J Environ. Science & Engg. Vol. 57, No. 1, p. 64-73, January 2015

Use of Optimization Technique for Optimal Scheduling of Booster Chlorination in Drinking Water Distribution Systems

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Chlorine concentration is an important parameter used to assess the quality of water supplied by a distribution network. Incontrast to conventional methods that apply disinfectant only at the treatment works or source, booster disinfection reapplies disinfectant at strategiclocations within the distribution system to compensate for the losses that occur as it decays over time. Booster disinfection strategy can reduce the mass of disinfectant required to maintain a detectable residual at points of consumption in the distribution system, which may lead to reduced formation of disinfectant by products such as Trihalomethanes also. The aim of present study is to formulate an optimization model using Liner Programming in Excel by coupling the results of residual chlorine obtained using EPANET software for selection of location of Booster chlorination stations as well as to optimize the Chlorine mass rate injections for the steady state flow conditions. Results from application of the formulated model suggest that schedule minimizes the total dose required to satisfy residual constraints of 0.2 mg/L (IS 10500-1991) at all the locations within distribution network as compared to conventional chlorination in which chlorine is applied at source only.The use of optimization method to select the scheduling of Booster stations can be used as the decision making tool for the water supply authority for the selection of location and number of booster station along with the application of chlorine mass rate to maintain the residual chlorine as 0.2 mg/L at all the locations in Drinking Water Distribution system.

Key words: *Drinking water distribution system, Booster chlorination, optimization model, linear programming*

Introduction

To control the pathogenic microorganisms in drinking water distributionsystems generally disinfectant is added at the supply source commonly known as conventional method. Since disinfectants arereactive, the residence time of water in the distribution network can deplete the disinfectant residual at the edges of thedistribution network and in storage reservoirs. Therefore, the source concentration must be large enough to maintain adequatedisinfectant residuals throughout the distribution system,which may cause taste and odour complaints by consumers receivingthe higher disinfectant concentrations. Additionally,disinfectants, such as chlorine and chloramines, have also beenshown to be potential carcinogens at various concentrations[1]. Thus, the quality of water supplied by a distribution network is usuallyassessed by evaluating residual chlorine concentrations, if they aremaintained between lower and upper bounds, to ensure good disinfectingproperties and avoid poor tasting water.The booster chlorination strategy allows the water utilities to meet disinfection goals by providing proper balance between the minimum and maximum concentration of chlorine[1-2].

The determination of chlorine concentrations throughout a pipe network under steady or unsteady hydraulic and water quality conditions is of particular interest. Determination of the best disinfection strategy is also a critical step in water distribution network management.Chlorine concentration simulators like EPANET[3] are currently available and enable the prediction of chlorine distribution in a network under

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steady or unsteady conditions. The optimal control of chlorine concentrations at the application point is very essential to balance betweenexcessive disinfectant concentrations near the source or loss of pathogen control at the network periphery. Decision maker sneed optimization tools to determine the best chlorine injection schedule for each source and booster station in a distribution system.Various researchers used the optimization technique for scheduling and optimal locations of booster disinfectant in drinking water distribution system. Boccelli utilized the principle of linear superposition for optimal scheduling of booster disinfectant in drinking water distribution system[1]. Tryby presented the model related to the general fixed-charge facility location problem and is formulated as a mixed integer linear programming problem which allows the optimal location andscheduling of booster injection stationsin drinking water distribution networks[2].An optimal scheduling model was formulated in terms of a nonlinear optimization problem to determine the chlorine dosage at the water quality sources subjected to minimum and maximum constraints on chlorine concentrations at all monitoring nodes by linking EPANET with a genetic algorithm (GA)[4]. Investigation was carried out about the booster facility location and injection scheduling problem in water distribution networks using the theory of linear super position in water quality modeling for calculating concentration profiles at network nodes[5]. The methodology and application of a genetic algorithm (GA) scheme, tailor-made to EPANET for simultaneously optimizing the scheduling of existing pumping and booster disinfection units, as well as the design of new disinfection booster chlorination stations, under unsteady hydraulics was developed[6]. A linear least-squares problem and a mixed-integer quadratic programming (MIQP) was formulated to determine the optimal disinfectant injection rates that minimize variation in the system residual space-time distribution[7,8]. Formulation of a real-time optimal valve operation coupled with booster disinfection problem as a single objective optimization model and solved using a genetic algorithm (GA) linked with EPANET carried out to improve water quality[9]. An optimization model for locating optimal booster chlorination stations in water distribution systems using hybrid PSO, combined with GA algorithms was proposed [10]. Safety and maintenance issues, related to the physical location and operation of an actual booster station, may be a practical concern but should not prohibit utilities from implementing booster disinfection. Safety and maintenance issues, related to the physical location and operation of an actual booster station, may be a practical concern but should not prohibit utilities from implementing booster disinfection.

