Int. J. Environ. Res., 5(2):321-332, Spring 2011
ISSN: 1735-6865

Quality Management of Water Distribution Networks by Optimizing Dosage and Location of Chlorine Injection

Tabesh, M.[1*], Azadi, B.[2] and Roozbahani, A.[2]

[1]Center of Excellence for Engineering and Management of Infrastructures, School of Civil Engineering, University of Tehran, P.O.Box: 11155-4563, Tehran, Iran

[2]School of Civil Engineering, University of Tehran, Tehran, Iran

Received 5 Oct. 2009; Revised 17 June 2010; Accepted 25 July 2010

ABSTRACT: A methodology is presented in this paper to find optimal location and dosage of chlorine injection in water distribution networks. The objective is to minimize the chlorine consumption while keeping the residual chlorine at each node within the standard range. Unfortunately because of wrong water quality management in water distribution networks in many parts of the world, many problems such as bacterial growth or formation of by-products occur in these systems. In this paper with integrating two models, hydraulic model of EPANET2 with ability of quality simulation and optimization model of Genetic Algorithm (GA), the best locations for chlorine injection and its optimum dosage in the water networks are obtained. To evaluate the presented method, two test examples are studied. The results of this study show the reduction in total consumed chlorine in the system obtained by chlorine injection in optimal locations with optimum dosage, in comparison with other researches.

Key words: Genetic Algorithm, hydraulic model,Optimization, Quality analysis, Residual chlorine

INTRODUCTION

Supplying the human's water requirements in different parts of the society such as commerce, industries and domestic consumers is the main duty of water distribution networks. Water quality must be in the standard range for drinking uses. For this purpose the chemical, physical, microbiological and also superficial properties in water must have the standard value.

Water quality issue has direct relation with the urban water distribution networks. Therefore, water disinfects are necessary to obtain the fresh and healthy water, but important subject is the acceptable injection of chemical materials into the water networks. For example, because the prevalent and inexpensive way for purification of water is the chlorine injection in the water network, residual chlorine must satisfy the minimum and maximum standard values. The residual chlorine is amount of effective chlorine that must be sufficient in total points of the system. Considering 20^0C as daily average temperature and PH>8-9 and PH>6.5-8, the minimum allowable residual chlorine is equal to 0.4 mg/l and 0.2 mg/l, respectively (ISIRI 1997). According to the WHO guidelines it may suggest the range of 0.2-0.5 mg/l as favorable range for this parameter in water distribution networks. In many water systems chlorine is injected in the treatment plan, wells or reservoirs before the water entrance to the system. This operation leads to high concentration of residual chlorine in the closer nodes to the quality sources and insufficient values in the further nodes to these points. Hence, for quality management of the water system, scheduling of chlorine sources and amount of chlorine injection in these sources are necessary. There are many researches about quality optimization of water distribution networks. These researches are divided into two groups. First group tries to find the optimized locations of monitoring stations in water distribution networks. Lee and Deininger (1992) presented a model for optimal locations of monitoring stations. Their model was solved for one and two consumption patterns. Also, Al-Zahrani and Moied (2003) applied the Genetic Algorithm for optimization of monitoring stations. These methods have the limitations such as considering the limited number of consumption patterns using trial and error approach. Hence, these methods can not be applied for the complex water distribution networks, easily.

Second group of researches tries to optimize chlorine dosage which is injected into the water

---

*Corresponding author E-mail: mtabesh@ut.ac.ir

distribution networks. Boccelli et al. (1998) used linear optimization to minimize the total chlorine consumed in the water distribution network as the residual chlorine value in the system remains in the standard range. Minimum and maximum standard values were considered as 0.2mg/l and 0.4 mg/l, respectively. Their objective function satisfied two purposes: to standardize the residual chlorine in infinite time period and to minimize the total chlorine dose in the boosters.

Munavalli and Mohan Kumar (2003) used the case of Boccelli et al. (1998) for optimization of chlorine dosage by application of Genetic Algorithm. In these works, suitable places for installation of boosters were selected by trial and error method. Then, the amount of chlorine injection in these boosters was optimized. This injection procedure was performed periodically and objective function was nonlinear. The results showed higher amount of consumptive chlorine in comparison with researches of Boccelli et al. (1998), because the objective function, pipe wall reaction coefficient and other parameters were changed.

Rouhiainen et al. (2003) presented the multi-objective model to optimize the chlorine dosage in water distribution networks. The objectives were: control of disinfectant, control of water tasting and smelling, minimizing the total consumptive chlorine and minimizing the variations of chlorine injection in the systems.

Broad et al. (2005) studied on expansion design of water distribution network in New York. In this study it was assumed that injection was done only in one point in the system and minimum standard value for residual chlorine was 0.3 mg/l. This optimization was implemented by genetic algorithm and artificial neural network was applied as a simulation model. Final goal of this study was to standardize the pressure and chlorine values in the water network.

Ostfeld and Salamons (2006) extended previous work on optimal booster chlorination injection design and operation in water distribution systems by solving the scheduling problem of pumping units in conjunction with the design and operation problem of booster chlorination stations. Two models were formulated and solved using a genetic algorithm scheme tailor-made to EPANET: minimizing the costs of pumping and the chlorine booster design and operation, and maximizing the system protection by maximizing the injected chlorine dosage.

May et al. (2008) applied a newly non-linear Input Variable Selection (IVS) algorithm to the development of Artificial Neural Network (ANN) models to provide a 1-hr forecast of chlorine concentration in water distribution systems. The intention was to reduce the need for arbitrary judgment and extensive trial-and-error during model development. The algorithm utilized the concept of partial mutual information (PMI) to select inputs based on the analysis of relationship strength between inputs and outputs, and between redundant inputs.

This paper presents a methodology to find optimal locations and chlorine dosage and scheduling of chlorine sources in water systems. In this paper by definition of nonlinear objective function for the problem, two test examples are presented and amount of chlorine injection and total consumptive chlorine in the system are controlled to satisfy the standard limits. Additionally, unlike the researches of Boccelli et al. (1998) and Munavalli and Mohan Kumar (2003) that only have tried to find the optimal chlorine dosage in the system, the methodology of this paper is able to find the most appropriate scheduling for chlorine injection which leads to lower chlorine consumption in the system.

