Integrating booster chlorination and operational interventions in water distribution systems

Denis Nono, Innocent Basupi, Phillimon T. Odirile and Bhagabat P. Parida

ABSTRACT

Booster chlorination reduces the risks associated with conventional disinfection such as high chlorine residuals near water treatment plants and low chlorine residuals at remote parts of water distribution systems (WDSs). Network operational interventions have a significant influence on water age and chlorine decay in WDSs. In this study, an integrated booster chlorination method is developed to obtain optimal designs that reduce the risks associated with conventional disinfection in WDSs. The method integrates booster chlorination with network operational interventions to reduce water age and improve chlorine residuals in WDSs. A multi-objective booster optimisation problem is formulated based on risks associated with chlorine disinfection and solved using a non-dominated sorting genetic algorithm (NSGA-II) and the EPANET hydraulic and water quality solver. The proposed methodology was tested in the Phakalane WDS in Botswana. The integrated booster disinfection method significantly improves chlorine residuals in a WDSs with lower mass and cost of chlorine than conventional disinfection. Furthermore, the study indicates that integrated booster chlorination designs are influenced by changes in network conditions such as water demand and chlorine decay coefficients. Therefore, periodic monitoring of these parameters is required to ensure that the acceptable performance of chlorine boosters in WDSs is maintained.

Key words | booster chlorination, disinfection risks, operational interventions, optimisation, water distribution system

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INTRODUCTION

Water disinfection plays an important role in water treatment to kill pathogenic bacteria and prevent water quality deterioration from microbial growth in water distribution systems (WDSs). Chlorine is the most widely used disinfectant in water treatment because of its ability to provide a residual effect, which inhibits microbial growth (Vasconcelos *et al.* 1997). The major challenges associated with chlorine disinfection are rapid decay of the residual and formation of disinfectant by-products (DBPs) (Deborde & von Gunten 2008; Chowdhury *et al.* 2009). The common practice that is used to maintain appropriate levels of chlorine residual in many WDSs has been the injection of large amounts of disinfectant at the treatment plant which is

referred to as conventional disinfection in this paper. However, conventional disinfection is associated with excessive disinfectant residual at places near the water treatment plant which may lead to the formation of DBPs, some of which cause cancer after a long period of exposure (Chowdhury *et al.* 2009). Also, conventional disinfection is associated with low disinfectant residual at remote parts of the WDSs, which exposes WDSs to the risks of multiplication of pathogenic bacteria in drinking water (Pavlov *et al.* 2004). Many countries regulate chlorine residual in WDSs with different standard limits to reduce the related health problems. The minimum standard residual limit (usually 0.2 mg/L) controls bacteriological growth whereas

the maximum standard residual limit (usually about 4 mg/L) controls taste, odour and disinfectant by-product (DBP) formation (Prasad *et al.* 2004; Behzadian *et al.* 2012; WHO 2014). In Botswana, chlorine residual is regulated between 0.3–0.6 mg/L in the network and 0.6–1.0 mg/L at dosing points (Central Statistics Office 2009).

Over the past two decades, booster disinfection has been used to solve problems related to conventional disinfection. The problems of booster disinfection design have been studied using a number of optimisation approaches. The aim of this paper is to develop an approach that integrates chlorine booster disinfection and alternative network operational interventions to obtain optimal disinfection in WDSs. The operational interventions referred to here are fixed alternative conditions to be selected by the optimisation algorithm. The optimisation problem is based on the analysis of risks associated with chlorine disinfection in WDSs. The remaining sections of this paper present a brief background, followed by the methodology and the application of the proposed integrated booster chlorination approach.

BACKGROUND

The background presents a brief overview of literature on booster disinfection optimisation and the effect of network operational interventions on chlorine disinfection in WDSs. A considerable amount of literature has been published over the past two decades on the optimisation of booster disinfection in WDSs. One of the earliest studies by Boccelli *et al.* (1998) optimised the disinfectant mass injection rates (MIR) at known booster locations as a linear programming problem to reduce the water disinfection cost and formation of DBPs in WDSs. The principle of linear superposition was applied to determine the concentration of disinfectant at the monitoring nodes as a summation of the influence from the individual booster injections. Similarly, Tryby *et al.* (2002) extended the work of Boccelli *et al.* (1998) and incorporated booster locations as second decision variables and compared constant and flow proportional booster types. The MIR and booster locations were minimised as a mixed integer linear programming problem using branch and bound techniques. The

monitoring nodes were reduced by pruning demand nodes based on water residence times. In another study by Munavalli & Kumar (2003), chlorine injection rates were minimised at multiple booster sources as a nonlinear least-square optimisation problem using a single objective genetic algorithm. The optimisation problem was formulated as the sum of square differences between simulated and minimum standard limits of chlorine residuals at the monitoring nodes in the network. The first multi-objective booster optimisation approach was proposed by Prasad *et al.* (2004) to minimise the total MIR and maximise the volume of safe drinking water supplied to the network. The optimisation problem was solved by a non-dominated sorting genetic algorithm (NSGA-II). All the demand nodes were considered as the monitoring nodes, unlike in Tryby *et al.* (2002) where the demand nodes were pruned to reduce the monitoring nodes. A linear least-square booster optimisation problem was formulated by Propato & Uber (2004) to minimise the sum of square deviations of disinfectant residuals from the standard limits. The optimisation problem was solved by quadratic programming to determine the optimal injection rates for a known number of booster locations. There are a number of studies that integrated single objective optimisation of booster disinfection with, for example, pumping schedules (Ostfeld & Salomons 2006) and valve schedules (Kang & Lansey 2009) using genetic algorithms. A hybrid linear programming and genetic algorithm booster optimisation technique that reduces the long simulation time required to determine the response coefficients for computation of the residual concentration at the monitoring nodes was proposed by Lansey *et al.* (2007). The optimisation problem was posed to determine booster locations and their injection rates. Also, Behzadian *et al.* (2012) extended the booster optimisation approach proposed by Prasad *et al.* (2004). They instead presented a two-phase multi-objective booster optimisation approach where chlorine residual and DBP formation were concurrently optimised in the WDS. The first phase optimised the total disinfectant dosages and volumetric demand (as a percentage of safe drinking water) whereas the second phase optimised volumetric demand and trihalomethane (THM) formation. The optimisation problems were solved using a non-dominated sorting genetic algorithm (NSGA-II). Some of the recent studies have demonstrated the application of

a water quality index (Islam *et al.* 2013), and mixed integer linear programming (Al-Zahrani 2016; Goyal & Patel 2017) in booster disinfection optimisation.

The majority of the literature reviewed above on booster chlorination addressed the problems of minimising the number of boosters, locations and injection rates (booster designs) in the WDSs. Limited attempts were made to consider network operational interventions such as water transmission, pressure and flow regulation (i.e. valve setting), pump scheduling and storage (i.e. capacity, mixing, location and refilling cycles), yet they significantly affect chlorine residuals and hence booster chlorination in WDSs. For instance, incomplete mixing of water in storage facilities creates dead spaces that increase water age and chlorine decay in the network (Clark *et al.* 1996). Tank design and pumping cycles are linked to an increase in water age and chlorine decay in WDSs (Gauthier *et al.* 2000). An elevated tank located inside the water supply area with short refilling cycles decreases the water age significantly while the tank located outside the water supply area increases the water age (Edwards & Maher 2008). Also, noted from the literature reviewed, booster optimisation problems were mainly formulated in terms of: (1) mass injection rate; (2) disinfectant residual concentration; (3) volume of safe drinking water; (4) disinfectant by-products; and (5) water quality index. Although there are booster optimisation problems formulated in terms of volume of safe drinking water (i.e. water with acceptable chlorine residuals), it is also essential to consider formulation based on risks associated with chlorine disinfection (i.e. water with unacceptable chlorine residuals).

