and the larger head losses occur along connected pipes.

Like for other optimization problems requiring the exploration of a combinatorial search space with a discrete number of alternatives for each variable (i.e., element failed/not failed), the Genetic Algorithms (GA) [*Goldberg et al*., 1989] are used here. In more details, the OTPImized Multi Objective GA (OPTIMOGA) [*Laucelli and Giustolisi*, 2011] is used since its efficiency and efficacy was already proved in many different problems pertaining WDN design and operation [e.g., *Giustolisi and Berardi*, 2009; *Giustolisi et al*., 2012b]. The search for solutions is performed in OPTIMOGA by managing an archives of dominant individuals whose size might promote the "exploration" of the search space or the "exploitation" of current set of optimal solutions; further details are reported in *Laucelli and Giustolisi* [2011].

In OPTIMOGA, the evolution is driven by the fitness of each solution e (i.e., combinations of failure events in this case) based on Pareto dominance. In more details, each solution e is assigned with a *rank* according to the methodology proposed by *Fonseca and Fleming* [1993]:

$$rank(e,t)=1+p^{(t)} \tag{1}$$

where $p^{(t)}$ is the number of individuals dominating e at generation t according to the Pareto dominance criterion. Note that a nondominated individual at generation t has $rank = 1$ since $p^{(t)} = 0$. Figure 2 exemplifies different solutions assigned with $rank = 1$, 2, and 3 (i.e., designated with *r1*, *r2*, and *r3*) in the two-objectives space of WDN vulnerability assessment problem (i.e., number of simultaneous events versus percent of water demand supplied to customers). Each solution with $rank > 1$ (i.e., squares *r2* or triangles *r3*) is dominated by the points in the left bottom area delimited by the dash-dotted lines.

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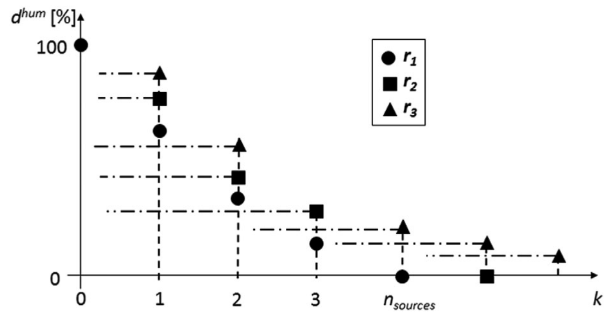

Figure 2. Representation of failure scenarios in the two-objective search space.

The most disruptive combination of k events correspond to the solutions (i.e., failure scenarios) whose *rank* equals 1 in the final OPTIMOGA population (i.e., circles in Figure 2). In fact they represent the minimum number k of simultaneous failures, resulting into the minimum supplied demand. $n_{sources}$ is the minimum number of failures (*segment* or *nodal*) which simultaneously detach "sources" of water and/or energy (e.g., reservoirs, tanks, and pumps) from the network, which is known a priori from WDN layout. In the special case of gravity systems, reservoirs and tanks provide both water and energy. When all these "sources" are detached no water is supplied to customers.

In addition, Figure 2 reports as squares and triangles the combinations of k events with $rank = 2$ and $rank = 3$ in the final OPTIMOGA population, respectively. This means that, for a given number of k simultaneous events (e.g., $k = 2$ failures), the procedure returns two more scenarios pertaining different topological modifications and hydraulic states of WDN. Although the value of supplied demand is slightly larger than the solution with $rank = 1$ (and $k = 2$ failures), such scenarios are of technical interest to support planning works.

The procedure permits to set the maximum allowable rank r_{max} to be included in the final set of solutions (e.g., $r_{max} = 3$ in Figure 2; $r_{max} = 5$ in section 5). This, in turn permits to decide the maximum number of scenarios for each k, which can be visually inspected and checked by technicians for consistency based on prior knowledge of the network.

It is possible that, for a given k, the number of scenarios returned by the procedure is less than r_{max}: for example, in Figure 2 there are two scenarios with $k = 3$, none showing $rank = 3$. From WDN vulnerability analysis perspective this means that there are not other combinations of $k = 3$ events whose impact is more severe than those due to $k - 1 = 2$ events.

