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A novel approach for water quality management in water distribution systems by multi-objective booster chlorination

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Abstract

Compared to conventional chlorination methods which apply chlorine at water treatment plant, booster chlorination has almost solved the problems of high dosages of chlorine residuals near water sources and lack of chlorine residuals in the remote points of a water distribution system (WDS). However, control of trihalomethane (THM) formation as a potentially carcinogenic disinfection by-product (DBP) within a WDS has still remained as a water quality problem. This paper presents a two-phase approach of multi-objective booster disinfection in which both chlorine residuals and THM formation are concurrently optimized in a WDS. In the first phase, a booster disinfection system is formulated as a multi-objective optimization problem in which the location of booster stations is determined. The objectives are defined as to maximize the volumetric discharge with appropriate levels of disinfectant residuals throughout all demand nodes and to minimize the total mass of disinfectant applied with a specified number of booster stations. The most frequently selected locations for installing booster disinfection stations are selected for the second phase, in which another two-objective optimization problem is defined. The objectives in the second problem are to minimize the volumetric discharge avoiding THM maximum levels and to maximize the volumetric discharge with standard levels of disinfectant residuals. For each point on the resulted trade-off curve between the water quality objectives optimal scheduling of chlorination injected at each booster station is obtained. Both optimization problems used NSGA-II algorithm as a multi-objective genetic algorithm, coupled with EPANET as a hydraulic simulation model. The optimization problems are tested for different numbers of booster chlorination stations in a real case WDS. As a result, this type of multi-objective optimization model can explicitly give the decision makers the optimal location and scheduling of booster disinfection systems with respect to the trade-off between maximum safe drinking water with allowable chlorine residual levels and minimum adverse DBP levels.

Keywords: Optimal location, Booster chlorination, Multi-objective optimization, THM formation, Water distribution system

1. Introduction

To supply safe drinking water to customers, disinfection of water as a chemical treatment process for water quality should be performed as an essential and common step at a water treatment plant, called here conventional method of disinfection. The most predominantly used water treatment disinfectant is chlorine [1]. Chlorine is usually injected after all treatments at a water treatment plant to disinfect potable water and maintain a residual within a water distribution system (WDS) preventing regrowth of pathogenic bacteria [2]. As chlorine reacts with organic materials in the water, it decays over time. Therefore, to meet water quality standards at customers' consumption points, it is necessary to maintain free chlorine residuals throughout the WDS between minimum and maximum levels for various reasons [3]. Chlorine residuals with minimum levels (generally 0.2 mg/L) must be maintained to control bacterial regrowth [2, 3]. A maximum level (4.0 mg/L) is also needed to avoid potential health effects from long-term exposure and control taste and odor problems [4].

Three potential problems of conventional method of disinfection with chlorine in a WDS are (1) high dosages of chlorine residuals near water sources; (2) lack of chlorine residuals in the remote points in relation to water sources and (3) formation of some potentially carcinogenic disinfection by-

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products (DBPs) at a level higher than maximum contaminant level (MCL) regulated by environmental agencies. The first two problems have almost been addressed directly by various researchers through introducing optimal location and scheduling of booster disinfection within the system [5, 6].

Injection of disinfectant at optimally-located booster stations, in addition to the source, may reduce the total disinfectant dose while keeping residuals within specified limits. This reduction can be attributed to more uniform distribution of disinfectant residuals in space and time, and less contact time with the water. The objectives of such a booster facility location problem are (1) to minimize the total disinfectant dose; (2) to minimize the total cost of booster stations including the reduction of total number of booster stations and operational cost; (3) to maximize the volume of water supplied to consumers with chlorine residuals within specified limits; and (4) to maximize the volume of water supplied to consumers with DBP levels less than MCL.

The optimal location and scheduling of booster disinfection systems have been addressed by previous researchers considering explicitly the first three objectives [2, 3, 5, 6, 7]. However, the formation of some potentially carcinogenic DBPs such as trihalomethane (THM) and Haloacetic acids (HAA5) needs especial attention to meet standard levels. Some health and environmental organizations have included the control of DBP formation in the primary drinking water regulation for all water utilities because the concentration higher than standard levels would increase the risk of cancer for the customers of drinking water (e.g. THM less than 0.080 mg/L and HAA5 less than 0.060 mg/L) [4]. Previous researchers have believed that minimization of the total disinfectant dose will normally lead to reduced DBP formation. Few studies have been carried out on the effect of rechlorination schemes on DBP levels in the system [8]. However, we will show in this paper that the direct trace of THM formation in the optimization problem of booster disinfection system proves that DBPs need to be directly addressed in the analysis so that DBPs safely controlled throughout the system.

In light of the importance of THM formation in a booster disinfection system, this study seeks to model a novel approach for multi-objective booster disinfection in which THM formation and chlorine residuals are concurrently optimized and controlled in a WDS. In the following, a background of the advanced researches is briefly described. The methodologies and the optimization problems used in this paper are then presented. Finally, the application of the model to a real case study is presented to demonstrate the effectiveness of the proposed model.

2. Background

2.1. Optimal location and scheduling of booster disinfection

A number of studies for optimal location and scheduling of booster disinfection system have been successfully carried out over the past two decades. Boccelli et al. (1998) were the first to solve a linear programming problem for booster injection scheduling [7]. Their problem involves the minimization of total disinfectant consumption from a specified number of booster stations at specified locations, subject to maintaining residual concentrations at monitoring nodes.

