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ORIGINAL ARTICLE

Optimal design and management of chlorination in drinking water networks: a multi-objective approach using Genetic Algorithms and the Pareto optimality concept

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Abstract This paper presents the development of multi-objective Genetic Algorithms to optimize chlorination design and management in drinking water networks (DWN). Three objectives have been considered: the improvement of the chlorination uniformity (healthy objective), the minimization of chlorine booster stations number, and the injected chlorine mass (economic objectives). The problem has been dissociated in medium and short terms ones. The proposed methodology was tested on hypothetical and real DWN. Results proved the ability of the developed optimization tool to identify relationships between the healthy and economic objectives as Pareto fronts. The proposed approach was efficient in computing solutions ensuring better chlorination uniformity while requiring the weakest injected chlorine mass when compared to other approaches. For the real DWN studied, chlorination optimization has been crowned by great improvement of free-chlorine-dosing uniformity and by a meaningful chlorine mass reduction, in comparison with the conventional chlorination.

Keywords Multi-objective · Optimization · Chlorination · Uniformity · Genetic Algorithms · Drinking water networks

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Introduction

Drinking water quality is generally valued by its physical–chemical and bacteriological features. Maier and Powell (1996) underlined that the disinfectant rate in supplied drinking water constitutes a good indicator of its quality and informs on its contamination risks.

Numerous constraints face the acceptable disinfectant rate maintenance on DWN. Haas et al. (1998) and Kooij (2003) specified that for the chlorinated networks, the most frequent in the drinking water industry, the important residence time conduct to free chlorine residual loss and dissolved oxygen, and favourable conditions for bacteria development, therefore, expose consumers in the extremities to contamination risks. Organic matter, deposits, and corrosion products react with free chlorine, the dosage of which decreases with contact time (Levy 2004), and important chlorination imbalances will be observed then on extended networks.

On the conventional chlorination, it is usually applied important chlorine dosage at the chlorination sources, to guarantee the minimal acceptable-free chlorine dosage at the DWN extremities. As a result of this management mode, it is generally recorded tastes and odours (Turgeon et al. 2004). In addition, Monarca et al. (2004), Brown and Emmert (2006), and Hua and Reckhow (2007) underlined that chlorine reacts with natural organic matter to produce halogenated disinfection by-products (DBP), such as trihalomethane and haloacetic acids. Uyak et al. (2007) have demonstrated that DBP formation depends essentially on chlorine doses and on water pH.

Several studies have pointed out that CBPs are suspected to have negative effects on consumer health (Morris et al. 1992; Cantor et al. 1998; WHO 2004; Krasner et al. 2006; Uyak et al. 2007; Richardson et al. 2007; Wang et al.

2007; Bove et al. 2007; Gopal et al. 2007). To protect consumers against such by-products, the World Health Organization (WHO) has set guidelines for maximum admissible limits of chlorination by-product concentrations in drinking water (WHO 2004).

Thus, the DWN manager role is to maintain in network nodes "*n*" and at time steps "*t*" free chlorine dosage "*c**" capable, on one hand, to protect against contaminations and microbiological re-growth. On the other hand, the optimal-free chlorine dosage must permit to avoid taste and odour and to limit CBP formation.

Published works have proved that free chlorine regulation in DWN can be assured by the chlorine injection in particular network nodes. In this case, the manager has to face two problems: (1) where to inject chlorine? (2) What dosage to impose in each of the injection points?

Boccelli et al. (1998), Rouhiainen and Tade (2003), and Propato and Uber (2004) have demonstrated that chlorine scheduling optimization, for known booster stations, permits to maintain acceptable-free chlorine rates on DWN. In addition, Uber et al. (2001), Tryby et al. (2002), Constans (1999), Propato and Uber (2004), and Nouiri and Lebdi (2006) demonstrated, by simulation, that the optimization of booster stations locations permits to improve the spatiotemporal-free chlorine uniformity. Propato and Uber (2004) proved also that the re-allocation of chlorine doses in networks leads to a meaningful reduction of the chlorine masse injected in the network.

Three main approaches have been adopted to formulate the chlorination optimization. As a first approach, Boccelli et al. (1998), Uber et al. (2001), Tryby et al. (2002), and Constans (1999) proposed as the main objective to reduce the total chlorine mass injected into the network. Free chlorine rate regulation is considered as constraint to the optimization problem. The second approach disregards the chlorination economic aspect. Propato and Uber (2004) underlined that the ideal chlorination script is to get in every consumption node, at every time, an optimal-free chlorine dosage "*c**". They proposed to use the spatiotemporal deviation to evaluate the distributed water quality. In the third approach, it takes into consideration several chlorination objectives. Rouhiainen and Tade (2003) expressed the chlorination optimization by four objective functions. The first values the cost of pathogen germ exposition. The second values the cost of the exposition to water presenting tastes and odours. The authors also proposed an objective function to minimize the volume of chlorine used. The last objective function tries to minimize the large variations of the injected chlorine doses. Nouiri and Lebdi (2006) considered two mains chlorination objectives: the improvement of the spatiotemporal-free chlorine rate uniformity and the reduction of the number of booster stations used to inject chlorine into the DWN. Kurek and Ostfeld (2013) proposed two quality objectives (free chlorine rate uniformity and the water age) and design cost objective (tank cost) in their problem formulation. In Ohar and Ostfeld (2014), the objective function includes two parts: the booster chlorination operational injection cost and the booster chlorination capital cost.

Various methods have been used to resolve such optimization problems. Boccelli et al. (1998) and Tryby et al. (2002) used the linear programming. Propato and Uber (2004) used the quadratic programming.