Figure 2 shows also some solutions with a number of failures $k \geq n_{sources}$, depending on WDN topology and IVS. They entail different topological modifications (not necessarily involving all water sources) that cause severe WDN malfunctioning (e.g., $k = n_{sources} + 2$ in Figure 2).

All scenarios returned by this methodolgy contain a number of asset elements (i.e., pipes and nodes belonging to the isolated segments) whose simultaneous disruption should be avoided since they are likely to result into high WDN vulnerability.

Based on the explanations above, the optimization problem underlying the vulnerability assessment strategy can be formulated as follows:

$$\begin{cases} e=\{F_1,\ldots,F_k\} \in C_k^{nF} \quad (\text{decision variable}) \\ \\ [\text{Generalized PDA model } (\theta_e(IVS))] \\ \min_e \{f_1(IVS,e)\}=\min_e \{k(IVS)\} \\ \min_e \{f_2(\theta_e,P_1,\ldots,P_n)\}=\min_e \left\{\sum_{i=1}^{n} d_i(\theta_e,P_i)\right\} \\ \text{with } rank(e) \leq r_{max} \end{cases} \tag{2}$$

where the decision variable e is one of the combinations of k failures F_j out of nF possible failure events. In case of *segment* failures, nF is the number of segments identified by the IVS; in case of *nodal* failures, nF is

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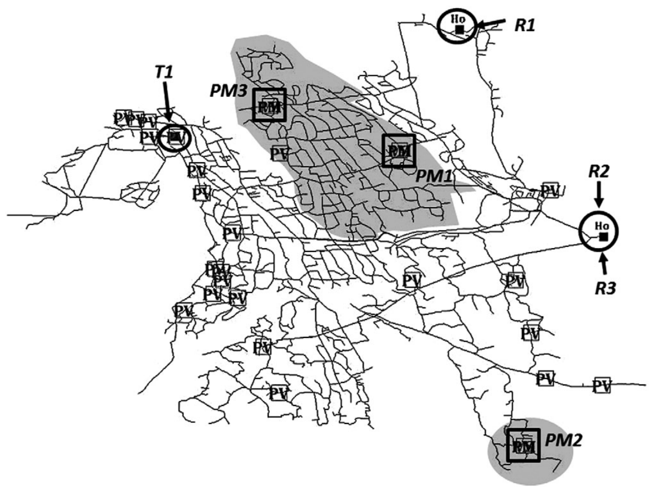

Figure 3. Network layout: circles indicate reservoirs (R1, R2, and R3) and tank (T1); squares (PM1, PM2, and PM3) are pumps; PV are pressure reduction valves.

the number of nodes adjacent to two or more segments. θ_e is the topological WDN configuration subsequent to segment(s) isolation, also accounting for unintended isolations. d_i is the demand supplied at ith node which depends on relevant pressure P_i, as simulated by the Generalized WDN model [*Giustolisi et al.*, 2012a, 2012b, 2012c] accounting for current WDN topology θ_e and pressure-driven analysis.

5. Case Study

Water and Wastewater Department in Oslo municipality is currently estimating the reliability of the water distribution system including the level of robustness, redundancy, and preparedness of the system under today and future demand. A major ongoing project on revision and safeguarding of Oslo water supply system also includes analysis of the both *hydraulic* and *mechanical* WDN reliability.

In this work, the mechanical vulnerability assessment is applied to one of the areas of Oslo WDN (see Figure 3), where the pressure table in some parts of the system (shadowed in Figure 3) in ensured by pumps. In addition, the available WDN model included also 25 pressure control valves (PCV).

Such area has been ranked as at high level of criticality within a previous "risk and vulnerability analysis" project focused on the integrated water cycle of Oslo [*Røstum et al.*, 2010].

The network comprises 5322 pipes and 5059 nodes, with four water sources (i.e., three reservoirs (R1, R2, and R3), one tank (T1)) and three pumping stations. Unfortunately data on the existing IVS were not provided; thus, it is realistically assumed here that gate valves are located close to reservoirs and tank, and at end nodes of pumps and pressure control devices. In addition, gate valves are assumed to be close to nonserial nodes (i.e., joining more than two pipes). The resulting IVS comprises 2813 isolation valves and 1446 pipe segments. It also results into 1106 possible *nodal failure* scenarios, each involving the isolation of two or more adjacent segments.

It is worth to remark that locating valves close to only nonserial nodes is just a working hypothesis here which was also approved by experts on this water utility. Nonetheless the following analysis could be performed considering the actual IVS, if data were available.

