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OPTIMAL DESIGN OF NETWORK PARTITIONING FOR WATER DISTRIBUTION SYSTEM PROTECTION FROM INTENTIONAL CONTAMINATION

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Water network partitioning and sectorization can be an effective way to protect water system from intentional contamination respecting also the criteria of *dual-use value*. In previous studies, the authors investigated how different layouts of permanent DMAs (District Meter Areas) or i-DMAs (isolated-DMAs) can reduce the risk of contamination for the network and limit the effects of a malicious act achieved with a backflow attack that occurs when a small pump is utilized to overcome the local pressure in order to introduce a contaminant in the water system. In this work, the positioning of gate valves and flow meters required to define DMAs and i-DMAs was optimized with a complex objective function in order to minimize the alteration of hydraulic performance due to partitioning and to minimize the effects of intentional contamination. The malicious attack was assumed to be perpetrated with cyanide finding the worse insertion point for each network layout. The analysis was carried out on a real water distribution network comparing different sectorization scenarios obtained in a previous study. The simulation results showed the effectiveness of the optimization approach with a significant reduction of risk for users.

INTRODUCTION

The intentional contamination of water distribution systems represents one of the mayor risks for citizens, consequently after September 11, 2001 many international organizations have been concerned about it, as reported in CER (Centre for European Reform) [1], HSPDs [2], US EPA [3] and Kroll [4]. The water contamination can be perpetrated in different ways, being the backflow attack, that occurs when a pump is utilized to overcome the local pressure, a simple but dangerous way for an intentional contamination. Some studies have faced this type of possible contamination attack trying to reduce the health risk for users.

The development of new monitoring and control technologies and the recent growth of computational power used by simulation software introduce new opportunities to the traditional approach of analysis, design and management of Water Distribution Systems (WDSs). Indeed, the availability at low cost of new monitoring and management devices, controlled by a remote system, allows to define different layouts of the water network in a new paradigm of dynamic layouts of water distribution systems in which an important role is played by water network partitioning and sectorization, as reported in Tzatchkov *et al.* [5], Di Nardo and Di Natale [6], Di Nardo *et al.* [7] and Di Nardo *et al.* [8].

Recently the advantages of these techniques have been investigated to analyse their application to the problem of water network protection from contamination, as reported in Grayman *at al.* [9], Di Nardo *et al.* [10, 11]. The possibility of designing districts and sectors reduces the risk of affecting many people because several points of contaminant introduction would be needed to produce a wide negative impact on the network. Furthermore, the closure of the sectors, in which the backflow attack occurs, allows to protect significantly the users from the contamination. The water network partitioning respects the criteria of dual-use value because the districts and sectors, in addition to protect the network from contamination, are essentially defined for other aims (water balance, pressure management, etc.) optimizing the costs. The design of the water network partitioning is essentially based only on the reduction of the negative effects on hydraulic performance due to the insertion of gate valves in the network that are necessary to define the districts and sectors and can decrease the level of the service for the users, as explained in [6], but not on a minimization of the negative effects of a possible contamination. In this study a novel methodology is proposed that allows to optimize the design of water network partitioning both for compliance of hydraulic performance and for water protection. The methodology is based on heuristic optimization techniques (graph partitioning and genetic algorithms) that minimize a constrained multi objective function.

BACKFLOW ATTACK MODEL

The backflow attack scenario was borrowed from Di Nardo *et al.* [10] with some little modifications that increase the effects of contamination. Specifically, the backflow is created with a small pump – easy to find on the market – which introduces a contaminant into the water system by overcoming the local pressure and disseminates it into the network affecting progressively the areas surrounding the introduction point. The malicious attack is carried out at a single point and, theoretically, by a single terrorist equipped with a small number of simple devices (a small pump, a backpack to transport the pollutant, etc.) that would allow him or her to commit the crime unnoticed. A backflow attack can be easily accomplished mixing cyanide with water in a bathroom tub in any house and pumping the solution into the water network, as illustrated in Di Nardo *et al.* [11]. The introduction point can be everywhere in the system.