MATERIALS & METHODS

In this section a procedure for optimization of chlorine injection sources and dosage in the water distribution networks are proposed. This procedure consists of two models: 1- hydraulic & quality model (EPANET2), 2- optimization model (Genetic Algorithm). single and combined models have been widely used in water quality management studies (Naik and Manjapp, 2010; Ardestani and Sabahi, 2009; Rajasimman et al., 2009; Etemad-Shahidi et al., 2009; Etemad-Shahidi et al., 2010; Jeong et al., 2010; Zhang et al., 2010; Santhanam and Amal Raj, 2010). The purpose of this section is to introduce an optimization algorithm to be used simultaneously with water quality model to keep the nodal residual chlorine in the standard range at all times nodes with minimum chlorine consumption. For hydraulic modeling the freely available software of EPANET presented by Environmental Protection Agency (EPA) for water distribution networks analysis (Rossman, 2000) is used in this research. Hydraulic simulation model estimates the nodal hydraulic pressures and pipe's velocity for series of water level of reservoirs and tanks and water consumption in different nodes at each time. The pressure head and velocity values are obtained by solving the energy and continuity equations for each junction and head loss equation in each pipe simultaneously. To solve the continuity and head loss equations and determining the hydraulic condition of networks, the Gradient method (Todini and Pillati 1987) is applied.

Besides the hydraulic parameters of pressure head and velocity, to obtain the quality parameter values of the water distribution network such as residual chlorine, water age, etc., a quality simulator engine is required as well.

The advantage of EPANET2 model is the ability to simulate both hydraulic and quality parameters dynamically using extended period simulation. The basis of the quality model is as follows:The transformation equation in pipe i in the water distribution networks is illustrated in equation (1):

$$(\partial c_i / \partial t) = -u_i (\partial c_i / \partial x) \pm R(c_i) \qquad (1)$$

where, C_i is chlorine concentration in pipe i as the temporal and spatial function (mg/l), u_i is velocity of flow in pipe i (m/s) and $R(c_i)$ is the reaction rate for chlorine (Rossman 2000). In the junctions with connected multi-pipes, flow is considered to be fully mixed. Thus, amount of output material in water is equal to summation of inflow concentration of entrance pipes into the junctions. Then, chlorine concentration in node j and time t is obtained as bellow:

$$C_{jt} = \left(\left(\sum_{i=1}^{I} Q_i C_i + Q_{E_j} C_{E_j}\right) / \left(\sum_{i=1}^{I} Q_i + Q_{E_j}\right)\right) \qquad (2)$$

in which, j=1,…., NN, I is number of entrance pipes to node j, NN is the total number of nodes in the water network, Q_i is the flow rate in pipe i (m^3/s), Q_{Ej} and C_{Ej} are discharge and chlorine concentration entering the network in the jth node (mg/l), respectively.

The quality model of water network is solved by Lagrangian Time-Driven Method (LTD) method (Liou and Kroon 1987). This method is useful for calculation of chlorine dose variations.

Optimization model

Optimization is one of the important and basic management tools in different fields. Selecting the effective way to solve the optimization problems needs to understand restrictions, objectives and decision variables of the systems. Several optimization methods are used to solve the management problems. Linear or non linear programming, gradient method, direct search method, integer programming and search based methods are ordinary optimization approaches. Among the search based methods, Genetic Algorithm is very useful and powerful method to solve the complex systems with complicated framework having the function with nonlinear restrictions. The Genetic algorithm procedure has been shown in Fig. 1.

Genetic Algorithm has been used in many optimization problems in water distribution networks such as Dandy et al. (1996), Reis et al. (1997); Savic & Walters (1997); Rouhiainen et al. (2003); Munavalli and Mohan Kumar (2003). In this research the decision variable are the amounts of chlorine dose in the quality sources of network. Fitness function value is estimated based on the objective function and residual chlorine is restricted between the maximum and minimum standard limits. To obtain the objective function, two points must be considered: 1- To force the residual chlorine to the standard minimum limit and 2- Weighting the nodes based on their consumption at each time. Chlorine in the quality sources has been injected with constant and periodic rates. Boccelli et al. (1998) explained the periodic performance of water quality.

The simulation period depends on the time pattern's repetition start time of chlorine injection of controlled nodes in water distribution networks. The purpose of the optimization is to obtain the best chlorine dosage for all of the chlorine injection sources in the system. If $N_{(sn)}$ is the number of injection sources in the water network and $PI_{(s)}$ is the value of periodic injections in the quality sources, $A_{(cl)}$ is the total amounts of injection in all quality sources i.e.

$$A_{cl} = \sum_{s=1}^{N_{sn}} PI(s) \qquad (3)$$

As explained before, the decision variables in Genetic Algorithm are amount of chlorine dosage in the system. Values of residual chlorine at each node must be in the standard range and have minimum difference with minimum standard level of residual chlorine.

Objective function

Because of this fact that large amount of residual chlorine in the water distribution networks gives rise to chlorine by-products which pose health risks (WHO, 1993), controlling residual chlorine between standard limits is compulsory. The formation of such by-products depends on the presence of dissolved organic matter in the water. In this paper, objective function is square of difference between estimated and allowable minimum residual chlorine. Also in this function importance of each node is characterized by weighting them based on their consumption. The objective function is:

$$\text{Min } F = \sum_{j=1}^{NN} \sum_{t=1}^{NT_j} \left[\left(\left| Q_{jt} \right| / \sum \left| Q_{jt} \right| \right) (C_{jt} - C_{\min})^2 \right] \qquad (4)$$

Subject to:

$$C_{\min} \le C_{jt} \le C_{\max} \quad j = 1,..., NN; \quad t = 1,..., NT_j \qquad (5)$$

