Chapter 5

Coupled Simulation - Optimization Model for Chlorine Management in Drinking Water Distribution Systems

5.1 Introduction

Optimization is the act of obtaining the best result under given circumstances. In design, construction, and maintenance of any engineering system, engineers have to take many technological and managerial decisions at several stages. The ultimate goal of all such decisions is either to minimize the effort required or to maximize the desired benefit. Optimization tools allow the user to evaluate a large number of options and to select the specific alternative that gives the best results in terms of predefined objective functions. The optimization algorithms work efficiently if number of design variables are small therefore, choose a few design variables as possible and the outcome of optimization procedure may indicate whether to include more design variables in revised formulation or to replace earlier design variables. Optimization algorithms are becoming increasingly popular in engineering design activities, because the availability and affordability of high speed computers. (Deb 2009; Raju 2009). In the area of water distribution system analysis, optimization models are used for calibration, design, and operational purposes (USEPA 2005). Models can be used to optimize operations of a distribution system (Goldman et al. 2000). The most common areas of operation where such models have been applied are in energy management and water quality. Chase et al. (1994) describe a computer program to control energy costs that incorporates a hydraulic model, a pump optimization program, and an interface. In the water quality area, Uber et al. (2003) used optimization techniques to determine optimal location and operation of chlorine booster stations.

5.2 Need for Simulation-Optimization Model

The combined simulation-optimization models greatly enhance the utility of simulation models by directly incorporating management goals and constraints into the modelling process (Barlow 2005). In the simulation-optimization approach, the modeller specifies the desired attributes managing chlorine disinfection at various locations in DWDS such as minimum residual chlorine required at critical nodes within DWDS. The model determines, from a set of several possible strategies, a single management strategy that best meets the desired attributes for optimum location of booster station with minimum mass rate of chlorine satisfying the minimum residual chlorine concentration at control nodes. In some cases, however, the model may determine that none of the possible strategies are able to meet the specific set of management goals and constraints. Such outcomes, while often not desirable, can be useful for identifying problematic area where the management of chlorine is difficult. The basic methodology for the development of simulation optimization model for water quality management within DWDS simulation model interaction is outlined in Fig. 5.1.

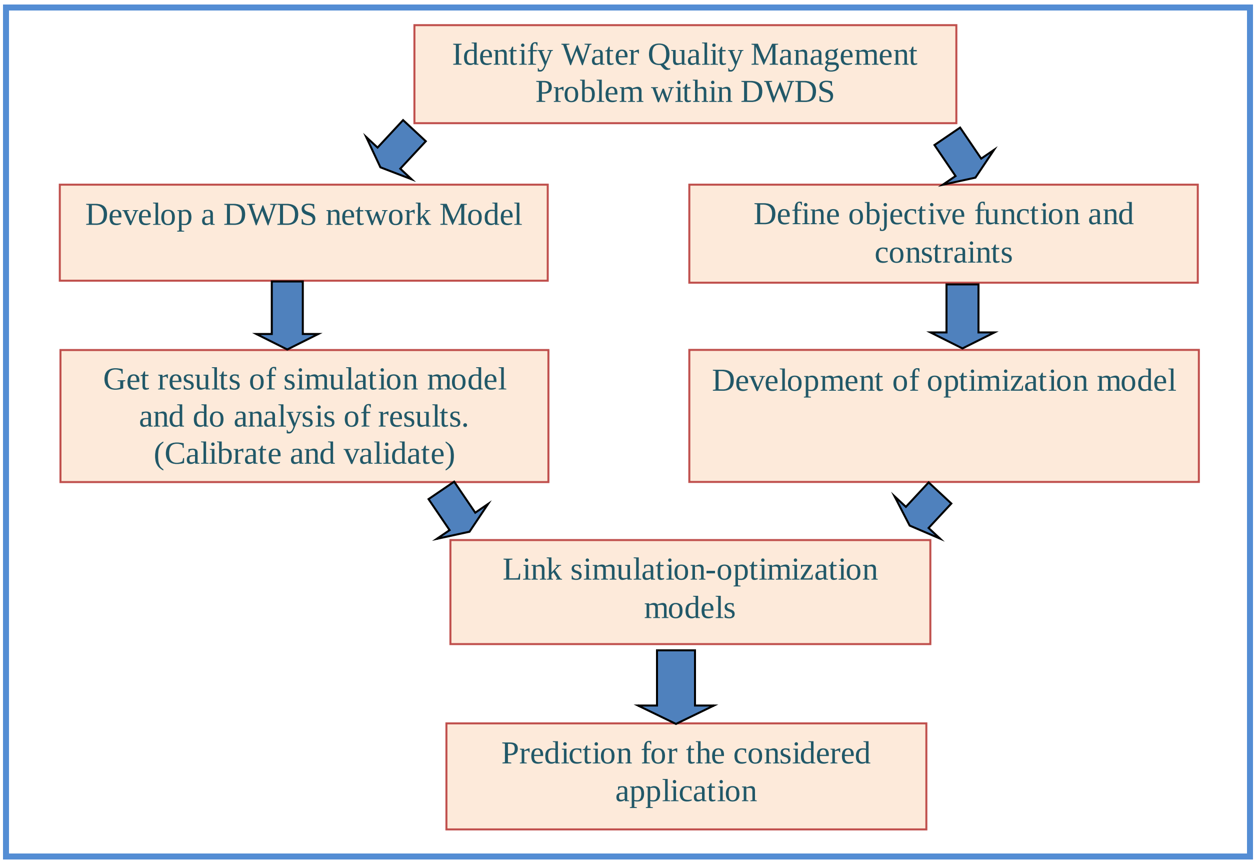


Fig. 5.1: Steps in the development of simulation-optimization model for water quality management in DWDS.

Determination of the best disinfection strategy is also a critical step in water distribution network management. For this the chlorine concentrations throughout a pipe network under steady or unsteady hydraulic and water quality conditions is of particular interest. Chlorine concentration simulators like EPANET are currently available and enable the prediction of chlorine distribution in a network under steady or unsteady conditions. The optimal control of chlorine concentrations at the application point is very essential to balance between excessive disinfectant concentrations near the source or loss of pathogen control at the network periphery. Decision makers need 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 (1998) utilize the principle of linear superposition for optimal scheduling of booster disinfectant in drinking water distribution system. Tryby et al. (2002) 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 and scheduling of booster injection stations in drinking water distribution networks. 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.

For the present study the coupled simulation optimization model is developed for optimum location and scheduling of mass rate of chlorine using linear programming (LP) and particle swarm optimization (PSO) method.

5.3 Linear Programming Optimization Method

Linear programming is considered a revolutionary development of 20th century that permits us to make optimal decisions in complex situations (Raju 2009). George B. Dantzig formulated the general linear programming problem and devised the simplex method of solution in 1947. This has become a significant step in bringing linear programming into wider use. It is the most widely used method of constrained optimization which is applicable to 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. The general linear programming problem can be stated in the following standard scalar form as given by:

$$\text{Minimize } f(x_1, x_2, \ldots, x_n) = c_1x_1 + c_2x_2 + \cdots + c_nx_n \quad (5.1)$$

Subject to the constraints

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

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

....

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \quad (5.2)$$

$$x_1 \geq 0$$

$$x_2 \geq 0$$

...

$$x_n \geq 0 \quad (5.3)$$

where c_j , b_j , and a_{ij} ($i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$) are known constant, and xj 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.

There are number of applications of linear programming in the Engineering field. Few researchers used this technique for the optimization of scheduling of booster stations for management of chlorine in DWDS. Boccelli et al. (1998) and Tryby et al. (2002) have used principle of linear superposition and first-order reaction kinetic assumptions to formulate the chlorine booster station operation problem as a linear programming (LP) model, where the objective is to minimize the total chlorine mass injected into the system. Boccelli et al. (1998) formulated a linear optimization model for the scheduling of disinfectant injections into water distribution systems to minimize the total disinfectant dose required to satisfy residual constraints. Their approach used network water quality models to quantify disinfectant transport and decay as a function of the booster dose schedule. Tryby et al. (2002) extended the study of Boccelli et al. (1998) to incorporate booster station location as a decision variable within the optimization process. The formulation is similar to the general, mixed-integer linear programming, fixed-charge facility location problem, and is solved using a branch-and-bound solution procedure.

Booster Disinfection Design Analysis software (BDDA) developed by Uber et al. (2001) interfaces with the simulation software EPANET (Rossman 1994) and standard linear programming algorithms. Ezgi & Burcu (2015F) developed the coupled simulation model using EPANET and linear programming algorithm for chance constrained optimization of the water distribution network of Cherry Hill and Brushy Plains with slight modification. The objective is to obtain minimum amount of injection mass subjected to maintaining more uniformly distributed chlorine concentrations within the limits, while considering the randomness of chlorine concentration by probability distributions. In this research the simulation model is coupled with linear programming optimization and particle swarm optimization (PSO) method for managing chlorine disinfection in DWDS. Initially the model was developed using linear programming (LP) method.

5.4 Development of Optimization Model Using Linear Programming Optimization Method

The optimization techniques are required for decision making and used for the optimal scheduling , operation and location of booster stations (Boccelli et al. (1998); Try by et al. (2002); Prasad et al. (2004); Carrico & Singer (2009); Kang &Lansey (2010); Wang Hongxiang (2010); Ohar & Ostfeld 2014)).

In the subsequent case studies the linear programming and particle swarm optimization (PSO) methods are used for the optimum scheduling and location of booster chlorination station. The main objective of adopting optimization technique is to minimize the mass rate of chlorine at source and optimal location of booster stations which helps in minimizing the cost of chlorine as well as formation of DBP. For coupling of the simulation model with the optimization technique the impulse response coefficients are obtained using EPANET simulation model.

5.4.1 Impulse Response Coefficients

Boccelli (1998) utilized principle of linear superposition which implies that the effect of any single disinfectant dose on the concentration is linear in disinfectant dose. The concentration is the sum of all individual disinfectant dose effects, which allowed the determination of impulse response coefficients to relate the effect of a unit mass injection at a given location and time on the disinfectant concentration at other locations and times. The impulse response coefficients as mentioned by Boccelli (1998) is mentioned as $K_{i,j}$ in equation 5.5 used for applying the constraints in the general formulation of optimization model for booster chlorination, which are obtained by using values of chlorine concentrations at critical locations.

5.4.2 General Formulation of Optimization Model for Booster Chlorination

The general formulation for application of booster chlorination dose scheduling problem is mathematically formulated as

Objective function is to

Minimize:

$$\sum_{i=1}^{n} \mathrm{Mi} \tag{5.4}$$

Subject to Constraints:

$$C_j = \sum_{j=1}^{m} \sum_{i=1}^{n} K_{i,j} M_i \geq 0.2$$

(5.5)

Non negativity constraints,

$M_i \geq 0$

(5.6)

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, mg/L.

$K_{i,j}$= impulse response coefficients corresponding to injection nodes.

M_i = mass rate injected at injection node (i) at source or booster stations, mg/min.

5.4.3 The impulse response coefficients for Sample and Example Network:

The impulse response coefficients are found for the sample network (Fig. 3.4) used for the general formulation for water quality model in the form of constants. The impulse response coefficients are obtained for the unit mass injection rate when chlorine is applied at source alone i.e. M_0, only at booster station 1 i.e. M_1, only at booster station 2 i.e. M_2, only at booster station 3 i.e. M_3 and obtaining the chlorine concentration at critical nodes. The impulse response coefficients for this sample network are shown in Table 5.1.

Table 5.1: Impulse response coefficients for the sample network (Fig 3.4)

Critical Node / Node No.	Values of Impulse response coefficients with application of chlorine mass rate at critical nodes (mg/L) / (mg/min)							
	Only at Source, M_0	Equation	Only at Booster 1 , M_1	Equation	Only at Booster 2, M_2	Equation	Only at Booster 3 , M_3	Equation
CN 1, 4	$K_{0,1}$	0	$K_{1,1}$	X_3X_4	$K_{2,1}$	X_5	$K_{3,1}$	0
CN 2, 5	$K_{0,2}$	$X_1X_6X_8$	$K_{1,2}$	X_7X_8	$K_{2,2}$	0	$K_{3,2}$	X_9

Similarly the impulse response coefficients are found for the example network (Fig 3.5) used for the computation for water quality model. The impulse response coefficients for this example network are shown in Table 5.2.

Table 5.2: Impulse response coefficients for the example network (Fig 3.5)

Critical Node / Node No.	Values of Impulse response coefficients with application of chlorine mass rate at critical nodes (mg/L) / (mg/min)							
	Only at Source, M_0	**Value**	**Only at Booster 1 , M_1**	**Value**	**Only at Booster 2, M_2**	**Value**	**Only at Booster 3 , M_3**	**Value**
CN 1, 4	$K_{0,1}$	0	$K_{1,1}$	0.00017	$K_{2,1}$	0.000622	$K_{3,1}$	0
CN 2, 5	$K_{0,2}$	0.000256	$K_{1,2}$	0.000295	$K_{2,2}$	0	$K_{3,2}$	0.000989

For the large network it is difficult to obtain the value of impulse response coefficients using such equations, hence the EPANET simulation model is used to find out the impulse response coefficients for real DWDS network of Vadodara city.

5.4.4 Methods to Compute Impulse Response Coefficients for Large Network

For the booster chlorination strategy with source application of chlorine along with chlorine injected from selected number of booster nodes, the values of above mentioned impulse response coefficients is obtained from the results of residual chlorine at different critical nodes selected at different locations covering the whole network using EPANET simulation model. To find out the impulse response coefficients, EPANET software is run for the extended period simulation separately when chlorine is applied at source alone i.e. M_0, Only at Booster Station 1 i.e. M_1, Only at Booster Station 2 i.e. M_2, only at Booster Station 3 i.e. M_3, only at Booster station 4 i.e. M_4 and only at Booster station 5 i.e. M_5. For example the value of residual chlorine is obtained after 10 days simulation in EPANET software at critical node 2 as C_2 by applying the chlorine mass rate M_0 at source only and $K_{0,1}$ is obtained as C_2/M_0 by using formula $C_2= M_0K_{0,1}$ gives the value of $K_{0,1}$. Similarly $K_{1,1}$ is obtained using formula $C_2= M_1K_{1,1}$ for application of chlorine at only booster station 1, $K_{2,1}$ is obtained using $C_2= M_2K_{2,1}$ for application of chlorine at only booster station 2, $K_{3,1}$ using $C_2= M_3K_{3,1}$ for application of chlorine at only booster station 3. $K_{4,1}$ using $C_2= M_4K_{4,1}$ for application of chlorine at only booster station 4. $K_{5,1}$ using $C_2= M_5K_{5,1}$ for application of chlorine at only booster station 5. Similarly the values of other impulse response coefficients are obtained for all the critical nodes. The summary of the all impulse response coefficients is arranged in tabular form and used in general mathematical formulation for optimization model for application of booster chlorination used for linear programming (LP) and particle swarm optimization (PSO) method both.

Using optimization model and coupling the impulse response coefficients obtained from EPANET software are used for the optimal scheduling and location of booster stations for the DWDS the linear programming optimization method and particle swarm optimization (PSO) methods are used.

Different optimization models were developed for the optimal scheduling and location of booster chlorination station for the Manjalpur and North Harni DWDS network, Vadodara, Gujarat, India as shown in Fig 5.2.