Nicklow et al. (2010) concluded that Genetic Algorithms (GAs) were one of the more successful robust optimization techniques employed for water resources and environmental engineering management (Nouiri 2014). Rouhiainen and Tade (2003) developed a single-objective GA to optimize scheduling of chlorine dosing in DWN. Nouiri and Lebdi (2006) proposed a single-objective GA to optimize the number and to identify chlorine booster stations locations in DWN. Ohar and Ostfeld (2014) used single-objective GA to optimize the design and the operation of booster chlorination stations layout. In the last works, the weighted sum of objectives is used to transform the multi-objective problems to single-objective ones. To keep the multi-objective aspect of the chlorination problem, the method used by Kurek and Ostfeld (2013) was based on a modified k-nearest neighbor approach and the Pareto optimality concept.

Single-objective approach adopted by most of the above-cited works leads to the identification of one solution in a single run. Thus, at every change of the objective priorities, other run must be applied to identify the new global optimal solution. To palliate to this limitation and in the objective to create a decision support tools, multi-objective methods were developed. Using a population of solutions in their research procedure, single GA has been easily transformed in multi-objective GA (MOGA) to identify a set of optimal solutions in a single run. Applications on DWN have concerned the pumping stations management (Savic et al. 1997; Kurek and Ostfeld 2013), water networks rehabilitation (Savic 2002), DWN management (Carrijo et al. 2004), and design and water quality optimization (Kurek and Ostfeld 2013; Ohar and Ostfeld 2014).

In the previous cited works, chlorination objectives are considered at the same time in the problem formulations and resolutions, although they depend on physical process occurring at different time scales. Indeed, identification of chlorination station locations is a medium-term management problem depending on the network structure (number and location of water sources; extension and complexity of the network), whereas the chlorine-dosing determination fits into the short-term network management depending mainly on the hydraulic behaviours and the water and chlorine qualities.

The aim of this work is the development of multi-objective approach to optimize DWN chlorination in medium and short terms. The novelties of this contribution are the multi-objective methodology that allows optimizing chlorination design and management from healthy and economic points of views. The proposed methodology allows also the establishment and the understanding of relationships between economic and healthy chlorination objectives in short and medium time scale. Decision variables are the number and the locations of chlorination stations for medium term and the hourly dosing of chlorine in each of them at short-term scale.

The next section presents the methodology. Model applications for DWN, results, and discussions are presented in "Results and discussions". The last section summarizes the main conclusions.

Methodology

Problem formulation

The problem formulation proposed in this contribution considers simultaneously the healthy and the economic chlorination objectives. The first objective is to ensure the best spatiotemporal-free chlorine dosage in the network consumption nodes. It can be expressed by the minimization of the deviation sum square "$E(N_c, T)$", between free chlorine dosage "$c(n_c, t)$" in consumption nodes "n_c", at time steps "t", and the optimal dosage "c^*":

$$\text{Min} \quad E(N_c, T) = \sum_{n_c=1}^{N_c} \sum_{t=t_{ini}}^{t_{ini}+T} (c(n_c, t) - c^*)^2 \qquad (1)$$
$$n_c = 1 \text{ to } N_c \text{ and } t = t_{ini} \text{ to } (t_{ini} + T)$$

where "N_c" is the number of consumption nodes, "t_{ini}" is the first time step to calculate "$E(N_c, T)$", and "T" is the simulation period. "T" and "T_{ini}" are defined to eliminate the effect of the chlorination initial conditions. The perfect situation is getting a uniformity function "$E(N_c, t)$" equal to zero. It means that all consumption nodes receive the optimal dosage "c^*" over time. Greater values of the "$E(N_c, t)$" mean larger spatiotemporal heterogeneity of free chlorine dosage.

Of an economic point of view, the DWN manager is interested by two objectives to reduce the design and the management costs. The first is the minimization of the total injected chlorine mass "M_t", in all chlorination sources "s_c": management objective. In addition to the chlorine concentration source type, largely used in water tanks (Rossman 2000), three principal booster station types can be used to inject chlorine in DWN: mass booster (MB), flow-paced booster (FPB), and set-point booster (SPB) sources. MB adds a fixed mass flow to that entering the node from other points in the network. FPB adds a fixed concentration to that resulting from the mixing of all inflow to the node from other points in the network. SPB fixes the concentration of any flow leaving the node, as long as the concentration resulting from all inflows to the node is below the set point (Rossman 2000). While considering complete and instantaneous-free chlorine mixtures in "N_{sc}" chlorination sources, this economic objective is formulated in the following equation:

$$\text{Min} \quad M_t = \sum_{s_c=1}^{N_{sc}} \sum_{t=t_{ini}}^{t_{ini}+T} m_i(s_c, t) \qquad (2)$$

where "$m_i(s_c, t)$" is the chlorine mass injected in the source "s_c" at time step "t".

As a second chlorination economic objective, the DWN manager tries to reduce the number of chlorination station "N_{sc}". This design objective is formulated in the following equation:

$$\text{Min} \quad N_{sc}. \qquad (3)$$

As constraints, it is considered that free chlorine dosage, in network consumption nodes "n_c", must be maintained in the admissible interval, at time steps "t":

$$\varepsilon_{min} \leq c(n_c, t) \leq \varepsilon_{max} \qquad (4)$$
$$n_c = 1 \text{ to } N_c \text{ and } t = t_{ini} \text{ to } (t_{ini} + T)$$

where "ε_{min}" and "ε_{max}" are, respectively, the minimal and maximal acceptable-free chlorine dosages, in consumption nodes.

Besides, in chlorination sources "s_c" (treatment stations, tanks, pumping stations, and chlorination booster stations) at time steps "t", free chlorine concentrations "$C_s(s_c, t)$" must obey to the following equation:

$$C_s(s, t) \leq C_{max} \quad s_c = 1 \text{ to } N_{sc} \text{ and } t = t_{ini} \text{ to } (t_{ini} + T) \qquad (5)$$

where "C_{max}" is the maximal free chlorine dosage in chlorination sources.

Managers generally impose, for each DWN, a maximum booster stations number "N_{scmax}" and/or propose possible locations. Thus, the following constraint must be respected in the optimization process:

$$N_{sc} \leq N_{scmax}. \qquad (6)$$

The global chlorine optimization model is then formed by the objective functions in Eqs. (1)–(3) and by the constraints in Eqs. (4)–(6).

