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Exploring the use of operational interventions in water distribution systems to reduce the formation of TTHMs

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Abstract

Trihalomethanes (TTHMs) are water disinfection by-products whose consumption via drinking water may eventually be harmful for human health, as they could have carcinogenic effects, also for the exposure to them via non-ingestion routes [1]. In the present work the possibility to reduce the vulnerability of the population exposed to TTHMs by the optimal operational interventions in water distribution systems is explored. The proposed approach is formulated as a multi-objective optimization problem with two objective functions, the number of the operations and the maximum TTHMs concentration that occurs at each node in the network during time, both to minimize. The feasible operational actions concern opening/closing valves and hydrants and turning pumping stations for a fixed time. The AMGA 2 optimizer [2] is used herein for solving the problem, coupled with a module coded in C++, where the implementation of the EPANET Programmers Toolkit functions allows to run the hydraulic and water quality simulations and to calculate the objective functions.

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Keywords: Drinking water quality; operational interventions; multi-objective optimization; trihalomethanes;

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1. Introduction

Water companies are required to ensure proper quantity and quality of drinking water to the population. Regarding the water quality, a residual concentration of chlorine in drinking water ensures the protection of the users to microbial regrowth or contamination occurring in the network downstream the treatment plant [3]. Unfortunately, despite the described benefit, the use of this substance may also lead to the formation of disinfection by-products (DBPs), such as trihalomethanes (TTHMs), deriving from the reaction of sodium hypochlorite (Cl_2) with the normal organic matter in source water, which may have carcinogenic effects on human health [4,5].

For this reason, in many countries water system operators are required to meet certain TTHMs levels at different points of their distribution networks, including the customers' taps. As TTHMs formation in supply networks is related to the time required for the water to travel from the sources to the users, a possible way to solve the problem is to reduce the water age at demand nodes by optimizing the setting of the operational changes to do in a water distribution system (WDS).

The approach proposed to deal with the issue introduced herein and described in details in the following paragraphs, is similar to the one proposed by [6], where the problem to solve is to minimize the contact time of the population with a non-reactive pollutant, supposed deliberately injected in a specific node of the network for a fixed time, by finding the optimal valves, pumps and hydrant schedules.

In the literature, most of the methods propose to optimize the operation of the network focus their attention on the economic aspect (costs of the energy for the pump stations, costs of the disinfection, etc.), considered as one of the objective functions to minimize, while the water quality is taken into account as a constraint and defined mostly in terms of minimum residual concentration of disinfectant to ensure in the system or, in some cases, as a fixed upper threshold for the water age. In [7] a literature review on how the water quality has been taken into account in the optimization of the operational interventions in the networks is presented.

In the present work we pose a multi-objective optimization problem and solve it to find optimal operational interventions in WDSs. The formulation aims at reducing the vulnerability of the population exposed to TTHMs. The objective functions in the proposed approach are to minimize the number of operations in the network and to minimize the maximum TTHMs concentration that occurs at each node in the network during the considered simulation time. Constraints on the maximum/minimum pressure and on the minimum residual chlorine concentrations in the system are imposed. The decision variables taken into account are the operational statuses of valves, hydrants and pumps, which can be open or closed during a fixed period of time.

The optimization approach presented below has been performed by coupling the optimizer Archive-based Micro Genetic Algorithm (AMGA 2) [2] and an implementation in C++ language of the EPANET Programmers Toolkit functions for the hydraulic/water quality simulation and to estimate the two objective functions.

The described methodology has been applied to two different case studies.

Nomenclature

t	time (sec)
$q(t)$	actual demand node (l/s)
Cl_2	sodium hypochlorite
TTHMs	total trihalomethanes
$[Cl_2]_0$	initial Cl_2 concentration (mg/l)
$[Cl_2]_{i,t}$	Cl_2 time variable concentration (mg/l)
$[TTHMs]_0$	initial TTHMs concentration (μg/l)
$[TTHMs]_{i,t}$	TTHMs time variable concentration (μg/l)
$[TTHMs]_{i,t}^{max}$	maximum TTHMs concentration occurring in the network (μg/l)
D	TTHMs yield coefficient (μg/mg)
k_b	bulk chlorine decay coefficient (1/h)
ObF1	number of operations (objective function one)
ObF2	$[TTHMs]_{i,t}^{max}$ (objective function two)
P_{min}	constraint - minimum pressure allowed in the network (m)

P_{max}	constraint - maximum pressure allowed in the network (m)
$[Cl_2]_{i,t}^{min}$	constraint - minimum Cl_2 concentration occurring in the network (mg/l)

2. Methodology

The methodology have three components, namely a step-based procedure, the formulation of the optimization problem and the model of water quality and quantity.