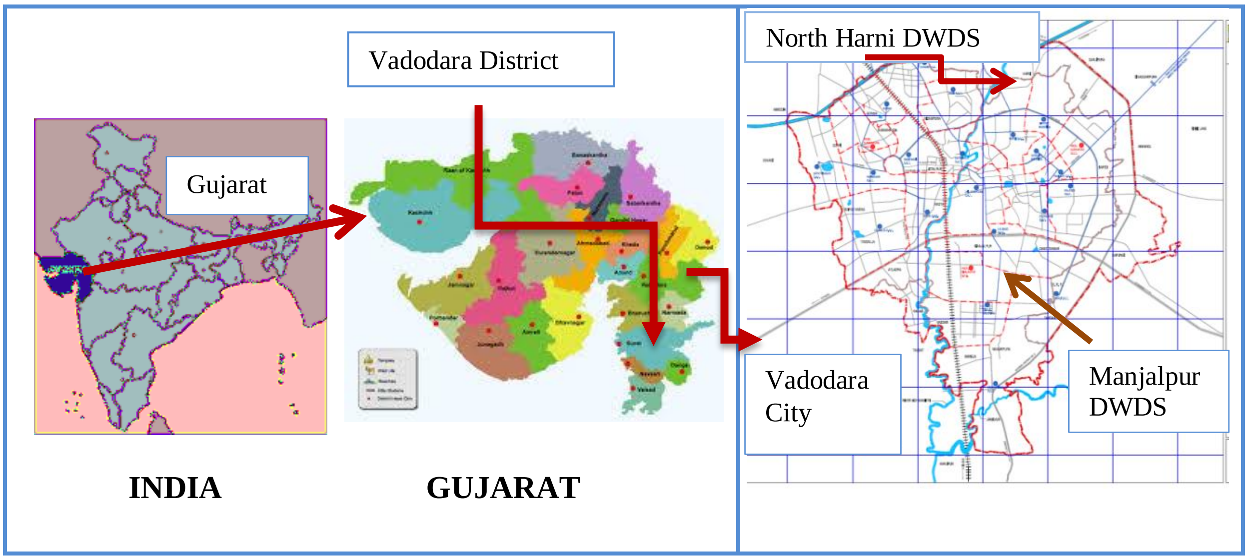


Fig. 5.2: Manjalpur and North Harni Drinking Water Distribution System Network, Vadodara, Gujarat, India.

The first case study was carried out for large distribution network of Manjalpur DWDS for optimal location and scheduling of booster chlorination stations using combinations of five booster stations along with source chlorination. The optimization models were developed to check the effect of supply hours on selection of booster stations.

5.5 Details of Study Area (Manjalpur)

Manjalpur Drinking Water Distribution System (DWDS) covering part of southern area of Vadodara, Gujarat, India, is selected for the application of the optimization problem. The distribution network supply the drinking water to the total command area of 6.57 Km^2, the population of 43,857 persons for year 2011. The existing capacity of ESR is 1.8 ML and GSR is 7.2 ML making total existing capacity of 9.0 ML. The demand at each node is computed based on population density and area served by each node. The total demand of the DWDS is 9452 m^3/h for a day .The water distribution network for the study area is shown in Fig. 5.3. The network modelled has 153 consumer nodes, 5 booster nodes (BS_1, BS_2 , BS_3, BS_4 , BS_5), one source node R_1, one pumping station, one storage tank (Node T_1), and 208 links. Consumer nodes (nodes 1-154) represent water demand locations for nearby areas while booster nodes (nodes BS_1 to BS_5) represent locations of inline disinfectant addition. The link data includes connectivity, length, diameter, and roughness information. The cylindrical tank at node T_1 is modelled as a continuous flow stirred tank reactor.

The demand at various nodes is considered to be steady state and satisfied by supplying the water in one and two hours a day as per the case study. The consumers have a practise to store the water for daily requirements in underground storage tank. The simulation is done by supplying the water for supply hours and there will be no flow in rest of the time as per the existing practice of the study area. The water distribution system simulation model EPANET is used to analyse the hydraulic and water quality parameters.

Two cases are simulated to study the effect of chlorination. Case I represents the chlorine application only at source near pumping station. Case II uses the strategy of Booster chlorination at booster locations (Booster stations BS_1 to BS_5) along with source chlorination. The locations and rate of chlorine injection of Booster stations are selected based on the trial and error methods to maintain the chlorine concentration range of 0.2 mg/L (minimum) to 2 mg/L (maximum) at all the consumer nodes except Tank. The mass injection time of chlorine is 1 hour that repeats every 24 hours. The critical nodes (CN 1 to 19) covering the whole network are assigned at various nodes to monitor the concentration of residual chlorine at that particular nodes. The critical nodes selected are node number 14, 38, 46, 47, 49, 51, 57, 59, 70, 74, 102, 118, 122, 123, 126, 128, 5, 13 and 154. Water is supplied under constant pressure from source tank and the pressure drops due to the friction losses which are computed using Darcy Weishbach equation in EPANET (Rossman, 2000) simulation model. Water quality modelling in EPANET uses first order chlorine decay for prediction of residual chlorine in drinking water distribution system which has been applied by many researchers (Clark et al. 1995; Boccelli et al. 1998; Tryby et al. 1999, 2002; Ucaner & Ozdemir 2003; Pedro Castro et al. 2003; Munavalli & Kumar 2003; Propato & Uber 2004 a, b; Ostfeld & Salomons 2004, 2006; Prasad et al. 2004; Gomez et al. 2006; Nagatani et al. 2008 ; Sreten et al. 2010; Kang & Lansey 2010; Meng et al. 2013). The disinfectant decay rate constant

(k_b) is assumed to be 0.55 d^{-1} from literature (Rossman et al. 1994) for the all the links while wall decay coefficient is assumed to be negligible.

When the water supply hours is kept as 1 hour, the maximum velocity in the pipe is obtained as 4.52 m/s in the pipe supplying water from tank to the pipe whereas average velocity is about 0.92 m/s for all pipes, which are within permissible limit. For the 2 hour water supply the maximum velocity in the pipe is obtained as 2.26 m/s in the pipe supplying water from tank to the pipe whereas average velocity is about 0.46 m/s for all pipes, which are within permissible limit The residual pressure obtained at each node is greater than 7 m as per requirement (MoUD ,CPHEEO, 1999). The value of friction factor varies from 0.016 to 0.03 which is calculated based on Reynold's number and relative roughness of 0.26 mm for cast iron pipes.

The details of Manjalpur DWDS network as shown in Fig. 5.3 is used for the development of various optimization model using linear programming (LP) and particle swarm optimization (PSO) method under different simulation scenario and conditions.

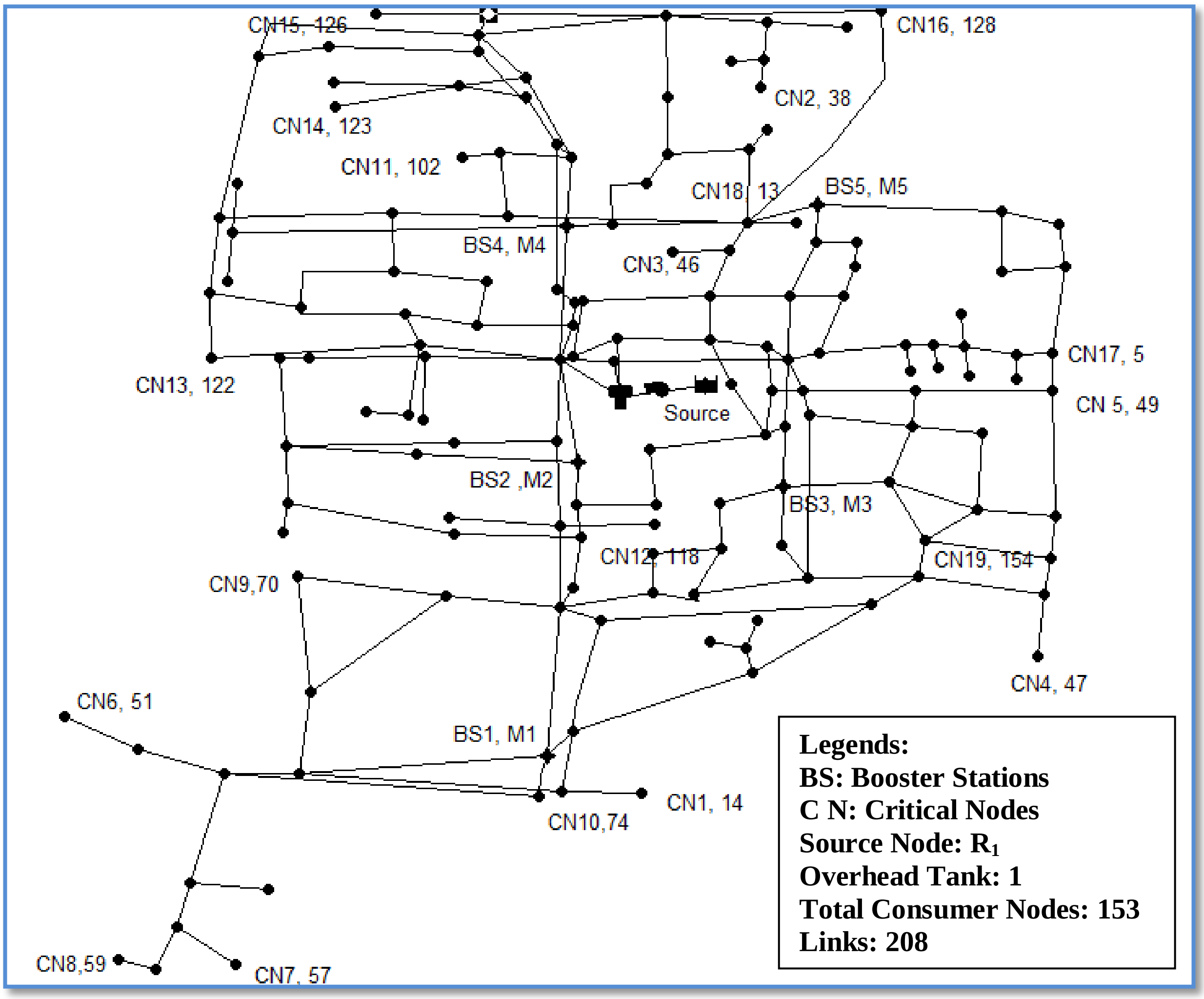


Fig. 5.3: Manjalpur DWDS network.

5.6 Case Study 6: Optimal Location and Scheduling of Booster Stations for One Hour Water Supply (MJ-1H-LP)

The objective of present work done is to develop a mathematical model to optimize the location of booster stations along with the chlorination doses with the help of linear programming method of optimization. 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.

(2) Maintenance of minimum 0.2 mg/L of residual chlorine at all the critical nodes within distribution network.

(3) To find out the optimum location of booster stations along with the source chlorination.

In the present study the water is supply duration is kept as one hour a day and the pump is operated for the same duration. Two cases of Booster chlorination along with source application of chlorine are considered for optimization problem. Case I represents the conventional chlorine nation in which the chlorine is applied at source alone. While case II represents the source application of chlorine along with booster doses applied at two Booster stations which give minimum chlorine dose. The water distribution network for the study area is shown in Fig. 5.3. For the same network only the source chlorination is applied to check the effectiveness of the Booster chlorination. The objective of using optimization technique for scheduling of booster dose at booster stations is intended as additional benefit of minimizing both DBP formation and chemical costs, though actual reduction in DBP formation cannot be quantified at this time since the factors affecting DBP formation kinetics are poorly understood. The mass injections are required to satisfy lower bound constraints (0.2 mg/L as per IS 10500, 2012) on residual chlorine at all the locations of DWDS. EPANET software is used to identify the nineteen critical nodes i.e. Node numbers 14, 38, 46, 47, 49, 51, 57, 59, 70, 74, 102, 118, 122, 123, 126, 128, 5, 13 and 154. The optimal location and scheduling of the booster station is selected for the source application along any two Booster Nodes which gives minimum chlorine dose to optimize the location of booster stations for Case II.

5.6.1 Development of Optimization Model for Study Area (Manjalpur)

For development of optimization model in excel, the booster chlorination dose scheduling problem is mathematically formulated for Manjalpur DWDS as

Minimize:

$$\sum_{i=1}^{n} \mathrm{Mi}$$

(5.7)

Subject to Constraints:

$$C_j = \sum_{j=1}^{m} \sum_{i=1}^{n} K_{i,j} M_i \geq 0.2$$

(5.8)

Non negativity constraints,

$$M_i \geq 0$$

(5.9)

Where,

i = injection nodes

j = critical nodes

m = total numbers of critical nodes (19)

n = total number of Injection nodes (5)

C_j = chlorine concentration at junction node 1 to 19 corresponding to critical node number 14, 38, 46, 47, 49, 51,57, 59, 70, 74, 102, 118, 122, 123, 126, 128, 5 ,13 and 154 respectively, mg/L.

$K_{i,j}$= impulse response coefficients corresponding to injection nodes 1 to 5 and critical nodes 1 to 19.

M_i = Mass rate injected at injection node 1 to 5 corresponding to injection location at Source, booster stations BS_1, BS_2, BS_3, BS_4 and BS_5 respectively, mg/min.

The inbuilt solver function in excel 2000 is used to solve linear and nonlinear optimization problems. The solver option which is add in function available in Microsoft excel is written in VBA. It is used for linear programming model as it has user friendly interface uses the simplex algorithm which is consistent and robust used to solve the equations with desired precision of 10^{-7}. 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. The optimization model with objective function as mentioned in equation 5.7 is organized in excel spread sheet. Various impulse response coefficients as mentioned in table 5.3 are used to apply the formula for the constraints in each cell of the excel spread sheet. Non negativity constraints are applied on the chlorine mass rate application. Once the model is implemented in a spread sheet, use of the solver function gives the optimum solution of total mass rate to be applied to satisfy all the constraint at critical nodes. For the optimal location of booster station, various combinations of booster stations are selected and linear programming is run to get the minimum mass rate application of chlorine with constraints of minimum 0.2 mg/L at each critical node.

The mathematical formulation as mentioned in Equations 5.7, 5.8 and 5.9 are used for the development of mathematical model for the optimal scheduling and location of booster stations. The values of Impulse response coefficients is obtained from the results of residual chlorine at critical nodes 14, 38, 46, 47, 49, 51,57, 59, 70, 74, 102, 118, 122, 123, 126, 128, 5 ,13 and 154 using EPANET software by running the extended period simulation separately when chlorine is applied at source alone i.e. M_0, Only at booster station 1 i.e. M_1, Only at booster station 2 i.e. M_2, only at booster station 3 i.e. M_3, only at booster station 4 i.e. M_4 and only at booster station 5 i.e. M_5. For example the value of residual chlorine is obtained after 10 days simulation in EPANET software at critical node 1 i.e node number 4 as C_1 by applying the chlorine mass rate M_0 at source only and $K_{0,1}$ is obtained as C_1/M_0 by using formula $C_1= M_0K_{0,1}$ gives the value of $K_{0,1}$ as 0.000003636, similarly $K_{1,1}$ is obtained using formula $C_1= M_1K_{1,1}$ for application of chlorine at only booster station 1, $K_{2,1}$ is obtained using $C_1= M_2K_{2,1}$ for application of chlorine at only booster station 2, $K_{3,1}$ using $C_1= M_3K_{3,1}$ for application of chlorine at only booster station 3. $K_{4,1}$ using $C_1= M_4K_{4,1}$ for application of chlorine at only booster station 4. $K_{4,1}$ using $C_1= M_4K_{4,1}$ for application of chlorine at only Booster station 5. Similarly the values of other impulse response coefficients are obtained for all the critical nodes. The summary of the impulse response coefficients at critical nodes obtained is given in Table 5.3.