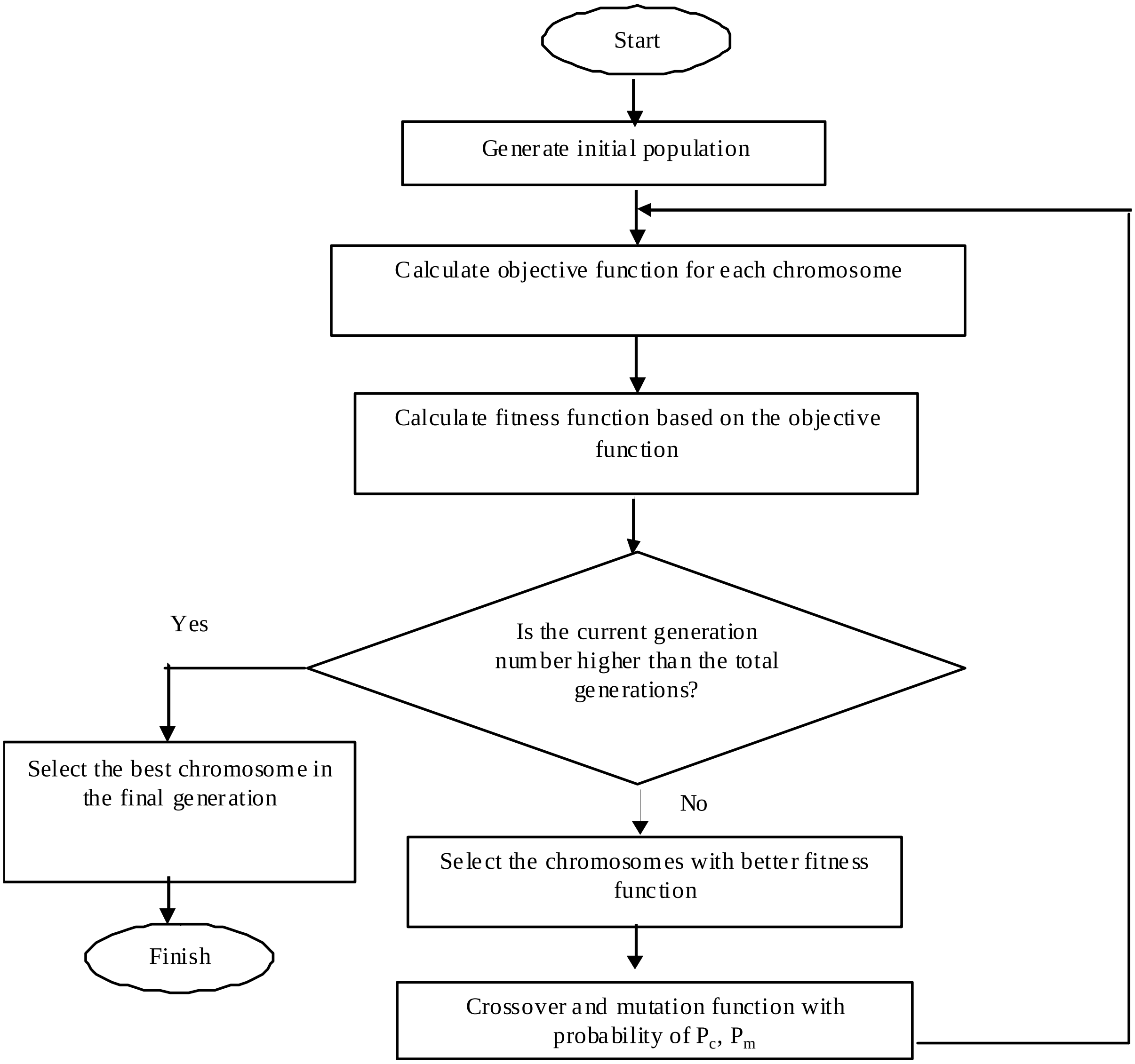

Fig. 1. Genetic Algorithm Procedure

where, NN is number of nodes, NT_j is number of time steps in node j, C_{min} is the minimum allowable chlorine concentration value in the system (mg/l), C_{max} is the maximum allowable chlorine concentration value and Q_{jk} and C_{jk} are water consumption and chlorine concentration in node j and time k, respectively.

Penalty function

In the Genetic Algorithm method, constraints of the problem are formulated as a penalty term which is added to the object function. The ultimate objective function has been shown in equation (6).

$$\text{Min} \quad F = \sum_{j=1}^{NN} \sum_{t=1}^{NT_j} \left[\left(\left| Q_{jt} \right| / \sum \left| Q_{jt} \right| \right) \left(C_{jt} - C_{\min} \right)^2 \right] + \frac{\left| Max\,(C_{jt}) - Min\,(C_{jt}) \right|}{\left(\dfrac{\sum_{j=1}^{NN} \sum_{t=1}^{NT_j} C_{jt}}{NN} \right)} \tag{6}$$

$$+ \sum_{j=1}^{NN} \sum_{t=1}^{NT_j} [P_1 [\max(0, C_{\min} - C_{jt})]^2 + \sum_{j=1}^{NN} \sum_{t=1}^{NT_j} [P_2 [\max(0, C_{jt} - C_{\max})]^2$$

where, P_1 and P_2 are penalty coefficients for overrunning of constraints of the problem. Other parameters of the objective function were introduced in the previous section. The second term in this equation shows the residual chlorine range in the network by comparing it with the average residual chlorine value. This term helps to concentrate residual chlorine in water distribution networks uniformly. It means that this term forces the residual chlorine to be closed to the average value and keeps this variable in the allowable standard range. The third and forth terms of this function force the residual chlorine to remain in the allowable range besides the second term.

The ratio of $\left(\frac{|Q_{jt}|}{\Sigma|Q_{jt}|}\right)$ is a coefficient shows the importance of each node depending on its water consumption. In other word, each node is weighted by this coefficient. In fact, the consumption rate in each node denotes its population and importance. Thus, by this method objective function and constraints are mixed.

Optimization procedure

In this paper by using the MATLAB7 software, the hydraulic-quality model, EPANET2, is integrated with Genetic Algorithm model and the optimization procedure is performed. A Pentium 4 computer with 1024 MB RAM and 3.2 GB CPU was used to perform this procedure. Consumption and chlorine dose values are estimated by EPANET2 and these results are entered as the inputs to the Genetic Algorithm model. Outputs of this optimization are entered again to the EPANET2 model. This repetitive procedure continues till obtain the best and optimal solution. Fig. 2 shows the algorithm of the optimization procedure.