For the sake of the example, the pressure to correctly supply water to customers is set to 40 m, while leakages are not considered since they are negligible under pressure-deficient conditions, as mentioned above. Customers' demand were provided at nodal level, although the assumption of valves at nonserial nodes and the severe level of topological disruption makes the inaccuracy due to lumping demands at nodes not actually influencing on final results. Moreover, it is assumed here that, under extreme events like those considered herein, all pressure control valves are automatically open in order to allow the maximum pressure to be reached at all nodes. All isolations valves are kept open, except for those that isolate failed segments.

The vulnerability assessment procedure has been applied considering *segment* and *nodal failures* separately. The search for the most disruptive combinations of events by OPTIMOGA run for 1000 generations returning up to five alternative scenarios (i.e., $r_{max} = 5$) for each number (k) of simultaneous events. In addition, the size of OPTIMOGA dynamic archive of solutions was set between 50 (minimum) and 100 (maximum); while the number of solutions involved in the evolution was set to 200. During the exploration of the search

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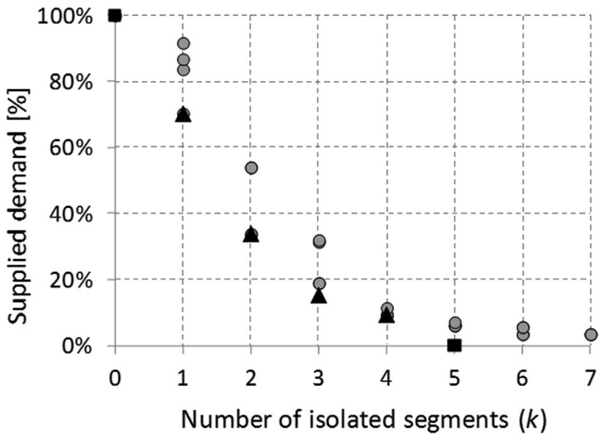

Figure 4. Vulnerability assessment: multiple *segment failure* scenarios.

space, a multipoint crossover is applied with probability 40% and a mutation of genes with probability 10%. Nonetheless, it has to remark that the OPTIMOGA was observed to be not sensitive to the variation of its settings, which have been applied in a number of different problems [*Laucelli and Giustolisi*, 2011].

It is evident from Figure 3 that detaching the four water sources (T1, R1, R2, and R3) prevents for any water to be supplied in the network; such worst scenario requires the isolation of five segments joining water sources to the network since the three reservoirs are connected to WDN by one segment each, while two segments are connected to T1.

Figure 4 reports the multiple *segment failure* scenarios obtained by applying the procedure; the black squares refer to 100% (no failures) and 0% (all links to reservoirs and tank interrupted) supplied demand.