The objective of present paper is to develop a mathematical model to optimize the booster chlorination doses with the help of linear programming method of optimization. North Harni Drinking Water Distribution Network, Vadodara, Gujarat is selected for development of optimization problem. The systems approach presented here identifies such opportunities, by simultaneously selecting different mass rates of chlorine doses at multiple booster locations based on several competing objectives, subject to constraints and first order decay of chlorine throughout the distribution system. The objectives considered includes: (1) minimization of the total mass rate of chlorine at Booster stations and (2) maintenance of minimum 0.2 mg/L of residual chlorine at all the critical nodes within distribution network.

Solver function of Excel is used for solving optimization problem. The result of the optimization method suggests that the selection of number and location of Booster station as well as the mass rate to be applied at various locations reduces while maintaining the minimum residual chlorine concentration of 0.2 mg/L at all the locations in DWDS as compared to conventional chlorination.

Optimization technique

Optimization problems are real world problems we encounter in many areas such as mathematics, engineering, science, business and economics. In these problems, we find the optimal, or most efficient, way of using limited resources to achieve the objective of the situation. Mathematically the process of optimization is to find out the conditions which maximize / minimize (extremize) the function.The aim of the optimization is to find values of the variables that minimize or maximize the predefined objective function while satisfying the constraints. For the given problem, we formulate a mathematical description called a mathematical model to represent the situation.The general form of an optimization model is given by following formula:

Min or Max $f(x_1,...,x_n)$ (Objective function)

Subject to $gi(x_1,...,x_n) \geq 0$

(Unequality constraints)

$\phi i\ (x_1,...,x_n) = 0$ (Equality constraints)

$x_1 \geq 0, x_n \geq 0$ (Non negativity constraints)

$x_1,...,x_n$ are called design/decision variables

Number of Optimization algorithms is suitable to solve a particular type of optimization problem. The choice of a suitable algorithm for an optimization problem is dependent on the user's experience in solving similar types of problems. The various methods of mathematical programming or optimization techniques are Calculus methods, Calculus of variations, Nonlinear programming, Geometric programming, Quadratic programming, Linear programming, Dynamic programming,Integer programming, Stochastic programming , Separable programming, Multi objective programming network methods: CPM and PERT, Game theory, Stochastic process techniques such as Statistical decision theory, Markov processes, Queueing theory, Renewal theory, Simulation methods, Reliability theory, Modern or nontraditional optimization techniqueslikeGenetic algorithms, Simulated annealing, Ant colony optimization, Particle swarm optimization, Neural networks and Fuzzy optimization[11,12].

Linear programming

Linear programming is an optimization method applicable for the solution of problems in which the objective function and the constraints appear as linear functions of the decision variables. The constraint equations in a linear programming problem may be in the form of equalities or inequalities. Linear programming is considered a revolutionary development that permits us to make optimal decisions in complex situations[11].

The general linear programming problem can be stated in the following standard scalar form as given by:

$$\text{Minimize } f(x_1, x_2, \ldots, x_n) = c_1x_1 + c_2x_2 + \ldots + c_nx_n \quad \ldots(1)$$

subject to the constraints

$$a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n = b_1$$

$$a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n = b_2$$

$$\ldots$$

$$a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n = b_m \quad \ldots(2)$$

$$x_1 \geq 0$$

$$x_2 \geq 0$$

$$x_n \geq 0 \quad \ldots(3)$$

where c_j, b_j, and a_{ij} ($i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$) are known constants, and x_j are the decision variables.

Although several other methods have been developed over the years for solving LP problems, the Simplex method continues to be the most efficient and popular method for solving general LP problems. The Simplex Algorithm developed by Dantzig (1963) is used to solve linear programming problems. This technique can be used to solve problems in two or higher dimensions.