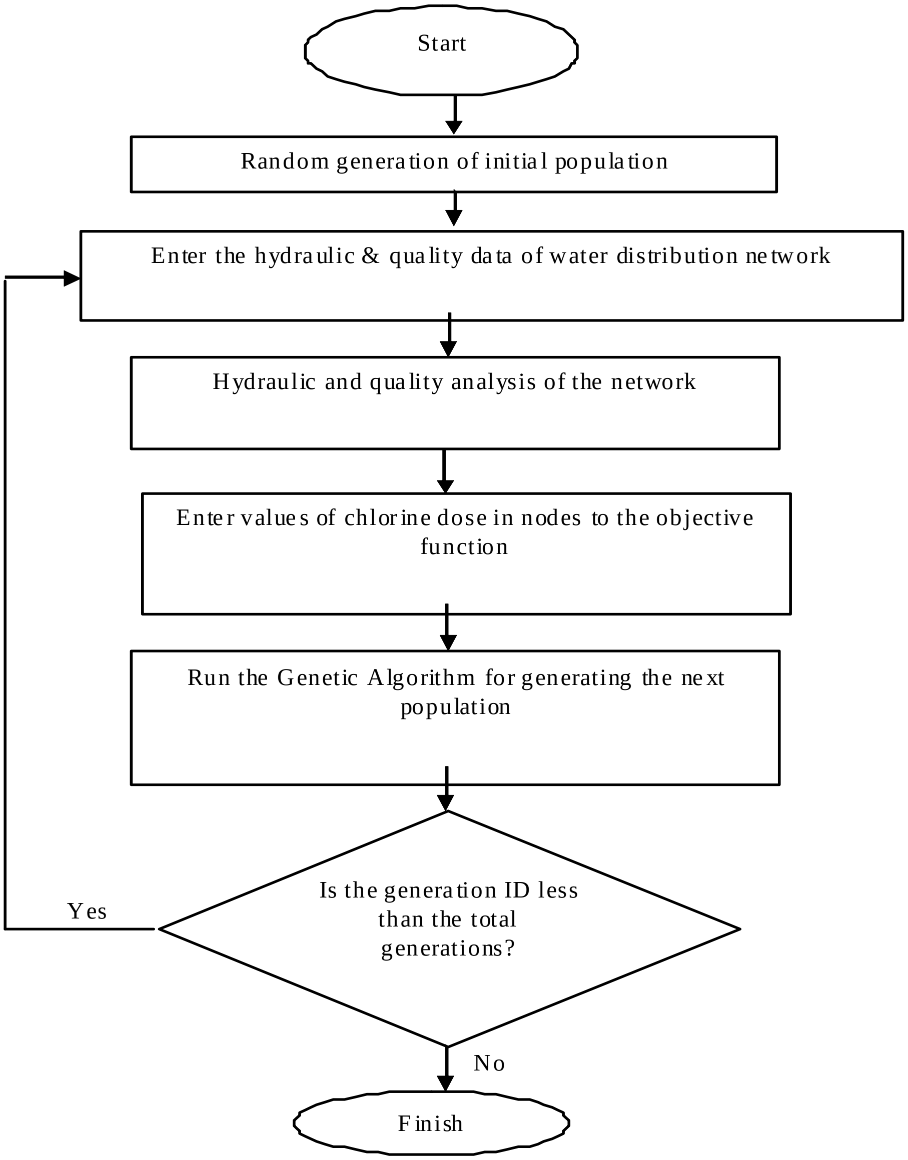

Fig. 2. The algorithm for chlorine dosage optimization

Other part of this research is to determine the optimal sources for chlorine injection in water networks. Munavalli and Mohan Kumar (2003) and Boccelli et al. (1998) used a trial and error method for this purpose. This method leads to find two different scenarios for the same water distribution network. However, in the complex networks with large number of nodes, finding the best places for installation of injection boosters by trial and error procedure is impossible.

Finding optimum locations

The purpose is to obtain the suitable nodes for chlorine injection. In this new method, chlorine injection can be performed by constant or periodic rates and also the computation time can be decreased. The method consists of two following steps.

Step 1: In the presented method in this paper, firstly it is considered that boosters are installed in total nodes of the water system and with assumption of injection in all nodes; the chlorine dosage is optimized as the concentration of residual chlorine in each node satisfies the standard range. By studying the results, this fact is detected that some nodes show little amount of injection and some other nodes face considerable proportion in chlorine supplying in water network. It means that after the optimization procedure in total nodes, results show each node's proportion of chlorine injection into the system. Thus, nodes with inconsiderable chlorine dose are omitted from the analysis and nodes with considerable chlorine dose remain for the next part of the optimization.

Step 2: In this part not only the amount of chlorine injection into the water network is optimized but also number of injection points is decreased as all of the constraints of model are satisfied. If M nodes are selected as the effective nodes for booster installation from step 1, in this step K nodes (Kd”M) are selected as the best points for booster installation. For this purpose initial value for K is entered to the optimization procedure. If the favorite solution is obtained, then the value of K is decreased until the solutions of problem have the preference in comparison with results of the latest value of K. On the other hand if the results of residual chlorine for initial value of K is not in the standard range, K value must be increased. Algorithm of this procedure is shown in Fig. 3.

Test Examples

For evaluating the proposed methodology in this research, two test examples are used that have been studied in some other researches. The procedure is followed by some steps. Firstly, different scenarios for injection of chlorine in the water distribution networks are defined and importance of chlorine injection in multi quality sources is explained. Then, after denoting the number of required quality sources, the chlorine dosage is optimized in two phases: constant and periodic rates. For the periodic injection each day divides into four 6-hours periods.

As example 1 the water distribution network of Jeppson (1976) is studied for hydraulic and quality modeling and different scenarios are applied for chlorine injection via available reservoirs. The second example is the water distribution network of Central Connecticut State (SCC) which was used in some previous researches for water quality modeling (Clark et al. 1993; Rossman et al. 1994; Boccelli et al. 1998; Munavalli and Mohan Kumar 2003). In this section results of the proposed method for optimization of chlorine dose are compared with the results of previous researches.

Test Example No. 1

In water distribution network of Jeppson (1976) (shown in Fig. 4), chlorine is injected through different scenarios into the three reservoirs. Also, the amount of chlorine is injected with two constant and periodically variable rates. Aim of the second phase is obtaining the optimized amount of chlorine injection with periodic rate and this optimized solution is occurred when residual chlorine in water network nodes is closer to the minimum standard. In this network, the bulk flow reaction and pipe wall reaction coefficients are equal to $1d^{-1}$ and 0, respectively. Other information and data of this network have been shown in Tables 1 and 2. The available heads at reservoirs A, B and C are 1275, 1300 and 1280 (ft), respectively.

Different injection scenarios in quality sources

As illustrated before, the final goal of this study is to keep the residual chlorine concentration within the standard domain. In this case study it is assumed that chlorine is injected only in the reservoirs. Different scenarios are defined depend on number of the reservoirs and without any optimization procedure. The residual chlorine concentration in the closest node to the reservoirs is equal to the maximum standard value (here, 0.5mg/l). The proper number of required reservoirs for injection is then selected and the optimal amount of chlorine injection in these reservoirs is determined.