Optimization models

It is chosen in this contribution to separate the medium- and short-term chlorination problems. Two iterative steps' optimization methodology is then proposed. In the first step: medium term, it is proposed to optimize booster stations number and locations in DWN. It is suitable that this step be ensured when there are tangible network structure modifications (pipes' length, pipes' connections, or valves' status) or an important consumption deviation is observed, due to variation of consumers' number or class. It is recommended that this step be performed if a fundamental hydraulic behaviour is recorded.

In the second step: short term, it is proposed to optimize chlorine-dosing scheduling for known booster stations. This task should be performed at every water supply variation leading to a change of flow rates, velocities, and, therefore, affecting the water age between water sources and consumption nodes. In DWN, it is generally observed instantaneous demand modulation. Therefore, chlorine dosing must schedule, theoretically, in parallel. To simplify the problem, without lost of accuracy, we consider that a daily chlorine-dosing optimisation, considering an hourly demand pattern, is acceptable. Figure 1 explains the iterative medium- and short-term optimization process.

With this problem separation, two optimisation models can be written. The first, concerning medium-term optimization, is formed by the objectives functions in Eqs. (1) and (3), under constraints in Eqs. (4) and (5). The second optimization model, using results of booster station location optimization, is formed by the objectives functions in Eqs. (1) and (2) under the same constraints.

Model 1: Chlorination design optimisation:

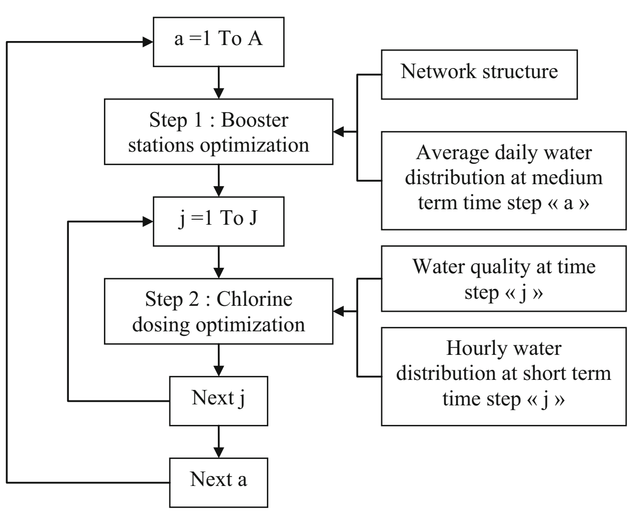

Fig. 1 Organization chart for chlorination design and operation optimization in DWN

$$\text{Min}\quad E(N_c, T) = \sum_{n_c=1}^{N_c} \sum_{t=t_{ini}}^{t_{ini}+T} (c(n_c, t) - c^*)^2$$

$$\text{Min}\quad N_{sc}$$

$$\varepsilon_{min} \leq c(n_c, t) \leq \varepsilon_{max}$$

$$C_s(s, t) \leq C_{max}.$$

Model 2: Chlorination management optimisation:

$$\text{Min}\quad E(N_c, T) = \sum_{n_c=1}^{N_c} \sum_{t=t_{ini}}^{t_{ini}+T} (c(n_c, t) - c^*)^2$$

$$\text{Min}\quad M_t = \sum_{s_c=1}^{N_{sc}} \sum_{t=t_{ini}}^{t_{ini}+T} m_i(s_c, t)$$

$$\varepsilon_{min} \leq c(n_c, t) \leq \varepsilon_{max}$$

$$C_s(s, t) \leq C_{max}$$

where "a" is the medium-term index time step, "A" is the medium-term period, "j" is the short-term index time step, and "J" is the short-term period.

To resolve the formulated problems, MOGAs are used. They present the same basic schema as the single-objective GA: variables coding, selection, crossover, and mutation are generally the same. However, evolution strategies and solution comparisons are different. The synthesis of numerous comparative studies on MOGA (Lis and Eiben 1997; Zitzler and Thiele 1998; Knowles and Corne 1999; Esquivel et al. 1999; Deb et al. 2000 and Leiva et al. 2000) brought us to develop a Multi-Sexual Genetic Algorithm (MSGA) to resolve the present minimization problems. These algorithms are elitists and characterized by a weak number of parameters. To identify the optimal solutions, Goldberg (1991) recommends the use of the Pareto optimality concept, explained as follows: for minimization problems of "i" objectives, solution "x" dominates a solution "y", of the research space "E", if and only if

$$\forall i,\quad f_i(x) \leq f_i(y). \tag{7}$$

In addition, it exists at least an objective "i" as

$$f_i(x) \prec f_i(y). \tag{8}$$

If a solution "x" is not dominated by any other solution, it is called "non-dominated". The set of non-dominated solutions of "E" form the Pareto front. According to the objectives priority, the decision maker can choose solutions directly from the Pareto front.

Two MSGA are developed: $MSGA_m$ and $MSGA_s$ to resolve the medium- and the short-term chlorination problems, respectively. Their main computation steps are described below:

1. **Create** randomly an initial population of "T_{pop}" solutions. For every one, the MSGA assigns a

α(1)	…	α(n)	…	α(N_{sc})	Sex

Fig. 2 Solution structure of the medium-term chlorination problem

randomly sex "Sex". The sex number is equal to the number of objectives. For booster stations design problem, it is used a binary-coded solutions. Figure 2 presents the solutions structure for medium-term problem:
where: $\alpha(n) = 1$ if the node "n" is a chlorine booster station; $\alpha(n) = 0$ if not.
However, for chlorine-dosing problem, it is used real-coded solutions with the structure, as presented in Fig. 3:

2. **Evaluate** solutions, computing objective functions, and constraint verification. This step requires hydraulic and water quality modelling. For the short-term problem, solutions "x" are evaluated by the fitness functions in Eqs. (9) and (10):

$$f_1(x) = M_t \quad (9)$$

$$f_2(x) = E(N_c, T) * (1 + P(\varepsilon_{\min}) + P(\varepsilon_{\max})) \quad (10)$$

where $P(\varepsilon_{\min})$ and $P(\varepsilon_{\max})$ are the maximal violations of the lower and upper free chlorine acceptable bounds, as formulated in Eqs. (11) and (12):

$$P(\varepsilon_{\min}) = \mathrm{Max}(0, \varepsilon_{\min} - c(n_c, t)) \quad n_c = 1 \text{ to } N_c \text{ and } t = t_{\mathrm{ini}} \text{ to } (t_{\mathrm{ini}} + T) \quad (11)$$

$$P(\varepsilon_{\max}) = \mathrm{Max}(0, c(n_c, t) - \varepsilon_{\max}) \quad n_c = 1 \text{ to } N_c \text{ and } t = t_{\mathrm{ini}} \text{ to } (t_{\mathrm{ini}} + T). \quad (12)$$

For the medium-term problem, solutions are evaluated by Eqs. (13) and (14):

$$f_2(x) = E(N_c, T) * (1 + P(\varepsilon_{\min}) + P(\varepsilon_{\max})) \quad (13)$$

$$f_3(x) = N_s * (1 + P(N_{s\max})) \quad (14)$$

where $P(N_{s\max})$ is the violation of the maximal booster station number, as formulated in the following equation:

$$P(N_{s\max}) = \mathrm{Max}(0, N_s - N_{s\max}). \quad (15)$$

3. **Identify** non-dominated solutions (optimal) by the Pareto optimally concept.
4. **Create** a set of non-dominated solutions identified: archive of size "T_{arch}".
5. **Evolution**: New population is created using the solutions of the previous population.

5.1 **Elitism**: "P_e" percent of the "T_{pop}" solutions of the new population are copied from the archive of non-dominated solutions.
5.2 **Selection**: Two solutions are selected from the previous population, according to their fitness functions, to participate to the crossover.
5.3 **Crossover**: The selected solutions are used to produce two new solutions, with a probability "P_c". For real-coded solutions, arithmetic crossover is used; however, for binary-coded solutions, two points crossover is applied.
5.4 **Mutation**: Some "bits" of each created solution can be randomly changed, in the research space, with a probability "P_m".

6. **Evaluate** created solutions, as in step 2.
7. **Identify** non-dominated solutions of the current population, as in step 3.
8. **Insert** non-dominated solutions of the current population in the archive.
9. **Update** the archive by the Pareto optimality concept.
10. **If** "T_{arch}" is not reached, then return to step 5.
11. **If** generation number is less than the maximum one, **then** repeat steps from 5 **to** 11.

The EPANET software, version 2.0 (Rossman 2000), is used for hydraulic and free chlorine dosage modelling in DWN. The informatics programming language "VB6" is used to compute the MSGA. A linkage with the EPANET toolkit is performed to compute the fitness functions, requiring hydraulic and quality modelling of the DWN.

Results and discussion

Cases study presentations

In this section, we aim to optimize chlorination for bibliographic DWN, provided by the EPANET toolkit (Rossman 2000), and a real one in Tunisia. The bibliographic DWN was previously studied by Boccelli et al. (1998), Constans (1999), Propato (2003), and Propato and Uber (2004). This case study is formed by 46 links and 41 nodes. Water source is the pumping station (Fig. 4a). The tank

C_s (1, t_{ini})	…	C_s (1, T)	…	C_s (N_{sc}, t_{ini})	…	C_s(N_{sc}, T)	Sex

Fig. 3 Solution structure of the short-term chlorination problem

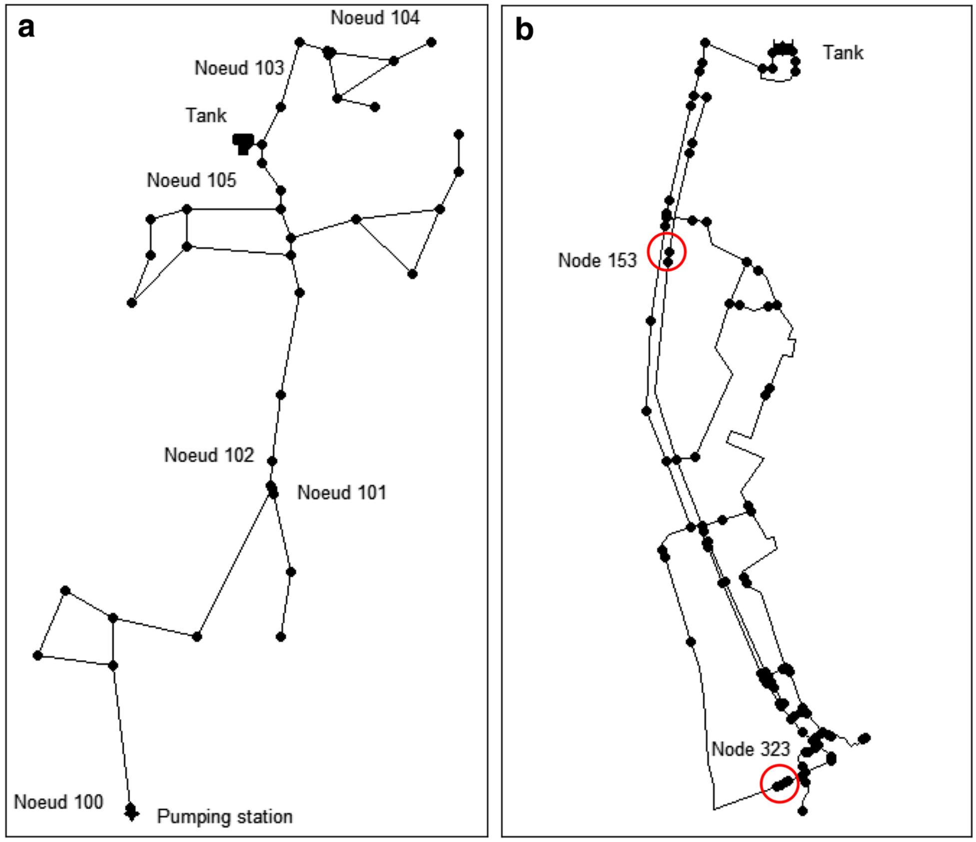

Fig. 4 Hypothetic (**a**) and real (**b**) DWN maps

ensures the regulation between the pumping station flows and the water demand (Fig. 4a).