Tryby et al. (2002) extended the study of Boccelli et al. (1998), by treating booster locations as variables and solving a mixed-integer linear programming (MILP) problem with a branch and bound technique [5]. They showed that the optimal total dosage of disinfectant decreases with (1) increasing the number of optimally located booster stations; (2) operating booster disinfection in multiple intervals compared to single interval and (3) using flow proportional rate booster type rather than constant mass rate. However, the drawbacks associated with the solution algorithm of these works were handled by evolutionary algorithms such as genetic algorithm (GA), ant colony (AC) and particle swarm optimization (PSO) [9, 10, 11, 12]. Prasad et al. (2004) used a multi-objective genetic algorithm (MOGA) to minimize the total disinfectant dose and maximize the volumetric demand within specified chlorine limits [6]. They showed a trade-off relationship between the disinfectant dose and the volumetric demand satisfied for a given number of booster stations.

Ozdemir and Ucaner (2005) also applied GA to optimize the locations, injection rates and scheduling of chlorine booster stations [13]. The results indicated that booster disinfection can significantly increase the residual concentrations above a desired minimum limit, while helping to reduce variability in nodal concentrations.

In a recently-developed research, Kang and Lansey (2010) used GA to solve the problem of real-time optimal valve operation combined with booster disinfection in which valves were used to direct disinfectant laden water to necessary locations [3]. One of their results was that lower chlorine doses were required while improving water quality and little significant pressure reduction.

2.2 Chlorine decay and THM formation in WDS

Chlorine decays over time within the WDS as it reacts with organic materials in the water. Various reaction kinetic models have been developed to describe chlorine decay. Generally, they can be divided into two categories of first-order and non-first-order reaction kinetic models. The first-order decay model has received more attention from various researchers because of (1) its simplicity; (2) its reasonable accuracy to represent chlorine decay in water; and (3) its adaption for using principle of linear superposition [1, 14, 15, 16, 17].

The first-order chlorine decay model includes expressions to describe reactions occurring in the bulk fluid and at the pipe wall. The differential form of the decay model for the bulk fluid is

$$dC / dt = -k_b C \tag{1}$$

where C=chlorine concentration in the bulk fluid (mg/L); t=time (days or hours); and k_b=bulk decay coefficient (days^{-1} or hours^{-1}) [1, 14, 15].

The form of the first-order chlorine decay model for reactions at the pipe wall is

$$dC / dt = -k_w / r_h C_w \tag{2}$$

where k_w=wall decay coefficient (m/day) which is a function

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of the pipe material and age; r_h=hydraulic radius (m); and C_w= chlorine concentration at the wall (mg/L), which is a function of the bulk chlorine concentration [14]. k_w is usually calculated by the difference between an overall decay coefficient (k_T) obtained from pipe-loop experiments [15] or field data [1, 14] and the bulk decay coefficient (k_b)

$$k_w = k_T + k_b \tag{3}$$

In the optimization problems of booster disinfection system, many researchers have widely exploited the principle of linear superposition and response coefficients assuming first-order decay model in order to overcome the computational effort of dynamic water quality simulations within the optimization process [3, 5, 6, 7].

When assuming non-first-order reaction kinetics, the principle of linear superposition cannot be applied for solving optimization problems and water quality simulation modelling has to be included within optimization model. For instance, Munavalli and Kumar (2003) optimized scheduling of chlorine injection using GA with non-first-order reactions in the water quality simulation model [2].

Previous research has shown that THM formation can be modeled solely as a function of chlorine decay [18]. Boccelli et al. (2003) observed a strong linear relationship between THM formation and chlorine consumption from experimental data under various chlorination scenarios [19]. Singer et al. (2002) also observed a strong linear relationship between THM formation and chlorine consumption when applied to data from five water sources chlorinated at both pH 6 and 8 [20]. The following linear relationship can be presented:

$$\text{THM} = Y(Cl_2 \text{ Consumption}) + M \tag{4}$$

where THM=total THM formation (μg/L) and Y=yield parameter μg of THMs formed/mg of Cl_2 consumed). The THM yield parameter (Y) is dependent on many factors including the chemical composition and structure of the organic material in the water, pH, and temperature [19, 21]. The term M in Eq. (4) is the intercept from linear regression analysis of experimental data [19].

Carrico and Singer (2009) used a linear relationship between THM formation and chlorine consumption to evaluate the effect of booster chlorination on chlorine residuals and THM formation in a drinking WDS [8]. The results indicated that booster chlorination stations can provide more uniform chlorine residuals throughout the distribution system when compared to conventional chlorination. Also, they showed that the average formation of THMs may be lowered in many parts of the distribution system by using booster chlorination.

3. Methodology

In the present model, a multi-objective optimization problem is defined to determine optimal location and scheduling of booster disinfection. The objective functions are evaluated utilizing the principle of linear superposition for the dynamic water quality simulation. It is assumed that the network is fully calibrated and follows first-order kinetics for disinfectant decay, and that the hydraulic solution is periodic. Results are shown as trade-off curves between the defined objectives. Here, four objectives of booster disinfection systems are subsequently included in the optimization problem within two phases which will be described in the following sections.