This paper addresses the problems of optimising both booster chlorination and network operational interventions simultaneously. A novel method is developed that integrates chlorine disinfection with network operational interventions in order to obtain optimal booster designs that maintain adequate and uniform residuals in WDSs. The methodology introduces network operational interventions as additional decision variables to the widely used booster number, booster locations and injection rates. The methodology identifies suitable network operational conditions such as water transmission, pressure and flow regulation (i.e. valve setting), pump scheduling and storage (i.e. capacity, location and refilling cycles) and the widely used

variables (booster designs) simultaneously in order to improve chlorine disinfection in the network. Also, this approach is complemented by an optimisation problem based on the risk analysis of chlorine disinfection. A multi-objective booster optimisation problem is formulated to minimise the MIR and risk of chlorine disinfection in WDSs.

METHODOLOGY

Problem description

The proposed methodology integrates network configurations and operational interventions into booster optimisation processes based on the analysis of risks associated with chlorine disinfection in WDSs. The new approach is referred to in this study as integrated booster disinfection. In this approach, the network configurations and operational interventions are considered in the booster disinfection optimisation problem as decision variables in addition to the common injection rates, number and locations of boosters. The network configurations and operational interventions include the use of different combinations of alternative water transmission lines, storage capacity, refilling/pumping cycles and valve settings. Proper combinations of network configuration and operational interventions reduce water age, chlorine decay rate and demand in a WDS (Edwards & Maher 2008). The booster optimisation problem is formulated in terms of chlorine MIR and risks of chlorine disinfection (RCD). The major RCD in the WDS are inadequate residual (usually below 0.2 mg/L), high residual (usually above 4 mg/L), which leads to a multiplication of pathogenic bacteria and formation of DBPs, respectively. Optimal booster disinfection design (i.e. proper choice of the number, locations and injection rate) is required to maintain standard residual limits and obtain uniform distributions throughout the network.

Chlorine booster optimisation problem formulation

The two objective functions for the booster chlorination problem are formulated as follows: The first objective is to minimise the chlorine MIR, as expressed by Equation (1),

and the second objective is to minimise the RCD, as expressed by Equation (2):

$$Minimise\ MIR = \sum_{i=1}^{n_i} \sum_{k=1}^{n_k} u_i^k Q_i^k \tag{1}$$

$$Minimise\ RCD = \sum_{j=1}^{n_j} P_j\ \varepsilon_j \tag{2}$$

where $n_i =$ number of booster stations, $n_k =$ number of chlorine injection period, $u_i^k =$ injection rate (mg/L) leaving the injection/booster location i at injection period k, $Q_i^k =$ total flow rate (L/s) leaving injection location i at injection period k, $n_j =$ number of monitoring nodes (all the nodes are considered as the monitoring nodes), $P_j =$ probability that a monitoring node j has unacceptable chlorine residual (i.e. <0.3 mg/L or >0.6 mg/L), $\varepsilon_j =$ consequences associated with having unacceptable chlorine residual in monitoring node j.

The probability that a monitoring node has unacceptable chlorine residual is computed as shown in Equations (3) and (4):

$$P_j = \frac{\sum_{m=t}^{t+n_h-1} \gamma_j^m}{T} \tag{3}$$

$$\gamma_j^m = \begin{cases} 0 & if\ c_j^{\min} \le c_j^m \le c_j^{\max} \\ \Delta t_h & otherwise \end{cases} \tag{4}$$

where $n_h =$ number of hydraulic time steps (monitoring time steps), $t =$ start time in the steady periodic chlorine concentration at the monitoring node j, $\gamma_j^m =$ hydraulic time step m with unacceptable chlorine residual at node j, $T =$ total time step per hydraulic cycle, $\Delta t_h =$ length of hydraulic time step m, c_j^{min} and c_j^{max} are the lower and upper chlorine residual limits at monitoring node j, respectively, $c_j^m =$ chlorine residual concentration at monitoring node j and hydraulic time step m, given by Equation (5):

$$c_j^m = \sum_{i=1}^{n_i} \sum_{k=1}^{n_k} \alpha_{ij}^{km} u_i^k \tag{5}$$

where $\alpha_{ij}^{km} =$ response coefficient at monitoring node i due to chlorine injection at injection location j for injection

period k and hydraulic time step m. The response coefficients are determined by running the EPANET (Rossman 2000) hydraulic and water quality model for a unit chlorine injection rate at the injection stations. The values of α_{ij}^{km} are given by the chlorine residual concentration at the monitoring nodes due to the unit injection rate at each injection station. The concentration c_j^m at a monitoring node is computed using Equation (5) and summed over the injection stations by applying the principle of linear superposition. In the principle of linear superposition, it is assumed that the chlorine decay rate is linear and the chlorine residual concentrations at the monitoring nodes are a linear superposition of responses (i.e. chlorine residual) due to individual injection rates at injection stations (Boccelli *et al.* 1998; Tryby *et al.* 2002). Therefore, two or more booster responses are added to obtain the resultant residual concentrations at a monitoring node.

The consequences associated with having unacceptable chlorine residual at the monitoring nodes are computed in terms of water demands, as shown in Equation (6):

$$\varepsilon_j = \frac{\sum_{m=t}^{t+n_h-1} d_j^m}{D} \tag{6}$$

where $d_j^m =$ water demand in monitoring node j at hydraulic time step m with unacceptable chlorine residual, $D =$ total water demand in the network. Note that consequences can be expressed here in different quantities, such as the number of people affected by poor water quality.

Solution evaluations

The candidate solutions are evaluated by simulation-optimisation processes using the EPANET hydraulic and water quality solver and the optimisation algorithms. The composite response coefficients are first generated for each network operational scenarios (NOS), as shown in Table 1, using water quality simulation in the EPANET model. The water quality simulation is run with unit injection rates at the treatment plant and at each potential booster station to obtain steady chlorine residual in the monitoring nodes. The steady chlorine residual at the monitoring nodes for the last day (24 hours) are saved as the composite response coefficients. The response coefficients

are then used in all evaluations of the chlorine concentrations and objectives to determine the optimal solutions for each optimisation run. The response coefficients are generated once for each optimisation run to reduce the computation time.

Optimisation method

To date, various methods have been developed to solve multi-objective optimisation problems. In this study, the method used to obtain the solutions for the above booster optimisation problem is the non-dominated sorting genetic algorithm (NSGA-II) that is proposed by Deb *et al.* (2002). NSGA-II is one of the widely used approaches that solve multi-objective optimisation problems because it can maintain diversity (good spread of solutions) and converge close to the optimal solutions (Prasad *et al.* 2004). The search method explores the solution space and obtains Pareto-optimal solutions by applying optimisation processes such as chromosome encoding, population initialisation, objective function evaluation, selection, crossover, and mutation.

The decision variables, which represent the potential solutions, are coded as real and integer values. The decision variables considered are network configurations and operational interventions, booster station locations and injection dosages (rates). The network configuration and operation interventions are presented as an array of integer values that represent NOS (s). If n is the number of booster stations required, the booster station locations in the network are presented as an array of integer values $(I_1, I_2, \ldots I_n)$, each specified by the node index. The injection rates at each booster station are represented as an array of real numbers $(u_1, u_2, \ldots u_n)$. Figure 1 illustrates the decision variables for this optimisation problem.