The most dangerous for the users introduction points can be identified employing the EPANET2 [12] water quality tool. Different assumptions have been made for evaluating the hazardous effects: a) every network node corresponds to a given number of users; b) a given amount of potassium cyanide (flow rate and concentration) is introduced into the water network for 2 hours (at 8.00 am and at 10.00 am) (a two-hour interval is enough to refill the tub and mix cyanide, as reported in [10]); c) the lethal concentration of potassium cyanide in water for a user whose bodyweight is 70 kg is 200 mg/l, as indicated in Patnaik [13]. Cyanide contamination has been simulated by means of EPANET2, a water quality simulation module that allows to model the transport of a dissolved species travelling along pipes with the same average velocity as the carrier fluid and reacting with it (either growing or decaying) at a given rate. In this study, the reaction rate was assumed to be zero assuming that the reaction of cyanide with water is negligible during the time considered; more details are provided in Di Nardo *et al.* [10]. In this way the total number of exposed users (N_{eu}), the number of exposed users that ingest more than the lethal dose LD_{50} (N_{eu50}) and the length of contaminated pipes L_{ep} were computed.

OPTIMIZATION OF THE WATER NETWORK PARTITIONING

The water network partitioning was obtained using the procedure proposed by Di Nardo *et al.* [8] adapting the Multi Level Recursive Bisection (MLRB) algorithm, originally proposed by Karypis and Kumar [14] as a highly effective methods for computing a *k*-way partitioning of a graph in Computer Science, especially in large-scale numerical simulations on parallel computers. The MLRB algorithm, based on coarsening, partitioning and uncoarsening algorithms [14], allows to minimize the number of edge-cuts (or links between the districts) and to balance the number of nodes that belong to each district. The *k*-way partition is recursively solved by performing a sequence of *2*-way partitions (or bisections).

If the edges and vertices of the graph are weighted, the goal becomes to minimize the sum of associated weights on the edge-cuts and to balance the sum of node weights for each districts. The goal is to partition the vertices into k disjoint subsets D_k, such that the Objective Function 1 ($OF1$) to be minimized is equal to the sum of the number of edge-cuts e_{ij} or of the associated weights ε_{ij}, whose incident vertices belong to different subsets:

$$OF1 = \left(N_{ec} = \sum\nolimits_{i \in D_p \Rightarrow j \notin D_p} e_{ij} \right) or \left(W_\varepsilon = \sum\nolimits_{i \in D_p \Rightarrow j \notin D_p} \varepsilon_{ij} \right) \tag{1}$$

The goal (1) has to be obtained balancing the number of vertices n_p or the associated weights ϖ_p for each subset. This constraint is achieved by *minimizing* the *balance index* I_B:

$$\text{constraint} = I_b = \frac{k \cdot \max(d_p)}{n} \tag{2}$$

where n is the number of vertices of the original graph and $\max(d_p)$ can be the size of the largest subset n_p or the maximum weight ϖ_p obtained by the *k*-way partitioning algorithm. The authors modified the MLRB algorithm [8] to adapt the procedure to a water network defining an oriented graph and suitable weights by hydraulic simulation.

Once defined the district, the positioning of gate valves and flow meters was achieved with a Genetic Algorithm (GA), proposed in Di Nardo *et al.* [8], that maximizes the following Objective Function 2:

$$OF2 = \gamma \sum_{i=1}^{n} Q_i H_i \tag{3}$$

where γ is the specific weight of water, and Q_i and H_i are the water demand and head at each network node respectively.

In this paper, a new complex weighted Multi Objective Function 3 was used to minimize simultaneously the alteration of the resilience (and, consequently, to preserve the hydraulic performance of the water network) and the disastrous effects of an intentional contamination:

$$MOF3 = \left(I_{rd} + \sum_{p=1}^{k} \alpha_p \frac{N_{eu,p}}{N_{eu}^{*}} + \sum_{p=1}^{k} \alpha_p \frac{N_{eu50,p}}{N_{eu50}^{*}} \right) \quad (4)$$

where $N_{eu,p}$ and $N_{eu50,p}$ refer, respectively, to the number of exposed users and the users that ingest more than the lethal dose of the p-th district (or sector) of the network, N_{eu}^{*} and N_{eu50}^{*} refer, respectively, to the number of exposed users and the users that ingest more than the lethal dose of the original network without partitioning or sectorization, I_{rd} is the Resilience deviation index [6], and α_p is a weight calibrated by a "trial and error" approach in order to obtain the best results with p=1...k.

Some Performance Indices (PIs) were also computed to compare different scenarios and to help operators to choice the better solution in a Decision Support System; specifically: the mean, h_{mean} and min, h_{min}, node pressure indices.

CASE STUDY

In order to demonstrate the proposed methodology and to investigate the positive effects of Water Network Partitioning (WNP), the real water distribution network of Parete (Caserta, Italy), already studied by the authors [8], has been used.