3.1 First phase of multi-objective booster disinfection systems

In the first phase, a two-objective optimization problem is defined as the objectives are the minimization of the total disinfectant dose and maximization of the volumetric demand (or percentage of safe drinking water supplied) within specified residual limits. The decision variables are the locations of these boosters and the injection rate. The objective of minimizing the total cost of booster stations is replaced with a surrogate objective of minimizing the total number of booster stations. This objective function is also considered in this phase by frequently solving the optimization problem each time with different specified numbers of booster stations. Finally, trade-off curves between the total disinfectant dose and the volumetric percentage of the water with residuals within a specified range for different numbers of booster stations are obtained. Given a number of booster stations nb, the mathematical formulation for the two-objective optimization problem is

$$\text{Minimize } f_1 = \sum_{i=1}^{n_b}\sum_{k=1}^{n_k} M_i^k \tag{5}$$

$$\text{Maximaze } f_2 = \frac{\sum_{m=\mu}^{\mu+n_h-1}\sum_{j=1}^{n_m} V_j^m}{V} \times 100 \tag{6}$$

where

$$V_j^m = \begin{cases} Q_j^m \times \Delta t_h & \text{when} \quad c_j^{\min} \le c_j^m \le c_j^{\max} \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where f_1=total disinfectant dose; f_2=percentage of the total volume of water supplied during a hydraulic cycle with residual within specified limits; M_i^k=disinfectant mass (mg) added at booster station i in injection period k; V=total volume of demand over a hydraulic cycle; Q_j^m=demand at node j in monitoring period m; Δt_h=hydraulic (monitoring) time step; c_j^m=disinfectant concentration (mg/L) at monitoring node j and during monitoring interval m; c_j^{min} and c_j^{max}=lower and upper bounds on disinfectant concentrations (mg/L) at monitoring nodes; μ=start of monitoring time; n_k=number of time steps in dosage cycle; n_h=number of time steps in hydraulic cycle (number of monitoring time steps); and n_m=number of monitoring nodes in which residual chlorine concentrations are controlled. The aforementioned optimization problem is subject to the following constraints:

$$f_2 \ge C_1 \tag{8}$$

$$M_i^k \ge 0; \qquad i = 1,...,n_b; \qquad k = 1,...,n_k \tag{9}$$

$$c_j^m = \sum_{i=1}^{n_b}\sum_{k=1}^{n_k} \alpha_{ij}^{km} x_i^k \tag{10}$$

$$c_j^m \le c_j^{\max} \qquad j = 1,...,n_m; \qquad m = \mu,...,\mu + n_h - 1 \tag{11}$$

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where C_1=specified value representing Pareto optimal front for a range of f_2 greater than C_1; x_i^k=multiplier of dosage rate at Booster i and during Injection Period k; α_{ij}^{km}=composite response of concentration at Node j and Monitoring Time m due to dosage rate at Booster i and during Injection Period k. Eq. (11) ensures that the concentration at the monitoring nodes is always less than the upper concentration limit.

3.2. Second phase of multi-objective booster disinfection systems

The most frequently selected locations for installing booster stations are chosen for the second phase in which another optimization problem is defined for booster disinfection systems. The decision variables are the amount of disinfection dose for each booster station installed in the chosen locations. The objectives of this optimization problem are the maximization of the volumetric demand within specified residual limits and the maximization of the volume of water supplied with produced THM concentration less than the MCL.

Mathematical formulation of the objective functions in this optimization model is almost the same as the one in the first phase. The only difference is the first objective function which is

$$\text{Maximaze } f_1 = \frac{\sum_{m=\mu}^{\mu+n_h-1}\sum_{j=1}^{n_m} W_j^m}{V} \times 100 \tag{12}$$

where

$$W_j^m = \begin{cases} Q_j^m \times \Delta t_h & \text{when} \quad THM_j^m \le THM_j^{\max} \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

where f_1=percentage of the total volume of water supplied during a hydraulic cycle with produced THM concentration lower than the MCL; THM_j^m=produced THM concentration at Monitoring Node j and during Monitoring Time m; THM_j^{max}=maximum contaminant level (MCL) of the THM concentration formed at Monitoring Node j. Another constraint related to the first objective function is also added to the set of previous constraints in this model:

$$f_1 \ge C_2 \tag{14}$$

where C_2=specified value representing Pareto optimal front for a range of f_1 greater than C_2.

3.3. Multi-objective Genetic Algorithm

Here, a multi-objective evolutionary algorithm known as the Non-dominated Sorting Genetic Algorithm II (NSGA-II) is used [22]. NSGA-II alleviates all of the following difficulties of previous multi-objective genetic algorithms (MOGAs): (1) considerable computational effort, (2) non-elitism approach, (3) the need for the specification of a sharing parameter. The selection operator in NSGA-II combines the parent and offspring populations in a single population and then selects the best solutions with respect to fitness and spread criteria. More details of this approach can be found in [22].

Each chromosome consists of two types of genes including integer values indicating the location of booster stations and real values indicating the chlorine dose used for each booster station. The number of genes equals twice the maximum number of booster stations, each of which represents the position of one booster station or chlorine dose associated with one booster station in WDS.

4. Case study

The case study used here is Mahalat WDS located in the central part of Iran. The WDS covers approximately 46 km^2, with a population of around 160,000. Model demands are predominantly domestic with some commercial users. To reduce the high pressure head induced by steep slope of the city, six pressure reduced vales (PRVs) are used to decrease pressure heads to a fixed pre-specified values. The main characteristics of the pipes are shown in Table 1. The majority of the main pipes material is ductile iron and the majority of small-size pipes are made of PVC; and asbestos cement pipes cover the larger part of middle-size pipes material in the system. An EPANET hydraulic model was constructed including 1814 pipes with the total length of approximately 101 Kilometers, 1771 junctions, 2 tanks, and six PRVs based on the available data.