- Injection in one reservoir

In many water distribution networks, chlorine is injected in just one point in the system before entrance of fresh water to the network. As a result, it can be observed that some nodes which are close to the chlorine source have the higher residual value than the maximum standard limit and farther nodes face

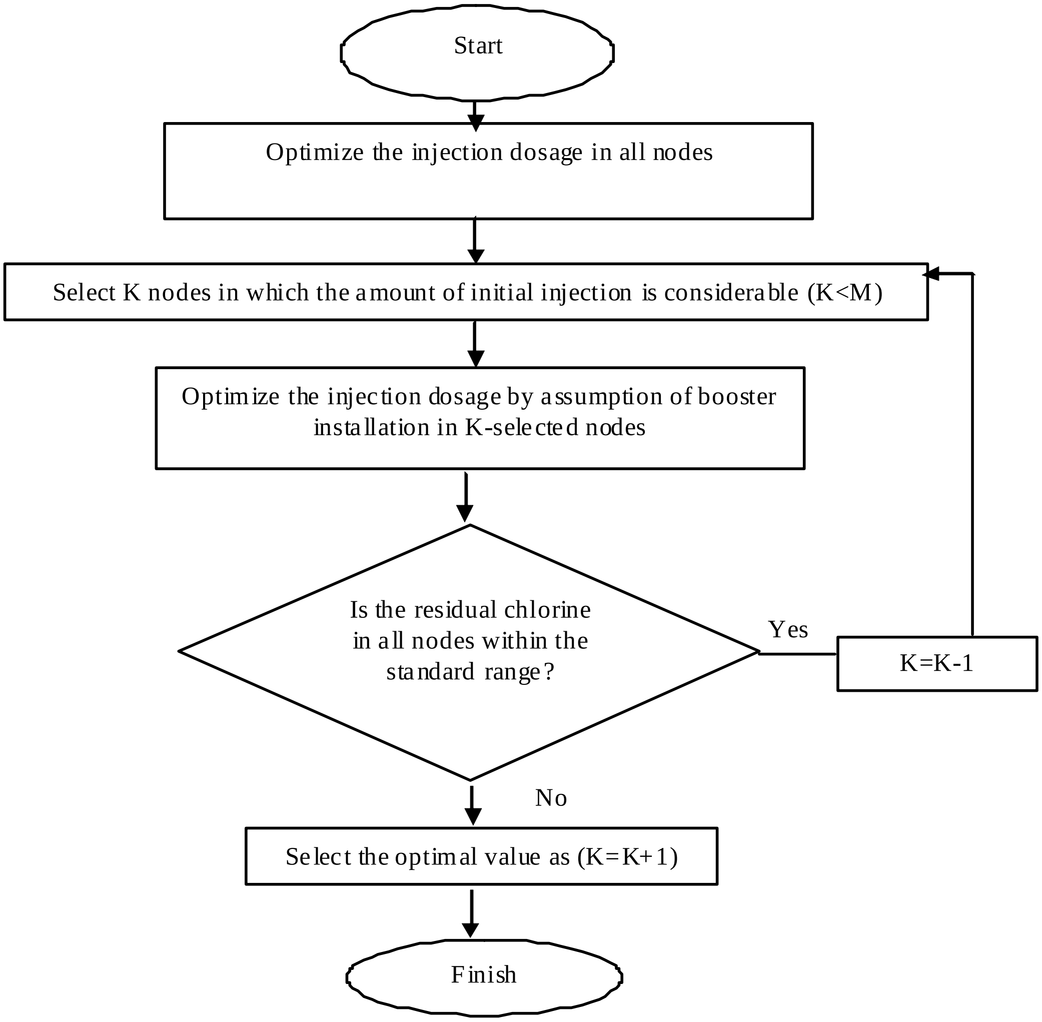

Fig. 3. The algorithm for finding the best chlorine injection nodes

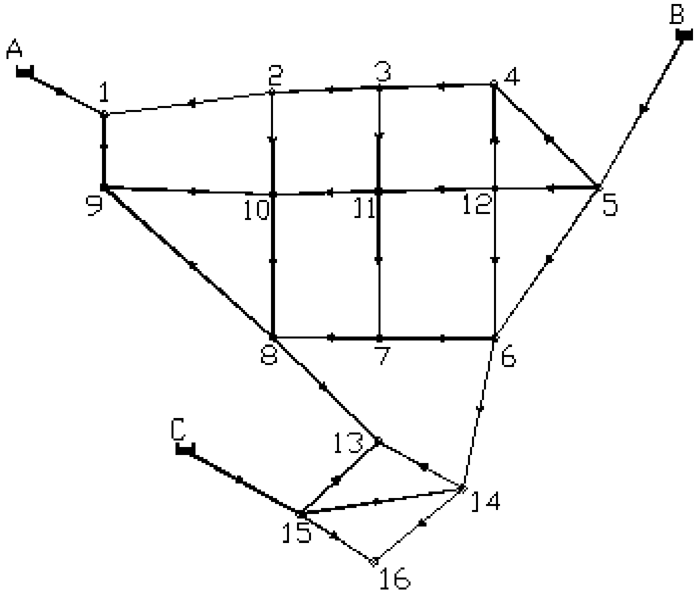

Fig. 4. Water distribution network in case study No. 1 (Jeppson, 1976)

Table 1. Pipe and nodal data for the network of Fig. 4

Node No.	Elevation (ft)	Demand (ft^3/s)	Pipe No.	First Node	End Node	Length (ft)	Diameter (in)	Roughness Coefficient
1	1120	0	1	1	2	9000	10	130
2	1100	0	2	2	3	6000	8	130
3	1080	0	3	3	4	7200	10	120
4	1083	1.11	4	4	5	12000	10	120
5	1150	0	5	5	6	16800	10	120
6	1080	0.89	6	6	7	6600	6	120
7	1085	0	7	7	8	6000	8	120
8	1076	0	8	8	9	15000	4	120
9	1100	1.34	9	9	1	5000	10	100
10	1080	0	10	9	10	7800	6	100
11	1082	1.56	11	10	11	6000	6	100
12	1100	0	13	12	5	6000	12	130
13	1086	1.11	14	10	8	9600	6	120
14	1080	1.34	15	2	10	6600	6	120
15	1110	0.89	16	7	11	9600	6	120
16	1074	1.11	18	6	12	6900	6	120
			19	12	4	7800	6	120
			20	13	14	6000	4	130
			21	13	15	7200	8	120
			22	14	16	6200	8	120
			23	16	15	6600	8	120
			24	15	14	10800	10	120
			28	14	6	6600	12	120
			17	3	11	7200	6	130
			12	11	12	6600	10	130
			29	13	8	1000	8	100
			26	1	17	1010	12	100
			27	5	18	2010	16	100
			30	15	19	1000	16	100

Table 2. Time patterns of water consumption

Time (hr)	0	1	2	3	4	5	6	7	8	9	10	11
Demand Factor	0.63	0.59	0.55	0.6	0.71	0.81	1.02	1.23	1.32	1.3	1.19	1.08
Time (hr)	12	13	14	15	16	17	18	19	20	21	22	23
Demand Factor	0.98	0.87	0.85	1.04	1.15	1.25	1.5	1.46	1.34	1.27	1.11	0.74

chlorine shortage. In this section, injection is performed with constant rate only in reservoir B, because this reservoir has the better hydraulic condition for chlorine distribution in the system than the other reservoirs.