After encoding the variables, the NSGA-II creates a random initial population depending on a specified
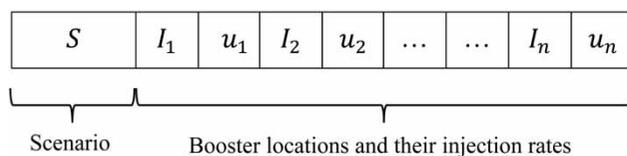
number. Random numbers between specified lower and upper bounds are generated to form the initial population. The objective functions and the constraints are then evaluated to find the fitness values for each potential solution in the randomly generated population. Based on the fitness values, rank and crowding distance are assigned to each potential solution. The selection operator is the first NSGA-II operator that is applied to select good strings of the population for the crossover, based on the rank and crowding distance. The NSGA-II used in this study only supports the binary tournament selection. When good strings are selected from the population, the crossover operator recombines them to produce offspring for a new population based on crossover fraction. The last operator, mutation, maintains genetic diversity from one generation of a population to the next and safeguards against premature loss of important genes (elitism) according to user-defined probability. The above optimisation processes are repeated until the stopping criterion is met. For the NSGA-II used in this study, the optimisation processes stop when the specified maximum number of generations considered adequate to converge to optimal solutions is reached.

CASE STUDY

A case study is presented to demonstrate the application of the integrated booster chlorination to obtain optimal chlorine booster designs and NOS for a WDS. This chlorine booster optimisation approach is tested on a real network of Phakalane WDS in Botswana.

Description of Phakalane WDS

Phakalane WDS (Figure 2) is part of the larger Gaborone city WDS in Botswana. The network is selected for this study because it has more reliable data, is expanding very fast and its remote parts always have low chlorine residuals according to the routine monitoring records from water utilities corporation (WUC).

The main sources of raw water for the Gaborone WDSs are dams and a well field. The Phakalane network is supplied with water from the treatment plant, which has a

Figure 1 │ Presentation of decision variables.
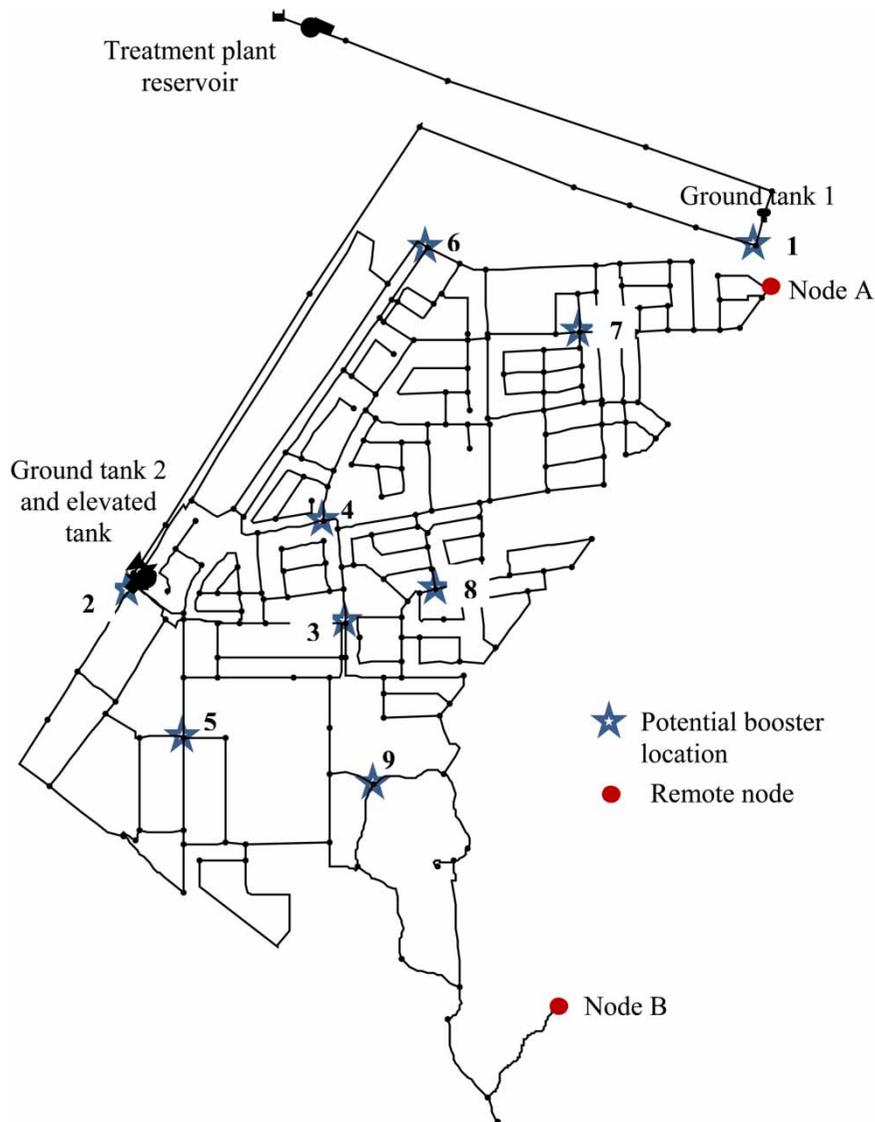
Figure 2 │ The Phakalane WDS showing positions of the treatment plant, ground tank, elevated tank and potential booster locations.

nominal capacity of 96,000 m³/day and an overload capacity of 110,000 m³/day. From the treatment plant, water is pumped to ground tank 1 (18,000 m³) located on top of the hill. Water is then transmitted by gravity to ground tank 2 (5,000 m³) that is located within the Phaka-lane WDS and to other parts of Gaborone city. From ground tank 2, water is pumped to an elevated tank (750 m³) and supplied to the network by gravity at night. During the day, water is supplied directly by gravity from ground tank 1 to the Phakalane WDS through pressure reducing valves (PRVs). The PRVs are used to reduce the

pressure from about 82 m at ground tank 1 to 30 m head of water at the WDS area.

The main types of pipes found in the network are un-plasticised polyvinyl chloride, glass fibre reinforced plastics and ductile iron. The network was skeletonised into 319 pipes of various diameters (ranging from 63 to 1,200 mm), 232 junctions, a reservoir at the treatment plant, two ground tanks, an elevated tank, two pumps, and two PRVs. The network has three existing chlorination locations, one at the treatment plant and the other two are at booster locations 1 and 2 which are not functional. In

addition to the existing booster locations 1 and 2, seven potential booster locations (3–9) are proposed for optimisation as shown in Figure 2. The booster locations 3–9 were determined by running the hydraulic and water quality simulations and areas with inadequate chlorine residuals in the network identified. The potential booster locations are then proposed along the pipe mainlines which are mainly associated with supplying water to the areas with inadequate chlorine residuals.

Network configurations and alternative operational interventions

The optimisation approach explores the viability of introducing alternative operational interventions (AOIs) to network configurations to improve water age and chlorine residual in the Phakalane WDS. The AOIs considered include the following (refer to Figure 2):

A. Operating ground tank 2 at full capacity and supplying the Phakalane WDS via the elevated tank at night.

B. Operating ground tank 2 at half capacity and supplying the Phakalane WDS via the elevated tank at night.

C. Supplying the Phakalane WDS directly from ground tank 1 via PRVs during the day.

D. Operating ground tank 2 at full capacity and supplying the Phakalane WDS via the elevated tank during the day and at night.

E. Operating ground tank 2 at half capacity and supplying the Phakalane WDS via the elevated tank during the day and at night.