The WDS is supplied by gravity from three wells and two service tanks (reservoirs) around the city. The average water demand is 158.9 L/S. The water is pumped into the system with a constant rate. The reservoirs store and balance the fluctuations of water daily consumption. Due to the huge number of pipes and junctions in the case study, the WDS model was skeletonized within two steps by WATERGEMS software [23]. In the first step, removing dead-end branches were removed ten times until there was no meaningful trimming performed; i.e., dead-end branches have been removed up to ten sequential times if they have satisfied the criteria for branch trimming in each time. At the second step, series pipes were removed five times until no significant removal occurred. Finally, the skeletonized WDS model was made of 237 pipes and 195 junctions, which is shown in Fig. 1.

5. Results and discussion

The multi-objective optimization problem of booster location and injection scheduling is applied to Mahalat WDS model. Application of the model is carried out to assess (1) the trade-off between the disinfectant dose and the percentage of safe drinking water (SDW) within specified residual limits; (2) the trade-off between the percentage of SDW within specified residual limits and the number of booster stations for a specified amount of total disinfectant dose; and (3) the trace of

Table 1. Summary of pipes materials and diameter

No.	Original Material	Number of Pipes	Range of Diameter (mm)
1	Asbestos Cement	406	80-250
2	Ductile Iron	470	100-500
3	Galvanized Iron	113	25-125
4	PVC	657	25-110
5	Steel	166	20-65

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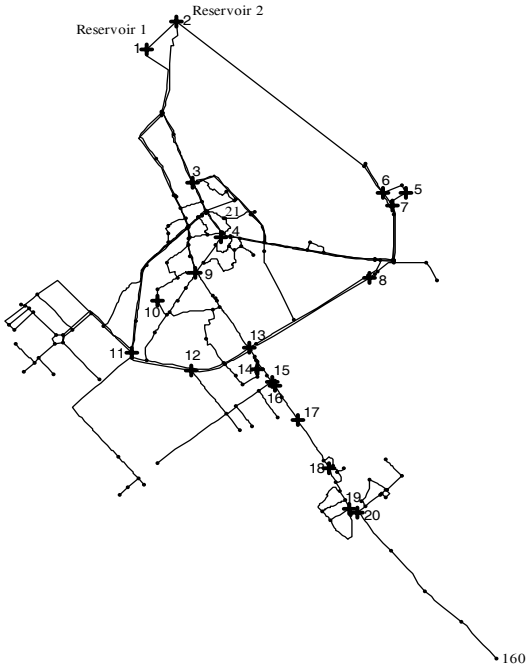


Fig. 1. Mahalat WDS model with + indicating the potential location for installing booster station

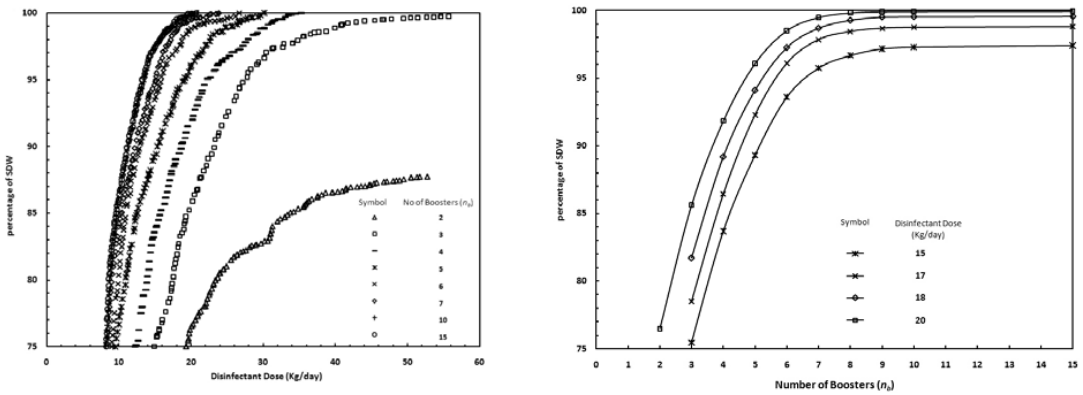
THM concentration within WDS nodes with respect to optimal booster locations and scheduling.

Two existing stations for chlorine injection are located at the water treatment plants (reservoirs). If all of the nodes of the network are to be considered as potential locations, the network setup would require a very high computational time and a large memory to store cumulative response coefficients. However, not all locations would be suitable due to prohibitive costs, network hydraulics, and existing infrastructure. Therefore, 20 potential locations including two existing locations and 18 potential boosters were assumed to be available for installing booster station. These locations are shown in Fig. 1. Some of these potential locations are located near the reservoirs, and the others are spread at critical points throughout the network. The global bulk (k_b) and wall (k_w) coefficients for disinfectant dynamics are assumed to be 0.5 day^{-1} and 0.25 m.day^{-1} , respectively. The limits on the residual disinfectant at the nodes are assumed to be c^{min}=0.2 and c^{max}=4.0 mg/L, respectively [2, 4, 6, 13]. The value of C_1 in Eq.(8) is taken to be 75%. The hydraulics and booster injections are assumed to be periodic with a period of 24 h. The water quality simulation duration is set to be 144 h and the final 24-h results are used in the calculation of composite response coefficients. Optimal trade-off analyses were carried out using flow proportional type boosters due to their performance rather than constant mass type boosters [6]. A comparison is also made among the solutions with varying numbers of booster locations.