As can be seen in Table 3, residual chlorine concentration in nodes 1, 2, 9, 10, 13, 14, 15 and 16 has smaller value than the minimum standard limit (here, 0.2 mg/l) because of the hydraulic condition. Therefore, it is concluded that more than one chlorine source is required to satisfy the standard range in this network.

- Injection in two reservoirs

In this scenario injection is performed with constant rate in two reservoirs at all times as the residual chlorine concentration in the closest node to the reservoirs is equal to the maximum standard value (here, 0.5mg/l). By studying the results in Table 3 it can be seen that by injection in reservoirs A and B, the residual chlorine concentration in nodes 13, 14, 15 and 16 and by injection in reservoirs B and C, the residual chlorine concentration in nodes 1, 2, 9 and 10 is smaller than the minimum standard value. Therefore, with

Table 3. Residual chlorine resulted from different injection scenarios in reservoirs (mg/l)

	Node No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Reservoirs	**B**	0	0	0.28	0.47	0.5	0.46	0.32	0.22	0	0	0.43	0.48	0.07	0.19	0	0.03
	A,B	0.49	0.42	0.28	0.46	0.5	0.46	0.35	0.34	0.46	0.41	0.46	0.48	0.11	0.19	0	0.03
	B,C	0	0	0.28	0.46	0.5	0.46	0.43	0.32	0.21	0	0	0.48	0.38	0.44	0.49	0.45
	A,B,C	0.5	0.44	0.28	0.48	0.5	0.46	0.35	0.35	0.48	0.43	0.48	0.49	0.45	0.46	0.5	0.46

maximum amount of injection in two reservoirs, some nodes do not still satisfy the standard range.

- Injection in three reservoirs

In this scenario, firstly chlorine is injected into the three reservoirs A, B and C as the residual chlorine in the nearest node to each reservoir is 0.5 mg/l. Injection value in reservoirs A, B and C are 0.151 mg/l, 0.508 mg/l and 0.51 mg/l, respectively. Based on Table 3, the residual chlorine concentration in all of nodes are within the standard range.

It can be concluded that injection in one quality source is not sufficient in many water distribution networks. In this case, sufficient chlorine value in the total nodes is obtained by the injection in all three quality sources. From these results, it is found that the total amount of chlorine injected into the network may be decreased by optimization of chlorine dosage. For this reason, the presented Genetic Algorithm method is applied for optimization of chlorine dose in three reservoirs of this case study in two states: injection with constant rate and injection with periodic rate.

Optimal injection with constant rate

Decision variables are three amounts of chlorine injection in reservoirs A, B and C. After the optimization procedure, the optimal injection rate at each reservoir is obtained and shown in Table 4. Also, the values of Genetic Algorithm's parameters are introduced in Table 5.

Injection with periodic rate

The goal of this section is to obtain the optimized chlorine injection in all of the reservoirs by periodic rate. In this scenario each day has been divided into 6-hour periods. Hence, number of decision variables is 12 (4 periods and 3 reservoirs). The optimal chlorine dose in reservoirs and values of Genetic Algorithm's parameters can be seen in Tables 4 and 5, respectively. Comparison of the results of Table 4 shows that with variable rate injection through a day, the total consumptive chlorine is reduced by 6%.

Table 4. Optimal chlorine dose with constant and periodic rate injection (mg/l)

Reservoir	Constant injection	Periodic injection				
		Period 1	Period 2	Period 3	Period 4	Daily Average
A	0.281	0.231	0.274	0.242	0.274	0.255
B	0.467	0.459	0.45	0.459	0.436	0.451
C	0.239	0.224	0.231	0.208	0.21	0.218
Total	0.987					0.924

Table 5. Genetic Algorithm's parameters

Genetic Algorithm parameters	Values for constant rate	Values for periodic rate
Population Size	50	70
Number of Generations	450	600
Probability of Crossover	0.7	0.8
Probability of Mutation	0.002	0.0015

Test Example No. 2

For the second example, water distribution network of Fig. 5 (taken from Munavalli and Mohan Kumar, 2003) is considered. This water network has 36 nodes that node 1 is pump station and node 36 is a storage tank. This tank has a cylindrical shape with 50 ft diameter and minimum water level of 50 ft and maximum water level of 70 ft. Chlorine is injected by some boosters.

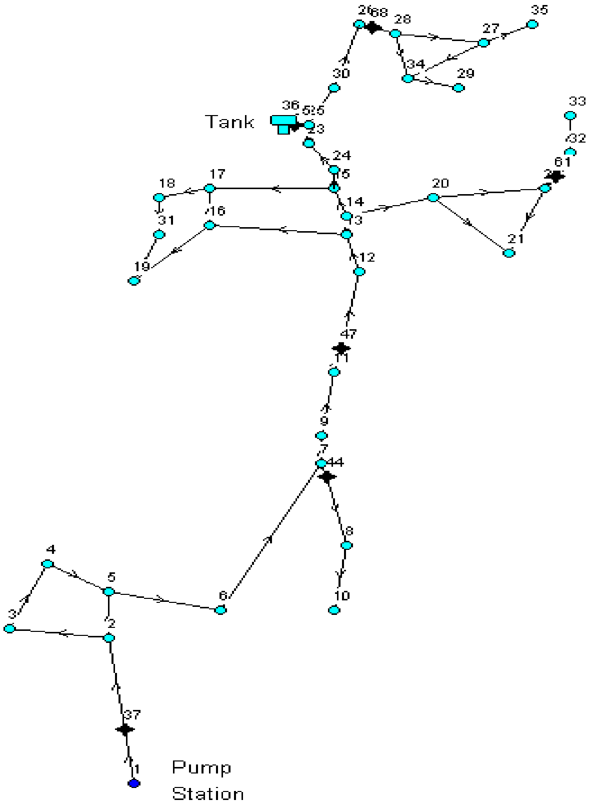

Fig. 5. Water distribution network in case study No. 2 (Munavalli and Mohan Kumar, 2003)

This test network has been modeled in two parts. In the first state, the proposed method is applied and the results are compared with outputs of Munavalli and Mohan Kumar (2003) for selection of chlorine sources. Munavalli and Mohan Kumar (2003) selected 6 nodes as the chlorine sources by trial and error method. In this paper by application of the proposed methodology, the optimized chlorine dose in these six boosters has been determined for 4 periods of simulation (Table 6). The results illustrate that application of the proposed optimization model could reduce the chlorine dosage in predetermined sources considerably. Except nodes 40 and 41 during time periods 1, 2 and 4, this reduction (up to 80%) is remarkable.