The water demand and the pumping station working are periodic, with 24 h cycles. Four time periods, each of 6 h characterize the network hydraulic behaviour. In periods 1 and 3, corresponding to 0–6 and 12–18 h, the pump station is on delivering water to the network and filling the tank. In periods 2 and 4, corresponding to 6–12 and 18–24 h, the pump station is off and water drains from the tank (Propato and Uber 2004).

It is considered the same bulk and wall chlorine reaction coefficients used in the previous mentioned studies ($k_b = -0.5$ day^{-1}; $k_w = 0.0$ day^{-1}). To ensure the health chlorination objectives, free chlorine dosages are considered acceptable between $\varepsilon_{min} = 0.2$ and $\varepsilon_{max} = 0.4$ mg/l. The optimal-free chlorine dosage "c*" is taken equal to 0.3 mg/l. Hydraulic and water quality simulations are performed for 288 h to eliminate the initial water quality condition effects (Propato and Uber 2004). Free chlorine dosing in monitoring nodes presenting positive base demand (40 nodes) for the last 24 simulation hours (265–288 h) is used for solution evaluations by the MSGA.

The real DWN supplies the coastal areas of Carthage, El Kram, and La Goulette in Tunis City from a main tank ensuring a total head of 38 m (Fig. 4b). The network is looped and composed by old iron pipes and is characterized

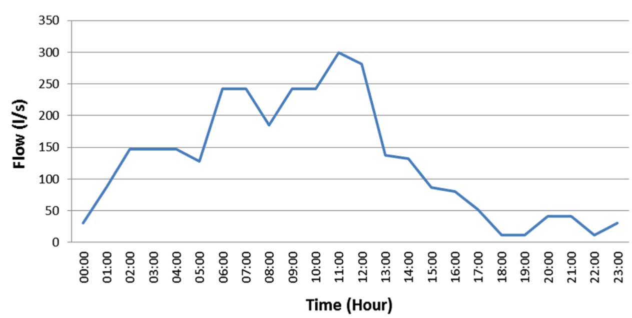

Fig. 5 Pattern of the hourly supply of the real DWN

by a long water residence time. The network is formed by 64 pipes and 96 nodes, and 38 of them present consumptions. The average daily supply is estimated to 6000 m^3. The hourly supply pattern is given in Fig. 5.

Besides, the bulk reaction coefficient of free chlorine "k_b" has been experimentally estimated to -0.2 day^{-1} and the wall coefficient "K_w" is estimated to -1.0 day^{-1}, due to the state of the contact surface between water and pipes (old iron).

To palliate to the height-free chlorine decrease due to long-residence time and reactions with pipes materials, the DWN manager achieved chlorination solely from the tank, with free chlorine dosing equal to 1.0 mg/l at the tank exit. This conventional chlorination management does not ensure acceptable-free chlorine dosing in consumption nodes at the network extremities, what exposes consumers to microbial contamination risks. In addition, height chlorine concentration in the tank increases the potential of DBP formation and exposes consumers to health risks. There is a need to find out a more efficient chlorination management.

Chlorination optimization for the bibliographic DWN

Medium-term chlorination optimization

Seen the free chlorine time declination and to ensure the optimal-free chlorine dosage ($c^* = 0.3$ mg/l) in monitoring nodes, concentration "$C_s(s, t)$" in all designed chlorination stations must be, in one hand, greater than 0.3 mg/l. In the other hand, "$C_s(s, t)$" must be less or equal to the upper limit of the acceptable-free chlorine interval ($\varepsilon_{max} = 0.4$ mg/l). Thus, it is chosen to study the effect of three "$C_s(s, t)$" values: 0.30, 0.35, and 0.40 mg/l on the number and locations of chlorination stations. The optimal chlorination scheduling should be identified in the short-term optimization step for each booster station design. To impose the target-free chlorine concentration "$C_s(s, t)$" in the designed booster station exits, SPB station type is used in this step, with single scheduling period of 24 h cycle. Like in the previous studies, the maximal acceptable number of chlorine booster stations "N_{scmax}" is set to 6.

For the present case study, $MSGA_m$ parameterization leads to use a 20 individual's population and 1500 generations. Thus, 30,000 solutions will be evaluated in each $MSGA_m$ run. Crossover and mutation probabilities are 80 and 10%, respectively. Elitism is ensured by "$P_e = 20\%$" non-dominated solutions.

Under the above conditions and with the chosen parameters values, the $MSGA_m$ has identified 41, 7, and 5 optimal solutions for "$C_s(s, t)$" equal to 0.30, 0.35, and 0.40 mg/l, respectively. Figure 6 presents the Pareto fronts of the optimal solution computed.

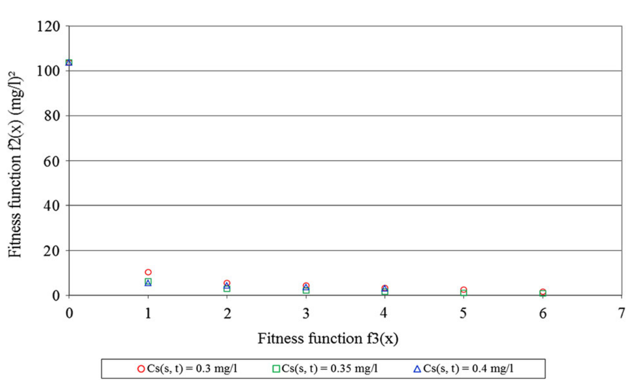

Fig. 6 Pareto front of optimal chlorine booster stations number for concentrations 0.30, 0.35, and 0.40 mg/l for the bibliographic DWN

A non-linear relationship between chlorination uniformity (healthy objective) and the used booster stations number (economic objective) is highlighted. Indeed, the use of two chlorine booster stations will bring always the best chlorination uniformity improvement, relatively to the conventional chlorination (only one chlorination station in the water source). For the three-studied concentrations, this improvement decreases when the booster station number increases.