Table 5.3: Value of Impulse response coefficients at critical nodes (Case Study 6: MJ-1H-LP)

Critical Node / Node No	Values of Impulse response coefficients with application of Chlorine mass rate at critical nodes (mg/L) / (mg/min)											
	Only at Source, M_0	Value	Only at Booster 1 , M_1	Value	Only at Booster 2, M_2	Value	Only at Booster 3 , M_3	Value	Only at Booster 4 , M_4	Value	Only at Booster 5 , M_5	Value
CN 1, 4	K0,1	0.000003636	K1,1	0.00001321	K2,1	0.000002	K3,1	0	K4,1	0	K5,1	0
CN 2, 38	K0,2	0.000003636	K1,2	0	K2,2	0	K3,2	0	K4,2	0.000014	K5,2	0.00001
CN 3, 46	K0,3	0.000003636	K1,3	0	K2,3	0	K3,3	0	K4,3	0	K5,3	0
CN 4, 47	K0,4	0.000003455	K1,4	0	K2,4	0	K3,4	0.000024	K4,4	0	K5,4	0.000002
CN 5, 49	K0,5	0.000003455	K1,5	0	K2,5	0	K3,5	0	K4,5	0	K5,5	0.000012
CN 6, 51	K0,6	0.000002182	K1,6	0.000015094	K2,6	0.000002	K3,6	0	K4,6	0	K5,6	0
CN 7, 57	K0,7	0.000002182	K1,7	0.000024528	K27	0.000002	K3,7	0	K4,7	0	K5,7	0
CN 8, 59	K0,8	0.000002182	K1,8	0.000016981	K2,8	0.000002	K3,8	0	K4,8	0	K5,8	0
CN 9, 70	K0,9	0.000003636	K1,9	0	K2,9	0.000004	K3,9	0	K4,9	0	K5,9	0
CN 10, 74	K0,10	0.000003636	K1,10	0.000013208	K2,10	0.000004	K3,10	0	K4,10	0	K510	0
CN 11, 102	K0,11	0.000003636	K1,11	0	K2,11	0	K3,11	0	K4,11	0.000026	K5,11	0
CN 12, 118	K0,12	0.000003636	K1,12	0	K2,12	0.00009	K3,12	0	K4,11	0	K5,12	0
CN 13, 122	K0,13	0.000003636	K1,13	0	K2,13	0	K3,13	0	K4,11	0	K5,13	0
CN 14, 123	K0,14	0.000003636	K1,14	0	K2,14	0	K3,14	0	K4,11	0.000012	K5,14	0
CN 15, 126	K0,15	0.000003636	K1,15	0	K2,15	0	K3,15	0	K4,11	0.000018	K5,15	0
CN 16, 128	K0,16	0.000003636	K1,16	0	K2,16	0	K3,16	0	K4,11	0.000006	K5,16	0.000036
CN 17, 5	K0,17	0.000002727	K1,17	0	K2,17	0	K3,17	0	K4,11	0	K5,17	0.000058
CN 18, 13	K0,18	0.000002364	K1,18	0	K2,18	0	K3,18	0	K4,11	0.000006	K5,18	0.000036
CN 19, 154	K0,19	0.000003636	K1,19	0	K2,19	0	K3,19	0.000046	K4,11	0	K5,19	0

5.6.2 Optimization Results

To find the optimum location of the booster stations out of all five booster nodes the linear programming is done for the various combinations of the booster nodes. Table 5.4 shows all the combinations of booster stations to select the optimum location of booster station. The combination of the booster stations ($M_0+M_1+M_5$) gives the minimum mass rate of chlorine which as 63696.81 mg/min which needs chlorine mass rate as 3821.81 g/d. The mass rate of chlorine to be applied for source chlorination and at source along with optimal location of two booster stations for case II after using the linear programming (LP) technique of optimization in excel is tabulated in Table 5.5. The mass rate to be applied for only source chlorination is obtained as 5500 gm/day while in case II with source and two booster stations the chlorine mass rate to be applied comes to be 3821.81 g/d which gives 30.51% reduction in chlorine mass rate compared to case I.

Table 5.4: Total mass rate of chlorine applied for combination of two booster stations with source application (Case Study 6: MJ-1H-LP)

Sr No	Combination of Booster stations	Total mass rate to be applied (mg/min)
1	$M_0 + M_1 + M_2$	(84615.39+1019.13+0) 85634.62
2	$M_0+M_1+M_3$	(84615.39+1019.13+0) 85634.62
3	$M_0+M_1+M_4$	(73333.33+2650+4444.44) 80427.78
4	$\mathbf{M_0+M_1+M_5}$	**(56838.91+5034.19+1823.71) 63696.81**
5	$M_0+M_2+M_3$	(91667.67+0+0) 91667.67
6	$M_0+M_2+M_4$	(91667.67+0+0) 91667.67
7	$M_0+M_2+M_5$	(91667.67+0+0) 91667.67
8	$M_0+M_3+M_4$	(91667.67+0+0) 91667.67
9	$M_0+M_3+M_5$	(91667.67+0+0) 91667.67
10	$M_0+M_4+M_5$	(91667.67+0+0) 91667.67
Minimum mass rate(mg/min) = 63696.81		

Table 5.5: Optimization results for chlorine application (Case study 6: MJ-1H-LP)

Chlorine Mass rate applied at various locations for 1 hour duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine (Case II)	
	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)
Source, (M_0)	5500	91667	3410.33	56838.91
Booster $BS_1(M_1)$	--	--	302.06	5034.19
Booster $BS_5(M_5)$	--	--	109.42	1823.71
Total Mass rate applied	5500	91667	3821.81	63696.81
%Reduction in mass rate of chlorine compared to case I	--		30.51	

The tank concentration for residual chlorine is obtained for both the cases. The residual chlorine concentration for the last 24 hours of the 10 days (240 hours) simulation (i.e. 216 hours to 240 hours) is shown in Fig. 5.4.

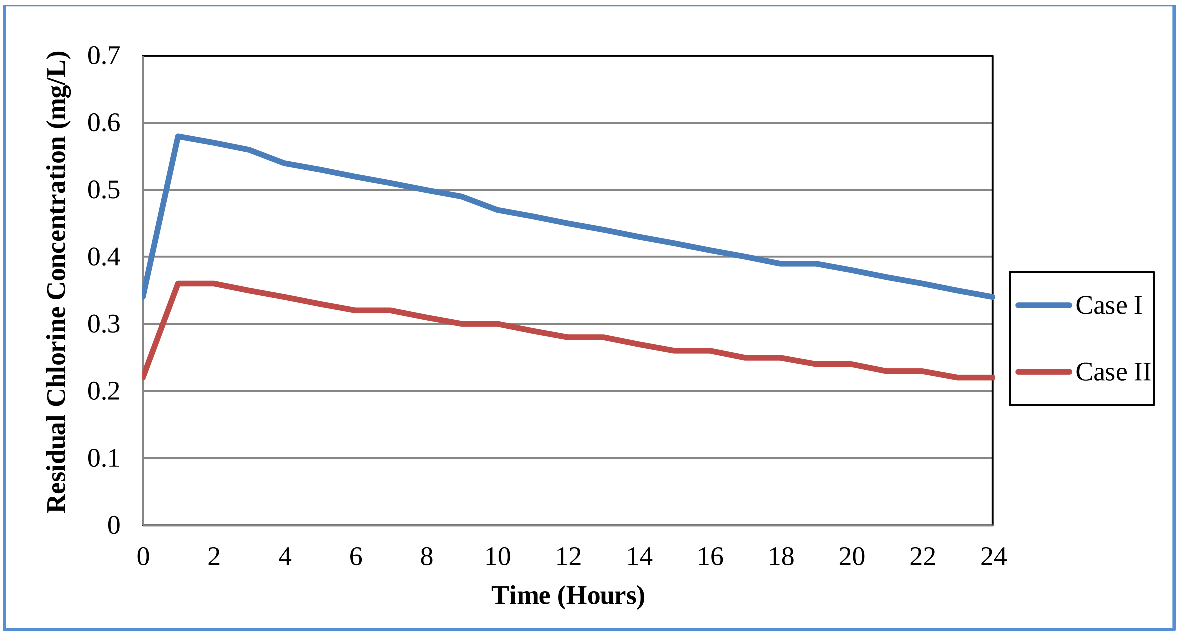


Fig. 5.4: Tank concentration for residual chlorine (Case I and Case II) for Case Study 6

The mass rate of chlorine to be applied at booster stations obtained after optimization is applied on DWDS network using EPANET software to check 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 (Case I) required 5500 g/day, while Booster chlorination for case II required 3821.81 g/d and to satisfy the constraints of 0.2 mg/L residual chlorine at all the locations in DWDS network. Fig. 5.5 and Fig. 5.6 show the graph of minimum, average and maximum concentration of residual chlorine at all the locations for conventional chlorination (Case I) and booster chlorination with two boosters and source application (Case II). Fig. 5.7 And 5.8 resent the graph of average and standard deviation for all nodes for case I and II respectively.

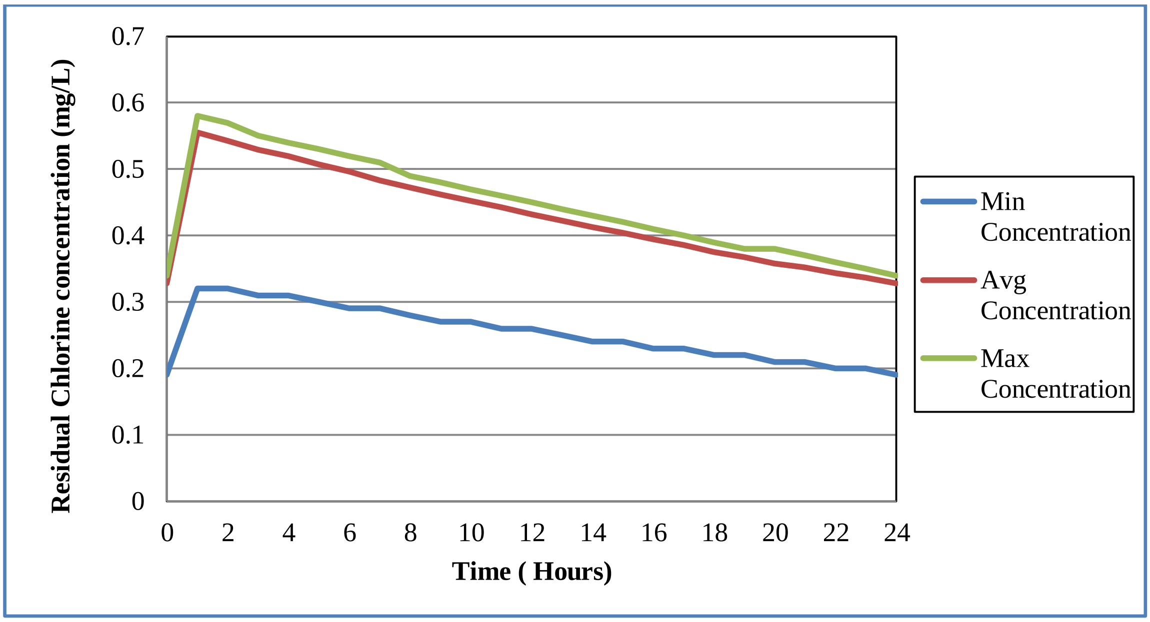


Fig. 5.5: Minimum, average and maximum concentration of residual chlorine for all nodes (Case I) for Case Study 6

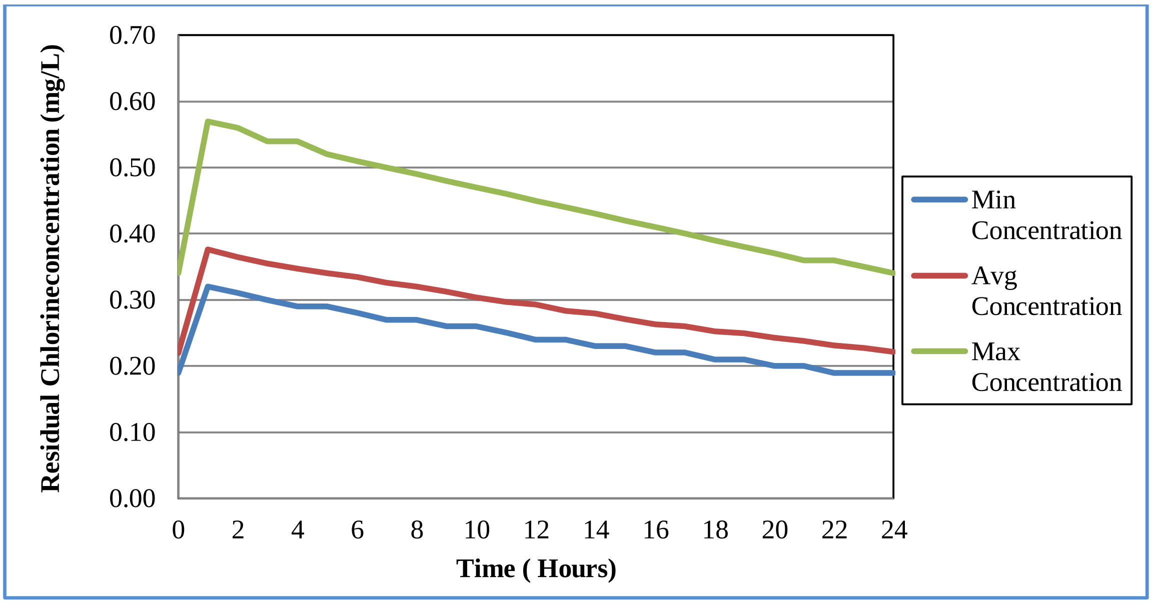


Fig. 5.6: Minimum, average and maximum concentration of residual chlorine for all nodes (Case II) for Case Study 6

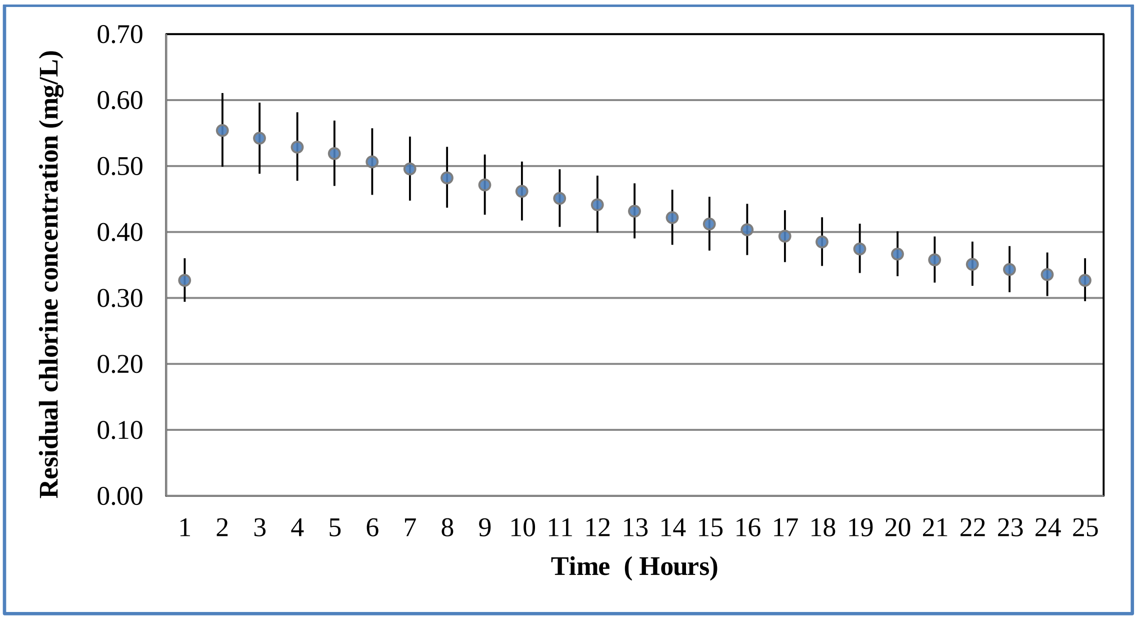


Fig. 5.7: Average residual chlorine concentration and standard deviation for all nodes (Case I) for Case Study 6

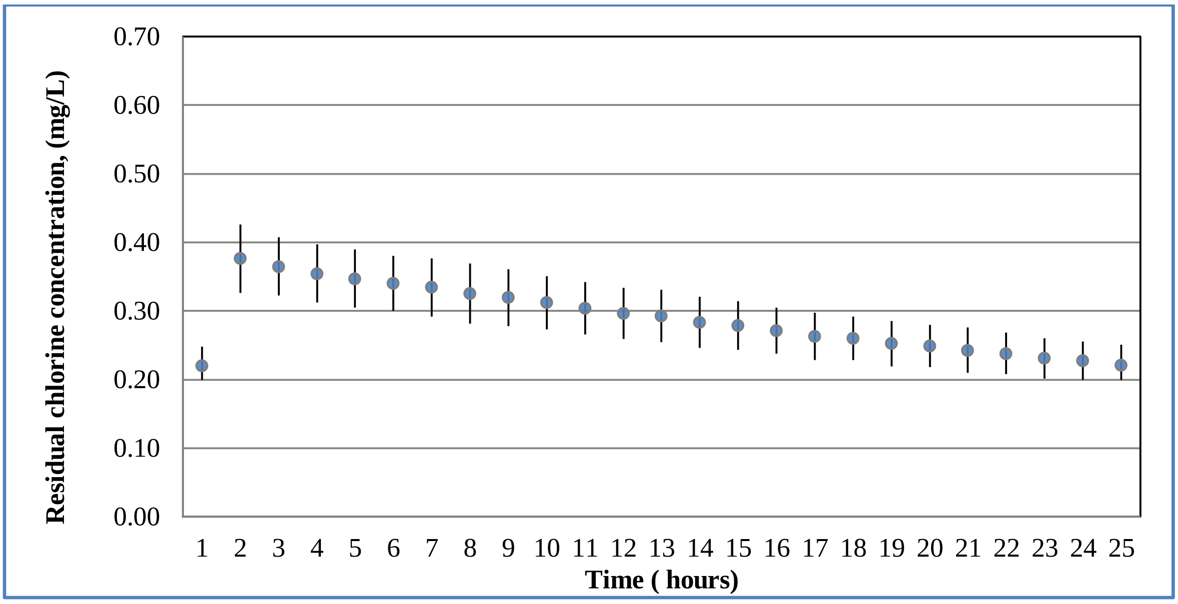


Fig. 5.8: Average residual chlorine concentration and standard deviation for all nodes (Case II) for Case Study 6

The overall value of standard deviation for all nodes for case I and II is obtained as 0.0805 and 0.0589. The sensitivity analysis was carried out to check the effect of bulk decay coefficient on application of chlorine mass rate. The value of $k_b$is reduced by 25% and 50% and increased by 50%. The value of total mass rate to be added using the different values of kb is presented in Table 5.6. Fig. 5.9 shows the graph of % increase and decrease in chlorine mass rate application for % increase and decrease in value of k_b

Table 5.6: Sensitivity analysis for bulk decay coefficient (Case Study 6: MJ-1H-LP).