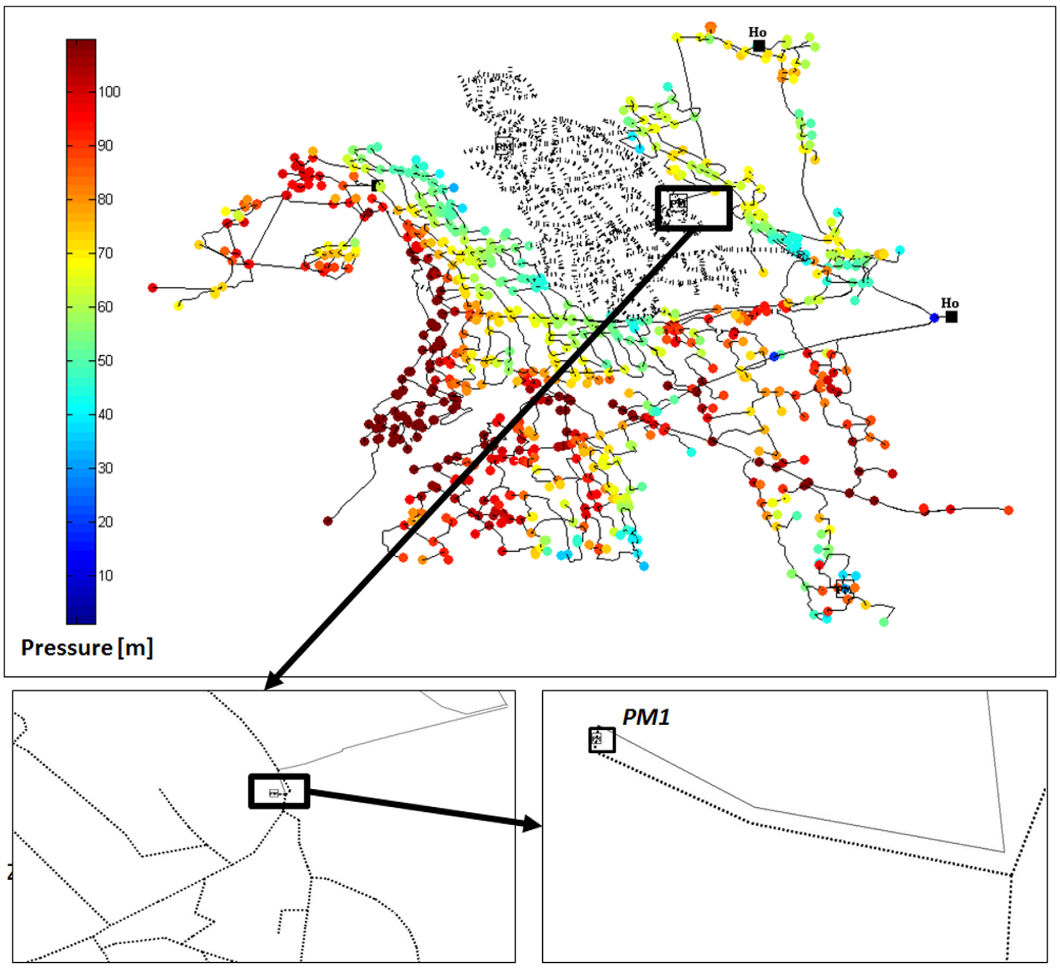

Figure 5. Vulnerability assessment: worst 1-*segment failure* scenario.