The Solver option in EXCEL 2000 and earlier versions may be used to solve linear and nonlinear optimization problems. Integer restrictions may be placed on the decision variables. Solver may be used to solve problems with up to 200 decision variables, 100 explicit constraints and 400 simple constraints[13].

Materials and methods

The proposed North Harni Drinking Water Distribution System covering part of northern area of Vadodara is selected for development of optimization problem. The network modelled has 74 consumer nodes, one source node R_1, one pumping station, one storage tank (Node 1), and 87 links. Consumer nodes (nodes 2-75) represent water demand locations for nearby areas while booster nodes (nodes A to D) represent locations of inline disinfectant addition. Two cases of Booster chlorination along with source application of chlorine are considered for optimization problem. Case I represents the source application of chlorine along with Booster doses applied at Booster station A to D, while in case II chlorine is applied with source application of chlorineand booster doses applied at Booster stations C and D only .The water distribution network for the study area for case I is shown in Fig. 1.For the same network only the source chlorination is applied to check the effectiveness of the Booster chlorination. The demand at various nodes is considered to be steady state and satisfied by supplying the water in two hours a day. The link data includes connectivity, length, diameter, and roughness information. The cylindrical tank at node 1 is modelled as a continuous flow stirred tank reactor. Consider minimization of the total chlorine mass rateapplied at known booster locations along with the source application at $R_1$is selected based on trial and error method to maintain 0.2 mg/L residual chlorine at all the nodes before application of optimization technique. The objective of using optimization technique fo

:heduling of booster dose at booster stations is tended as additional benefit of minimizing both DBP rmation and chemical costs, thoughactual reduction DBP formation cannot be quantified at thistime since e factors affecting DBP formationkinetics arepoorly iderstood. The mass injections are required to satisfy wer bound constraints (0.2 mg/L as per IS 10500,)91) on residual chlorine at all the locations of WDS.For optimization of Booster Chlorination doses the critical points are identified based on the trial and error method to obtain the 0.2 mg/L residual chlorine at all the nodes and covering all the directions at farthest locations. Using water quality simulation capability of EPANET software the six critical nodes i.e. Node No. 19, 27, 47,57 , 70 and 11 are identified for the source application along with booster chlorination at Nodes A, B, Cand D for case I and Booster Nodes C and D for Case II.