Bulk Decay Coefficient (k_b) d^{-1}	M_0 (mg/min)	M_1 (mg/min)	M_5 (mg/min)	Total Mass rate (mg/min)	Difference
0.275 (50% less)	42307.69	1881.657	668.8963	44858	18839
0.4125(25% less)	48768.47	3550.739	1231.527	53551	10146
0.55	56839	5034	1824	63697	--
0.6875(25% more)	67346.94	7931.973	2040.816	77320	13623

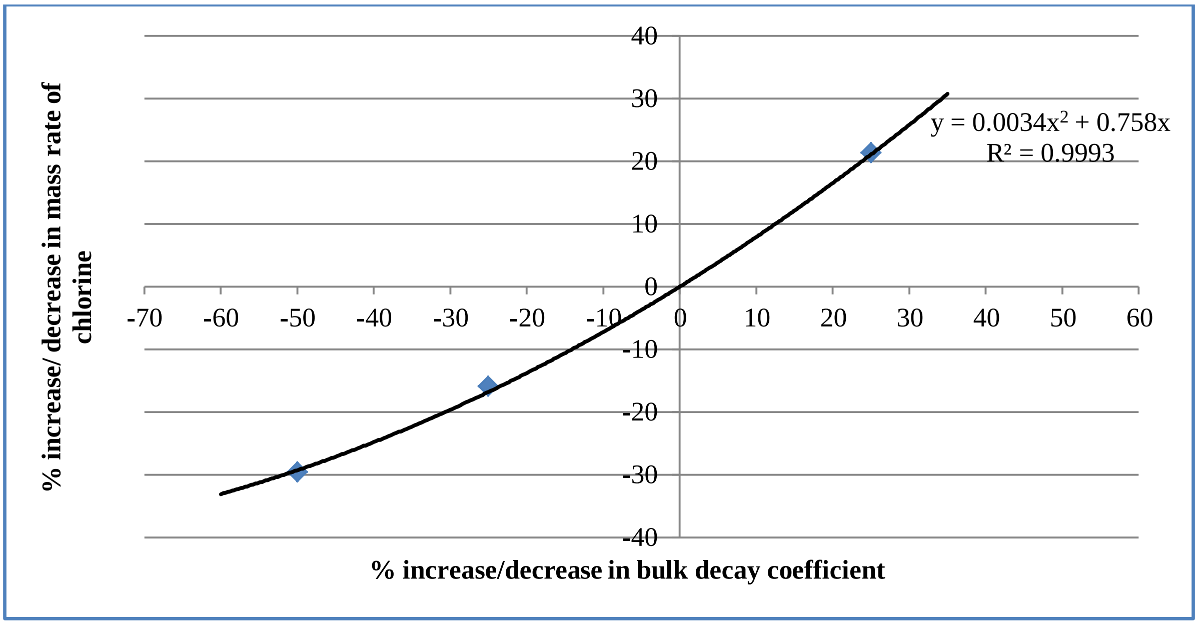


Fig. 5.9: Percentage variation in total chlorine mass rate for % variation in bulk decay coefficient (Case Study 6).

5.6.3 Discussions

A coupled optimization model is developed to get the optimal location of booster stations with minimizing 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 for the development of optimization model 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. The value of impulse response coefficients used in forming the constraints is obtained from the data of residual chlorine by running EPANET software. 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 solved by solver function of 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. For the optimal location of booster stations the linear programming in excel was run for all the combinations of the booster stations along with source application. The combination of M_0+M_1+M_5 gives minimum chlorine application dose; therefore it is selected as the optimum location of booster station. The optimization result shows that the scheduling of the mass rate of chlorine as suggested by the optimization gives 30.51 % reduction for case II as compared to case I having 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 (DBP). As seen from the Fig 5.5 to 5.8, it is observed that booster chlorination allows lower average residual chlorine throughout the DWDS as well as the standard deviation in case of booster station is less than for conventional chlorination which results in more uniform distribution of residual chlorine as compared to conventional chlorination. The selection of bulk decay coefficient is very important input parameter for any system hence the sensitivity analysis for the bulk decay coefficient was carried out. The results of the sensitivity analysis suggest that the value of decay coefficient with 50% decrease gives 29.59% decrease in the mass rate of chlorine application. Present case study shows that the coupling of data of EPANET software with linear programming(LP) 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(DWDS).

To check the effect of water supply hours for the large network the same network was run for the two hours water supply.

5.7 Case Study 7: Optimal Location and Scheduling of Booster Stations for Two Hours Water Supply (MJ-2H-LP)

For the present case study the same DWDS network as shown in Fig. 5.3 is used to develop the optimization model for optimum location and scheduling of mass rate of chlorine with water supply duration of 2 hours. The values of impulse response coefficients are obtained by running EPANET for water supply of 2 hours is shown in Table 5.7.

Table 5.7: Value of Impulse response coefficients at critical nodes (Case Study 7: MJ-2H-LP)

Critical Node / Node No	Values of Impulse response coefficients with application of Chlorine mass rate at critical nodes (mg/L) / (mg/min)											
	Only at Source, M_0	Value	Only at Booster 1 , M_1	Value	Only at Booster 2, M_2	Value	Only at Booster 3 , M_3	Value	Only at Booster 4 , M_4	Value	Only at Booster 5 , M_5	Value
CN 1, 4	K0,1	0.000007455	K1,1	0.000026415	K2,1	0.000002	K3,1	0	K4,1	0.00003	K5,1	0.00002
CN 2, 38	K0,2	0.000007273	K1,2	0	K2,2	0	K3,2	0	K4,2	0	K5,2	0
CN 3, 46	K0,3	0.000007455	K1,3	0	K2,3	0	K3,3	0	K4,3	0	K5,3	0.000004
CN 4, 47	K0,4	0.000007273	K1,4	0	K2,4	0	K3,4	0.00005	K4,4	0	K5,4	0.000022
CN 5, 49	K0,5	0.000007273	K1,5	0	K2,5	0	K3,5	0	K4,5	0	K5,5	0
CN 6, 51	K0,6	0.000004364	K1,6	0.000028302	K2,6	0.000002	K3,6	0	K4,6	0	K5,6	0
CN 7, 57	K0,7	0.000004364	K1,7	0.000050943	K27	0.000002	K3,7	0	K4,7	0	K5,7	0
CN 8, 59	K0,8	0.000004364	K1,8	0.000037736	K2,8	0.000002	K3,8	0	K4,8	0	K5,8	0
CN 9, 70	K0,9	0.000007455	K1,9	0	K2,9	0.000004	K3,9	0	K4,9	0	K5,9	0
CN 10, 74	K0,10	0.000007455	K1,10	0.000026415	K2,10	0.000004	K3,10	0	K4,10	0.000052	K510	0
CN 11, 102	K0,11	0.000007455	K1,11	0	K2,11	0	K3,11	0	K4,11	0	K5,11	0
CN 12, 118	K0,12	0.000007636	K1,12	0	K2,12	0.00009	K3,12	0	K4,11	0	K5,12	0
CN 13, 122	K0,13	0.000007636	K1,13	0	K2,13	0	K3,13	0	K4,11	0.000026	K5,13	0
CN 14, 123	K0,14	0.000007455	K1,14	0	K2,14	0	K3,14	0	K4,11	0.000036	K5,14	0
CN 15, 126	K0,15	0.000007455	K1,15	0	K2,15	0	K3,15	0	K4,11	0.000014	K5,15	0.000074
CN 16, 128	K0,16	0.000007455	K1,16	0	K2,16	0	K3,16	0	K4,11	0	K5,16	0.000022
CN 17, 5	K0,17	0.000007273	K1,17	0	K2,17	0	K3,17	0	K4,11	0.000014	K5,17	0.000074
CN 18, 13	K0,18	0.000006182	K1,18	0	K2,18	0	K3,18	0	K4,11	0	K5,18	0
CN 19, 154	K0,19	0.000007455	K1,19	0	K2,19	0	K3,19	0.000076	K4,11	0.00003	K5,19	0.00002

5.7.1 Optimization Results

To find the optimum location of the booster stations out of all five booster nodes the linear programming is done for the various combinations of the booster nodes. Table 5.8 shows all the combinations of booster stations to select the optimum location of booster station. The mass rate of chlorine to be applied for source chlorination and at source along with optimal location of two booster stations for case II after using the linear programming technique of optimization in excel is tabulated in Table 5.9. The combination of the booster stations (M_0+M_1+M_5) gives the minimum mass rate of chlorine which as 30553.92 mg/min which needs chlorine mass rate as 3666.47 g/d. The mass rate to be applied for only source chlorination is obtained as 5500 g/d which is same as to be applied for one hour water supply hours while in case II with source and two booster stations the chlorine mass rate to be applied comes to be 3666.47 g/day.

Table 5.8: Total mass rate of chlorine applied for combination of two booster stations with source application (Case Study 7: MJ-2H-LP)

Sr No	Combination of Booster stations	Total mass rate to be applied (mg/min)
1	$M_0+M_1+M_2$	(32352.94+2078.43+0) 34431.37
2	$M_0+M_1+M_3$	(32352.94+2078.43+0) 34431.37
3	$M_0+M_1+M_4$	(27500+2826.67+2142.86) 33469.52
4	$\mathbf{M_0+M_1+M_5}$	**(**27266.29+2862.70+424.92) **30553.92**
5	$M_0+M_2+M_3$	(45833.33+0+0) 45833.33
6	$M_0+M_2+M_4$	(45833.33+0+0) 45833.33
7	$M_0+M_2+M_5$	(45833.33+0+0) 45833.33
8	$M_0+M_3+M_4$	(45833.33+0+0) 45833.33
9	$M_0+M_3+M_5$	(45833.33+0+0) 45833.33
10	$M_0+M_4+M_5$	(45833.33+0+0) 45833.33
Minimum mass rate(mg/min) = 30553.92		

Table 5.9: Optimization results for chlorine application (Case study 7: MJ-2H-LP)

Chlorine Mass rate applied at various locations for 2 hours duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine (Case II)	
	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)
Source, (M_0)	5500	45833	3271.96	27266.29
Booster $BS_1(M_1)$	--	--	343.52	2862.70
Booster $BS_5(M_5)$			50.99	424.93
Total Mass rate applied	5500	45833	3666.47	30553.92
% Reduction in mass rate of chlorine compared to case I	--		33.34	

The tank concentration for residual chlorine concentration is obtained for both the cases. The residual chlorine concentration for the last 24 hours of the 10 days (240 hours) simulation (i.e. 216 hours to 240 hours) is shown in Fig. 5.10.

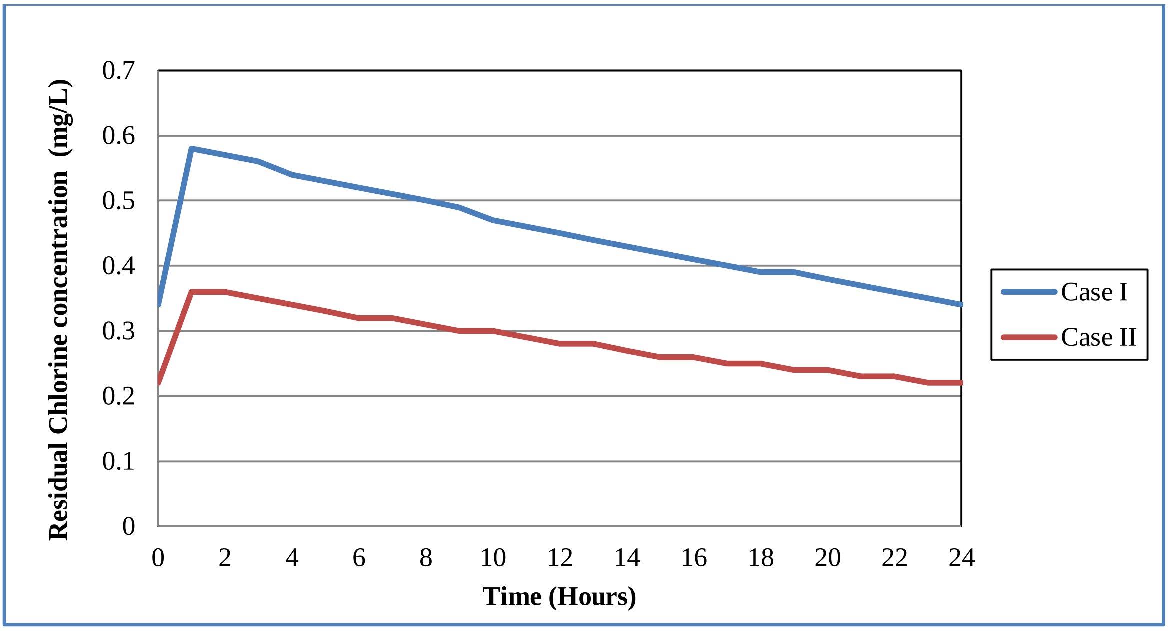


Fig. 5.10: Tank concentration for residual chlorine (Case I and Case II) for Case Study 7

The mass rate of chlorine to be applied at booster stations obtained after optimization is applied on DWDS network using EPANET software to check 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 (Case I) required 5500 g/day, while Booster chlorination for case II required 3666.47 g/day and to satisfy the constraints of 0.2 mg/L residual chlorine at all the locations in DWDS network. Fig. 5.11 and Fig. 5.12 show the graph of minimum, average and maximum concentration of residual chlorine at all the locations for conventional chlorination (Case I) and for booster chlorination with two boosters and source application (Case II) respectively. Fig. 5.13 and Fig. 5.14 present the graph of average and standard deviation for case I and II respectively.