From Fig. 6, it is also possible to underline that the schedule concentrations of "$C_s(s, t) = 0.35$ mg/l" offer always the best spatiotemporal-free chlorine uniformity: the weakest values of the fitness function "$f_2(x)$" for the same booster station number.

Using the healthy and the economic chlorination objective relationships, identified by the $MSGA_m$, it is possible to underline that chlorination of the studied DWN can be efficiently performed with three booster stations. The use of more chlorine injection stations, requiring additional investments and management costs, cannot improve meaningfully the chlorination uniformity. This precious information cannot be easily obtained with single-objective approaches.

Let us underline that for the three chlorination concentrations in booster station "$C_s(s, t)$" equal to 0.30, 0.35, and 0.40 mg/l, comparable results are reached. Indeed, for the same number of booster stations used, the chlorination uniformity is almost the same (Fig. 6).

For the schedule concentration "$C_s(s, t) = 0.35$ mg/l", Table 1 presents the optimal locations of chlorination stations and the minimum "C_{min}", the maximal "C_{max}", and the average "C_{ave}"-free chlorine dosage computed in consumption nodes. To characterize the chlorination uniformity, it is computed the root of the average of the uniformity objective function, called hereafter "deviation" function from the optimal-free chlorine dosing:

$$\sigma = \sqrt{\frac{1}{T} \times \frac{1}{N_c} \times E(N_c, T)} \quad (16)$$

Table 1 shows that the first SPB chlorination station must be built in the node 100, close to the water source (node 1): conventional chlorination. This design is characterized by a healthy objective function "$f_2(x)$" equal to 3.949 $(mg/l)^2$, a free chlorine deviation "σ" equal to 0.064 mg/l, and a minimal-free chlorine dosage "C_{min}" equal to 0.10 mg/l. Thus, the lower free chlorine acceptable bound violation is evaluated to: $\varepsilon_{min} - C_{min} = 0.10$ mg/l. To avoid this violation, the previous works (Propato and Uber 2004) proposed to use great values of the concentration "$C_s(s, t)$" and to accept the great values of the maximal free chlorine dosage

Table 1 Booster stations number and locations and optimal solutions performances for "$C_s(s, t) = 0.35$ mg/l" for the bibliographic DWN

N_{sc}	C_{min} (mg/l)	C_{max} (mg/l)	C_{ave} (mg/l)	σ (mg/l)	Booster station locations					
1	0.10	0.35	0.25	0.064	100					
2	0.14	0.35	0.29	0.054	100	25				
3	0.14	0.35	0.29	0.047	100	25	28			
4	0.16	0.35	0.30	0.039	100	25	28	33		
5	0.20	0.35	0.31	0.032	100	25	28	33	35	
6	0.23	0.35	0.31	0.029	100	25	28	33	35	8

"C_{max}". Large violations of the upper free chlorine dosage bound ($\varepsilon_{max} = 0.4$ mg/l) should then be accepted, and as consequence large CBP formation.

The addition of a second SPB chlorination station in node 25 improves the spatiotemporal-free chlorine dosage uniformity, by reducing "σ" to 0.054 mg/l and ensuring in the consumption nodes an average free chlorine dosage ($C_{ave} = 0.29$ mg/l) close to the optimal one ($c^* = 0.30$ mg/l). This design allows also to reduce the violation of the lower free chlorine acceptable bound to 0.06 mg/l.

When installing the third and fourth SPB chlorination stations, respectively, in nodes 28 and 33, the essential improvement is the reduction of the free-chlorine-dosing deviation "σ" to 0.039 mg/l. The installation of the fifth and sixth SPB, in nodes 35 and 8, presents important effects on the network extremities, controlling the minimal-free chlorine dosage "C_{min}", and on the spatiotemporal-free-chlorine-dosing uniformity ($\sigma = 0.029$ mg/l). It is important to underline that with the concentration "$C_s(s, t) = 0.35$ mg/l" in chlorination sources, five or more chlorination SPB stations are needed to ensure acceptable-free chlorine dosage in all the consumption nodes.

Short-term chlorination optimization

In the practice, chlorination operation in drinking water networks is made by adding in each of the chlorination sources a chlorine mass to ensure a target dosing "$C_s(s, t)$". Control and regulation tools are used to configure one of the chlorination station types: FPB, SB, or MB. Chlorine MB station type can be considered the most easy to apply in real word by applying a desired chlorine pump flow into the water network. Thus, it is considered in this optimization step that all chlorination stations are MB. Their optimal operation will be identified by the MSGA$_s$. The same value of the target-free chlorine dosage in consumption nodes is considered ($c^* = 0.30$ mg/l).

To compare MSGA$_s$ performances to these previous cited references, it is studied the same two chlorination strategies: conventional chlorination, from node 100, and chlorination from six known booster stations in nodes 100, 101, 102, 103, 104, and 105. For the conventional chlorination, the MSGA$_s$ has identified the 150 optimal solutions, as presented in Fig. 7.

The previous chart shows the non-linear relationship between chlorine mass used and the free chlorine uniformity function "$E(N_c, T)$". When small quantities of chlorine (0–500 g/day) are injected in the network, a linear improvement of the uniformity is guaranteed (red dotted line in Fig. 7). Figure 7 shows that between 500 and 1000 g/day of chlorine used the uniformity improvement still linear with a smaller slope (green dotted line in Fig. 7). If chlorine quantities exceed 1000 g/day, the improvement of chlorination uniformity decreases significantly and the Pareto front becomes almost horizontal starting from a chlorine mass of 1500 g/day (black dotted line in Fig. 7). Therefore, the use of great chlorine mass in the network cannot improve continuously the chlorination uniformity. An asymptotic limit characterizes the network and its hydraulic behaviour.