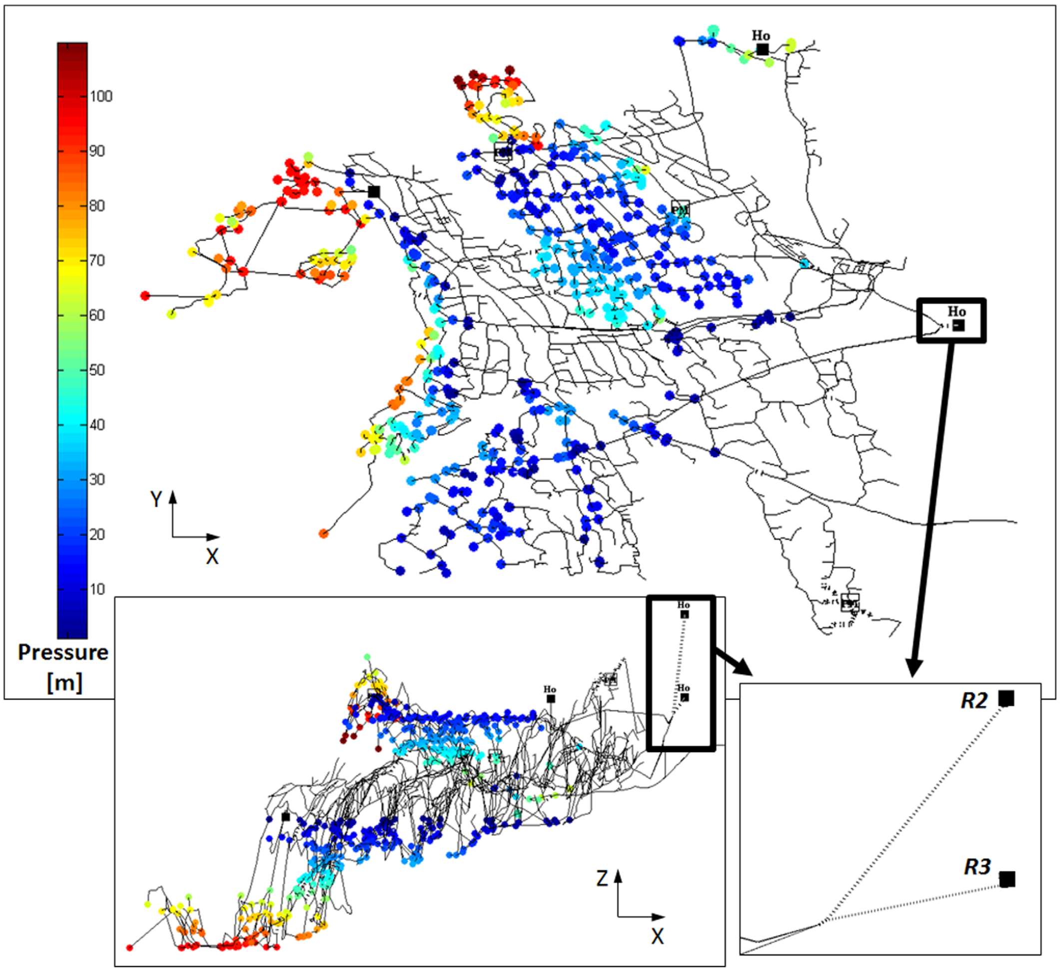

Figure 6. Vulnerability assessment: worst 2-*segment failure* scenario.

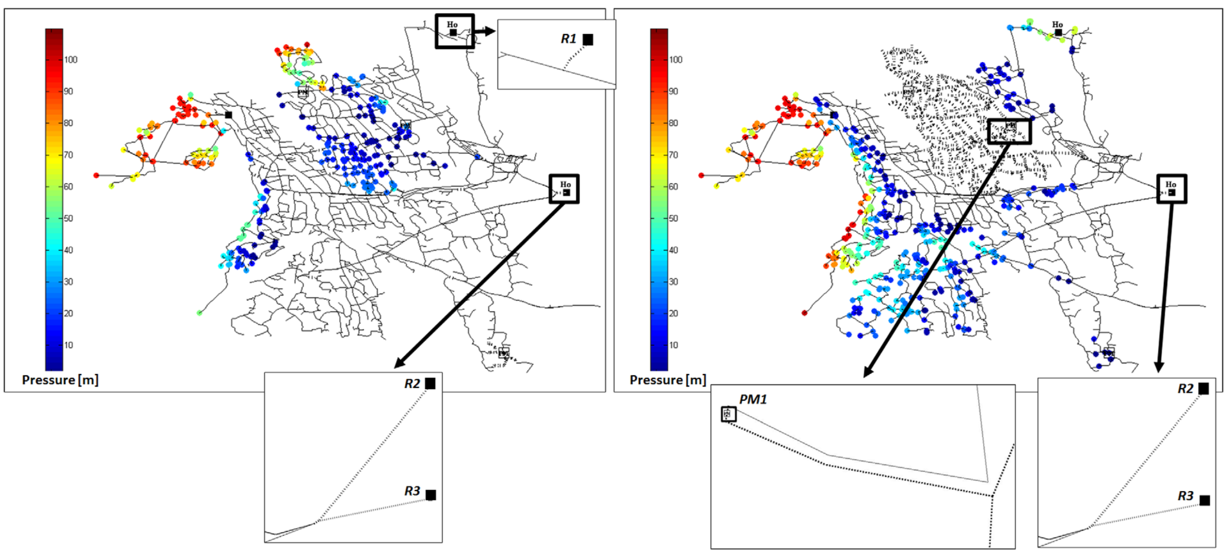

Figure 7. Vulnerability assessment: 3-*segment failure* scenario.