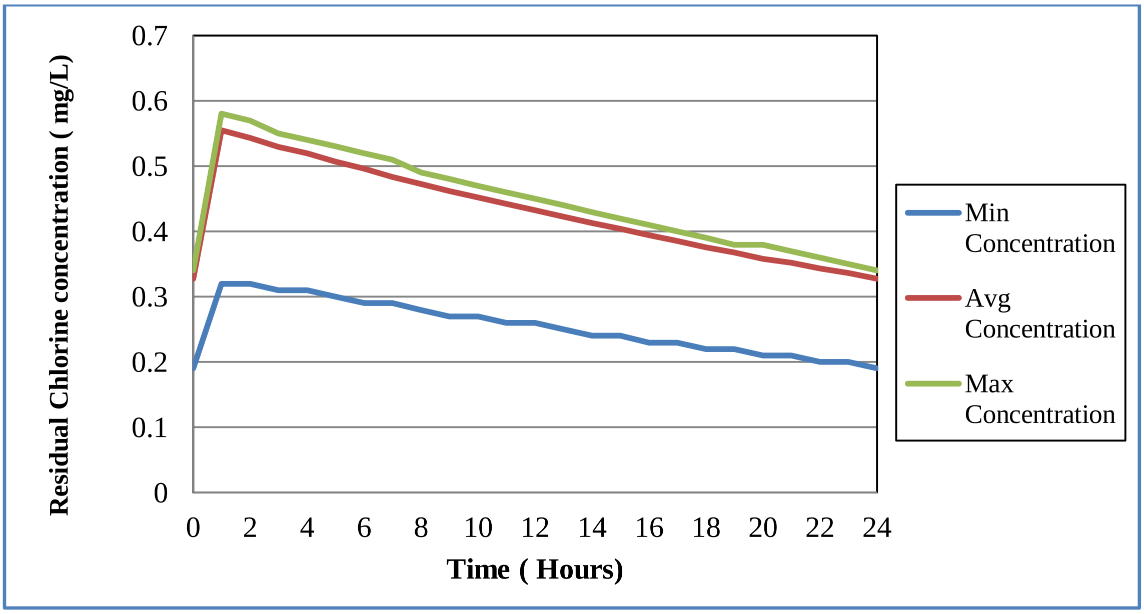


Fig. 5.11: Minimum, average and maximum concentration of residual chlorine for all nodes (Case I) for Case Study 7

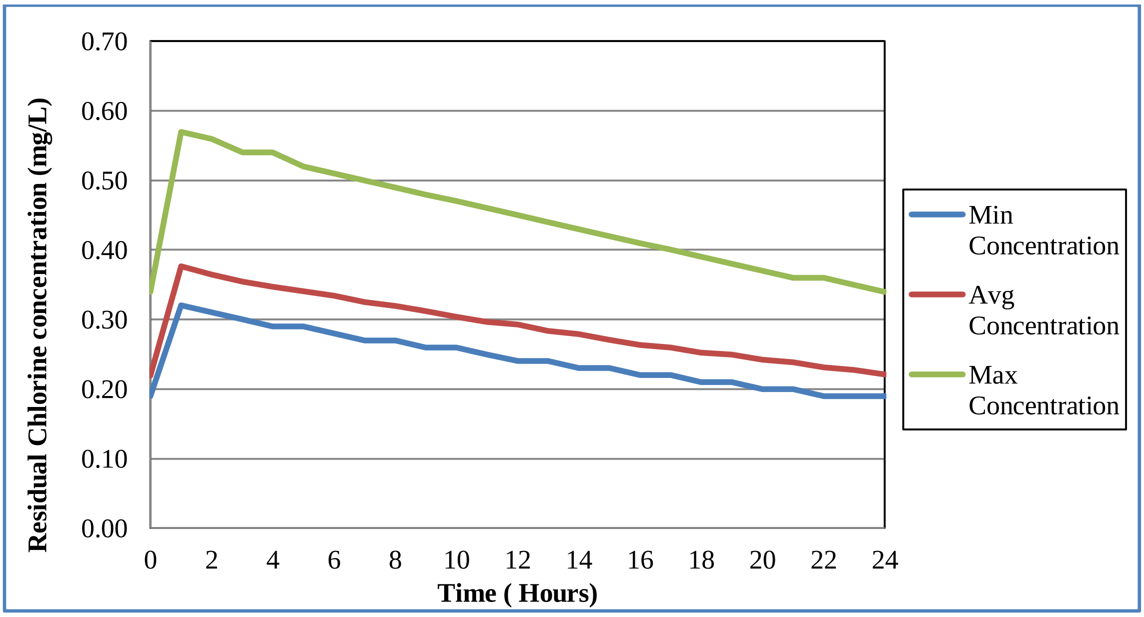


Fig. 5.12: Minimum, average and maximum concentration of residual chlorine for all nodes. (Case II) for Case Study 7

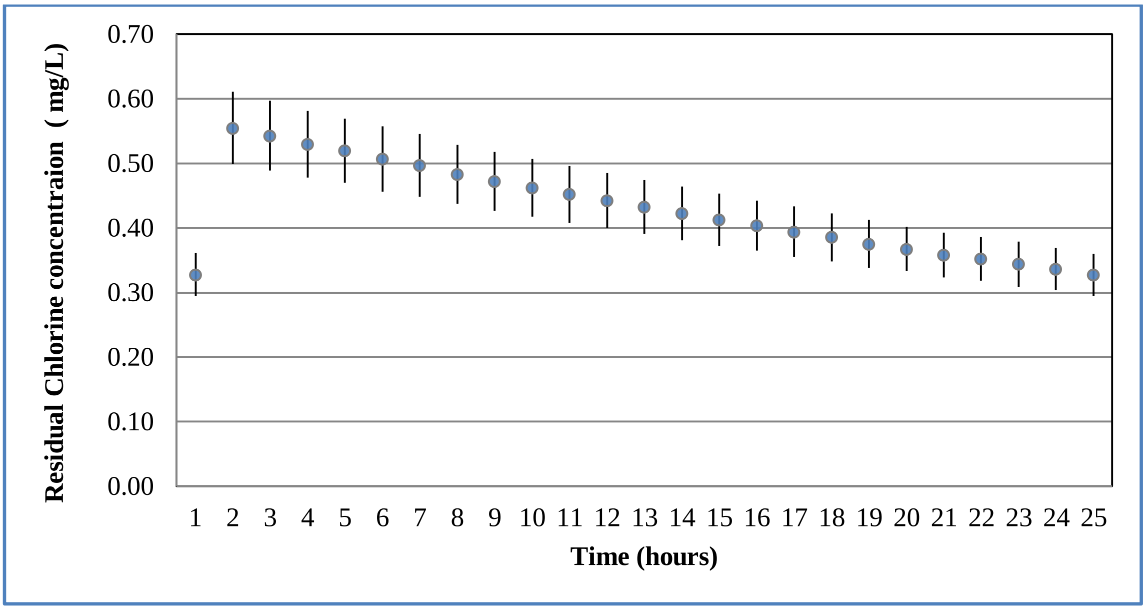


Fig. 5.13: Average residual chlorine concentration and standard deviation for all nodes (Case I) for Case Study 7

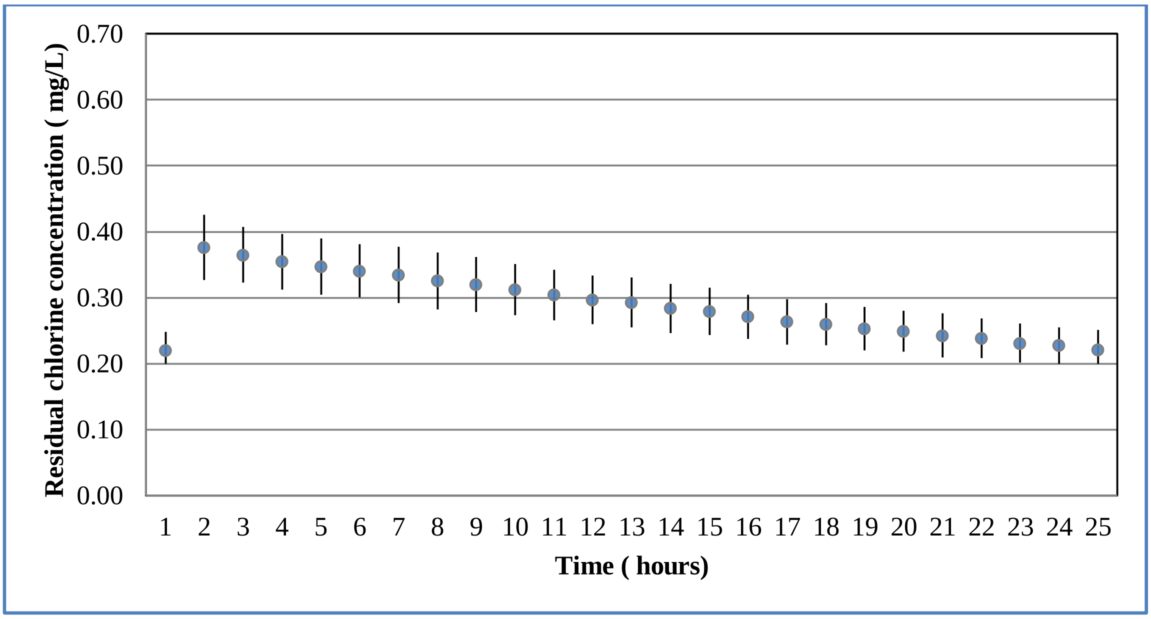


Fig. 5.14: Average residual chlorine concentration and standard deviation for all nodes (Case II) for Case Study 7

The overall value of standard deviation for all nodes for case I and II is obtained as 0.0805 and 0.0589. Sensitivity analysis was carried out to check the effect of selection of hydraulic time step and water quality time step. For all analysis the hydraulic time step was taken as 1 hour and water quality time step is taken as 5 minutes. It shows that the results are almost same for the hydraulic time step 1 hour or 5 minutes. There is a marked difference in residual chlorine concentration when the water quality time step is varied whereas the effect of variation of hydraulic time step is negligible on the concentration of chlorine. Therefore for all analysis the water quality time step is taken as 5 min only.

5.7.2. Discussions

The optimization results for water supply of two hours shows that the scheduling of the mass rate of chlorine as suggested by the optimization gives 33.33 % reduction for case II as compared to case I having conventional approach of application of chlorine at source alone. As seen from the Fig. 5.13 to 5.16 show the minimum, average and maximum concentration of residual chlorine, it is observed that Booster chlorination allows lower average residual chlorine throughout the DWDS as well as the standard deviation in case of booster chlorination is less than for conventional chlorination which results in more uniform distribution of residual chlorine as compared to conventional chlorination. From the results, it is observed that for the large network like Manjalpur the difference in the % reduction for two water supply hours is only not too much (only 3 %) . The proper selection of the water quality time step is very essential for the prediction of the residual chlorine concentration. It is advisable to select the minimum water quality time step to get the proper values of residual chlorine concentration. For checking the effect of network size and flow conditions the small network such as North Harni DWDS which is small as compared to Manjalpur network is selected for the optimal location and scheduling of booster station and to check the feasibility of using booster stations for such small network.

5.8 Details of Study Area (North Harni)

North Harni Drinking Water Distribution System (DWDS) covering part of northern area of Vadodara, Gujarat, India, is selected for the application of the optimization problem. The modelled network has total pipe length of 14597.11 m having command area of 3.18 km^2, population in 2011 was 28158 and projected population in 2040 is 54941. The capacity of OHT is 2.47ML and the capacity of GSR is 9.88 ML making total storage capacities of 12.35 ML. The link data includes connectivity, length, diameter, and roughness information while the node data includes the base demand and elevation. The cylindrical tank at node 1 is modelled as a continuous flow stirred tank reactor. The demand at each node is computed based on population density and area served by each node. The total demand of the DWDS is 4062 m^3/h supplying in one day. The demand at various nodes is considered to be steady state and satisfied by supplying the water in one and two hours a day as per the case study. To check the effect of low flow conditions on selection of booster stations, a special case case of deficit flow condition is also carried out in which the flow supplied is considered to be half of the design flow supplied in two hours per day. The consumers have a practise to store the water for daily requirements in underground storage tank. The simulation is done by supplying the water for supply hours and there will be no flow in rest of the time as per the existing practice of the study area. The water distribution system simulation model EPANET is used to analyse the hydraulic and water quality parameters. The modelled network is having 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 BS_1 to BS_5) represent locations of inline disinfectant addition. The critical nodes (CN 1 to 11) covering the whole network are assigned at various nodes to monitor the concentration of residual chlorine at that particular nodes. The critical nodes selected are node number 2, 11, 19, 27, 37, 40, 47, 57, 70, 75 and 53. Water is supplied under constant pressure from source tank and the pressure drops due to the friction losses which are computed using Darcy Weishbach equation in EPANET (Rossman 2000) simulation model. The Value of bulk decay coefficient k_b is assumed as 0.55 d^{-1} from literature (Rossman et al. 1994). When the water supply hours is kept one hour, the maximum velocity in the pipe is obtained as 5.2 m/s which is obtained at the pipe directly supplying water from the tank whereas the average velocity is obtained as 1.35 m/s which is within permissible limit. When the water supply hours is kept one hour The maximum velocity in the pipe is obtained as 2.65 m/s which is obtained at the pipe directly supplying water from the tank whereas the average velocity is obtained as 0.68 m/s which is within permissible limit. When the deficient flow condition is taken the maximum value of velocity comes to be 1.32 m/s and minimum velocity is 0.34 m/s. The residual pressure obtained at each node is greater than 7 m as per requirement (MoUD, CPHEEO 1999). The value of friction factor varies from 0.014 to 0.033 which is calculated based on Reynold's Number and relative roughness of 0.035 mm for DI pipes.

The details of North Harni DWDS network as shown in Fig. 5.15 is used for the development of various optimization model using linear programming and particle swarm optimization (PSO) method under different simulation scenario and conditions. The details of the different scenario and cases used for the particular study are mentioned in following paragraphs.

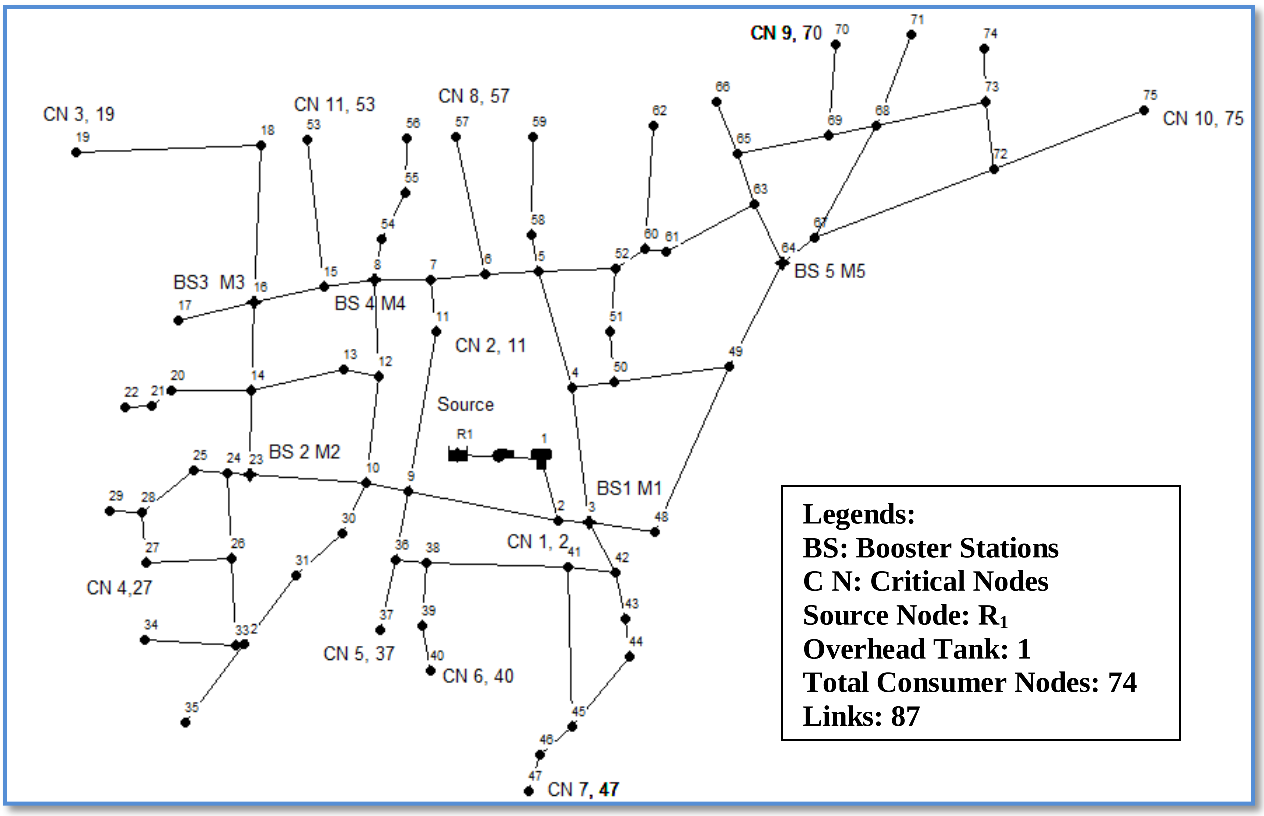


Fig. 5.15: North Harni DWDS network

5.9 Case Study 8: Optimal Location and Scheduling of Booster Chlorination for One Hour Water Supply (NH-1H-LP)

The North Harni DWDS network of Fig. 5.15 is used to develop a mathematical model to optimize the location of booster stations along with the chlorination doses with the help of linear programming method of optimization. The objectives considered includes

(1) Minimization of the total mass rate of chlorine at booster stations.