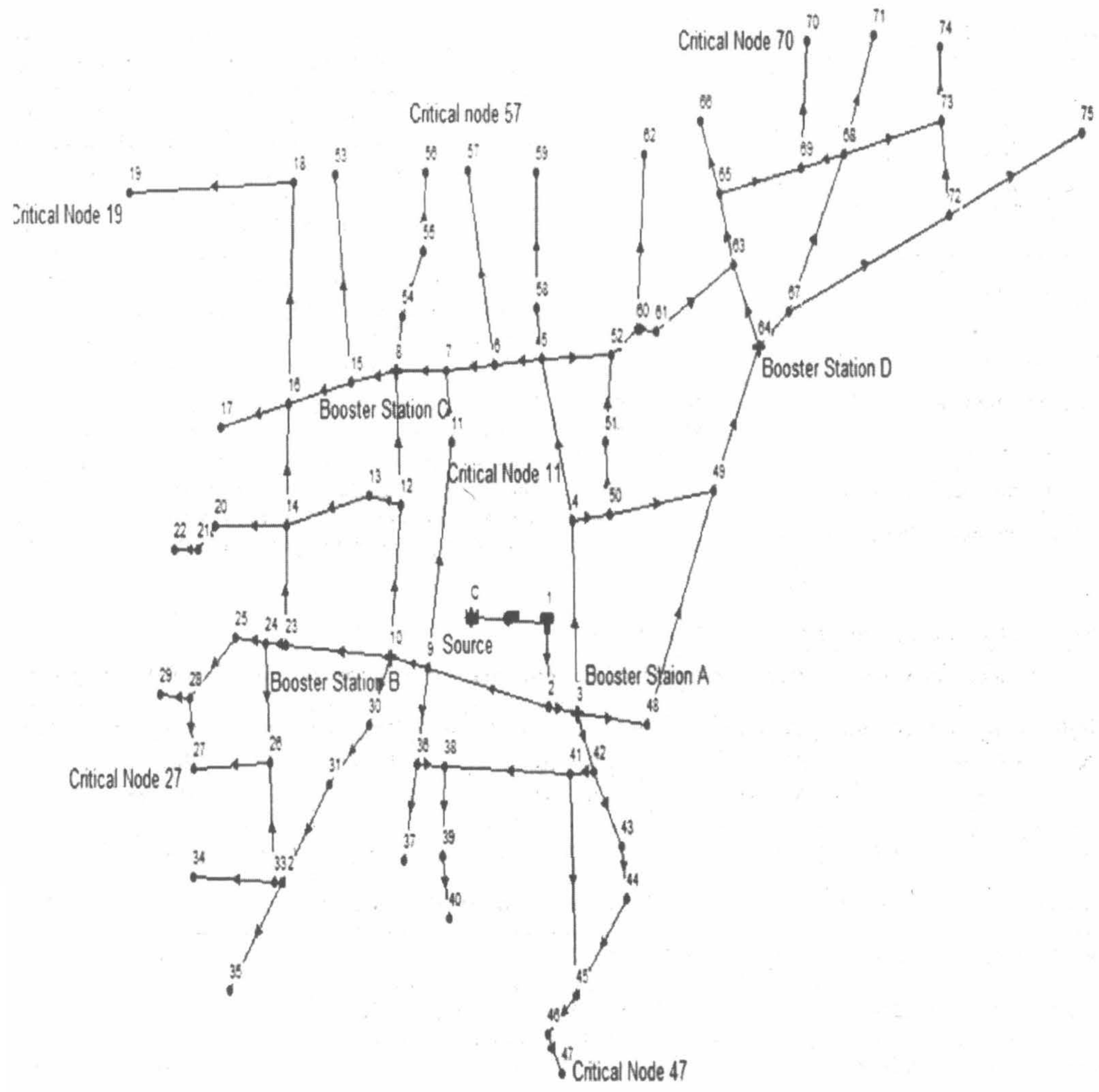

Fig 1: North Harni Drinking Water Distribution System Network for case I

For development of optimization model in excel, the booster chlorinationdose scheduling problem is mathematically formulated as

Minimize:

$$\sum_{i=1}^{n} Mi \qquad (1)$$

Subject to Constraints:

$$C_j = \sum_{j=1}^{m} \sum_{i=1}^{n} Ki,j\, Mi \geq 0.2 \qquad (2)$$

Non negativity constraints,

$$Mi \geq 0 \qquad (3)$$

Where,

i= Injection Nodes

j= Critical Nodes

m = Total numbers of critical nodes

n = Total number of Injection nodes

C_j = Chlorine concentration at junction node 1 to 6 corresponding to critical nodes 19, 27, 47, 57, 70 and 11 respectively, mg/L.

$K_{i,j}$= Constants corresponding to injection nodes 1 to 5 and critical nodes 1 to 6.

M_i = Mass rate injected at injection node 1 to 5 corresponding to injection location at Source, Booster Station A,Booster Station B, Booster Station C, Booster Station D respectively, mg/min.

Boccelli (1998) utilized principle of Linea superposition which implies that the effect of any singl disinfectant dose on the concentration is linear i disinfectant dose and that concentration is the sum o all individual disinfectant dose effects, which allowe the determination of impulse response coefficient t relate the effect of a unit mass injection at a give location and time on the disinfectant concentration a other locations and times[1]. The impulse respons coefficients mentioned by Boccelli (1998) ar mentioned as constants in equation 2, which ar obtained by using values of chlorine concentrations a critical locations using EPANET software.

For case I, with source application of chlorin along with chlorine injected from 4 booster nodes, th values of above mentioned constants are obtained fro the results of residual chlorine at node 19, 27, 47, 5 70, and 11 using EPANET software by running th extended period simulation separately when chlori