2.1. Procedure

The adopted procedure can be summarized with the following steps:

1. The code reads the .txt files given in input with the name of the decision variables, their initial status and the new status, which is given by the optimizer.
2. The functions of the EPANET toolkit solve the hydraulic and water quality simulations, while the calculation of the objective functions is done using in the same code the two kinetic equations described in the paragraph 2.3 and their value is written in the ObF.txt file.
3. The optimizer reads the values of the objective functions, finds the optimal operation of the decision variables considered in the case study and writes their new value in the status.txt file.
4. The new decision variables schedule, which represents the output of the optimizer, becomes the new data set for the hydraulic and water quality simulation used in the executable file compiled in C++. Therefore, the objective functions are calculated again.

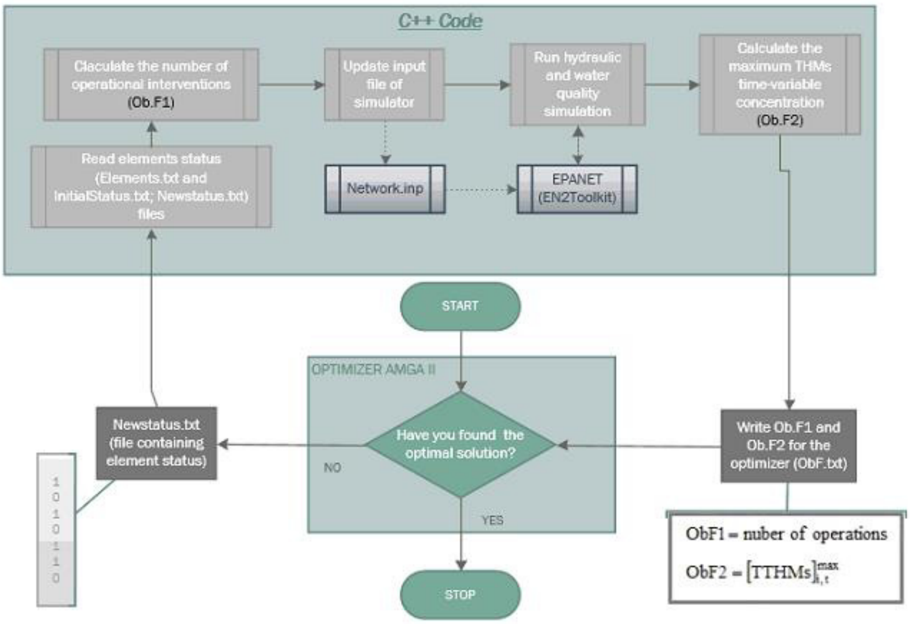


Fig. 1. Framework of the methodology.

2.2. Multi-objective optimization problem formulation

Objective functions

The optimization problem is formulated through two objective functions, namely the minimization of the number of operational interventions (1) and the minimization of TTHMs concentration that occurs in the system during the simulation time (2).

$$\text{ObF1} = \text{nuber of operations} \tag{1}$$

$$\text{ObF2} = [\text{TTHMs}]_{i,t}^{max} \tag{2}$$

Decision variables

Water quality in water distribution systems is influenced by the time required for the resource to reach the consumer's tap (water age). In particular, the longer water stays in the pipes, the worse its quality gets, in terms of increasing of TTHMs concentration. In fact, the formation, according to the equation (5), is strictly linked to the chlorine consumed and to the residence time of the water in the system.

The water age, and so the TTHMs, can be limited through specific operational interventions, as they can regulate the velocities in the system. In the study presented herein, the decision variables taken into account are valves, hydrants and pumps. Furthermore, they assume integer and binary values: pump on/off, and hydrant and valve open/close. It means, for instance, that for a hydrant if the value of the status is 0 it is closed, otherwise (equal to 1) it is open.