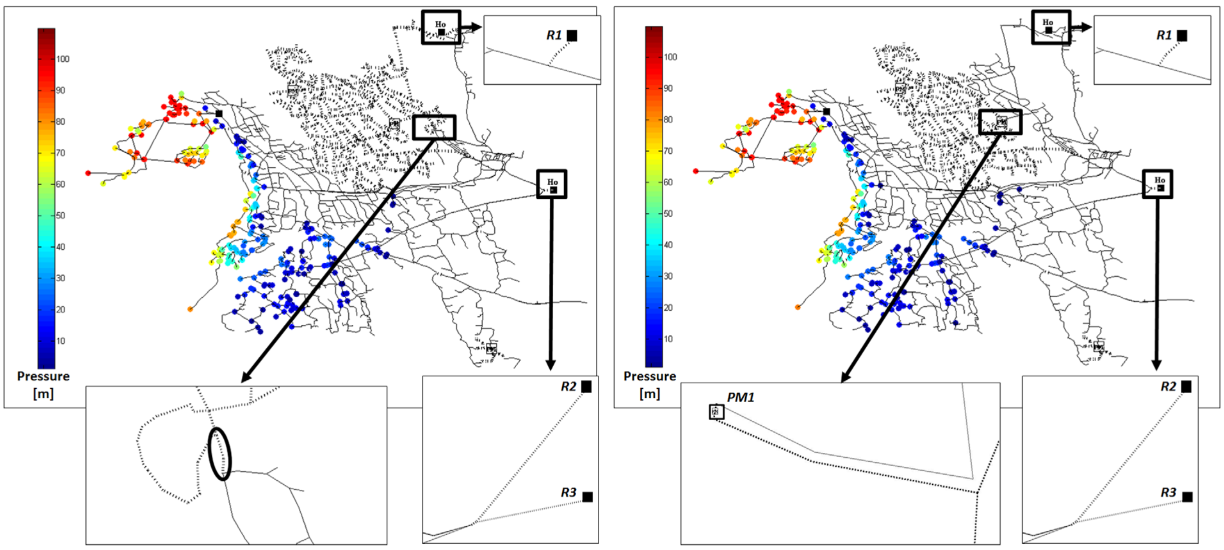

Figure 8. Vulnerability assessment: 4-*segment failure* scenario.

The scenarios with 1, 2, 3, and 4 simultaneous *segment* failures entailing the lowest WDN supply capacity are plotted as black triangles and are detailed in Figures 5–8, respectively. In order to facilitate the visual inspection of these figures, only nonserial nodes with pressure higher than 1 m are plotted; nodes with pressure lower than 1 m are not reported. Moreover, in all figures Z is the vertical axes of elevations; graph Z-X in Figure 6 is the projection of the network on the plane Z-X orthogonal to Z.

In Figure 5, the detachment of the segment containing pump PM1 causes the disconnection of pipes reported in dotted lines (i.e., in the upper shadowed area in Figure 3). This, in turns, results

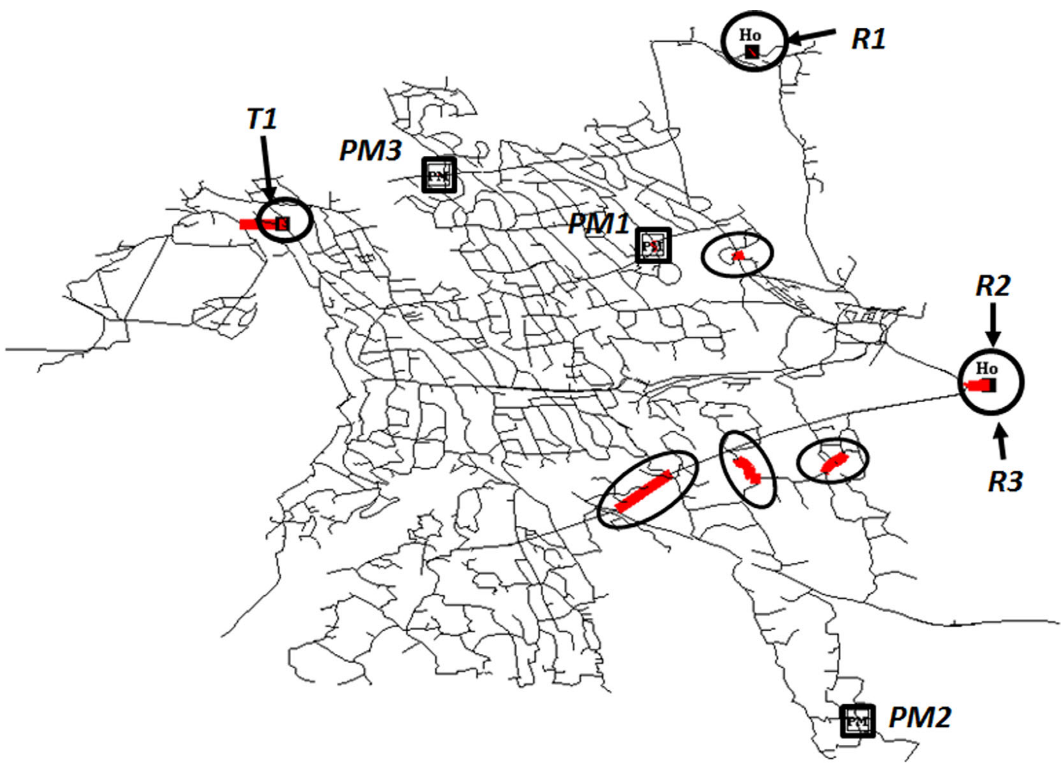

Figure 9. Vulnerability assessment: location of *segment failures*.