Table 1: Value of constants at critical nodes for case I

Node No	Values of Constants with application of Chlorine mass rate at critical nodes (mg/l) / (mg/min)									
	Only at Source, M_1	Value	Only at Booster A , M2	Value	Only at Booster B , M3	Value	Only at Booster C , M4	Value	Only at Booster D , M5	Value
Node 19	$K_{1,1}$	8.46E-06	$K_{2,1}$	6.67E-06	$K_{3,1}$	1.25E-05	$K_{4,1}$	0.000114	$K_{5,1}$	0
Node 27	$K_{1,2}$	1.15E-05	$K_{2,2}$	0	$K_{3,2}$	6.25E-05	$K_{4,2}$	0	$K_{5,2}$	0
Node 47	$K_{1,3}$	1.23E-05	$K_{2,3}$	2.67E-05	$K_{3,3}$	0	$K_{4,3}$	0	$K_{5,3}$	0
Node 57	$K_{1,4}$	1.23E-05	$K_{2,4}$	2.67E-05	$K_{3,4}$	0	$K_{4,4}$	0	$K_{5,4}$	0
Node 70	$K_{1,5}$	0.00001	$K_{2,5}$	2.67E-05	$K_{3,5}$	0	$K_{4,5}$	0	$K_{5,5}$	6.67E-0
Node 11	$K_{1,6}$	1.54E-05	$K_{2,6}$	0	$K_{3,6}$	0	$K_{4,6}$	0	$K_{5,6}$	0

is applied at source alone, only at Booster Station A, only at Booster Station B, only at Booster Station C and only at Booster station D. For example the value of residual chlorine is obtained after 10 days simulation in EPANET software as C_{19} by applying the chlorine mass rate M_1 at source only and $K_{1,1}$ is obtained as $C_{19}/M_1$by using formula $C_{19}= M_1K_{1.1}$gives the value of $K_{1.1}$ as 8.46E-06, similarly $K_{2,1}$ is obtained using formula $C_{19}= M_2K_{2.1}$for application of chlorine at only Booster Station A, $K_{3.1}$ is obtained using $C_{19}= M_3K_{3.1}$ for application of chlorine at only Booster Station B, $K_{4.1}$ using $C_{19}= M_4K_{4.1}$for application of chlorine at only Booster station C and $K_{5.1}$using $C_{19}= M_5K_{5.1}$for application of chlorine at only Booster Station D. Similarly the values of other constants are obtained for case I and Case II both. The summary of the constant obtained for case I is given in Table 1.

The optimization model with objective function as mentioned in equation 1 is organized in excel spreadsheet. Various constants as mentioned in Table 2 are used to apply the formula for the constraints in each cell of the excel spreadsheet. Non negativity constraints are applied on the chlorine mass rate application. Once themodel is implemented in a spreadsheet, use of the Solver function gives the optimum solution of Total mass rate to be applied to satisfy all the constraint at critical nodes. The results obtained after applying the linear programming technique in excel for case I and II gives the following results.

Results and discussion

The mass rate of chlorine to be applied at source along with four booster stations for case I and two booster stations for Case II after using the linear programming technique of optimizationin excel is tabulated in Table 1. The mass rate to be applied for only source chlorination is obtained as 1350 g/day.

The mass rate of chlorine to be applied at Booster stations obtained after optimization is applied on DWDS network using EPANET software to check

Table 2: Chlorine mass rate to be applied at various locations after using optimization.

Chlorine mass rate applied at various locations for 1 hour duration	Only source chlorination		Booster chlorination along with source application of chlorine			
			Case I		Case II	
	Total mass rate	Chlorine injection rate	Total mass rate	Chlorine injection rate	Total mass rate	Chlorine injection rate
	(g/day)	(mg/min)	(g/day)	(mg/min)	(g/day)	(mg/min)
Source	1350	22500	780	13000	1050	17500
Booster A	—	—	90	1500	—	—
Booster B	—	—	48	800	—	—
Booster C	—	—	36.75	612.5	26.25	437.5
Booster D	—	—	27	450	29.40	490
Total Mass rate applied,(g/day)	1350	22500	981.75	16362.5	1105.65	18427.5
% Reduction in mass rate of chlorine witha respect to source chlorination	—		27.28		18.1	