It has to be specified that the usage of hydrants and pumps should occur only if strictly necessary since, respectively, the loss of precious resource and the cost of energy.

Constraints

The operational interventions in the water distribution systems have to satisfy the required service deliverables both for water quality and for water quantity. For this reason, on the one hand, the required levels of disinfectant residuals (3) at the consumption points have to be maintained; on the other hand, the value of the pressure has to be included in a fixed range (4).

$$[\text{Cl}]_{i,t}^{min} \tag{3}$$

$$P_{min} < P_{i,t} < P_{max} \tag{4}$$

Different values of the described constrains have been assumed in the two case studies analyzed and presented below.

In addition, due to the fact that the optimization method is random-based, it could happen that during the hydraulic simulation one or more demand nodes become disconnected (due to the closure of all the delivery pipes for that point). Negative pressures may also occur for the same reason. These errors are not allowed and the corresponding solutions are not feasible and, therefore, rejected by assuming high values for the objective functions.

2.3. Water quality model

TTHMs concentration has been calculated in this study using the equation (5) suggested by [8], as a function of chlorine consumption. In fact, in the literature has been widely demonstrated the close relationship connecting TTHMs formation to chlorine decay as in [9, 10].

$$[TTHMs]_{i,t} = [TTHMs]_0 + D * ([Cl_2]_0 - [Cl_2]_{i,t}) \quad (5)$$

In the equation (5) $[TTHMs]_{i,t}$ and $[Cl_2]_{i,t}$ are, respectively, TTHMs (µg/l) and Cl_2 (mg/l) time variable concentrations in each i demand node while $[TTHMs]_0$ and $[Cl_2]_0$ are the concentrations at the beginning of the water quality simulation; D is the yield coefficient (µg/mg), representing the amount of TTHMs formed per mg of chlorine consumed.

Chlorine decay has been evaluated using a first kinetic order model (6) [11], characterized by good performance in representing the analysed phenomena, and taking into account just the effect of the bulk reaction.

$$[Cl_2]_{i,t} = [Cl_2]_0 * e^{-kb*t} \quad (6)$$

Where k_b (1/h) is the bulk chlorine decay coefficient and t (sec) is the time.

The coefficients used to predict TTHMs formation and chlorine decay (D, k_b) in the equations (5) and (6) assume values that depend on many aspects, the main one is the system hydrodynamics. Their evaluation can be done considering literature suggestions or through the calibration process using measured data.

3. Case studies

The methodology is applied to two different case studies.

The case study 1 (Fig. 2), is a very simple system, characterized by 41 pipes (all with the same length and diameter), 25 junctions (with the same base demand and a constant demand pattern) and one reservoir. The elements that can be operated to reduce the TTHMs concentration are two hydrants and five valves.

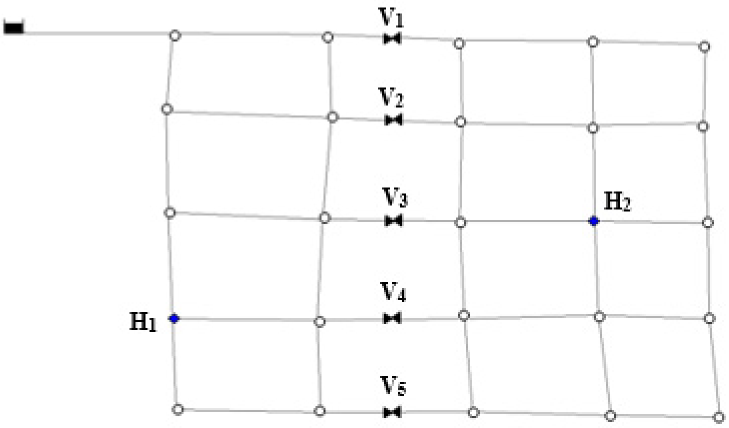


Fig. 2. Scheme of Case study 1.