To compare the MSGA$_s$'s results with those of the previous study, considering the chlorination as a single-objective problem, we choose solution "S1", highlighted in Fig. 7, witch heed the chlorination uniformity objective. Comparison will carry on the chlorine mass "m" and the minimum "c_{min}" and the maximum "c_{max}" free chlorine rates computed in the network nodes. The next table summarizes the principal performances of the optimal solutions

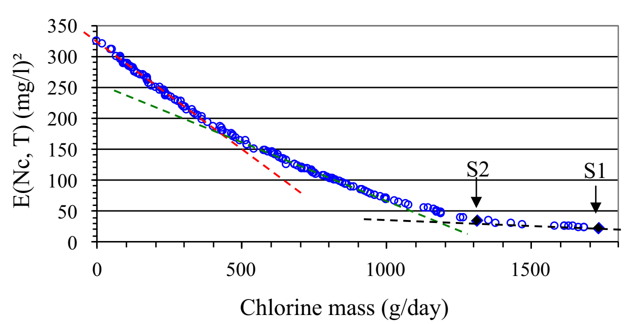

Fig. 7 Pareto front for chlorine scheduling optimization: chlorine station 100 of the bibliographic DWN

Table 2 Performance of optimal solutions "S1" for conventional chlorination of the bibliographic DWN

References	m (g/day)	c_{min} (mg/l)	c_{max} (mg/l)
Boccelli et al. (1998)	3180	0.20	4.10
Propato and Uber (2004)	2925	0.20	5.69
$MSGA_s$	1730	0.20	0.98

identified by Boccelli et al. (1998), Propato and Uber (2004) and by the $MSGA_s$: "S1".

Results in Table 2 show that the $MSGA_s$'s calculated solution with the weakest difference between the minimum (c_{min} = 0.20 mg/l) and the maximal-free-chlorine dosing (c_{max} = 0.98 mg/l). The free-chlorine-dosing uniformity was characterized by "σ" = 0.18 mg/l. Although the $MSGA_s$ solution disregards the chlorination economic objective, it required the weakest injected chlorine mass (1730 g/day). While tolerating a weak loss of uniformity, it is possible to achieve more chlorine mass economy, by choosing another optimal solution in the asymptotic zone of the Pareto front: solution "S2", for example, (Fig. 7).

For the DWN chlorination with six booster stations, the $MSGA_s$ has identified 59 optimal solutions. The one which heeds the chlorination uniformity objective is selected for comparison with the two references results, as presented in Table 3.

The $MSGA_s$ was able to find optimal solution with the lower maximal chlorine rate in the network over time (0.80 mg/l). The uniformity is characterized by "σ" = 0.16 mg/l. Solution computed in Boccelli et al. (1998) generates the higher maximal free chlorine rate (2.17 mg/l). In Propato and Uber (2004), optimal solution ensures the maximal free chlorine dosing of 1.66 mg/l.

In terms of used chlorine mass, Boccelli et al. (1998) optimal solution is the most economic (m = 1176 g/day). Propato and Uber (2004) optimal solution required the greatest mass (m = 1587 g/day) and the $MSGA_s$ solution occupies an intermediate position (m = 1242 g/day). This result is assigned to the different problem formulations adopted by the tree approaches. Indeed, Boccelli et al. (1998) have fixed the chlorine mass reduction the only objective of the optimization. The uniformity aspect is considered as a constraint. The objective considered by Propato and Uber (2004) is the minimisation of the deviation sum square of free chlorine rates in network, omitting the economic objective. The short-term problem formulation proposed in this paper considers in the same time the chlorination uniformity and the chlorine mass reduction objectives. This choice permitted to reduce significantly the chlorine mass used, in comparison with the Propato and Uber (2004) solution, and allowing better chlorination uniformity.

Table 3 Performances of optimal solutions for the bibliographic DWN: six booster stations

References	m (g/day)	c_{min} (mg/l)	c_{max} (mg/l)
Boccelli et al. (1998)	1176	0.20	2.17
Propato and Uber (2004)	1587	0.20	1.66
$MSGA_s$	1242	0.20	0.80

Chlorination optimisation for the real DWN

The MSGA applications for the real DWN have been achieved while considering the acceptable interval: [0.1–0.5] mg/l of free chlorine dosing, as agreed between the DWN manager and the water quality control authority (Ministry of Health). The conventional management manner (chlorination in the tank with a concentration of 1.0 mg/l) is characterized by a uniformity objective function equal to 233.00 $(mg/l)^2$ (σ = 0.25 mg/l) and an injected chlorine mass equal to 11,000 g/day.

Medium-term chlorination optimization

The $MSGA_m$ is used to determine the number and to identify locations of chlorination booster stations for the real DWN. Figure 8 shows the Pareto front of the computed optimal solutions.

Relationship between free-chlorine-dosing uniformity and chlorination stations number, clarified by Fig. 8, permitted to underline that the use of two chlorination stations generates the great reduction of the uniformity objective function "$E(N_c, T)$" (86.0%) when compared to the conventional chlorination. The use of more chlorination stations, requiring supplementary investments and management costs, cannot improve significantly free-chlorine-dosing uniformity. A reduction of about 7.0% can be reached by the use of a third chlorine booster station. The fourth and fifth ones cannot bring tangible improvements in terms of chlorination uniformity.

Thus, it is possible to conclude that for the studied real DWN, optimal medium-term chlorination can be reached by injecting chlorine in two booster stations in the network, in addition to the principal chlorination source in the tank. The free-chlorine-dosing uniformity will be characterized by σ = 0.18 mg/l. The optimal locations are nodes 153 and 323, as highlighted in Fig. 4b.