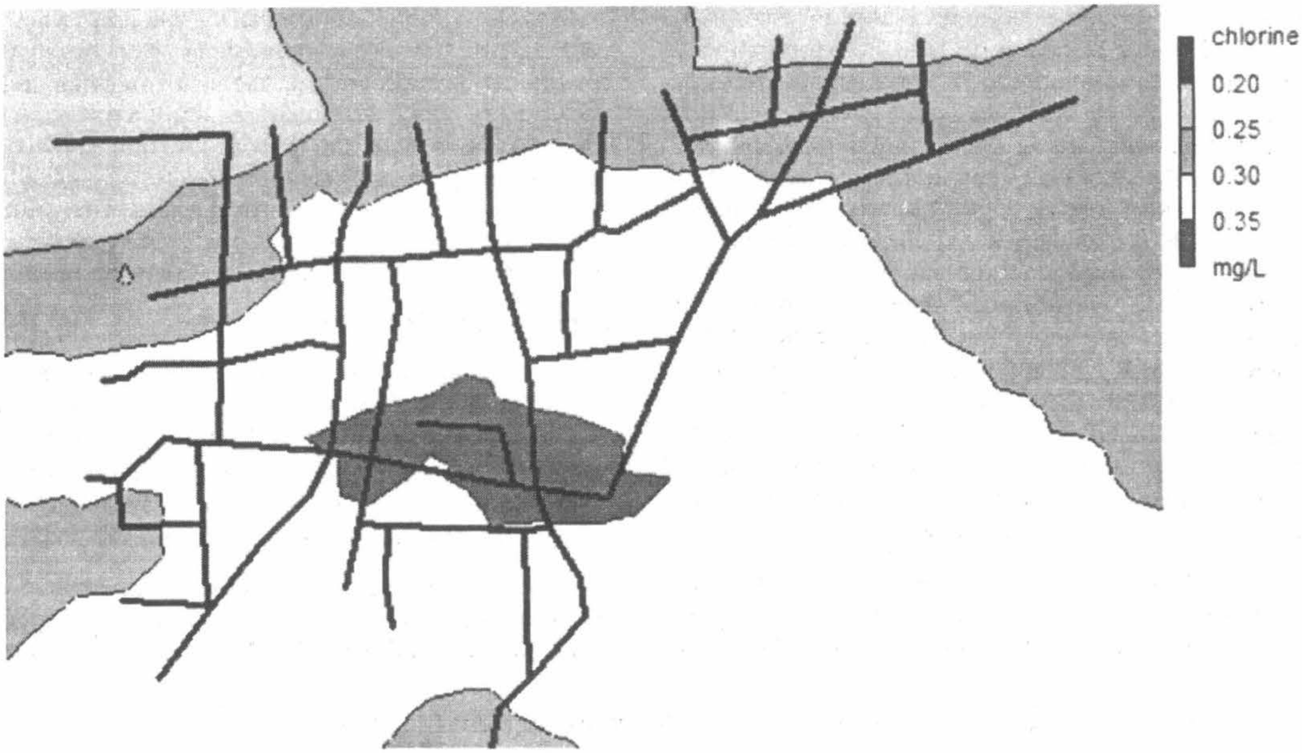

Fig 2: Contour plot of residual chlorine for conventional chlorination

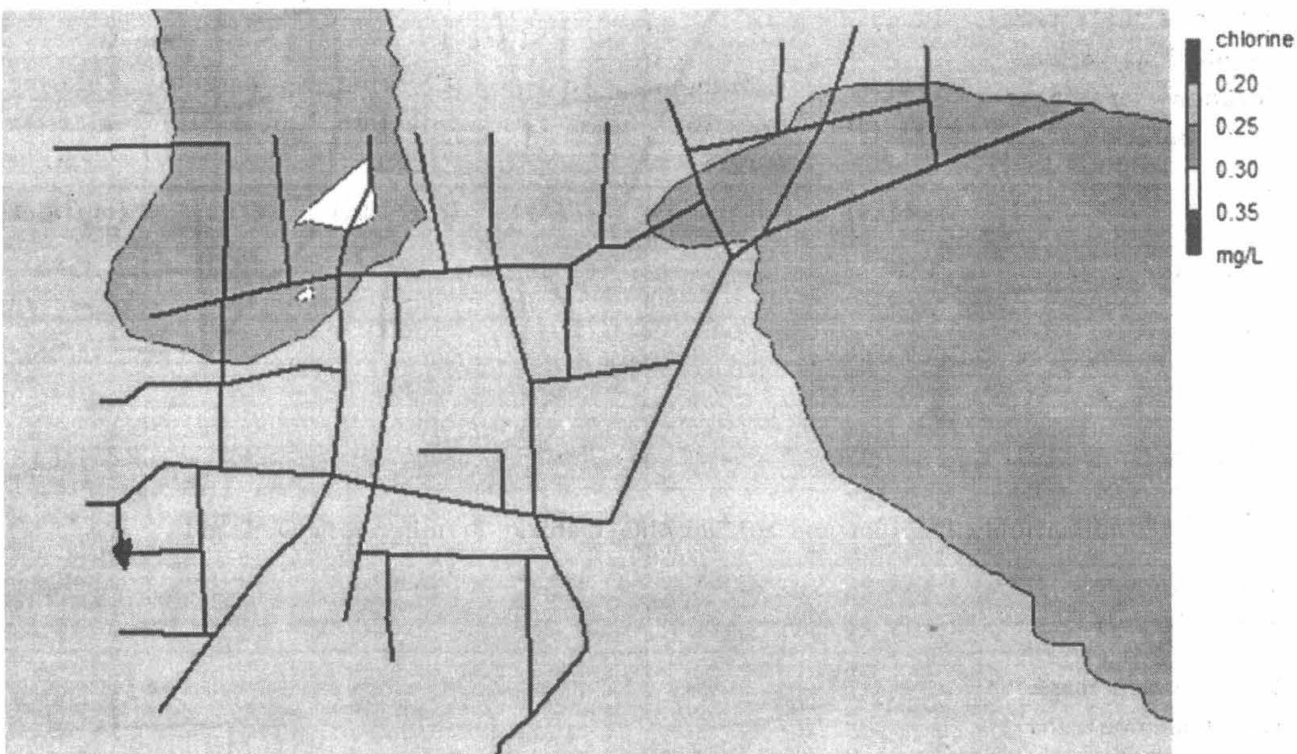

Fig 3: Contour plot of residual chlorine for booster chlorination for Case I

whether the constraints are satisfied at all the locations or not. Also the conventional strategy of chlorine application is applied to justify the use of booster chlorination. The application of chlorine mass rate only at source alone required 1350 g/day, while Booster chlorination for case I required 981.75 g/day and for case II it comes to be 1105.65 g/day to satisfy the constraints of 0.2 mg/L residual chlorine at all the locations in DWDS network.Fig. 2 shows the contour plot of residual chlorine at all the locations for conventional chlorination. Fig 3 and Fig 4 give the contour plot of residual chlorine at all the locations for Booster chlorinationalong with source application of chlorine for case I and case II respectively.

The results obtained suggest that the Network using conventional chlorination requires application of 1350 g/day chlorine mass rate at source alone to satisfy the constraint of 0.2 mg/L of chlorine concentration at critical node as well as all the locations. For the same network using optimization technique in excel with solver function suggests that for case I with 4 booster stations along with source application of chlorine at various locations in network satisfied the constraint with application of chlorine mass rate as 981.75 g/day which gives reduction of total mass rate of chlorine as 27.66%. For case II with 2 booster stations along source application of chlorine, requires 1105.65 g/day which gives 18.1% reduction in total mass rate of chlorine. Though, the percentage reduction is less in case II, but the installation operation and maintenance cost of Booster station may prove to be economical. As observed from the Fig. 2, 3 and 4, more uniform distribution of chlorine is observed for case I as compared to case II and only source chlorination, due to distribution of booster stations in all the direction. The results of residual chlorine concentration at various nodes using EPANET software for both the conditions, i.e. conventional chlorination and use of booster chlorination after using optimization technique suggest that the use of optimization is very important decision making tool for scheduling of chlorine injection rate. Booster chlorination strategy gives reduction in mass rate of chlorine at the same time the uniform distribution of chlorine is achieved throughout the distribution network while maintaining residual chlorine in the range of 0.2 mg/L at all the locations.