In the case study 2 the water is conveyed to an area fed by more than one source, which are anyhow treated in the same treatment plant and therefore have the same initial water quality. As shown in Fig. 3, this system is more complex, with 373 pipes, 259 junctions and 4 reservoirs. In this scheme 92 decision variables are considered to solve the optimization problem (30 hydrants, 60 valves and 2 pump stations).

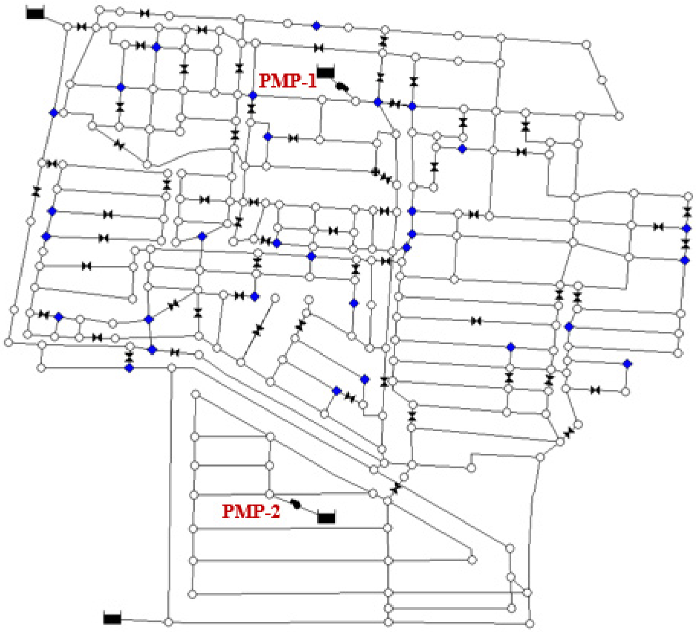


Fig. 3. Scheme of Case study 2.

The first value of the two objective functions is evaluated with the status of the variables which characterized the network before any intervention (initial status). In particular, in both case studies the initial operation status is set to zero (close) for the hydrants and the pump stations and to one (open) for the valves.

To perform the hydraulic and water quality simulations to evaluate the objective functions, the EPANET 2 Toolkit functionalities have been used, in the C++ programming language. The total simulation time for both the case studies is three days, but the interventions are supposed to take place just at the beginning of the second day, in order to leave the system to reach the steady condition. As regards the time of the operational changes, pumps and hydrants are open for few hours while the valves in the pipes, once closed, remain as such until the end of the analysis. This choice is related to the issue that opening hydrants implies the loss of resource already treated and the pump stations are energy consuming, implying high costs for the water utilities.

Using EPANET, the hydrants have been simulated using the emitter object, in order to have an outflow rate in the considered node depending on the value of the pressure in each time step.

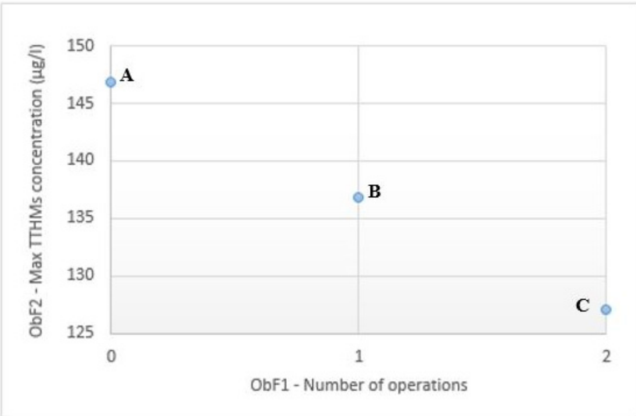
The water delivered in the two systems is supposed to be disinfected through sodium hypochlorite, injected with a constant dosage in the reservoirs. In principle, it is assumed that the initial TTHMs concentration is 10 μg/l for both networks, while chlorine initial concentration is 3.5 mg/l in case study 1 and 0.4 mg/l in case study 2.
The coefficients used in the equations (5) and (6) to predict TTHMs and chlorine concentrations have been properly chosen from the literature [12] and supposed to be the same for the whole network. As regards the values of the constraints, it has been assumed 10 m and 90 m as, respectively, the minimum and the maximum pressure in the case study 1 and 5 m and 100 m for the case study 2, while the lower limit for chlorine concentration is 0.2 mg/l.