Short-term chlorination optimization

In this step, chlorine-dosing scheduling in the tank and in the two optimal chlorine booster stations identified in the previous step will be optimized. The $MSGA_s$ application

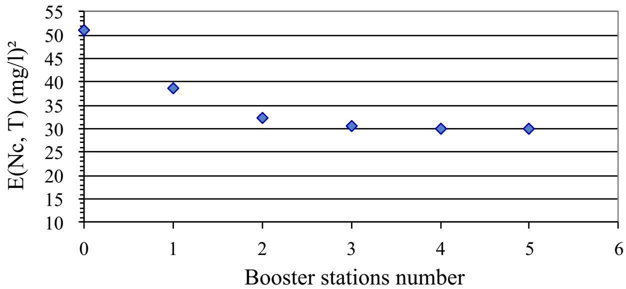

Fig. 8 Pareto front of computed optimal solutions for the real DWN

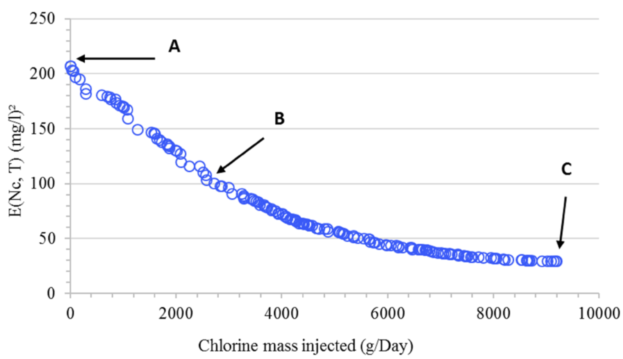

Fig. 9 Pareto front for optimal chlorine scheduling optimization: real DWN with two booster stations

identifies 176 non-dominated solutions, as presented in Fig. 9.

The Pareto front in the graph above allows the decision maker to choose the chlorine-dosing scheduling that responds to its priorities. Indeed, in view of the better economic profitability, the priority can be assigned to the reduction of the injected chlorine mass. This objective can be lead while choosing solution "*A*". This solution is considered optimal by the $MSGA_s$, because it not consume chlorine ($m = 0$ g/day). In this case, the chlorination uniformity will be the worst, characterized by $E(N_c, T) = 207.36$ (mg/l)^2 ($\sigma = 0.47$ mg/l). However, in real DWN, an importance must always be given to the quality aspect of the supplied water. When the two objectives present equivalent importance: compromise, the manager can apply solutions near "*B*". Chlorination uniformity will be acceptable, characterized by $E(N_c, T) = 115.81$ (mg/l)^2 ($\sigma = 0.35$ mg/l). The used chlorine mass will be $m = 2440$ g/day, 78.0% less than the quantity required with the conventional chlorination. When an absolute priority is given to the chlorination uniformity, it is recommended to apply solution "*C*". Chlorination uniformity will be the better, characterized by $E(N_c, T) = 29.41$ (mg/l)^2 ($\sigma = 0.18$ mg/l), and the consumed chlorine mass is the greater (9183 g/day). Solution "*C*" requires a chlorine mass 16.5% less than the quantity required in the conventional chlorination.

Optimization of the chlorination management using the multi-objective tool developed allowed, in one hand, the understanding of the relationships between the economic and the healthy objectives of the chlorination. On the other hand, the approach offers a more management flexibility according priorities and capabilities of the manager. It is also important to underline that the optimal solution disregarding the economic aspect (*C*) offers a more uniform pattern of free chlorine dosing and requires less chlorine mass than the conventional chlorination.

Results of both bibliographic and real DWN demonstrated that the conventional chlorination presents serious limitations. Even for small networks, as these studied here, it was "impossible" with this approach to reach a compromise between the objectives of the manager (economic) and the consumer (health). Structure and hydraulic characteristics of the networks are the main reasons. The situation will be more critical for larger DWN.

It is demonstrated in the previous works (Boccelli et al. 1998; Constans 1999; Propato 2003; Propato and Uber 2004; Kurek and Ostfeld 2013; Ohar and Ostfeld 2014) and confirmed with this contribution that the use of booster station is an efficient way to improve the chlorination uniformity and to reduce the management costs. Investment costs are required to install booster stations and apply such chlorination approach. An economic study about the profitability of the chlorine allocation approach is proposed as a research perspective.

Summary and conclusions

Results of the present research demonstrated that chlorination problem dissociation on medium and short terms, the multi-objective formulation, and the use of MSGA was an efficient methodology to design and manage chlorination with respect to economic and healthy objectives.

The approach allowed the identification of relationships between free-chlorine-dosing uniformity, the number of chlorination stations, and the mass of chlorine to be injected in the DWN, through Pareto graphs easy to use by managers and decision makers.

By considering at the same time healthy and economic chlorination objectives, the proposed methodology was able to identify compromised solutions among approaches dealing with only one of these conflictual objectives and considering the other one as constraint.

Chlorination optimization for the real DWN leads to considerable improvements of the spatial and temporal uniformities of free chlorine dosing, in comparison with the conventional management. Optimal solution that ensures compromise between healthy and economic objectives (solution "*B*" in Fig. 9) guarantees strong chlorination uniformity improvement (reduction of $E(N_c, T)$ from 233.00 to 115.81 $(mg/l)^2$), and requires the injection of 2440 g/day of chlorine. This proposed optimal management solution requires 78.0% less chlorine than the quantity required with the conventional chlorination. The optimal management performances of compromise solution allow the financial coverage of investment cost to build the required booster station along the network.

Chlorination constitutes a hard task and a big cost. The chemical and hydraulic involved processes are complicated and the manager is not able to take the right decision without modelling and optimization capacities. We recommend that the proposed multi-objective optimization tools, involving hydraulic and quality modelling, be a decision support system to improve the design of chlorine injection system considering the physical and hydraulic system characteristics as well as the supplied water quality. For management purposes, the proposed tool can help taking the right decision when one of the governing parameters changes at daily time step.

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