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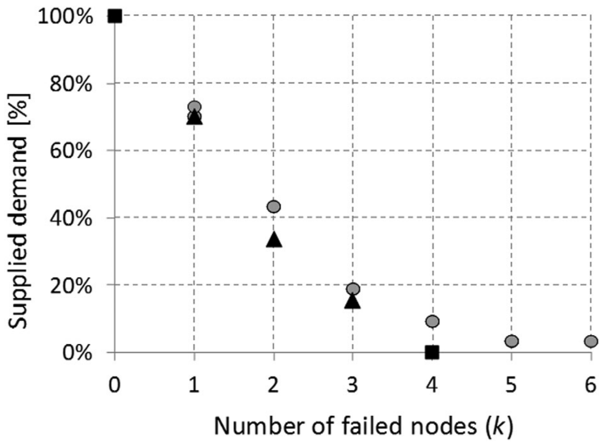

Figure 10. Vulnerability assessment: multiple *nodal failure* scenario.

into pressure drop in some other nodes and the reduction of supplied demand at about 70% of total request.

Figure 6 shows that the isolation of two segments connecting reservoirs R2 and R3 to the network causes the reduction of the supplied demand at less than 35% of total requests. Also a severe pressure drop happen in a number of nodes (not plotted because pressure is lower than 1 m), although still connected to other water sources. The side view (X-Z axes) shows that pressures slightly higher than 1 m are due to the locally low elevation of such nodes which are fed by R1 and T1.

The interruption of segments close to reservoirs R2 and R3 together with the failure the segment that links the reservoir R1 to the network (see Figure 7, left) further reduces the supplied demand at about 15% of total request. It is worth to observe (see Figure 7, right) that the interruption of pump PM1 in place of reservoir R1, also causes a severe reduction of WDN supply capacity (i.e., about 20% of total requests), although with different change of topology.

The most severe four-segments failure scenario (i.e., about 10% of demand supplied) is obtained by disconnecting reservoirs R1, R2, and R3 and closing the segment circled in Figure 8 (left). It is to remark that such segment is located far from reservoirs, tanks, and pumps but it is in a crucial position to feed a large portion