In the second part, optimal points for injection are obtained using the suggested model. As illustrated before, it is assumed that chlorine boosters are installed in all nodes and chlorine dosage in these nodes is then optimized. Based on the results, some of the nodes have very small chlorine dose value and few of them have considerable value. After considering the boosters in 34 nodes and running the model, results show that there are only 8 nodes with considerable chlorine dosage. Thus, these 8 points are selected as the suitable chlorine sources. Results of this optimization are shown in Table 7.

After this selection, in addition to the optimization of chlorine dose, number of chlorine boosters is decreased while all of the constraints are satisfied. Therefore, based on the proposed method, there is totally 8 nodes as potential injection points in this network (M=8) in which K nodes must be selected (K≤M) to find the best sources for chlorine injection and booster installation. Table 7 shows that the nodes

Table 6. Optimal Chlorine dose resulted from injection in selected boosters by Munavalli and Mohan Kumar (2003) (mg/min)

		Injection Nodes					
		37	38	39	40	41	42
Period 1	a	1250.02	11.18	629.13	16.16	3.14	699.7
	b	924.485	9.39	128.73	20.47	3.52	523.67
	c	26.04	16.01	79.54	-26.67	-12.1	25.16
Period 2	a	0	3.93	15.59	12.52	6.25	601.36
	b	0	3.64	10.3	16.23	6.18	466.07
	c	0	7.38	33.93	-29.63	1.12	22.5
Period 3	a	1394.98	9.38	531.73	12.04	0.85	526.5
	b	994.07	8.17	113.28	16.62	0.68	414.22
	c	28.67	12.9	78.7	38.04	20	21.33
Period 4	a	0	4.06	10.25	13.67	2.36	250.14
	b	0	3.85	10.3	18.08	2.6	203.18
	c	0	5.17	0.49	-32.19	-10.17	18.77

[a] Optimal Chlorine dose by Munavalli and Mohan Kumar (2003)
[b] Optimal Chlorine dose in this paper
[c] Percentage of reduction against Munavalli and Mohan Kumar (2003)

Table 7. Optimal Chlorine dose resulted from injection in eight selected nodes, K=8 (mg/min)

Injection Nodes	Period 1	Period 2	Period 3	Period 4
37	1209.66	0	1439.34	0
44	11.58	4.05	8.46	4.17
47	724.31	14.43	382.13	14.91
45	0	2.16	0	1.3
61	4.02	7.19	1.91	2.94
65	609.19	523.9	459.94	222.35
68	12.18	8.42	8.59	10.68
70	2.74	0.68	2.27	1.01

45, 61 and 70 have lesser chlorine dose in comparison with other nodes. By studying these results, the best value for K can be 5 or 6. If K=6, the results of dynamic modeling of water network with periodic rate of injection are calculated and shown in Table 8. Also, the results of optimization for five nodes, K=5, have been shown in Table 9. It is clear that residual chlorine concentrations for K=6 in this study is more acceptable than K=5. These nodes are highlighted in Fig. 5.

Table 8. Optimal Chlorine dose resulted from injection in six selected nodes, K=6 (mg/min)

Injection Nodes	Period 1	Period 2	Period 3	Period 4
37	952.61	0	1024.31	0
44	6.84	2.53	5.82	2.67
47	109.76	8.78	96.59	8.78
68	14.64	10.78	15.93	13.68
61	3.66	7.03	0.56	2.88
65	490.11	430.32	401.89	197.02

Table 9. Optimal Chlorine dose resulted from injection in five selected nodes, K=5 (mg/min)

Injection Nodes	Period 1	Period 2	Period 3	Period 4
37	1173.89	0	1349.31	0
47	161.22	20.73	230.32	20.73
68	12.72	8.84	12.06	10.26
61	2.03	4.23	0.51	1.52
65	569.04	501.32	458.08	209.41

Also, Table 10 presents the percentages of residual chlorine and total required chlorine in the network for different optimization scenarios, respectively. When six boosters are considered, 93.1% of residual chlorine is in the range of 0.2-0.5 mg/l and 100% of them are smaller than 0.8 mg/l).This results show 19.4% improvement in comparison with results of the model (optimum injection value in the selected boosters by Munavalli and Mohan Kumar, 2003) and 26.8% improvement in comparison with results of the trial and error method of Munavalli and Mohan Kumar (2003).

It can be seen that 73.7% of residual chlorine values are smaller than 0.5 mg/l and 100% of the results are smaller than 0.8 mg/l. But in the other research (Munavalli and Mohan Kumar, 2003) residual chlorine in 66.3% of nodes is smaller than 0.5 mg/l and 92% of them are smaller than 0.8 mg/l. Therefore, the results of this paper show improvement about 8%. Some reasons for this improvement may be change in Genetic Algorithm parameters, change in constraints of the problem and allocation of importance coefficient to nodes of the system based on their water consumption.

CONCLUSION

In this paper a comprehensive study for quality optimization of water distribution network was presented. Two quality-hydraulic simulation model (EPANET2) and Genetic Algorithm model were integrated by application of MATLAB 7 software. This study consisted of two parts: in the first part, by application of the integrated model, optimal chlorine dosage injected into the existing reservoirs was obtained which satisfies the standard range of residual chlorine in total nodes of water distribution system. In the second part, a method was introduced for the optimal placement of chlorine injection in the system. The ability of integrated model was examined by two test examples. In the first one chlorine injection in different number of quality sources was studied and then injection dose with constant and periodic rates was optimized. This fact was proved that selection of more than one point as the chlorine sources and application of periodic injection method for them can be very useful to keep nodal residual chlorine concentration within the standard range (0.2-0.5 mg/l).