5.1. Phase#1

In the first phase, the multi-objective optimization model is applied to find the trade-off between the disinfectant mass and the percentage of SDW with the number of booster stations as a third parameter. For flow proportional boosters, constant concentrations added at the booster nodes are decision variables. The maximum value of these variables is equal to 4.0 mg/L as the upper limit on residual concentrations. NSGA-II was solved for different numbers of booster stations. The Pareto-optimal fronts obtained for different values of n_b are shown in Fig. 2(a). It was observed from this Fig. that for n_b< 4, 99.9% SDW could not be achieved. These curves become almost flat after 99% SDW for n_b≥ 4. The optimal trade-off curves indicate that the SDW increases significantly with a small increase in the total dosage rate up to 95%. Then, the marginal improvement in SDW with the increase in the dosage rate diminishes. Furthermore, the improvement of SDW versus dosage rate is neglected for n_b> 7. This result is in accordance with the findings obtained by Prasad et al. (2004) [6].

When limiting the budget of total disinfectant dose, Fig. 2(b) can be applied which shows the trade-off between the variation of SDW and the number of boosters for different amount of total disinfectant dose. As it can be observed from this Fig., a significant increase in SDW can be achieved for n_b≤ 7. It could be concluded from Fig. 2 that the optimal number of booster stations can be chosen between four and seven, and the most efficiency can be achieved from seven optimal booster stations. Although further considerations such as operational and budgetary limitations may influence the final number chosen, seven booster stations seem to be the most efficient



(a) (b)

Fig. 2. (a) Pareto fronts of total dosage versus percentage of SDW for different values of nb; (2) Trade-off between percentage of SDW and number of boosters for different amounts of total dosage

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number of booster stations from Figs. 2(a) and 2(b).

A further analysis is made on the solutions obtained in Fig. 2 in order to choose the appropriate locations of booster stations. Relative frequencies of 20 potential nodes for installing booster station were analyzed in Table 2 for each Pareto front with specified number of boosters. The location of booster numbers of 1 and 2 are water treatment plants (reservoirs) which are the existing nodes for all solutions with the relative frequency of 1. As discussed in the previous section, the number of seven solutions is favorite. Therefore, relative frequency of seven boosters is considered in more details. The most frequently selected nodes for seven boosters are Nodes 1, 2, 8, 9, 11, 16 and 20. As it can be observed in Table 2, these locations have dominantly been selected in the Pareto front compared to other potential locations in the WDS.

Another two-objective optimization problem is again solved with the same objectives defined at the first section of case#1. The only difference between these two multi-objective problems is the structure of each chromosome in which decision variables are defined as genes. In the latter optimization problem, the locations of boosters are known and are not considered as decision variables or genes as opposed to the former in which the locations of boosters are unknown.

The Pareto-optimal front between disinfectant dose and percentage of SDW is shown in Fig. 3. As it can be observed, the Pareto-front rises steeply up to 95% SDW. The curvature reduces and becomes almost flat after 99% SDW. This indicates that there is a limit after which an increase in the disinfectant dose does not contribute to a substantial increase in the volume of SDW. Prasad et al. (2004) concluded that 99.5% SDW can be taken as the optimal limiting value since any increase in the disinfectant dose after this value may contribute to the increase in DBP formation. To verify this claim, THM formation as a main potentially carcinogenic DBP of chlorination is investigated for the solutions of this Pareto-front.

As discussed previously, THM formation in the process of chlorine disinfection is a function of only chlorine consumption in the system. For a WDS with a mix of chlorination in water treatment plants and booster stations, the overall chlorine consumption at each node downstream of a booster station was calculated as the sum of the chlorine consumption added at the treatment plant and the chlorine consumption added at the upstream booster station as shown in Eq. (15) [13].

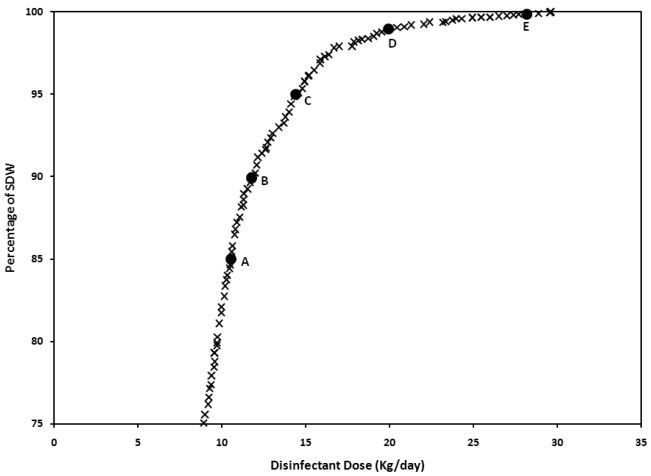

Fig. 3. Pareto optimal front of total dosage and percentage of SDW for n_b=7

$$C_{Dn} = [(1 - \sum T_{Bi}) \times (C_o - C_t)] + [\sum (T_{Bi} \times C_o + C_i - C_t)] \quad (15)$$

where C_{Dn}=chlorine consumption at each node downstream of a booster station; C_t=chlorine residual at Time t for that Node; C_o=chlorine added at water treatment plant; C_i=chlorine added at the upstream Booster station *i*. T_{Bi}=fraction of the total flow at each point in the system associated with a given booster station *i*. T_{Bi} is determined from running a water trace in EPANET. However, Eq. (15) can only be applied for the nodes downstream a booster station. To extend this Eq. for all nodes in a WDS, the following Eq. can be developed:

$$C_{Dn} = [\sum (T_{Br} * [(1 - \sum T_{Bi}) \times (C_o - C_t)] + (\mathrm{sgn}(T_{Bi})) \times [\sum (T_{Bi} \times C_o + C_i - C_t)]] \quad (16)$$

where C_i=chlorine added at any booster station *i*; T_{Br}=fraction of the total flow passing from the that node which supplied by Reservoir *r*; sgn()=sign function indicating 0 and 1. Note that sgn() is equal to 1 when the that node is affected by booster station *i*, otherwise it is equal to zero.