Parete is a town with 10,800 inhabitants in a densely populated area in the southern part of the province of Caserta (Italy). Its main hydraulic characteristics for the EPANET2 model are reported in Di Nardo *et al.* [11]. The network is supplied from two sources and water consumption is exclusively for residential use with a prevalence of buildings built in 1970's and 1980's, with 3 to 4 floors. After the hydraulic simulation, the WNP of Parete was defined using the MLRB algorithm, synthetically described in the previous section, that allows to obtain partitioning scenarios considering different weights for both edges and vertices (ε_j, ϖ_i).

Starting from the scenarios used in Di Nardo *et al.* [10, 11], the scenarios analyzed in this paper are as follows:

- S_{NND}) Network with No Districts (NND);
- S_{WNP}) Water Network Partitioning with four DMAs obtained with *OF2*;
- S_{OWNP}) Optimal Water Network Partitioning with four DMAs obtained with *MOF3*;
- $S_{WNS1...4}$) Water Network Sectorization with isolation of a single DMA (i-DMA1 or i-DMA2 or i-DMA3 or i-DMA4) at 8.00 am (one hour after the beginning of the attack) or at 10.00 am (three hours after the beginning of the attack) obtained with *OF2*.
- $S_{OWNS1...4}$) Optimal Water Network Sectorization obtained with *MOF3*.

As reported in Di Nardo *et al.* [10], the choice of closing the contaminated DMA one hour (at 8.00 am) or three hours (at 10.00 am) after the beginning of the malicious attack is a reasonable hypothesis for a water network that is not equipped with an early warning system (that allows shorter detection times). In this case, after a couple of hours, it can be realistically assumed that the authorities are alerted and they ordered to close the network district.

In this last case, in which a water network sectorization (WNS) can be achieved, it is necessary to find a different solution for the optimal positioning of gate valves and flow meters because simulation results highlighted that the first solution found for WNP was not optimal, also for WNS, so that two different scenarios S_{WNP} and S_{OWNP} were found.

The simulation results are reported in Table 1, in which a comparison between the Water Network Partitioning (S_{WNP}) and the Optimal Water Network Partitioning (S_{OWNP}) is illustrated in terms of percentage reduction of I_r, N_{eu}, N_{eu50}, L_{ep} and PIs with respect to the scenario with No Districts (S_{NND}).

The original network S_{NND}, with a design pressure h_i^* =25 m equal for each node, has the following indices: I_r=0.351, h_{mean}=31.05, h_{max}=50.47 and h_{min}=21.36.

Table 1. A comparison between simulation results obtained with S_{WNP} and S_{OWNP}

Scenario	I_r -	N_{eu} [%]	N_{eu50} [%]	L_{ep} [%]	h_{mean} [m]	h_{min} [m]
S_{WNP}	0.348	0.00	1.68	0.00	30.93	21.22
S_{OWNP}	0.342	3.59	12.80	66.09	30.59	21.12

The results show a slight reduction of N_{eu} (with only 3.59%) but a more significant reduction of N_{eu50} (with 12.80%) and L_{ep} (with 66.09%) preserving a good hydraulic performance: h_{mean} (with 30.59 m) and h_{min} (with 21.12 m), practically equal to S_{NND} and S_{WNP}.

In Tables 2 and 3 a comparison between the Water Network Sectorization (S_{WNS}) and the Optimal Water Network Sectorization (S_{OWNS}) is illustrated with reference to isolation at 8.00 am and 10.00 am, respectively.

Table 2. Comparison between simulation results obtained with $S_{WNS1...4}$ and $S_{OWNS1...4}$ at 8.00 am

Scenario 8.00 am	N_{eu} [%]	N_{eu50} [%]	L_{ep} [%]
S_{WNS1}	75.90	81.54	86.41
S_{OWNS1}	94.47	93.85	97.25
S_{WNS2}	95.18	96.97	96.14
S_{OWNS2}	95.22	97.49	96.46
S_{WNS3}	34.82	100.00	73.06
S_{OWNS3}	32.01	100.00	71.94
S_{WNS4}	83.29	98.10	77.85
S_{OWNS4}	86.23	98.10	80.08

In the optimization case S_{OWNS} at 8.00 am (Table 2) the reduction is significant for S_{OWNS1} (up to 94.47% for N_{eu} and 93.85 % for N_{eu50}), negligible for S_{OWNS2} and S_{OWNS4} (values practically equal to S_{WNS}) and slightly worse in terms of N_{eu} for S_{OWNS3} (32.01% vs 34,82%). This last result is due to the optimization of the position of gate valves in edge-cuts that changes the network layout and, consequently, may reduce the number of exposed users in some districts (in this scenario in i-DMA1, i-DMA2 and i-DMA4) but also increase them in other districts (in this scenario in i-DMA3). Therefore, in order to reduce this effect, a weighted multi objective function was selected choosing different weights α_p for each district k: in this case α_1=2, α_2=2 and α_1=3.