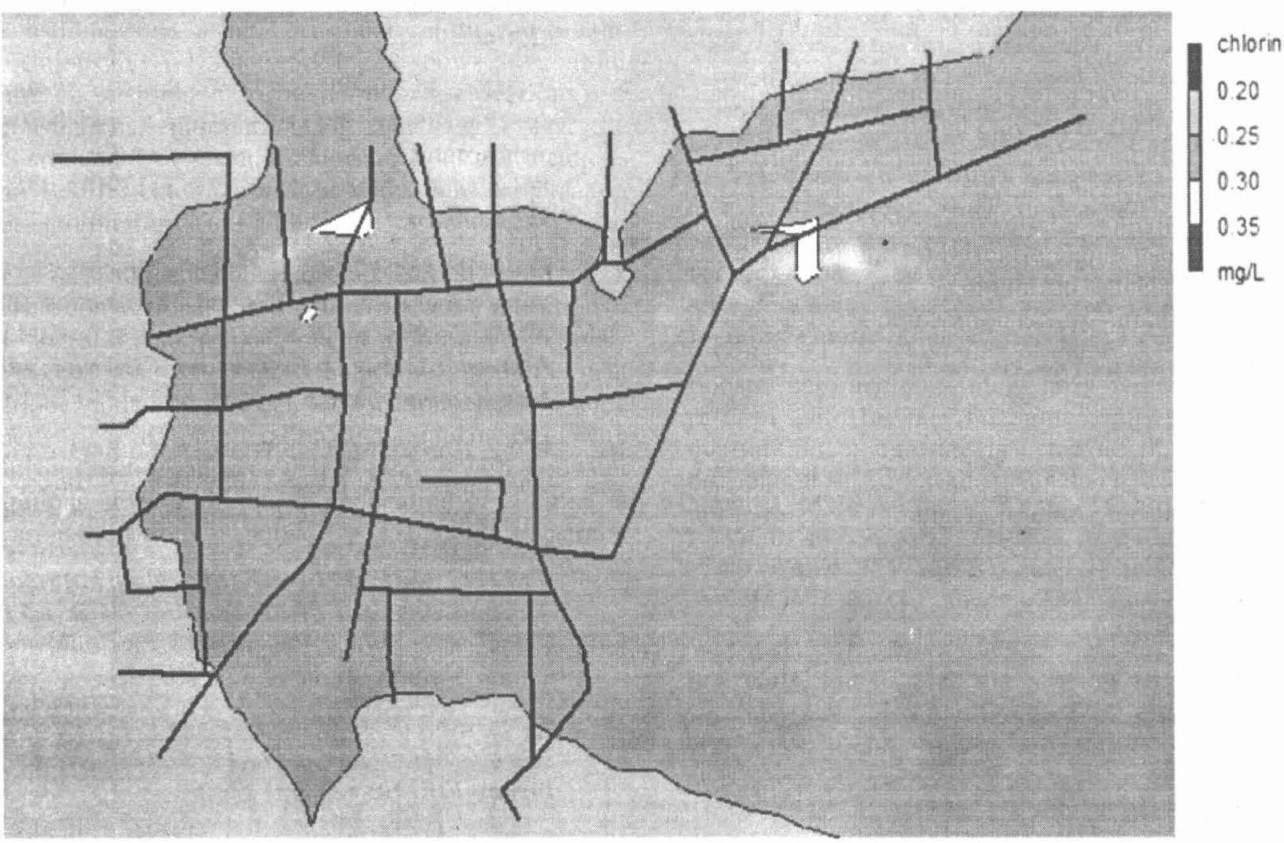

Fig4: Contour plot of residual chlorine for booster chlorination for Case II

Conclusion

An optimization model is developed to minimize the total mass rate of chlorine to be applied at multiple points in DWDS while satisfying the constraints of residual chlorine of 0.2 mg/L at all the locations. Principle of Linear Superposition is successfully used to develop the Optimization model to minimize the mass rate of chlorine. By selecting the few critical nodes, the size of the problem may be considerably reduced.As the problem is smaller in size, it can be solvedby solver functionof Excel to solve the linear equation of constrained optimization problem using linear programming optimization technique using the constant values obtained from the data of residual chlorine using EPANET software.The optimization result shows that the scheduling of the mass rate of chlorine as suggested by the optimization gives 27.66 % reduction for case I and 18.1% for case II as compared to conventional approach of application of chlorine at source alone. The selection of the Number of booster stations and scheduling of mass rate of chlorine may be selected based on the requirement of the water supply authority. The reduction of chlorine mass rate at Booster station or less number of booster stations results in overall economy for any project at the same time the reduced mass rate of chlorine results in reduced harmful disinfection by products. Booster chlorination allows lower average residual chlorine throughout the DWDS which results in more uniform distribution of residual chlorine as compared to conventional chlorination. Thus, coupling of data of EPANET software with Linear programming using Excel for optimization of chlorine mass rate is very important decision making tool for managing, scheduling and selection of number of Booster chlorination station for any Drinking Water Distribution System.

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