(2) Maintenance of minimum 0.2 mg/L of residual chlorine at all the critical nodes within distribution network.

(3) To find out the optimal location of booster stations along with source chlorination.

Solver function of Excel is used for solving optimization problem.

The demand at various nodes is considered to be steady state and satisfied by supplying the water in one hour a day. Two cases of Booster chlorination along with source application of chlorine are considered for optimization problem. Case I represents the conventional chlorine nation in which the chlorine is applied at source alone. While for case II chlorine is applied with source application of chlorine and booster doses applied at any two booster stations which gives minimum chlorine dose. Case III represents the source application of chlorine along with booster doses applied at all booster stations 1 to 5. For the same network only the source chlorination is applied to check the effectiveness of the Booster chlorination. Using water quality simulation capability of EPANET software the eleven critical nodes i.e. node no 2, 11, 19, 27, 37, 40, 47, 57, 70, 75 and 53 are identified for the source application along with booster chlorination at any two nodes which gives minimum chlorine dose to optimize the location of booster station for case II and all booster stations for Case III. The values of impulse response coefficients is obtained from the results of residual chlorine at node 2, 11, 19, 27,30 37, 40, 47, 57, 70, 75 and 53 using EPANET software as mentioned earlier by running the extended period simulation separately when chlorine mass rate is applied as M_0, M_1, M_2, M_3, M_4 and M_5 alone. The summary of the values of impulse response coefficients obtained is given in Table 5.10.

Table 5.10: Value of Impulse response coefficients at critical nodes (Case Study 8: NH-1H-LP)

Critical Node / Node No	Values of Impulse response coefficients with application of Chlorine mass rate at critical nodes (mg/L) / (mg/min)											
	Only at Source, M_0	**Value**	**Only at Booster 1 , M_1**	**Value**	**Only at Booster 2, M_2**	**Value**	**Only at Booster 3 , M_3**	**Value**	**Only at Booster 4 , M_4**	**Value**	**Only at Booster 5 , M_5**	**Value**
CN 1, 2	$K_{0,1}$	0.00000848	$K_{1,1}$	0	$K_{2,1}$	0	$K_{3,1}$	0	$K_{4,1}$	0	$K_{5,1}$	0
CN 2, 11	$K_{0,2}$	0.00000848	$K_{1,2}$	0	$K_{2,2}$	0	$K_{3,2}$	0	$K_{4,2}$	0	$K_{5,2}$	0
CN 3, 19	$K_{0,3}$	0.00000606	$K_{1,3}$	0.0000100	$K_{2,3}$	0.00001	$K_{3,3}$	0.00015	$K_{4,3}$	0.00006	$K_{5,3}$	0
CN 4, 27	$K_{0,4}$	0.00000758	$K_{1,4}$	0	$K_{2,4}$	0.00005	$K_{3,4}$	0	$K_{4,4}$	0	$K_{5,4}$	0
CN 5, 37	$K_{0,5}$	0.00000848	$K_{1,5}$	0	$K_{2,5}$	0	$K_{3,5}$	0	$K_{4,5}$	0	$K_{5,5}$	0
CN 6, 40	$K_{0,6}$	0.00000818	$K_{1,6}$	0.0000100	$K_{2,6}$	0	$K_{3,6}$	0	$K_{4,6}$	0	$K_{5,6}$	0
CN 7, 47	$K_{0,7}$	0.00000758	$K_{1,7}$	0.0000100	K_{27}	0	$K_{3,7}$	0	$K_{4,7}$	0	$K_{5,7}$	0
CN 8, 57	$K_{0,8}$	0.00000788	$K_{1,8}$	0.0000100	$K_{2,8}$	0	$K_{3,8}$	0	$K_{4,8}$	0	$K_{5,8}$	0
CN 9, 70	$K_{0,9}$	0.00000636	$K_{1,9}$	0.0000100	$K_{2,9}$	0	$K_{3,9}$	0	$K_{4,9}$	0	$K_{5,9}$	0.00003
CN 10, 75	$K_{0,10}$	0.00000697	$K_{1,10}$	0.0000100	$K_{2,10}$	0	$K_{3,10}$	0	$K_{4,10}$	0	K_{510}	0.00006
CN 11, 53	$K_{0,11}$	0.00000697	$K_{1,11}$	0.0000100	$K_{2,11}$	0	$K_{3,11}$	0	$K_{4,11}$	0.00008	$K_{5,11}$	0

The results obtained after applying the linear programming technique in excel for case II and III gives the following results.

5.9.1 Optimization Results

To find the optimum location of the booster stations out of all five booster nodes the linear programming is done for the various combinations of the booster nodes. Table 5.11 shows all the combinations of booster stations to select the optimum location of booster station. The mass rate of chlorine to be applied at source along with two booster stations for case II and all five booster stations for Case III after using the linear programming technique of optimization in excel is tabulated in Table 5.12. The mass rate to be applied for only source chlorination is obtained as 1980 g/day. While in case II with source and two booster stations the chlorine mass rate to be applied comes to be 1688 g/day.

Table 5.11: Total mass rate of chlorine applied for combination of two booster stations with source application (Case Study 8: NH-1H-LP)

Sr No	Combination of Booster stations	Total mass rate to be applied (mg/min)
1	$M_0+M_1+M_2$	(23571.43+5000+714.28) 29285.71
2	$M_0+M_1+M_3$	(26400+3200+53.33) 29689.33
3	$M_0+M_1+M_4$	(26400+3200+133.33) 29733.33
4	$M_0+M_1+M_5$	(26400+4000+0) 30400
5	$M_0+M_2+M_3$	(31428.57+0+63.49) 31492.06
6	$M_0+M_2+M_4$	(31428.57+0+158.73) 31587.30
7	$M_0+M_2+M_5$	(28695.65+2608.7+579.71) 31884.06
8	$M_0+M_3+M_4$	(31428.57+63.49+0) 31492.06
9	$M_0+M_3+M_5$	(28695.65+173.91+579.81) 29449.28
10	$\mathbf{M_0+M_4+M_5}$	**(26400+666.67+1066.67) 28133.34**
Minimum mass rate(mg/min)= 28133.34		

The combination of the booster stations ($M_0+M_4+M_5$) gives the minimum mass rate of chlorine which as 28139 mg/min which needs chlorine mass rate as 1688 gm/day.

Table 5.12: Optimization results for chlorine application (Case study 8: NH-1H-LP)

Chlorine Mass rate applied at various locations for 1 hour duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine			
			Case II		Case III	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate
	(g/d)	(mg/min)	(g/d)	(mg/min)	(g/d)	(mg/min)
Source, (M_0)	1980	33000	1584	26400	1414.29	23571.43
Booster $BS_1(M_1)$	--	--	--	--	128.57	2142.86
Booster BS_2 (M_2)	--	--	--	--	25.71	428.57
Booster BS_3 (M_3)	--	--	--	--	8.29	138.1
Booster BS_4 (M_4)	--	--	40	666.67	10.71	178.57
Booster BS_5 (M_5)			64	1066.67	57.14	952.38
Total Mass rate applied	1980	33000	1688	28133.34	1644.71	27411.9
% Reduction in mass rate of chlorine compared to case I	--		14.75		16.93	

The tank concentration of residual chlorine is obtained for all three cases. The residual chlorine concentration for the last 24 hours of the 10 days (240 hours) simulation (i.e. 216 hours to 240 hours) is shown in Fig. 5.16. Fig. 5.17 and Fig. 5.18 show the graph of minimum, average and maximum concentration of residual chlorine at all the locations for conventional chlorination (Case I) and for two locations for booster chlorination with two boosters and source application (Case II) respectively. Fig. 5.19 and Fig. 5.20 show the standard deviation and average concentration for all nodes for case I and Case II respectively.

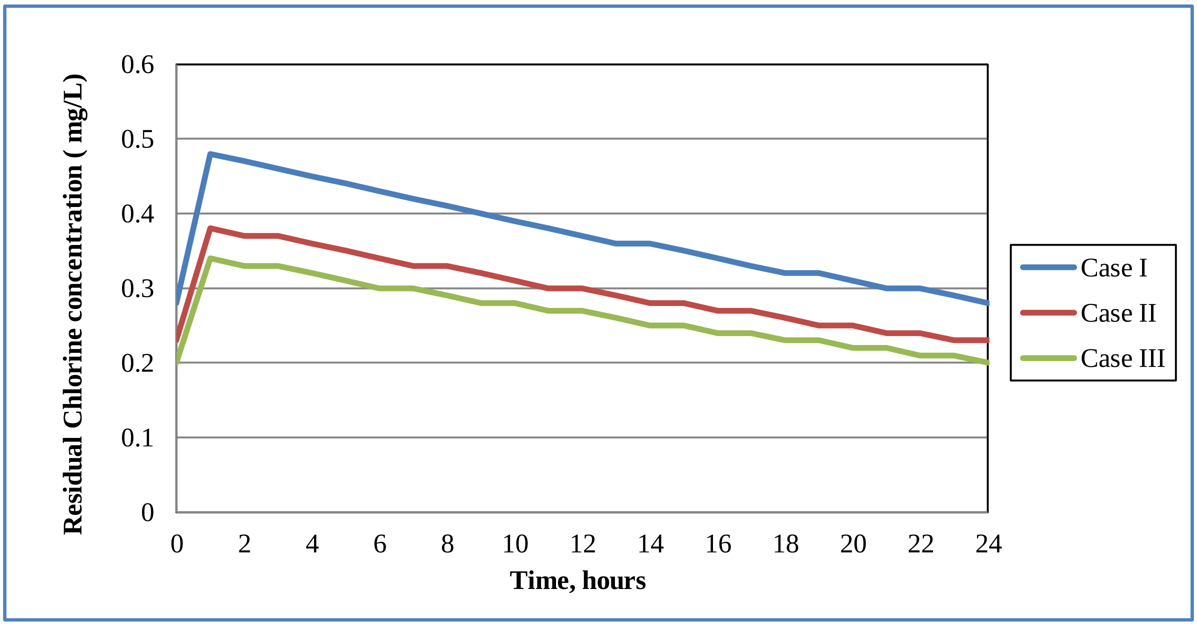


Fig. 5.16: Tank concentration for residual chlorine (Case I, Case II and Case III) for Case Study 8

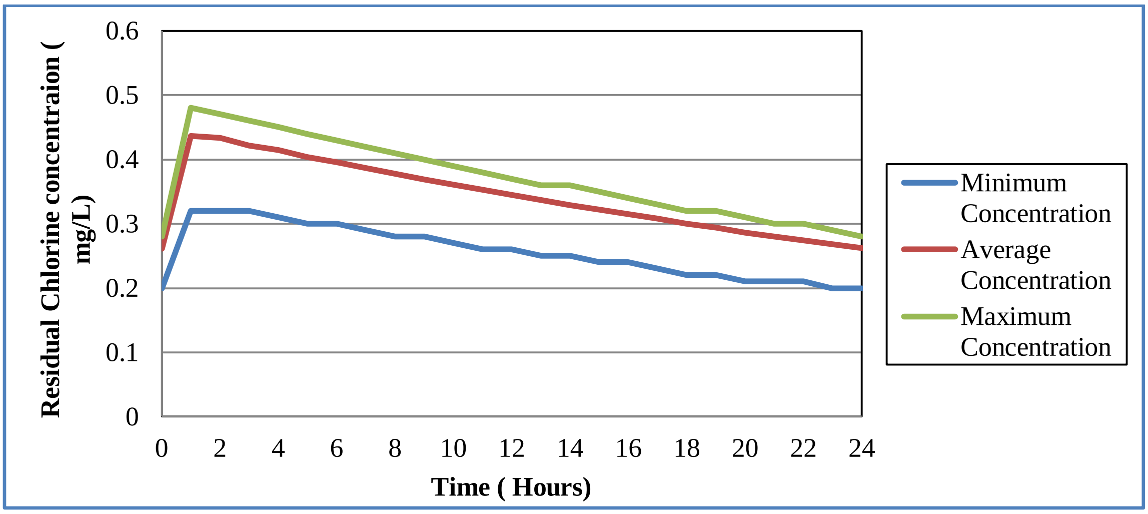


Fig. 5.17: Minimum, average and maximum concentration of residual chlorine for all nodes (Case I) for Case Study 8

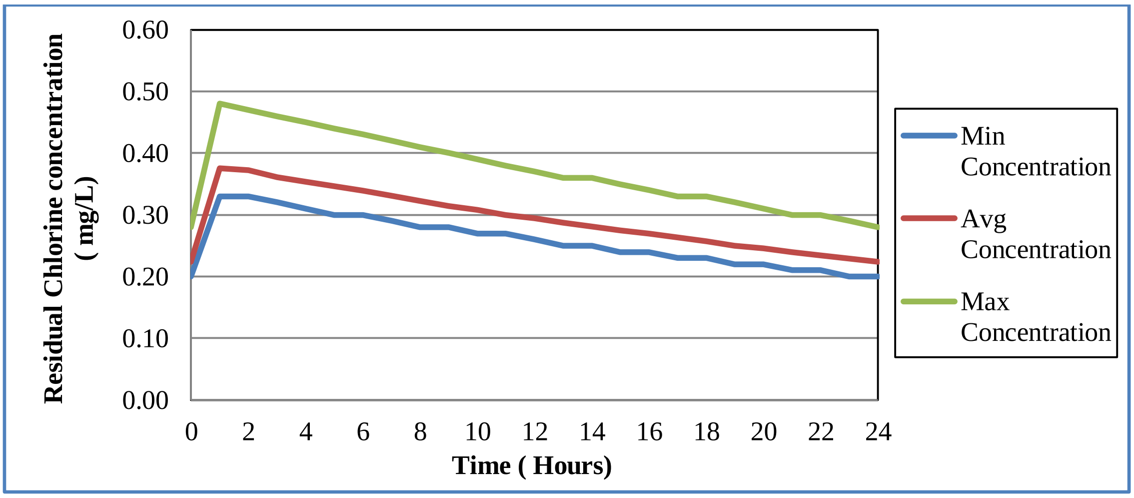


Fig. 5.18: Minimum, average and maximum concentration of residual chlorine for all nodes (Case II) for Case Study 8

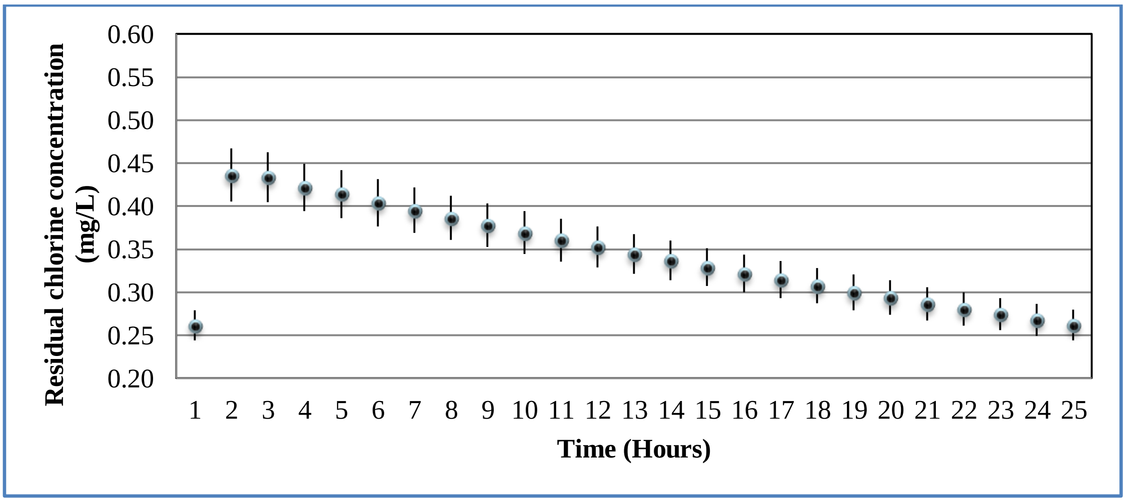


Fig. 5.19: Average residual chlorine concentration and standard deviation for all nodes. (Case I) for Case Study 8