4. Results

The outcome of the methodology proposed to solve the multi-objective optimization problem described in the previous paragraphs is the set of the efficient possible solutions that can be operated in the network to reduce the TTHMs concentration and it is represented by a Pareto front.

The results related to the case study 1 are shown in Fig.4. In particular, in addition to the A solution, which represents the case without any operational interventions, two are the feasible sets of the status of the decision variables taken into account to solve the issue. As we can see, in both the solutions the hydrants don't intervene, it means that in this very simple system, flushing water for a specific time is not necessary to reduce the TTHMs concentration, actually they can also have an opposite effect respect to the desired one. This is the ideal solution in the management of a network, because it implies that there is no precious resource loss.

Solutions B and C propose to close, respectively, one or two valves and the one named V1 (Fig. 2) is always operated; in this case study, the TTHMs concentration can be reduced from around 147 µg/l in the zero operations set (solution A), till approximately 127 µg/l of the solution C.



	V1	V2	V3	V4	V5	H1	H2
SOLUTION A	1	1	1	1	1	0	0
SOLUTION B	0	1	1	1	1	0	0
SOLUTION C	0	1	0	1	1	0	0

Fig. 4. Multi-objective optimization solutions: Case study 1.

As regards the case study 2, looking at the Pareto front in Fig.5, the feasible sets for the formulated problem are 12 and the maximum number of elements operated is 22 among the 92 decision variables that can be set. In all of the solutions the pump station PMP-1 (Fig. 3) is always working, while the PMP-2, located in the southern part of the network, is never used; some of the hydrants and valves are operated in each setting proposed. Furthermore, it has been noticed that some of the considered elements never represents possible operational interventions and that from 10 to 22 changes the TTHMs concentration is almost around the same value.

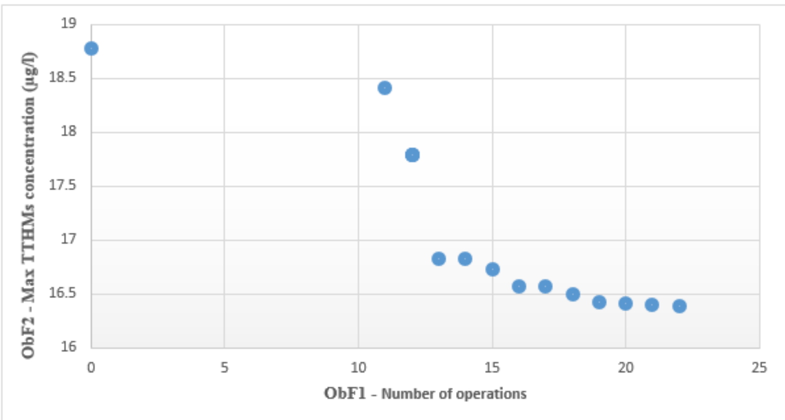


Fig. 5. Multi-objective optimization solutions: Case study 2.

In this specific case study, the proposed methodology allows to reduce the TTHMs concentration only of about 3 μg/l, from 19 μg/l in the original status of the network to around 16 μg/l with 22 operations, which involves 9 hydrants, one pump station and 12 valves. In particular, also by increasing the flushing time of the hydrants from 4 to 8 hours or by opening them in different moments of the simulation, instead of only at the beginning, the obtained results are very similar. This behavior can be easily explained because of the small water ages in the network (in almost of the demand nodes the maximum value reached during the simulation is around 5 hours) and then difficult to reduce significantly by only operating some valves in the network; better results can be obtained by flushing water from the hydrants for more than 8 hours each day, but it implies the loss of a huge amount of water, that is not tolerable.

5. Conclusions

The results of the described analysis for the presented case studies and current assumptions show a reduction of TTHMs' formation in the water distribution systems. However, to ensure a relevant reduction, especially in the case study 2, is required to flush away important amounts of treated water, for this reason it cannot be taken into account as an ordinary operational intervention. These results could be related to the models of the network analyzed in this paper; in order to verify the methodology and to generalize the obtained conclusions it will be necessary to test it on one or more real networks.

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