F. Supplying the Phakalane WDS directly from ground tank 1 via PRVs during the day and at night.

The network configurations considered here differ in the water transmission route from the treatment plant to the storage reservoirs. They include the following (refer to Figure 2):

I. The network configuration which transmits water from the treatment plant via ground tank 1 to ground tank 2.

II. The network configuration which could transmit water from the treatment plant directly to ground tank 2 without going via ground tank 1.

Table 1 presents seven possible NOS in the Phakalane WDS. The NOS are combinations of different network

Table 1 │ The network operational scenarios

Network operational scenarios (NOS)	Network configuration	AOIs
NOS-1	I	A + C
NOS-2	I	B + C
NOS-3	I	D
NOS-4	I	E
NOS-5	I	F
NOS-6	II	D
NOS-7	II	E

configurations and AOIs that could be used to transmit and supply water to the Phakalane WDS. For example, in NOS-1 water is supplied to the Phakalane WDS using network configuration I with AOIs A and C. In NOS-2 water is supplied to the Phakalane WDS using network configuration I with AOIs B and C. NOS-3 to NOS-7 are interpreted in a similar manner. Note that NOS-1 is the network configuration and operational interventions that are currently used to transmit and supply water to the Phakalane WDS.

Data and assumptions

In this study, the limit of chlorine residual used is 0.2–0.6 mg/L according to Botswana water quality standards (Central Statistics Office 2009). Flow proportional injection strategy (Tryby *et al.* 2002) is applied (i.e. the MIR is time varying depending on the flow leaving the injection locations). In this injection strategy, a continuous uniform input chlorine concentration leaves the injection stations into the network over the injection period. This is the injection strategy that is being used in the application network (Phakalane WDS). Base demands for the nodes were estimated from the monthly records of customer water consumption rate (billing records). The consequences at the monitoring nodes are computed using the water demand for the analysis period of 24 hours. Computation of the consequences at the monitoring nodes using the actual demand and base demand give similar values of the RCD for the entire network. It is assumed that chlorine is consumed only through bulk reaction and therefore the first order model for chlorine decay is adopted. The bulk decay coefficient considered is 0.888 per day, as estimated

by a bottle test experiment, and wall decay coefficient is assumed to be zero (insignificant). The hydraulic and water quality models are assumed to be properly calibrated and the principle of linear superposition is used to estimate the chlorine residual concentration at the monitoring nodes. The principle of linear superposition has been widely used in booster chlorination problems to estimate the chlorine residuals (Prasad *et al.* 2004; Behzadian *et al.* 2012). The lower and upper limits of the decision variables used in the NSGA-II are 0–9 for booster locations, 0.3–8 mg/L for injection rates at the treatment plant and 0.2–0.6 mg/L at booster stations. NSGA-II was run with 100 populations and 1,000 generations (considered adequate from trial runs). Three independent optimisation runs with different initial seeds were performed and the best Pareto fronts are considered. The optimisation process was terminated when the specified number of generations was reached.

Validation of the estimated chlorine residual in the network

A comparison of estimated chlorine residuals by principle of linear superposition with the actual/simulated chlorine residuals obtained by water quality simulation using the EPANET model was conducted for multiple disinfection locations with various assumed dosage rates in different NOS. For the purpose of illustration, validation in NOS-1, NOS-3 and NOS-5 are implemented here as follows:

1. NOS-1 with chlorine injected at the treatment plant at a dosing rate of 0.3 mg/L and one booster station at location 2 (see Figure 2) with a dosing rate of 0.4 mg/L.
2. NOS-3 with chlorine injected at the treatment plant at a dosing rate of 0.4 mg/L and three booster stations at locations 2, 5, and 6 (see Figure 2) with dosing rates of 0.5, 0.2, and 0.3 mg/L, respectively.
3. NOS-5 with chlorine injected at treatment plant at a dosing rate of 0.3 mg/L and four booster stations at locations 2, 4, 7 and 3 (see Figure 2) with dosing rates of 0.3, 0.5, 0.4 and 0.2 mg/L, respectively.

Any NOS and number of chlorine injection points may be used for the validation. The EPANET model was run to obtain steady chlorine residuals at the monitoring nodes and the resul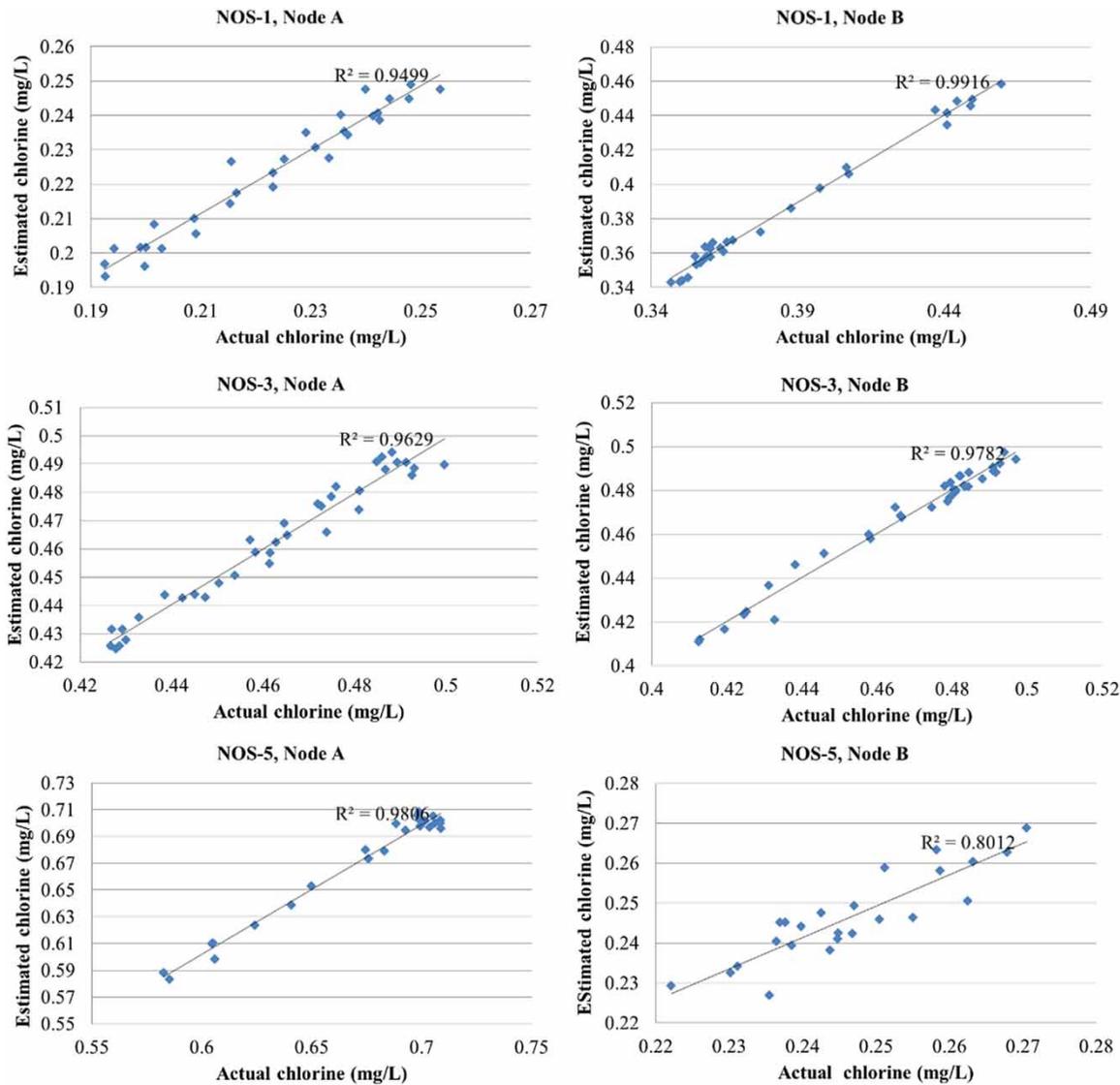ts for the last 24 hours were used for the validation. Figure 3 shows scatter plots of the actual against estimated chlorine residuals for NOS-1, NOS-3 and NOS-5 at monitoring nodes A and B (Figure 2) in the network. The plots indicate that the principle of linear superposition estimates well the chlorine residuals in the network. A statistical measure, percent bias (PBIAS), given by Equation (7) (Moriasi *et al.* 2007) was further used to compare the estimated and actual chlorine residuals. The PBIAS is used here as a statistical measure of how estimated chlorine residuals are larger or smaller than the actual chlorine residuals.