With district isolation at 10.00 am (Table 3), the simulation results are better in all scenarios ($S_{OWNS1-4}$) for N_{eu50} while in S_{OWNS3} and S_{OWNS4} a slight worsening of N_{eu} is observed.

The simulation results in terms of the index L_{ep} show, both at 8.00 am and 10.00 am, the same behavior observed for the other two indices N_{eu} and N_{eu50}.

Finally, Figure 1 presents a comparison of the index N_{eu50} for S_{WNS} and S_{OWNS} with isolation at 10.00 am, in which the yellow triangle indicates the insertion point in each district (more information about nodes, cyanide concentration and other simulation details are not provided in order to protect the Parete water supply system). As showed in the figure, the cyanide contamination is significantly reduced in all i-DMAs, except in i-DMA3.

Table 3. Comparison between simulation results obtained with $S_{WNS1...4}$ and $S_{OWNS1...4}$ at 10.00 am

Scenario 10.00 am	N_{eu} [%]	N_{eu50} [%]	L_{ep} [%]
S_{WNS1}	67.26	71.46	65.94
S_{OWNS1}	93.07	93.85	96.51
S_{WNS2}	62.24	72.29	56.58
S_{OWNS2}	71.75	73.60	67.75
S_{WNS3}	8.56	40.82	61.98
S_{OWNS3}	3.56	41.28	56.31
S_{WNS4}	6.19	47.61	4.61
S_{OWNS4}	1.97	59.69	2.56

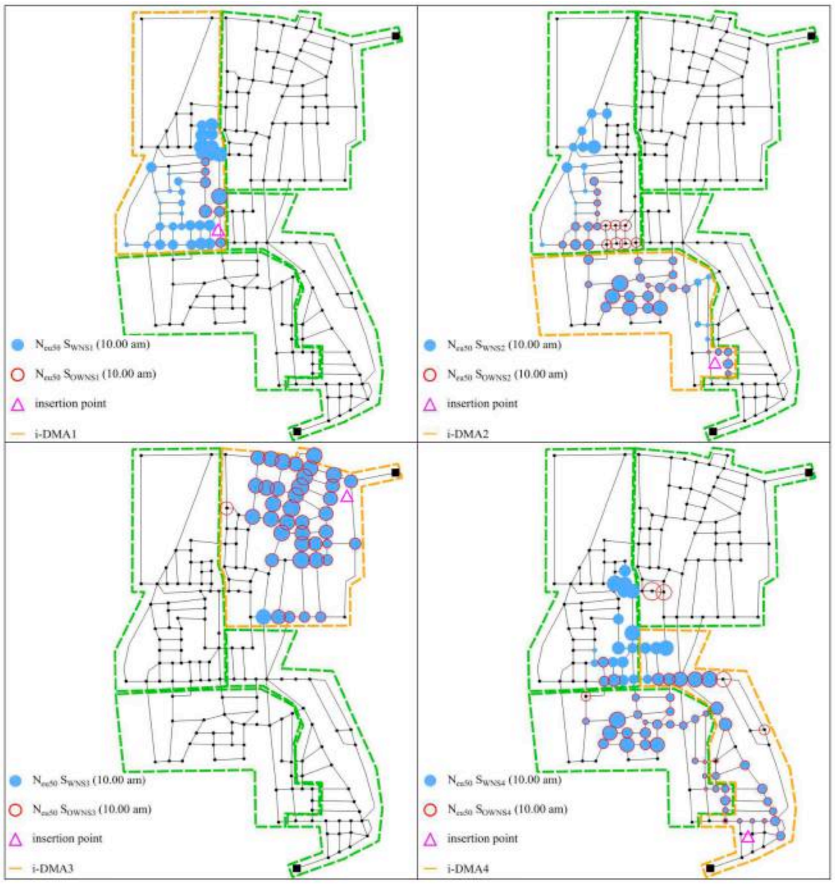

Figure 1. Effect of contamination in different scenarios S_{WNS} compared with S_{OWNS}

CONCLUSIONS

The study confirms that it is possible to improve significantly network protection from intentional contamination using a complex weighted multi-objective function (MOF) that simultaneously minimizes the alteration of hydraulic performance (due to water network partitioning and sectorization) and the number of exposed users.

It is necessary, however, to improve the weighted MOF in order to find solutions that minimize the exposed users in all districts.

Then further studies are possible to optimize also the first phase of the graph partitioning in order to improve the water protection.

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