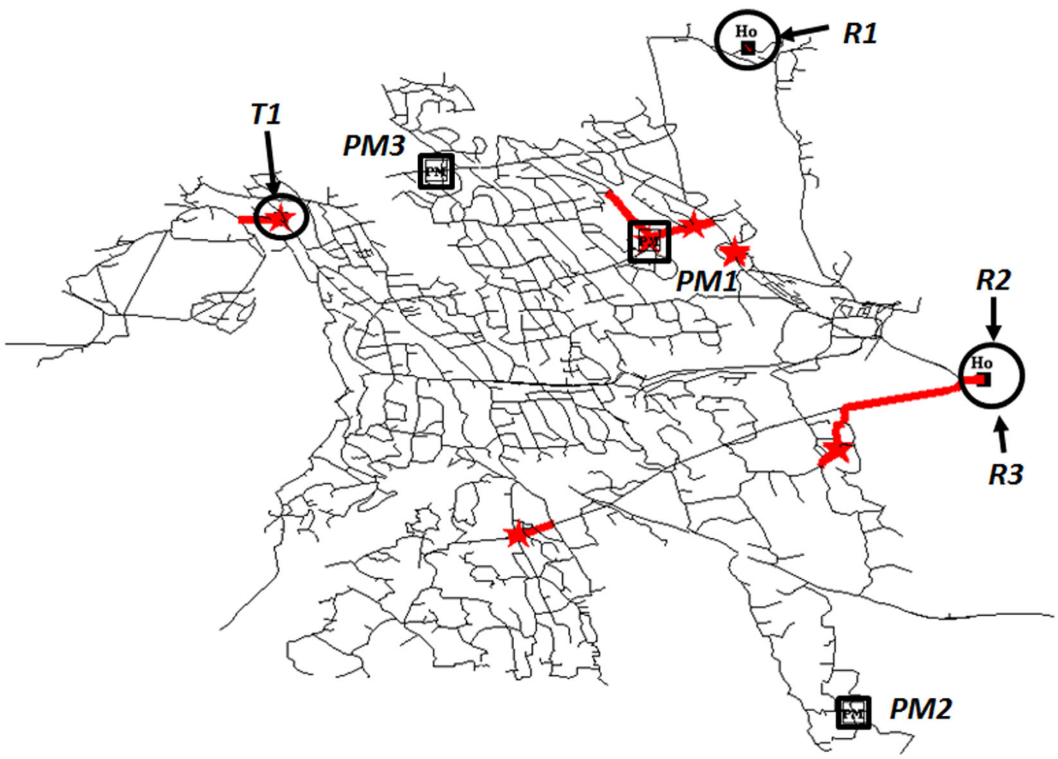

Figure 11. Vulnerability assessment: location of *nodal failure* events.

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of the network. A similar reduction of WDN supply capacity would be obtained interrupting pump PM1 in place of the above-mentioned segment (see Figure 8, right).

The gray circles in Figure 4 entail different failure scenarios which are equally useful for planning purposes since they cause severe mismatching of water requests in different WDN portions. Besides the segments close to PM1, reservoirs and tanks, other segments which might result into high WDN vulnerability are circled and plotted in red in Figure 9.

From WDN management perspective, all elements reported in these failure scenarios can be assigned with priority for inspection, rehabilitation, or reinforcement (e.g., by designing alternative water paths).

The same analysis was performed considering *nodal failure* scenarios and Figure 10 reports the percentage of total supplied demand in face of different disrupted nodes. The most vulnerable *nodal failure* events are those reported as black triangles in Figure 10.

Besides nodes coinciding with tank and reservoirs, Figure 11 shows with stars the location of nodes whose failure causes the detachment of segments plotted as thick red lines. This happen because these nodes are in crucial positions to feed some peripheral network subportions and their failure/inoperability result into severe malfunctioning of different parts of the WDN.

All analyses have been performed using the WDNetXL system [*Giustolisi et al*., 2011; *WDNetXL*, 2014].

6. Conclusions

The safeguarding of water supply systems includes the analysis of their vulnerability in order to increase the preparedness to tackle possible disruptions due to accidental or man-made extreme events. While doing so, assessing the impacts of events involving multiple mechanical failures is examined herein. The proposed vulnerability analysis is conceived to support water managers in (a) figure out the most critical failure scenarios which would put the system into crisis and (b) identifying those part of the network which would experience the most severe service disruptions.

The novel strategy to assess WDN vulnerability due to multiple simultaneous *mechanical* failures is based on solving a multiobjective optimization problem using genetic algorithms. Apart from the peculiarities of the Multi-Objective GA used here (i.e., OPTIMOGA), the core of this work is the strategy to efficiently explore the space of combinations of failure events which result into severe WDN service disruptions. In fact, the procedure returns up to r_{max} different scenarios involving k simultaneous failures, consisting into different topological modifications and WDN hydraulic states. This makes the vulnerability analysis more robust in face of all uncertainties surrounding the boundary conditions adopted to evaluate WDN residual supply capacity (e.g., the total supplied demand in this case). Thus, it goes beyond other methods to find just one set of system components that, when failed, causes the failure of the entire system (e.g., minimum cut-set method) with respect to predictable water request conditions.

The comparison among different failure scenarios also support technicians in identifying the most vulnerable system elements and take appropriate countermeasures. For example, the duplication of water paths might improve the maneuverability of the system when some elements (e.g., valve vaults) are actually inaccessible under extreme events. Alternatively, storage tanks internal to the network can improve local system reliability (e.g., close to hospitals, firefighting stations).

Of course, the proposed analysis can be performed also considering some network subportions only or neglecting those failures for which risk mitigation works have been planned already, thus resizing the space of possible combinations.

It is worth noting that, although the objective function used to drive the exploration here is the total demand supplied to customers, it can be formulated by accounting also for other, case-specific, criteria (e.g., the demand/volume supplied to critical nodes feeding hospitals or fire stations).

All information achievable by using the proposed strategies may provide useful advices to water managers and, thus, support the prioritization of planning inspection, rehabilitation, or reinforcement works in the near future.

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