$$PBIAS = \frac{\sum_{i=1}^{n} (A_i - E_i)^* 100}{\sum_{i=1}^{n} (A_i)} \tag{7}$$

where A_i = actual chlorine residual, E_i = estimated chlorine residual and n = number of observations. The statistical analysis indicates that the PBIAS values of estimated chlorine residual at node A are -0.245, 0.022 and 0.011% for NOS-1, NOS-3 and NOS-5, respectively, whereas at node B they are 0.154, -0.048 and 0.073% for NOS-1, NOS-3 and NOS-5, respectively. These values of PBIAS are all rated as good in accordance to criteria (performance rating) used by Moriasi *et al.* (2007). The positive and negative values of PBIAS indicate underestimation and overestimation of chlorine residuals, respectively, although they are within the satisfactory range. These results indicate that the principle of linear superposition fairly approximates the chlorine residual in the network.

RESULTS AND DISCUSSION

The optimum solutions for the proposed integrated booster chlorination are presented, discussed and compared with other chlorination methods. The solutions for the integrated booster chlorination are obtained when alternative NOS (i.e. wider range of options) are considered as decision variables in optimisation in addition to the number, locations and injection rates of the chlorine boosters. The optimum solution for the integrated booster chlorination, which is the point of focus in this study, is compared with the optimum solutions for conventional

Figure 3 │ Scatter plots of the actual against estimated chlorine residuals for NOS-1, NOS-3 and NOS-5 at monitoring nodes A and B in the network.

chlorination and NOS-1 booster chlorination. The solutions for the conventional chlorination are obtained when only the chlorine injection rates at the treatment plant in the NOS-1 are optimised. Note that for the NOS-1 booster chlorination, the NOS-1 is fixed in the optimisation to obtain best solutions (locations, injection rates and the number of chlorine boosters), which means the existing network situation is only improved by booster chlorination. This section further compares the optimum solutions for integrated booster chlorination obtained when fixed numbers of booster stations are specified for

optimisation. The last part presents the results of sensitivity analysis for the integrated booster chlorination.

Comparison of the optimal solutions

Figure 4 shows the trade-off curves of optimal solutions for the integrated booster chlorination, NOS-1 booster chlorination and conventional chlorination. The optimal solutions with similar RCD values were selected as shown in Figure 4 and are presented in Table 2 for analysis of decision variables (NOS, number of boosters, locations of
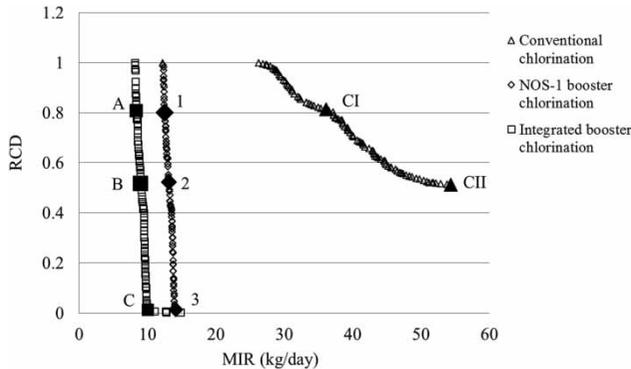
Figure 4 │ The optimal solutions for the integrated booster chlorination, NOS-1 booster chlorination and conventional chlorination.
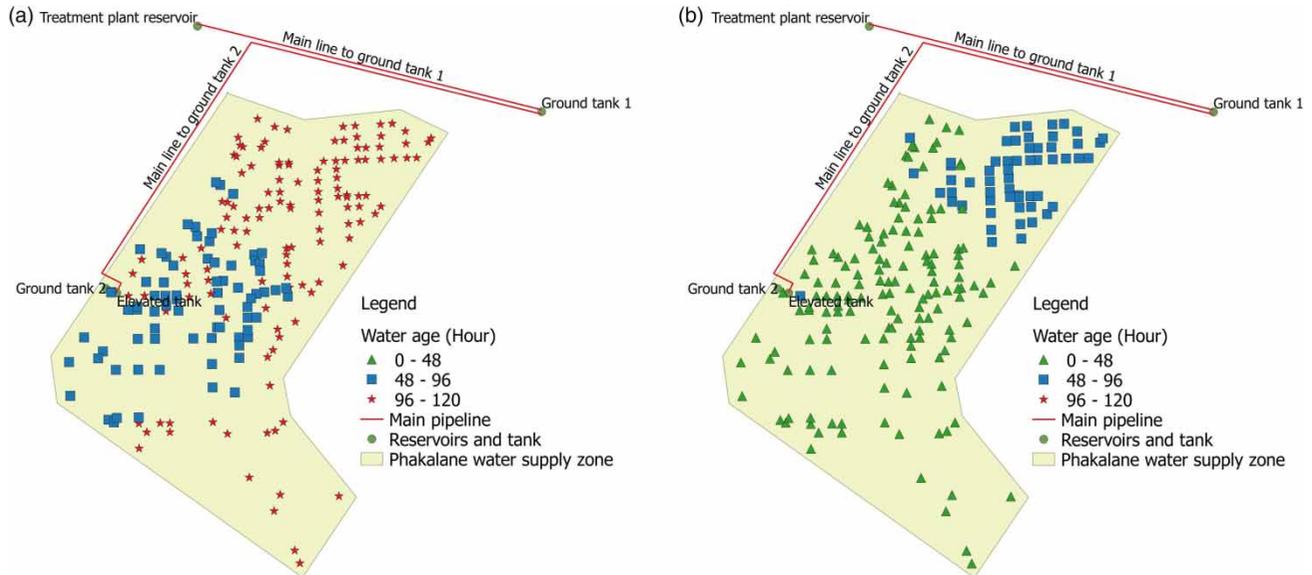
boosters and injection rates) and the respective objective functions (MIR and RCD). Solutions A, 1 and CI are selected at RCD values of 0.8, while solutions B, 2 and CII are at RCD values of 0.5, then solutions C and 3 are at RCD values 0.012.

It can be observed from Figure 4 and selected solutions in Table 2 that the MIR required for integrated booster

chlorination is lower than the MIR for both the NOS-1 booster chlorination and the conventional chlorination. For example, the MIR for solution CII of conventional chlorination and solution 2 of NOS-1 booster chlorination are 54.4 and 13.2 kg/day, respectively, while solution B of integrated booster chlorination is only 9.1 kg/day. The optimal solutions with nearly zero RCD is achieved by integrated booster chlorination and NOS-1 booster chlorination at MIR of 10 kg/day (solution C) and 14.2 kg/day (solution 3), respectively. However, in conventional chlorination, the lowest optimum solution is obtained at RCD of 0.511 and very high MIR of 54.4 kg/day (solution CII). The results suggest that when alternative NOS are considered in the optimisation of booster chlorination, the optimal booster designs obtained significantly reduce the MIR required for disinfection in the WDS. The integrated booster chlorination selects optimum solutions with NOS which meet the recommended chlorine residual limits. The NOS that is selected in the optimum solutions of the integrated booster chlorination has lower water age (refer to Figure 5).