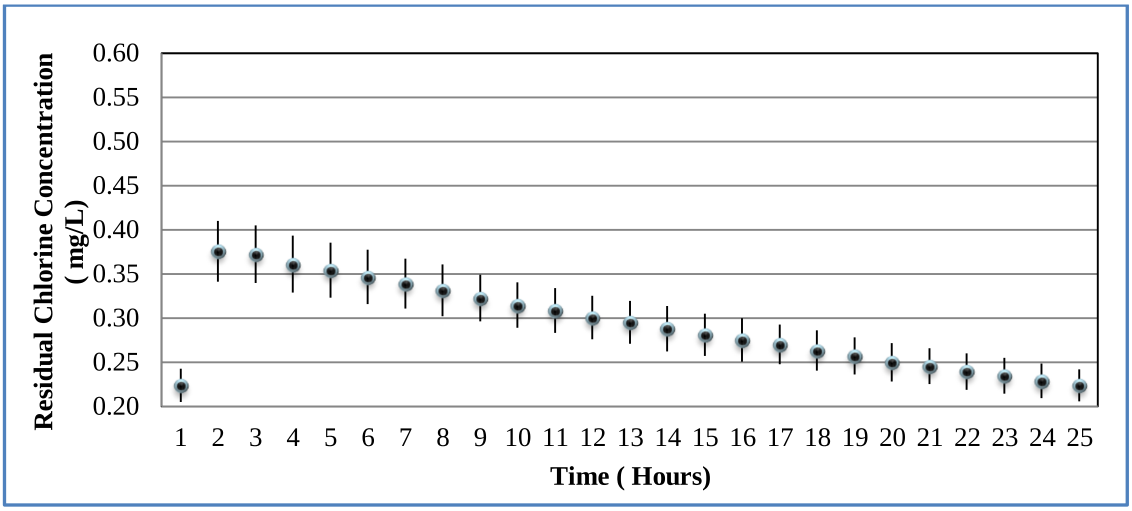


Fig. 5.20: Average residual chlorine concentration and standard deviation for all nodes. (Case II) for Case Study 8

The overall value of standard deviation for all nodes for case I and II is obtained as 0.0599 and 0.0553. The mass rate of chlorine to be applied at booster stations obtained after optimization is applied on DWDS network using EPANET software to check 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 (Case I) required 1980 g/d, while Booster chlorination for case II required 1688 g/d and for case III it comes to be 1644.71 g/d to satisfy the constraints of 0.2 mg/L residual chlorine at all the locations in DWDS network. Fig. 5.21 shows the contour plot of residual chlorine at all the locations for conventional chlorination (Case I). Fig 5.22 and Fig 5.23 gives the contour plot of residual chlorine at all the locations for Booster chlorination along with source application of chlorine for case II and case III respectively.

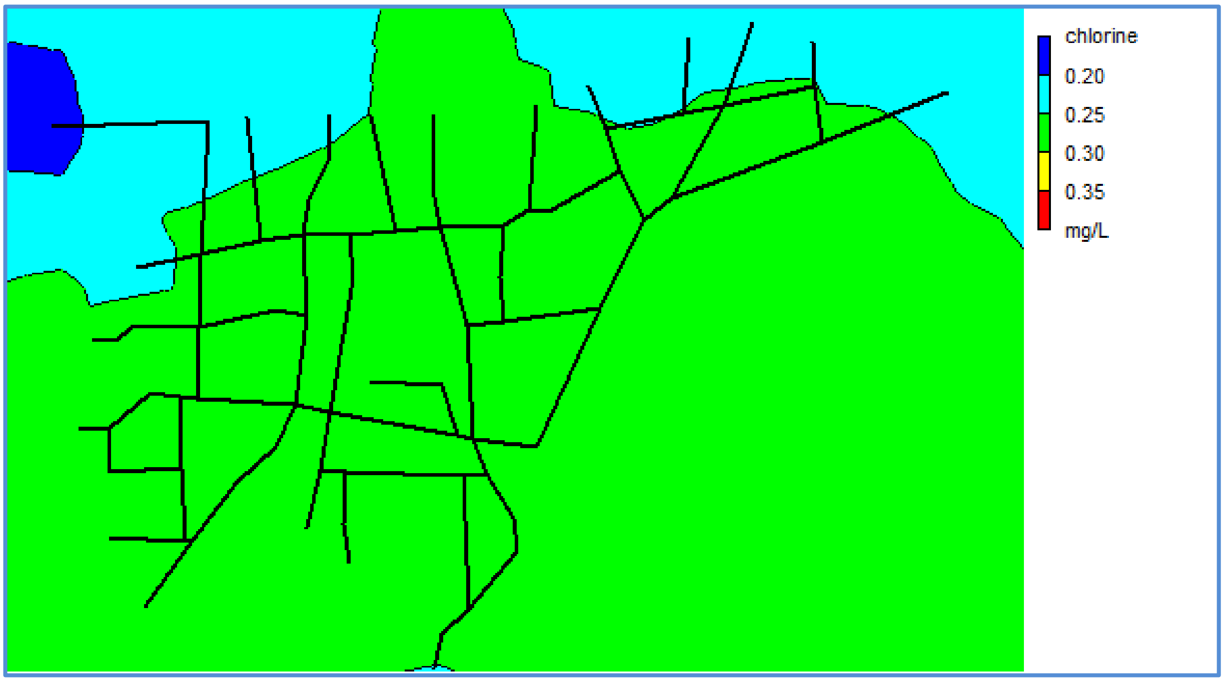


Fig. 5.21: Contour Plot of residual chlorine for Conventional Chlorination (Case I) for Case Study 8.

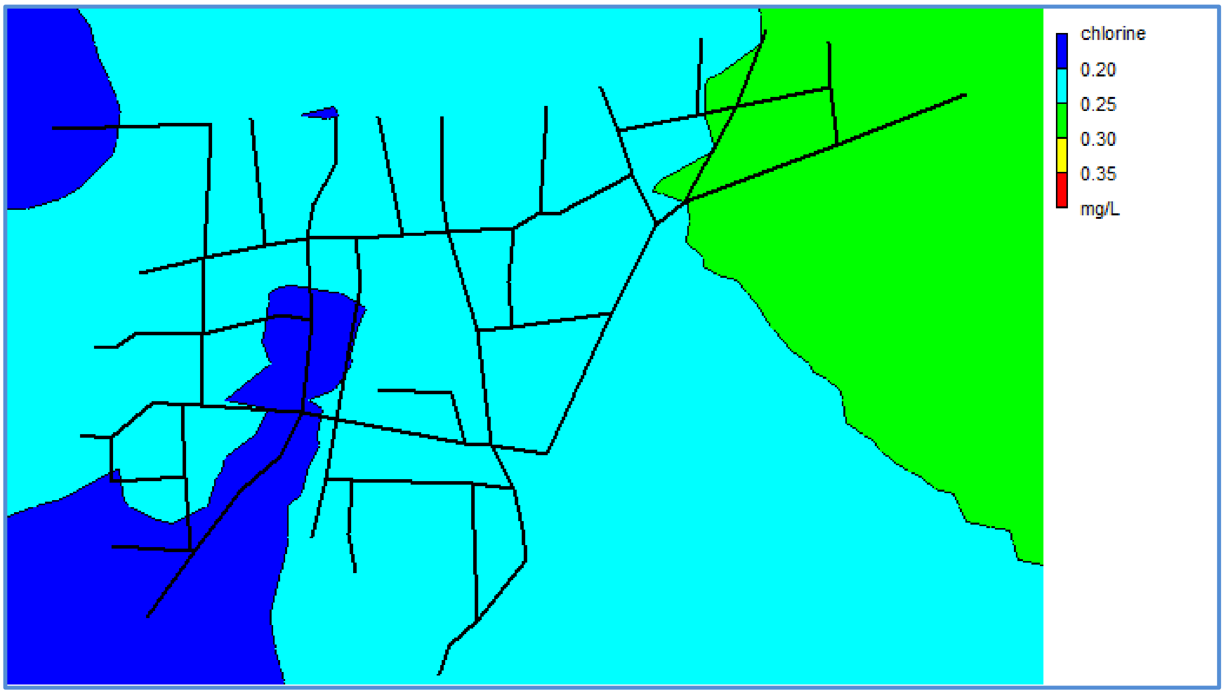


Fig. 5.22: Contour Plot of residual chlorine for Booster Chlorination (Case II) for Case Study 8.

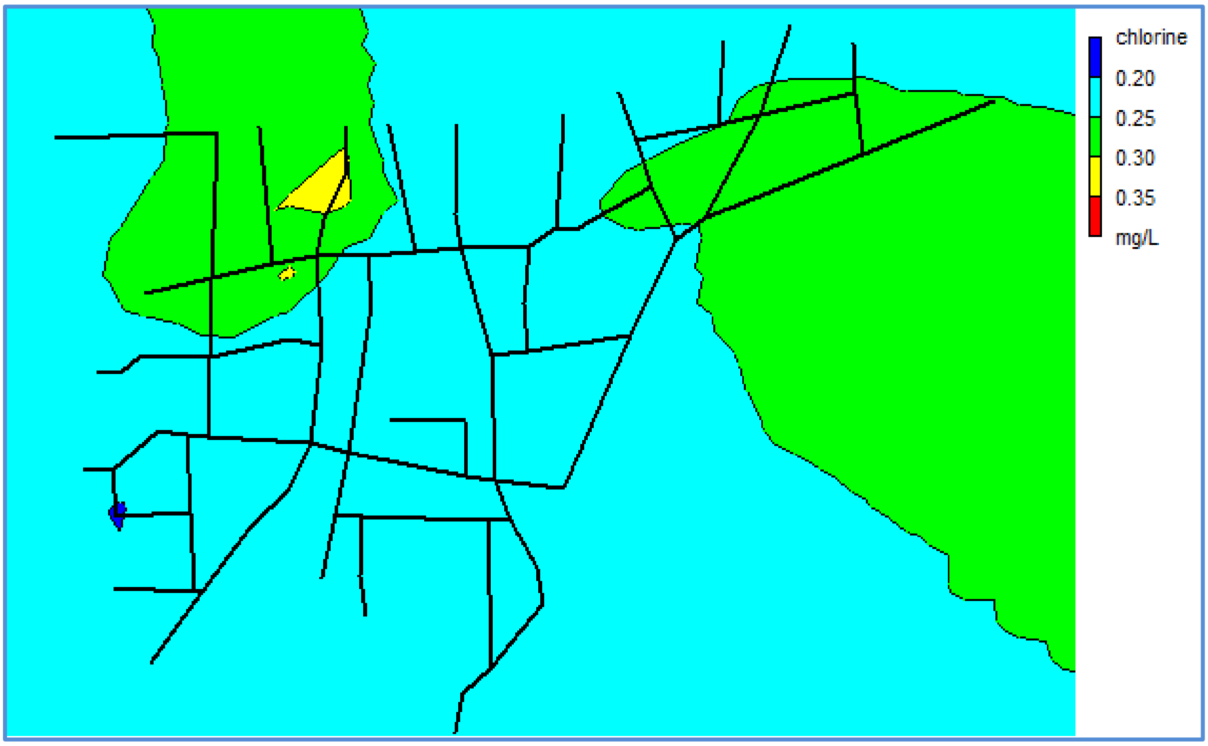


Fig. 5.23: Contour Plot of residual chlorine for Booster Chlorination (Case III) for Case Study 8.

5.9.2. Discussions

As observed from the Fig 5.17 to Fig. 5.23, more uniform distribution of chlorine is observed for case II and case III as compared to case I i.e. 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.

The results obtained suggest that the network using conventional chlorination (Case I) requires application of 1980 g/d 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 II with 2 booster stations along with source application of chlorine at various locations in network satisfied the constraint with application of chlorine mass rate as 1688 g/d which gives reduction of total mass rate of chlorine as 14.76%. For case III with 5 booster stations along source application of chlorine, requires 1644.71 g/d which gives 16.93% 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. Looking to the results case II is the better option as compared to case III. 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. 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. To check the effect of water supply hours for the small network the water supply hours was changed to 2 hours.

5.10 Case Study 9: Optimal Location and Scheduling of Booster Chlorination for Two Hours Water Supply (NH-2H-LP)

The same network as mentioned in Fig. 5.15 is used to check the effect of supply hours in development of optimization model. Therefore now the demand at various nodes is considered to be steady state and satisfied by supplying the water in two hours a day. Same control nodes are selected and optimization model was develop using linear programming in excel as well as using MATLAB tool. The value of impulse response coefficients at critical nodes is shown in Table 5.13.

Table 5.13: Value of Impulse response coefficients at critical nodes (Case Study 9: NH-2H-LP)

Node no	Values of Impulse response coefficients with application of Chlorine mass rate at critical nodes (mg/L) / (mg/min)											
	Only at Source, M_0	Value	Only at Booster 1 , M_1	Value	Only at Booster 2 , M_2	Value	Only at Booster 3 , M3	Value	Only at Booster 4 , M4	Value	Only at Booster 4 , M4	Value
Node 2	$K_{0,1}$	0.00001758	$K_{1,1}$	0	$K_{2,1}$	0	$K_{3,1}$	0	$K_{4,1}$	0	$K_{4,1}$	0
Node 9	$K_{0,2}$	0.00001727	$K_{1,2}$	0	$K_{2,2}$	0	$K_{3,2}$	0	$K_{4,2}$	0	$K_{4,2}$	0
Node 11	$K_{0,3}$	0.00001576	$K_{1,3}$	0.00002	$K_{2,3}$	0.00003	$K_{3,3}$	0.0003	$K_{4,3}$	0.00012	$K_{4,3}$	0.00012
Node 19	$K_{0,4}$	0.00001697	$K_{1,4}$	0	$K_{2,4}$	0.00013	$K_{3,4}$	0	$K_{4,4}$	0	$K_{4,4}$	0
Node 27	$K_{0,5}$	0.00001727	$K_{1,5}$	0	$K_{2,5}$	0	$K_{3,5}$	0	$K_{4,5}$	0	$K_{4,5}$	0
Node 37	$K_{0,6}$	0.00001697	$K_{1,6}$	0.00002	$K_{2,6}$	0	$K_{3,6}$	0	$K_{4,6}$	0	$K_{4,6}$	0
Node 47	$K_{0,7}$	0.00001667	$K_{1,7}$	0.00003	$K_{2,7}$	0	$K_{3,7}$	0	$K_{4,7}$	0	$K_{4,7}$	0
Node 57	$K_{0,8}$	0.00001667	$K_{1,8}$	0.00003	$K_{2,8}$	0	$K_{3,8}$	0	$K_{4,8}$	0	$K_{4,8}$	0
Node 70	$K_{0,9}$	0.00001636	$K_{1,9}$	0.00003	$K_{2,9}$	0	$K_{3,9}$	0	$K_{4,9}$	0	$K_{4,9}$	0
Node 75	$K_{0,10}$	0.00001606	$K_{1,10}$	0.00003	$K_{2,10}$	0	$K_{3,10}$	0	$K_{4,10}$	0	$K_{4,10}$	0
Node 53	$K_{0,11}$	0.00001636	$K_{1,11}$	0.00002	$K_{2,11}$	0	$K_{3,11}$	0	$K_{4,11}$	0.00017	$K_{4,11}$	0.00017

The optimization model with objective function as mentioned in equation 5.7 is organized in linear programming format using MATLAB. Various Impulse response coefficients as mentioned in Table 5.13 are used to apply the formula for the constraints in MATLAB. Non negativity constraints are applied on the chlorine mass rate application. Lower bound of residual chlorine concentration is set at 0.2 mg/L (as per IS-10500, 2012) at all the critical nodes. Once the model is implemented for linear programming in MATLAB, the function gives the optimum solution for the total mass rate to be applied to satisfy all the constraint at critical nodes. The code implemented for linear programming in MATLAB tool is as follows:

```
f=[1;1;1;1;1;1];
 A=[-0.00001758 0   0   0   0   0
-0.00001727 0   0   0   0   0
-0.00001576 -0.00002    -0.00003    -0.0003 -0.00012    0
-0.00001697 0   -0.00013    0   0   0
-0.00001727 0   0   0   0   0
-0.00001697 -0.00002    0   0   0   0
-0.00001667 -0.00003    0   0   0   0
-0.00001667 -0.00003    0   0   0   0
-0.00001636 -0.00003    0   0   0   -0.00007
-0.00001606 -0.00003    0   0   0   -0.00013
-0.00001636 -0.00002    0   0   -0.00017    0
];
b=[-0.2;-0.2;-0.2;-0.2;-0.2;-0.2;-0.2;-0.2;-0.2;-0.2;-0.2;];
lb=zeros(6,1);
 m=linprog (f,A,b,[],[],lb);
```

The results obtained after applying the linear programming technique in MATLAB for case III in which the chlorine is applied at source along with all five booster nodes. To find the optimal location of booster stations linear programming is used with excel as tool. For the optimum location of the booster station the various combinations of booster stations are run in Excel which gives following results

5.10.1 Optimization Results

For the optimum location the excel is used which gives results which shows all the combinations of booster stations to select the optimum location of booster station as shown in Table 5.14. The mass rate of chlorine to be applied for case I and two booster stations along with source for Case II after using the linear programming technique of optimization in excel is tabulated in Table 5.15.