From Pareto front in Fig. 3, five typical solutions (A, B, C, D and E), with SDW values of 85, 90, 95, 99.0, and 99.9%, respectively, are given in Table 3. These solutions are selected such that Solution A and B are on the upper rising part of the

Table 2. Relative frequency of optimal boosters for each Pareto front of specified number of boosters

Number of booster stations (n_b) \ Booster no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3	1	1	0	0.07	0	0	0	0	0	0	0	0	0	0	0	0.11	0.31	0.51	0	0
4	1	1	0	0.81	0	0	0	0	0.19	0	0	0	0	0	0	0.32	0.28	0.28	0.08	0.04
5	1	1	0.04	0.66	0	0	0	0	0.34	0.05	0	0	0.43	0	0.22	0.03	0.23	0.43	0	0.57
6	1	1	0.04	0.03	0.12	0.02	0	0.17	0.97	0.03	0.83	0	0.27	0	0.05	0.04	0.55	0.38	0.04	0.46
7	1	1	0.39	0.16	0	0.02	0	0.45	0.85	0.15	0.83	0.13	0.15	0	0.04	0.53	0.3	0.13	0	0.87
10	1	1	0.5	0.49	0.67	0.13	0.06	0.52	0.95	0.57	1.03	0.04	0.03	0.24	0.69	0.02	0.36	0.59	0.1	1.01
15	1	1	0.74	1.15	1.42	0.21	0.37	0.77	1.05	1.08	1.13	0.48	0.29	0.44	0.7	0.27	0.58	0.11	1.25	0.96

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Table 3. Comparison among 5 solutions on the Pareto front with n_b=7 and conventional design

Booster location	Concentration (mg/L)					
	Conventional design	Solution A	Solution B	Solution C	Solution D	Solution E
1	4.00	0.76	0.92	1.32	1.82	1.82
2	1.69	0.43	0.45	0.45	0.49	0.55
8	-	0.44	0.46	0.69	0.78	1.45
9	-	0.72	0.88	0.95	1.03	2.55
11	-	0.44	0.50	0.54	0.54	0.59
16	-	0.51	0.60	0.58	0.58	0.64
20	-	0.40	0.44	0.54	0.69	0.77
Total disinfectant dose (kg/day)	52.76	11.52	12.75	16.38	21.70	29.14
SDW (%)	87.74%	85.00%	90.00%	95.00%	99.00%	99.90%
Min. chlorine concentration (mg/L)	0.02	0.00	0.00	0.07	0.09	0.18
Max. chlorine concentration (mg/L)	3.74	0.92	0.99	1.15	2.28	3.19
Mean chlorine concentration (mg/L)	1.01	0.30	0.34	0.38	0.55	0.72
STD of chlorine concentration (mg/L)	0.71	0.15	0.17	0.18	0.34	0.53
Maximum THM concentration (µg/L)	158.54	95.51	106.01	124.69	197.35	212.46
Mean THM concentration (µg/L)	117.42	29.55	32.58	39.51	62.24	80.74
STD of THM concentration (µg/L)	31.09	23.15	25.48	29.65	52.35	55.55

Pareto curve, Solutions C and D are at the beginning of the flat part of the curve, and Solution E is at the end of the flat part of the curve. As it can be observed from the Table, the chlorine concentration injected at the water treatment plants in all optimal solutions decreases to less than 2 mg/L compared to the conventional chlorination in which chlorine injected at Water Treatment Plant 1 is 4 mg/L. Conventional method has to inject chlorine with this high concentration so that chlorine residual remains for the remote points of the network. Such an operation can cause the following problems: (1) complaining of bad taste of water by the customers near the water treatment plants due to high chlorine concentration such as 3.74 mg/L; (2) insufficient chlorine residuals for the main parts of remote points of the network (87.74% SDW); and (3) high amount of total disinfectant dose consumed (52.76 kg/day) compared to the optimal solutions; (4) high amount of THM concentration formed in the network with a mean of 117.42 µg/L. A similar solution to the conventional method in Pareto front is Solution A which has considerably reduced the amount of total disinfectant dose from 52.76 kg/day to 11.52 kg/day while keeping the percentage of SDW at 85% compared to 87.74% SDW in the conventional method. Furthermore, mean THM concentration at Solution A has significantly decreased from 117.42 µg/L to 29.55 µg/L. Although the increase in total disinfectant dose from Solution A to Solution E would cause the percentage of SDW to provide most of the network, it will definitely increase the risk of cancer as increasing maximum THM concentration from 95.51 µg/L for Solution A to 212.46 µg/L for Solution E. Note that THM concentration more than 80 µg/L would increase the risk of cancer [4].

To further analyze chlorine residuals and THM formation as a DBP throughout Mahalat WDS, two Nodes (21 and 160) are chosen in the WDS so that the variation of the above parameters are compared in more details between the conventional chlorination (i.e. chlorination in the water treatment plants) and optimal booster chlorination with seven optimal chlorination stations (i.e. two existing stations at water treatment plants and five boosters). Node 21 is chosen due to feeding from the two reservoirs indicating the fluctuations of water quality clearly (Fig. 1). Node 160 represents as a remote node in the WDS, describing the variation of water quality in locations with long water age (Fig. 1). Chlorine residual and THM formation for these two nodes are compared is shown in Fig. 3 for five typical solutions (B, C, D, E from Pareto front) and the conventional method.