Table 2 │ The optimal solutions for integrated booster chlorination, NOS-1 booster chlorination and conventional chlorination

| Trade-off curve | Selected optimal solution | NOS | Decision variables and the objective values | | | | |
			Treatment plant injection rate (mg/L)	Booster locations	Booster injection rates (mg/L)	MIR (kg/day)	RCD
Conventional chlorination	CI	NOS-1	0.901	–	–	36.5	0.813
	CII	NOS-1	1.335	–	–	54.4	0.511
NOS-1 booster chlorination	1	NOS-1	0.300	5	0.302	12.5	0.800
				8	0.308		
				9	0.589		
	2	NOS-1	0.300	3	0.550	13.2	0.522
				4	0.375		
				6	0.315		
				8	0.200		
	3	NOS-1	0.300	2	0.414	14.2	0.013
				3	0.200		
				6	0.216		
Integrated booster chlorination	A	NOS-4	0.300	2	0.282	8.4	0.808
				8	0.282		
				9	0.586		
	B	NOS-4	0.300	3	0.564	9.1	0.514
				4	0.393		
				6	0.330		
				8	0.214		
	C	NOS-4	0.300	2	0.417	10	0.012
				3	0.200		
				6	0.219		

Figure 5 │ The spatial distribution of average water age for (a) NOS-1 found in solutions CI, CII, 1, 2 and 3; (b) NOS-4 found in solutions A, B and C. Triangles represent nodes with water age below 48 hours (2 days). Rectangles represent nodes with water age between 48 and 96 hours (2–4 days). Stars represent nodes with water age above 96 hours (4 days).

Decreased water age reduces chlorine decay rate and hence the amount of chlorine required to maintain the recommended residual limits in the network.

Again, Figure 4 indicates that the trade-off curve for conventional chlorination has a gentle slope, whereas integrated booster chlorination and NOS-1 booster chlorination curves have steep slopes. The different slopes define the differences in MIR required for high and low RCD values, which is greater in conventional chlorination than integrated booster chlorination and NOS-1 booster chlorination. For example, the difference in MIR for solution CI and CII is 17.9 kg/day, while for solution 1 and 2 it is only 0.7 kg/day and for solution A and B it is only 0.7 kg/day (Table 2). Therefore, curves with steeper slopes indicate large differences between the RCD of the optimal solutions per unit MIR. The steeper slopes are due to small differences between the MIR values of the optimal solutions per unit RCD. Note that the MIR values for the optimal solutions depend on the booster injection rates which are randomly selected between the lower and upper bound of the injection rates (0.3–0.6 mg/L) that are very close to each other. Therefore, the MIR values for the optimal solutions were computed using very close values of the injection rates. The superimposed curves of the Pareto optimal solutions in Figure 4 may look straight, but they

are actually not straight. It should be noted that the chlorine residual decay and transport in the network are non-linear processes. The curves may look straight because of steep gradient due to small differences between the MIR values of the optimal solutions.

It is evident from Table 2 that the chlorine injection rates at the treatment plant in the conventional chlorination are higher than in both NOS-1 booster chlorination and integrated booster chlorination. For example, the injection rate in solution CII of conventional chlorination is 1.335 mg/L whereas in both solutions B and 2 of integrated booster chlorination and NOS-1 the booster chlorination is only 0.3 mg/L. These results imply that, when booster chlorination is used, the injection rates at the treatment plant reduce significantly. The reduction in injection rates at the treatment plant is attributed to the addition of chlorine booster stations at suitable locations in the network. Also, the risks associated with high chlorine residual near the treatment plant in the conventional chlorination are reduced when booster chlorination is used. Furthermore, the results in Table 2 reveal that the optimal booster design (number, locations and injection rates of booster stations) for the NOS-1 booster chlorination and integrated booster chlorination are similar at lower RCD values although the MIR differ significantly. For example, in

solution 3 of NOS-1 booster disinfection, the optimal booster locations are 2, 3 and 6 with their injection rates of 0.414, 0.2 and 0.216 mg/L, respectively. In solution C of integrated booster chlorination the optimal booster locations are 2, 3 and 6 with their injection rates of 0.417, 0.2 and 0.219 mg/L, respectively.

Figure 5 shows an example of spatial distribution of average water age obtained from NOS-1 and NOS-4 that are in the optimal solutions shown in Figure 4. Figure 5(a) shows the water age distribution for NOS-1 found in solutions CI and CII of conventional chlorination and solutions 1, 2 and 3 of NOS-1 booster chlorination. Figure 5(b) shows the water age distribution for NOS-4 found in solutions A, B and C of integrated booster chlorination. Note that even though there are other variables in the solutions mentioned here, only the NOS affects the water age and therefore the NOS are the only variables considered in this analysis. Figure 5(a) indicates that water age in 100% of the nodes is more than 48 hours (2 days), whereas in Figure 5(b) water age in about 80% of the nodes is less than 2 days. In NOS-4, half the capacity of ground tank 2 (Figure 3) is utilised, which decreases the time required to empty the tank during the re-filling cycle. The results demonstrate that integrated booster chlorination selects optimum solutions that are associated with lower water age in an attempt to meet the recommended chlorine residual limits in the WDS.

Figure 6 shows the spatial distribution of chlorine residual in the network for the selected optimal solutions (shown in Figure 4) of integrated booster chlorination and NOS-1 booster chlorination. Figure 6(a), 6(c) and 6(e) display spatial distributions of chlorine residual for solutions A, B, and C of the integrated booster chlorination while Figure 6(b), 6(d) and 6(f) show chlorine residuals for solutions 1, 2 and 3 of the NOS-1 booster chlorination. It can be observed from Figure 6 that the spatial distribution of chlorine residual for optimal solutions of integrated booster chlorination and NOS-1 booster chlorination are similar, mainly because in both approaches chlorine boosters are used. For example, the spatial distribution of chlorine residuals for both solution A (Figure 6(a)) and solution 1 (Figure 6(b)) indicate that few nodes in the network would have chlorine residual within the standard limits of 0.3–0.6 mg/L (represented by stars).

Although the spatial distribution of chlorine residual for optimal solutions of integrated booster chlorination and NOS-1 booster chlorination are similar, lower MIR is required in integrated booster chlorination (Table 2) because the method selects NOS with decreased water age and chlorine demand. However, the spatial distribution would differ when different levels of RCD are compared. For example, in Figure 6(a), which shows the distribution of chlorine residual for solution A, very few nodes have chlorine levels within the recommended limits of 0.3–0.6 mg/L, whereas in Figure 6(e), which shows the distribution of chlorine residual for solution C, nearly all the nodes have chlorine residual within the recommended limits. The booster stations found in solution A are located at 2, 8 and 9, while the booster stations found in solution C are located at 2, 3 and 6 (Figure 2). The results indicate that the booster stations in the solutions with low RCD (e.g. solution C) are distributed towards the area which would receive inadequate chlorine residual when the conventional chlorination is used.