Table 10. Comparison of the residual chlorine between different scenarios

Methodology	Residual Chlorine (%)		Total Required Chlorine (gr/day)
	Below 0.5 (mg/l)	Below 0.8 (mg/l)	
Munavalli andMohan Kumar (2003)	66.3	92	2167.7
This study: injection in 6 selected points by Munavalli and Mohan Kumar (2003)	73.7	100	1403.2
This study: K=5	90.9	98.8	1708.1
This study: K=6	93.1	100	1370.61

In the second example, optimization of booster's arrangement and amount of injection in these boosters were implemented. Results of this study showed some improvements in comparison with previous researches in two factors: smaller chlorine consumption in the system and higher percentage of residual chlorine in the standard range. Therefore, the proposed methodology can optimize the location of chlorine injection and chlorine dosage, simultaneously. The results of this study can be very helpful for increasing the reliability of water quality management in water distribution network and minimizing the total operating cost of these systems.

REFERENCES

Al-Zahrani, M. A. and Moied, K. (2003). Optimization water quality modeling stations using genetic algorithm. The Arabian Journal for science and Engineering, **28 (1B)**, 57-75.

Ardestani, M. and Sabahi, M. S. (2009). Inverse Method to Estimate the Mass of Contamination Source by Comparing Analytical with Numerical Results. Int. J. Environ. Res., **3 (2)**, 317-326.

Boccelli, D. L., Rossman, L. A., Tryby, M. E., Uber, J. G, Zierolf, M. L., and Polycarpou, M. M. (1998). Optimal scheduling of booster disinfection in water distribution system. Water Resources Planning and Management, **124 (2)**, 99-111.

Broad, D. R., Dandy, G. C. and Maier H. R. (2005). Water distribution system optimization using metamodels. Water Resources planning and management, ASCE, **131 (3)**, 172-180.

Clark, R. M., Grayman, W. M., Males, R. M. and Hess, A. F. (1993). Drinking-water distribution system. Environmental Engineering, ASCE, **119 (2)**, 349-364.

Dandy, G. C., Simpson, A. R. and Murphy, L. J. (1996). An improved genetic algorithm for pipe network optimization. Water Resources Research, **32 (2)**, 449-458.

Etemad-Shahidi, A, Afshar, A., Alikia, H. and Moshfeghi, H. (2009). Total Dissolved Solid Modeling; Karkheh Reservoir Case Example. Int. J. Environ. Res., **3 (4)**, 671-680.

Etemad-Shahidi, A., Faghihi, M. and Imberger, J. (2010). Modelling Thermal Stratification and Artificial De-stratification using DYRESM; Case study: 15-Khordad Reservoir. Int. J. Environ. Res., **4 (3)**, 395-406.

ISIRI, (1997). Institute of Standard & Industrial Research of Iran, Physical and chemical properties of drinking water. Standard No. 1053, Iran.

Jeong, K. S., Kim, D. K., Shin, H. S., Kim, H. W., Cao, H., Jang, M. H. and Joo, G. J. (2010). Flow Regulation for Water Quality (chlorophyll a) Improvement. Int. J. Environ. Res., **4 (4)**, 713-724.

Jeppson, R.W. (1976). Analysis of Flow in Pipe Networks. Ann/Arbor science publishers, Inc.

Lee, B. H. and Deineinger, R. A. (1992). Optimal locations of monitoring stations in water distribution system. Environmental Engineering, ASCE, **118 (1)**, 4-16.

Liou, C. P. and Kroon, J. R. (1987). Modeling the propagation of waterborne substances in water distribution networks. J. American Water Works Association, **79 (11)**, 54-58.

Munavalli, G. R. and Mohan Kumar, M. S. (2003). Optimal scheduling of multiple chlorine sources in water distribution systems. J. Water Resources Planning and Management, ASCE, **129 (6)**, 493-504.

May, R. J., Dandy, G. C., Maier, H. R. and Nixon, J. B. (2008). Application of partial mutual information variable selection to ANN forecasting of water quality in water distribution systems. Environmental Modeling & Software, **23 (10-11)**, 1289-1299.

Naik, V. K. and Manjapp, S. (2010). Prediction of Dissolved Oxygen through Mathematical Modeling. Int. J. Environ. Res., **4 (1)**, 153-160.

Ostfeld, A. and Salamons, E. (2006). Conjunctive optimal scheduling of pumping and booster chlorine injections in water distribution systems. J. Engineering Optimization, **38 (3)**, 337-352.

Rajasimman, M., Govindarajan, L. and Karthikeyan, C. (2009). Artificial Neural Network Modeling of an Inverse Fluidized Bed Bioreactor. Int. J. Environ. Res., **3 (4)**, 575-580.

Reis, L. F. R., Porto, R. M. and Chaudhry, F. H. (1997). Optimal location of control valves in pipe networks by genetic algorithm. J. Water Resources Planning and Management, **123 (6)**, 317-326.

Rossman, L. A. (2000). EPANET 2 user manual, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Rossman, L. A., Clark, R. M. and Grayman, W. M. (1994). Modeling chlorine residuals in drinking water distribution systems. Environmental Engineering, ASCE, **120 (4)**, 755-761.

Rouhiainen, C. J., Tade, C. and West, G. (2003). Multi-objective genetic algorithm for optimal scheduling of chlorine dosing in water distribution systems In: Maksimovic C., Butler D. and Memon F.A. (eds.). J. Advances in Water Supply and Management. Swets and Zeitlinger, Lisse, 459-558.

Santhanam, H. and Amal Raj, S. (2010). A new Fuzzy-LOGIC based Model for Chlorophyll-a in Pulicat Lagoon, India, Int. J. Environ. Res., **4 (4)**, 837-848.

Savic, D. A. and Walters, G. A. (1997). Genetic algorithms for least cost design of water distribution networks. J. Water Resources Planning and Management, **123 (2)**, 67–77.

Todini, F. and Pilati, S. (1987). A gradient method for the analysis of pipe networks. In: Proceedings of the International Conference on Computer Applications for Water Supply and Distribution, Leicester Polytechnic, UK, September 8-10.

WHO, (1993). Guidelines for drinking water quality -Vol. II, health criteria and other supporting information, Geneva.

Zhang, H. H., Zeng, Y. N. and Bian, L. (2010). Simulating Multi-Objective Spatial Optimization Allocation of Land Use Based on the Integration of Multi-Agent System and Genetic Algorithm. Int. J. Environ. Res., **4 (4)**, 765-776.