Node 21 is fed from both reservoirs such that Reservoir 1 feeds during all hours a day and Reservoir 2 feeds only during hours 10-14. As it can be observed from Fig. 4(a) and 4(b), the chlorine residuals and THM formation dropped sharply during hours 8-14 for all solutions. The main reason for this rapid decline is due to the significant difference (2-3 times) between the chlorine concentrations injected at the reservoirs (water treatment plants). As Node 21 is dominantly affected by Booster 9 during all hours except for hours 10-14, the chlorine residual of this node in Solution E (SDW=99.9%) during these hours is more than the conventional method because of high concentration of chlorination injected at Booster 9. In addition, THM produced at this node during these hours is more than other optimal solutions (B-D) due to high chlorine consumption injected at Booster 9 rather than other solutions (Fig. 4(a) and 4(b)). As a result from the Fig. 4(a) and 4(b), variation of chlorine residual at Node 21 is located in standard range (between 0.2 and 4 mg/L regulated by USEPA (2009) [4]) for all solutions while produced THM for the conventional method and Solution E (SDW=99.9%) avoided MCL (80 µg/L regulated by USEPA (2009) [4]) during most of the day.

Node 160 representing a remote point is far from the reservoirs and is located in the southern part of the network. This node is affected by both reservoirs and five optimal boosters in the network. As water age is very long for this node, for the conventional method, chlorine decays throughout the network to arrive at this node and consequently the chlorine residual is even less than minimum requirement of 0.2 mg/L (Fig. 4(c)). Furthermore, as the chlorine consumption is high through this long route (i.e. from a high concentration at water sources to nearly 0 at the farthest point of the network), THM formation for the conventional method is significant with a concentration of about 140 µg/L which is much higher than standard level (Fig. 4(d)). Unlike the conventional method, chlorine injection in the sources decreases in Solutions B-D and is carried out by

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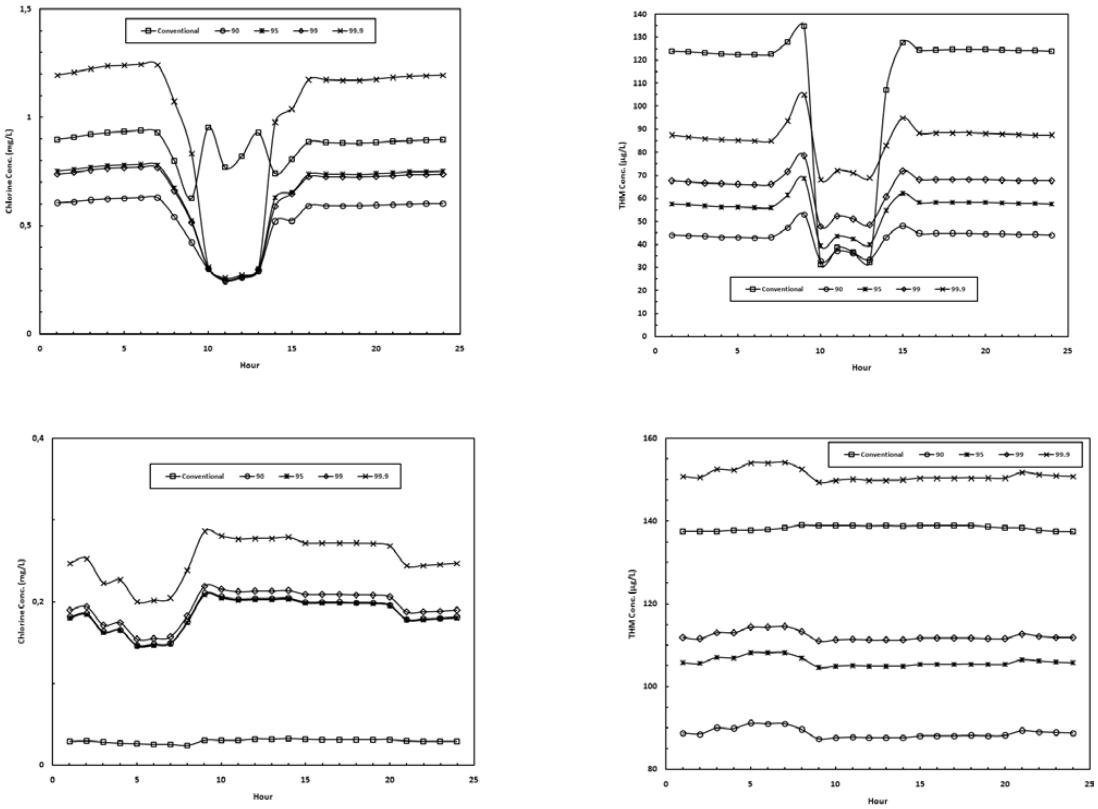

Fig. 4. Variation in chlorine residual at (a) Node 21and (c) Node 160; Variation in predicted THM formation at (b) Node 21 and (d) Node 160

boosters and consequently chlorine residual increase significantly for remote points such as Node 160 rather than conventional method (Fig. 4(c)). However, among four optimal solutions chlorine residual is more than minimum level of 0.2 mg/L during all times only for Solution E (SDW=99.9%) in which disinfectant injected in a considerably high concentration in order to satisfy the minimum requirements of chlorine residual for a few nodes such as Node 160 with a long retention time. Therefore, the increase in the amount of chlorine consumption causes produced THM for SDW=99.9% to become even more than conventional method (Fig. 4(d)). Other optimal solutions suffer from produced THM of higher than MCL (80 µg/L) for this node. Therefore, a compromise between percentage of SDW and produced THM in the network exists which will be addressed explicitly in the next section.