Figure 7(a) and 7(b) show a comparison of temporal variations (over 24 hours) of chlorine residual at remote nodes A and B that are shown in Figure 2 when the network is subjected to the selected solutions CII, 2 and B (shown in Figure 4). It can be observed from the graphs that solutions 2 (NOS-1 booster chlorination) and solution B (integrated booster chlorination) significantly improve the adequacy and temporal variations of chlorine residuals at the remote nodes A and B of the WDS compared to solution CII (conventional chlorination). Chlorine residuals for solutions 2 and B did not decrease below 0.15 mg/L in node A and 0.4 mg/L in node B over 24 hours, whereas for solution CII, the residuals decreased to less than 0.1 mg/L at both nodes. The temporal variation of the chlorine residual improves in the integrated booster chlorination and NOS-1 booster chlorination because of effective distribution of the chlorine booster stations in the network.
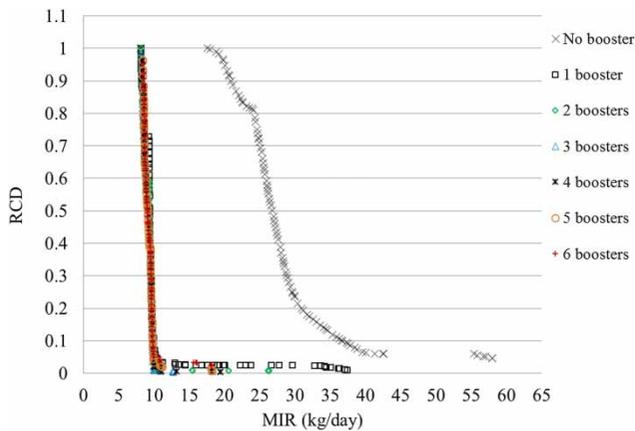
Figure 8 shows seven trade-off curves between total MIR and RCD for a specified number of booster stations obtained from integrated booster chlorination. The trade-off curves are for number of boosters ranging from 0 (i.e. chlorine injection at the treatment plant only) to 6. Figure 8 also
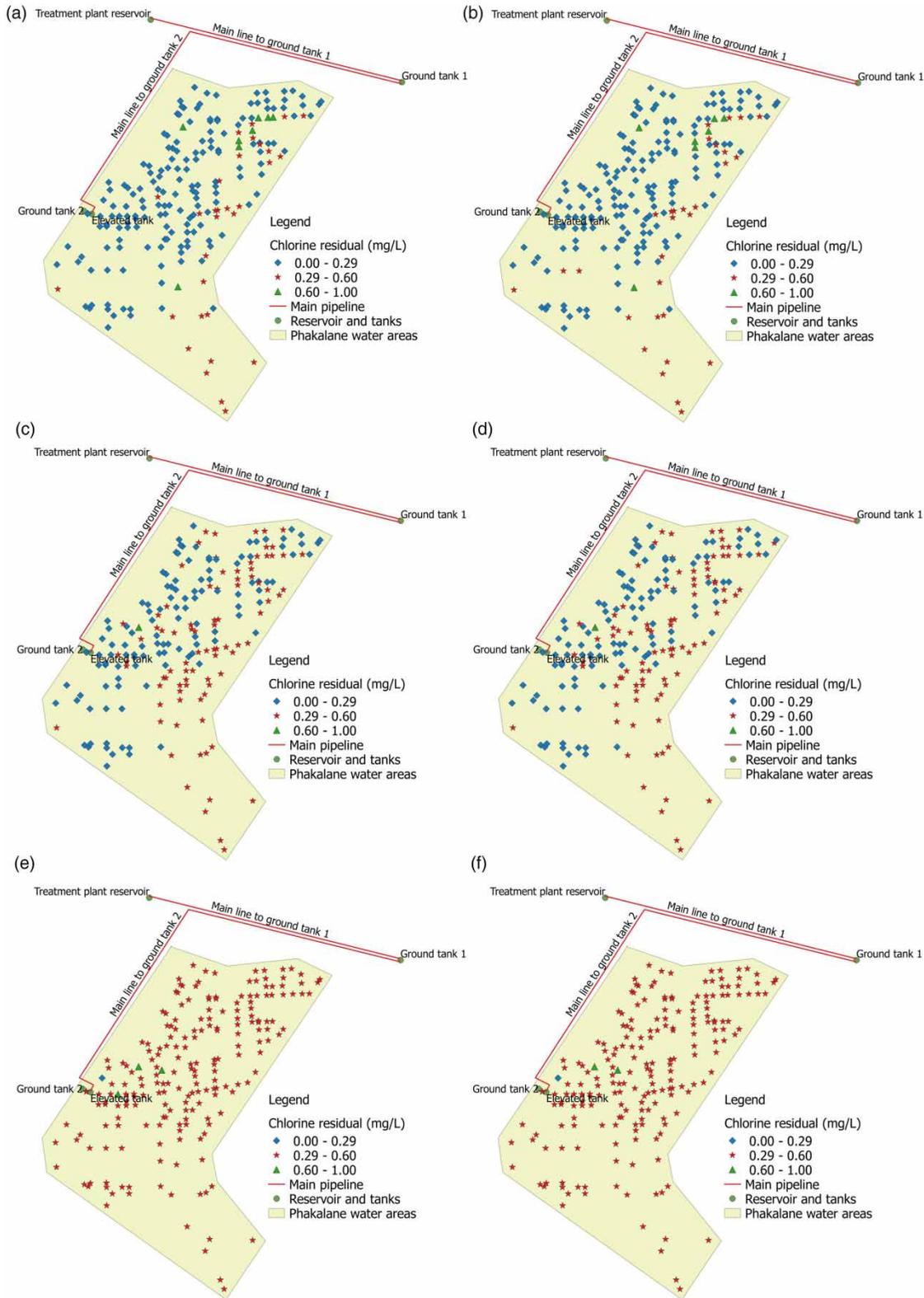
Figure 6 │ Spatial distribution of chlorine residuals in the network: (a) solution A; (b) solution 1; (c) solution B; (d) solution 2; (e) solution C; (f) solution 3. Rectangles represent nodes with chlorine residual less than 0.3 mg/L, Stars represent nodes with chlorine residual within 0.3–0.6 mg/L and triangles represent nodes with chlorine residual above 0.6 mg/L.
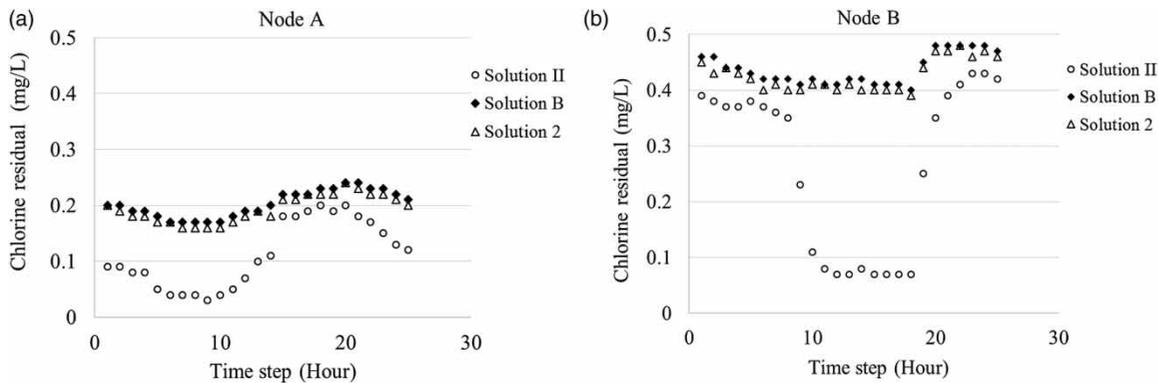
Figure 7 │ Temporal analysis of the optimal solutions (a) Node A, (b) Node B.

Figure 8 │ Trade-off curves between MIR and RCD for different number of booster stations obtained from integrated booster chlorination.

indicates that the MIR required in the network without boosters is higher than MIR required in the networks that have any number of boosters for equivalent RCD values. For example, the MIR required for RCD value of 0.1 in the network without boosters is more than 35 kg/day, whereas MIR is significantly reduced to below 10 kg/day when boosters are used.

Again, it is evident from Figure 8 that reducing RCD to zero could not be achieved in the network with or without booster stations. The lowest reduction in the MIR and RCD could be achieved with three or four boosters. However, three booster stations would require lower MIR to reduce the RCD to nearly zero compared with four booster stations. Therefore, three booster stations are considered as the best number that is required for disinfection in the network.

Sensitivity analysis

Parameter uncertainties can significantly influence the results of the simulation-optimisation process. Sensitivity analysis was carried out to investigate water demand and chlorine decay coefficients as the key parameters which are likely to influence the optimal solutions of the integrated booster chlorination. The sensitivity analysis was performed by varying the water demand and bulk decay coefficient using the most common one factor at a time (OFAT) approach. In this approach, one parameter (water demand or bulk decay coefficient) is changed at a time, while the other is kept at nominal or baseline value. In this paper, water demand or bulk decay coefficient was arbitrarily increased by 50%. The trade-off curves for the bulk decay coefficient and water demand sensitivity analysis (e.g. S1 and SI) were compared with the base trade-off curve. The base trade-off curve presents solutions for integrated booster chlorination when the bulk decay and water demand were kept at their baseline values, which were used to obtain solutions shown in Figure 4.

Figure 9 shows the base trade-off curve and the trade-off curves for bulk decay coefficient and water demand sensitivity analysis. Solutions A and B are selected from the base-trade-off curve, while solutions S1 and S2 are selected from the bulk decay coefficient sensitivity analysis trade-off curve, then solutions SI and SII are selected from the water demand sensitivity analysis trade-off curve. The decision variables and objective values for selected solutions A, B, S1, S2, SI and SII are presented in Table 3. Figure 9 indicates that optimal solutions for the integrated booster
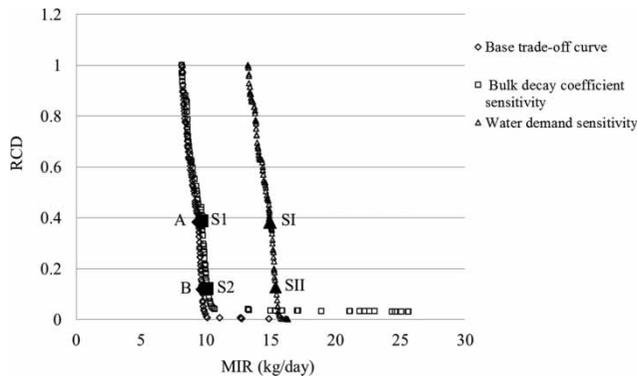
Figure 9 │ Comparison of sensitivity analysis trade-off curves with the base trade-off curve for integrated booster chlorination.

chlorination are sensitive to change in both bulk decay coefficient and water demand. Change in the water demand has more influence on the optimal solutions of integrated booster chlorination than the bulk decay coefficient. It is evident from Table 3 that MIR increases more with water demand than the bulk decay coefficient. For example, the MIR increases from 9.7 kg//day (solution B) to 10.1 kg/day (solution S2) and 15.4 kg/day (solution SII).

Furthermore, an increase in bulk decay coefficient and water demand affects the optimal solutions (NOS, number of boosters, locations and injection rates) of the integrated booster chlorination. For example, in solution B (base trade-off curve) the optimal solutions are NOS-4 and booster locations at 2 and 6 with injection rates of 0.362 and 0.2 mg/L, respectively. However, in solution S2 (bulk decay), the optimal solutions are NOS-4 and booster locations at 2, 3, 6 and 9 with injection rates of 0.2, 0.424, 0.202 and 0.216 mg/L, respectively. In solution SII (water demand) the optimal solutions include NOS-6 and booster locations at 2, 3 and 9 with their injection rates of 0.261, 0.2 and 0.2 mg/L, respectively. Also, an increase in water demand changed the network operation scenario in the optimal solutions from NOS-4 (base) to NOS-6. In NOS-6, ground tank 2 is operated at full capacity in the plausible network configuration, but in NOS-4, the tank is operated at half capacity in the current network configuration (Table 1). The results indicate that an increase in water demand requires increased capacity of the storage and may also need alternative network

Table 3 │ Decision variables and objectives values for comparable solutions

Trade off curve	Selected optimal solution	NOS	Treatment plant injection rate (mg/L)	Booster locations	Booster injection rates (mg/L)	MIR (kg/day)	RCD
			Decision variables and objectives values				
Base	A	NOS-4	0.300	2	0.320	9.5	0.383
				9	0.200		
	B	NOS-4	0.300	2	0.362	9.7	0.119
				6	0.200		
Bulk decay coefficient	S1	NOS-4	0.300	2	0.339	9.7	0.389
				3	0.200		
				8	0.200		
				9	0.236		
	S2	NOS-4	0.300	2	0.424	10.1	0.122
				3	0.200		
				6	0.202		
				9	0.216		
Water demand	SI	NOS-6	0.300	3	0.470	14.9	0.399
				4	0.281		
				5	0.201		
				6	0.253		
				8	0.215		
	SII	NOS-6	0.300	2	0.261	15.4	0.126
				3	0.200		
				9	0.200		

configurations for better performance of booster chlorination in the WDS.

CONCLUSIONS

An optimisation methodology that integrates booster chlorination with network operational interventions to obtain optimal booster designs in WDSs was developed and tested in the Phakalane WDS. The multi-objective booster optimisation approach that improves water quality minimises the MIR and RCD by selecting appropriate number of boosters, location of boosters, chlorine injection rates, network configurations and operational interventions simultaneously in the WDS. The optimisation problem was solved by a non-dominated sorting genetic algorithm (NSGA-II) and the WDS model (EPANET). The following conclusions are drawn from the results of the study:

1. The integrated booster chlorination selects optimal solutions (NOS, number of boosters, locations and injection rates) with lower MIR than both the conventional chlorination and NOS-1 booster chlorination. Higher MIR in conventional chlorination and NOS-1 booster chlorination practically means more mass of chlorine would be required and hence higher cost of disinfection in the existing WDS. The NOS in the optimum solutions decrease water age which in turn reduces chlorine decay rates and MIR required for maintaining the recommended chlorine residual limit in the network.
2. The integrated booster chlorination method captures possible network configurations and operations and offers flexibility in improving water quality in WDSs. This methodology optimises chlorine booster designs and network operation scenarios that effectively improve the adequacy and uniformity of chlorine residual in WDSs.
3. The results indicate that three booster stations are required to produce effective chlorine residuals in the Phakalane WDS. The booster stations selected for the solutions with low RCD are more distributed towards the area which receives inadequate chlorine residual (i.e. more than the high RCD solutions) when the conventional chlorination is used.
4. Sensitivity analysis revealed that both water demand and chlorine decay coefficient influence the optimal booster designs (number of boosters, locations and injection rates) network configuration and operations. The optimal booster designs and network operation scenarios are affected by variation in the water demand more than the variation in the chlorine decay coefficient. Uncertain parameters such as water demand and chlorine decay coefficients would require periodic monitoring in order to adjust the chlorine booster disinfection and operational interventions accordingly so that effective chlorine distribution in a WDS is maintained.

Future work is required to test the proposed methodology in a wide range of WDSs. The methodology presented in this study does not consider the inevitable uncertainty inherent in the network operations and parameters such as water demand and the rate of disinfectant decay. Therefore, the need to develop robust approaches that would consider unforeseen uncertainties in the booster disinfection design of WDSs becomes clearer.

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