5.2. Phase#2

In order to simultaneously optimize the percentage of SDW and THM formation in the network, the optimization problem previously described in section 3-2 is solved here in which the two objectives are to maximize the volumetric percentage of drinking water within standard range of chlorine residuals and to maximize the volumetric percentage of produced THM concentration less than MCL. Seven optimal locations for installing booster stations which were selected in the last section are considered here. The decision variables (genes in each chromosome) are the amount of chlorine concentration injected at each flow proportional type booster.

The optimization problem was solved with NSGA-II and the Pareto optimal front of percentage of SDW versus volumetric percentage of drinking water with THM less than MCL with seven boosters was obtained which is shown in Fig. 5. It can be observed from this Fig. that the more achievement of one objective would lead to less achievement of another objective and vice versa. Therefore, decision maker may choose a proper amount of injection at booster stations to concurrently meet the most percentage of SDW within specified limits and THM concentration less than MCL.

Nine typical solutions (A, B, C, D, E, F, G, H and I) representing different optimal solutions of Pareto front of Fig. 5 are given in Table 4. As it can be observed, mean chlorine

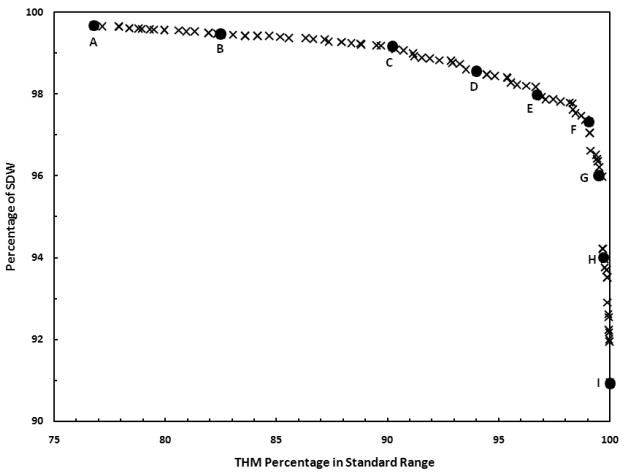

Fig. 5. Pareto optimal front of percentage of SDW versus volumetric percentage of water with THM less than MCL for 7 boosters

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Table 4. Comparison among 9 solutions on the Pareto front of SDW percentage versus volumetric percentage of water with THM within standard levels with n_b=7

	Solution A	Solution B	Solution C	Solution D	Solution E	Solution F	Solution G	Solution H	Solution I
Volumetric percentage of drinking water with THM within standard levels (%)	76.79	82.51	90.20	93.98	96.72	99.05	99.52	99.70	100.00
Percentage of SDW (%)	99.69	99.47	99.16	98.56	97.99	97.33	96.01	94.02	90.92
Min chlorine concentration (mg/L)	0.14	0.12	0.11	0.09	0.08	0.07	0.07	0.06	0.05
Max chlorine concentration (mg/L)	4.00	3.97	3.96	3.97	3.93	4.00	3.99	3.08	1.41
Mean chlorine concentration (mg/L)	0.86	0.84	0.77	0.76	0.73	0.72	0.69	0.50	0.42
Max THM concentration (µg/L)	182.99	171.71	166.25	155.31	155.31	139.70	135.91	88.49	79.99
Mean THM concentration (µg/L)	64.70	60.94	54.63	52.20	48.58	46.51	43.02	42.15	39.71

concentration ranges from 0.42 mg/L to 0.86 mg/L and mean THM concentration ranges from 39.71 µg/L to 64.70 µg/L. A decision maker may choose any optimal solution on the Pareto front with respect to the priorities of the relevant utilities. Among these 9 solutions, Solutions E and F can be selected as optimal in which both objectives are simultaneously maximized at an acceptable level. Of course, Solution I can be chosen when absolutely avoiding increased risk of cancer. Solution I can achieve 100% THM formation less than MCL while the achievement of the SDW for this solution is around 90%. As a result, Solutions F, G, H and I can provide a good percentage of THM concentration within standard range while providing the percentage of SDW is not fully satisfactory. On the other hand, Solutions A, B, C and D supply a good level of SDW percentage (more than 98.5%) while THM percentage less than MCL fall to less than 94%.

6. Conclusion

The problem of optimal location and scheduling of booster chlorination stations was addressed in this paper. A two-phase approach of multi-objective booster disinfection was proposed in which both chlorine residuals and THM formation were concurrently optimized within two multi-objective optimization problems in a WDS. From the result of the first phase, the location of boosters was determined and the most seven frequently selected booster locations were used for the second phase. Both optimization problems were solved by NSGA-II algorithm. The results showed that a compromise exist between percentage of SDW and volumetric percentage of produced THM within standard range. Finally, two points on Pareto front were chosen as superior solutions satisfying both objectives at an acceptable level. Also decision makers may choose any point on Pareto optimal front in which both water quality objectives especially potentially carcinogenic DBPs are well satisfied. This approach is able to optimize all objectives sequentially in the booster disinfection system although considering all three objectives in one multi-objective optimization problem can be tested in the future and its capability compared with the results of the present work.

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