Table 5.14: Total mass rate of chlorine applied for combination of two booster stations with source application (Case Study 9: NH-2H-LP)

Sr No	Combination of Booster stations	Total mass rate to be applied(mg/min)
1	$M_0+M_1+M_2$	(11578.95+526.32+321.64) 12426.90
2	$M_0+M_1+M_3$	(11785.71+357.14+29.76) 12172.62
3	$M_0+M_1+M_4$	(11785.71+357.14+71.43) 12214.29
4	$M_0+M_1+M_5$	(12692.31+0+0) 12692.31
5	$M_0+M_2+M_3$	(12452.83+0+12.58) 12465.41
6	$M_0+M_2+M_4$	(12452.83+0+30.19) 12483.02
7	$M_0+M_2+M_5$	(12222.22+246.91+28.49) 12497.63
8	$M_0+M_3+M_4$	(12452.83+12.58+0) 12465.41
9	$M_0+M_3+M_5$	(12222.22+24.69+24.49) 12275.4
10	**$M_0+M_4+M_5$**	**(12000+87.27+55.94) 12143.21**
Minimum mass rate(mg/min)= 12143.21		

The combination of the booster stations ($M_0+M_4+M_5$) gives the minimum mass rate of chlorine which as 12143 mg/min which needs chlorine mass rate as 1457.18 gm/day.

Table 5.15: Optimization results for chlorine application (Case study 9: NH-2H-LP)

Chlorine Mass rate applied at various locations for 2 hours duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine Case II (only two boosters)		Booster Chlorination along with source application of chlorine Case III (all boosters)	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate
	(g/d)	(mg/min)	(g/d)	(mg/min)	(g/d)	(mg/min)
Source, (M_0)	1523.8	12698	1440	12000	1389.72	11581
Booster $BS_1(M_1)$	--	--	--	--	27.84	232
Booster BS_2 (M_2)	--	--	--	--	3.24	27
Booster BS_3 (M_3)	--	--	--	--	3.12	26
Booster BS_4 (M_4)	--	--	10.47	87.27	4.20	35
Booster BS_4 (M_5)	--	--	6.71	55.94	6.48	54
Total Mass rate	1523.8	12698	1457.18	12143.21	1434.6	11955
%Reduction as compared to case I	--		4.35		5.85	

5.10.2. Discussions

The application of chlorine mass rate only at source alone required 1523.8 g/d, and for case III it comes to be 1434.6 g/d to satisfy the constraints of 0.2 mg/L residual chlorine at all the locations in DWDS network. The results obtained suggest that the Network using case I i.e. conventional chlorination requires application of 1523.8 g/d 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 while Booster chlorination for case II required 1434.6 g/d. For the same network using linear programming(LP) optimization technique using MATLAB suggests that for case III with 5 booster stations along with source application of chlorine at various locations in network satisfied the constraint with application of chlorine mass rate as 1434.6 g/d which gives reduction of total mass rate of chlorine as 5.85% compared to case I. The reduction in the total mass rate of chlorine is very less. This is due to increase in water supply hours from 1 hour to 2 hours. As the network is small and water supply hours is increased from one hour to two hours, the farthest nodes having travelling time greater than 1 hour has no much effect of booster chlorination.

For any drinking water distribution system having small network and less travel time of chlorine the booster stations may not require as during the supply hours the chlorine will reach to the farthest node. For such small network if supply hours are more than the travelling time of chlorine the need of booster chlorination is not justified. But if the flow is less as compared to the design flow it may change the scenario. To check the effect of low flow conditions on the selection of booster stations a special case of the deficit flow conditions is considered and applied to the same network and more number of booster stations to optimize the location of booster stations.

5.11 Case Study 10: Optimal Location and Scheduling of Booster Chlorination with Deficit Flow Conditions (NH-2HD-LP)

The same North Harni Drinking Water Distribution System shown in Fig. 5.24 is selected for the applying the optimization problem for optimal location and scheduling of booster chlorination station for deficit flow conditions. The flow applied to the system is reduced to half i.e. 2031 m^3/h which is supplied during total two hours per day. Case I represents the conventional method of applying chlorine i.e. at source alone. While in case II chlorine is applied with source application of chlorine and two booster stations selected for the optimum locations from booster stations BS_1 to BS_{10}. Using water quality simulation capability of EPANET software ten critical nodes i.e. Node no 2, 11, 19, 27, 37, 40, 47, 57, 70 and 75 are identified for the source application along with booster chlorination at Nodes BS $_1$ to BS $_{10}$ for Case II. The summary of the impulse response coefficient obtained is given in Table 5.16.

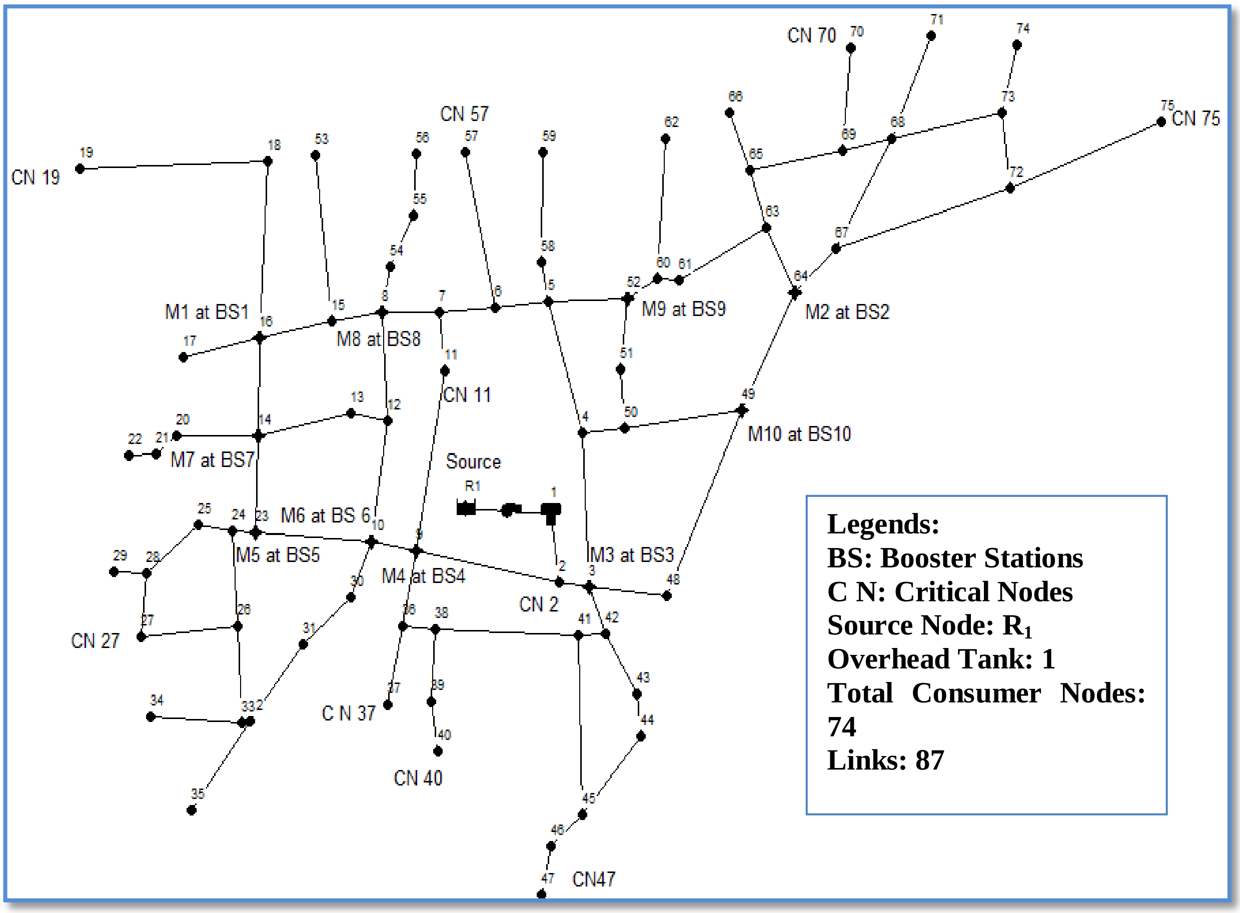


Fig. 5.24: North Harni Distribution network (Deficit flow conditions)

Table 5.16: Value of Impulse response coefficients at critical nodes for case II (Case Study 10: NH-2HD-LP)

Node No	Values of Impulse response coefficients Kij, with application of Chlorine mass rate at critical nodes (mg/L) / (mg/min)										
	Only at Source, M_0	Only at Booster BS_1 , M_1	Only at Booster BS_2 , M_2	Only at Booster BS_3 , M_3	Only at Booster BS_4 , M_4	Only at Booster BS_5 , M_5	Only at Booster BS_6 , M_6	Only at Booster BS_7 , M_7	Only at Booster BS_8 , M_8	Only at Booster BS_9 , M_9	Only at Booster BS_{10} , M_{10}
Node 2	0.00003312	0	0	0	0	0	0	0	0	0	0
Node 11	0.00003150	0	0	0	0.00010000	0	0	0	0	0	0
Node 19	0.00001858	0.00060000	0	0.00002801	0.00005000	0.0001000	0.00003279	0.00015000	0.0002509	0	0
Node 27	0.00002908	0	0	0	0.00010000	0.0003000	0.00013115	0	0	0	0
Node 37	0.00003150	0	0	0	0.00010000	0	0	0	0	0	0
Node 40	0.00003069	0	0	0.00004669	0.00005000	0	0	0	0	0	0
Node 47	0.00002746	0	0	0.00005602	0	0	0	0	0	0	0
Node 57	0.00002746	0	0	0.00005602	0	0	0	0	0	0	0
Node 70	0.00002423	0	0.0001401	0.00005602	0	0	0	0	0	0	0.0001000
Node 75	0.00002019	0	0.0002521	0.00005602	0	0	0	0	0	0.0002000	0.0002000

The optimization model with objective function as mentioned in equation 5.7, is organized in linear programming format using excel. Various impulse response coefficients as mentioned in table 5.16 are used to apply the formula for the constraints in excel for various combinations of booster stations. Non negativity constraints are applied on the chlorine mass rate application. Lower bound of residual chlorine concentration is set at 0.2 mg/L (as per IS-10500, 2012) at all the critical nodes. Once the model is implemented for linear programming in excel, the solver function gives the optimum solution of Total mass rate to be applied to satisfy all the constraint at critical nodes with different combinations of booster stations and locations. Initially total 10 combinations are tried for chlorine applied at source and one booster station and later on total 45 combinations are tried to get the optimal locations of booster stations. The combinations are tried such as M_0+M_1+M_2, M_0+M_1+M_3 and so on to find the optimal location of booster stations along with source application. The results obtained after applying the linear programming technique for 10 and 45 different combinations of booster stations in excel for case II gives the following results.

5.11.1 Optimization Results

The mass rate of chlorine to be applied at source with one booster station for case II is computed for all booster stations using the linear programming technique of optimization in excel using simplex algorithm is tabulated in Table 5.17.

Table 5.17: Total mass rate of chlorine applied for combination of one booster station with source application (Case Study 10: NH-2HD-LP)

Sr No	Combination of Booster stations	Total mass rate to be applied (mg/min)
1	M_0+M_1	(9904.8+26.67) 9931.47
2	M_0+M_2	(10766.0+0) 10766.09
3	M_0+M_3	(6878.33+2578.33) 9457.33
4	M_0+M_4	(9904.8+320) 10224.80
5	M_0+M_5	(9904.8+160)10064.80
6	M_0+M_6	(9904.8+488)10392.80
7	M_0+M_7	(9904.8+106.67)10011.47
8	M_0+M_8	(9904.8+63.77) 9968.57
9	M_0+M_9	(10766.09+0) 10766.09
10	M_0+M_{10}	(10766.09+0) 10766.09
Minimum mass rate(mg/min)= 9457		

As seen from Table 5.17, the combination of source along with BS_3 (M_3)gives the minimum mass rate of chlorine but to still reduce the mass rate of chlorine the combination of three booster station is tried with the same technique of linear programming in excel. The mass rate of chlorine to be applied at source with two booster stations for case II for all the 45 different options of combinations of booster stations is tabulated in Table 5.18. Table 5.19 gives the mass rate to be applied for the optimum location of booster stations.

Table 5.18: Total mass rate of chlorine applied for combination of two booster stations with source application (Case Study 10: NH-2HD-LP)

Sr No	Combination of Booster stations	Total mass rate to be applied (mg/min)	Sr No	Combination of Booster stations	Total mass rate to be applied (mg/min)
1	**M_0+M_1+M_2**	**(7282.94+107.84+210)7600.78**	24	M_0+M_3+M_{10}	(6878.33+2578.33+0)9456.57
2	M_0+M_1+M_3	(6878.33+69.44+1090.83) 8038.61	25	M_0+M_4+M_5	(9904.8+0+160)10064.8
3	M_0+M_1+M_4	(9904.8+26.67+0) 9931.47	26	M_0+M_4+M_6	(9904.8+0+320)10224.8
4	M_0+M_1+M_5	(9904.8+0+160)10064.80	27	M_0+M_4+M_7	(9904.8+0+106.67)10011.47
5	M_0+M_1+M_6	(9904.8+0+488)10392.80	28	M_0+M_4+M_8	(9904.8+0+63.77)9968.57
6	M_0+M_1+M_7	(9904.8+0+106.67)10011.47	29	M_0+M_4+M_9	(9904.8+320+0)10224.8
7	M_0+M_1+M_8	(9904.8+0+63.77) 9968.57	30	M_0+M_4+M_{10}	(9904.8+320+0)10224.8
8	M_0+M_1+M_9	(9904.8+26.67+0) 9931.47	31	M_0+M_5+M_6	(9904.8+160+0)10064.8
9	M_0+M_1+M_{10}	(7282.94+107.84+264.71)7655.49	32	M_0+M_5+M_7	(9904.8+0+106.67)10011.47
10	M_0+M_2+M_3	(6878.33+0+2578.83) 9456.67	33	M_0+M_5+M_8	(9904.8+0+63.77) 9968.57
11	M_0+M_2+M_4	(7282.94+210+1294.12) 8787.06	34	M_0+M_5+M_9	(9904.8+160+0)10064.8
12	M_0+M_2+M_5	(7282.94+210+647.56) 8140	35	M_0+M_5+M_{10}	(7282.94+647.06+264.71) 8194.71
13	M_0+M_2+M_6	(7282.94+210+1973.53) 9466.47	36	M_0+M_6+M_7	(9904.8+0+106.67)10011.47
14	M_0+M_2+M_7	(7282.94+210+431.37) 7924.31	37	M_0+M_6+M_8	(9904.8+0+63.77)9968.57
15	M_0+M_2+M_8	(7282.94+210+257.9)7750.84	38	M_0+M_6+M_9	(9904.8+488+0)10392.8
16	M_0+M_2+M_9	(10777.09+0+0) 10766.09	39	M_0+M_6+M_{10}	(7282.94+1973.53+264.71)9521.18
17	M_0+M_2+M_{10}	(10777.09+0+0) 10766.09	40	M_0+M_7+M_8	(9904.8+0+63.77)9968.57
18	M_0+M_3+M_4	(6039.51+1393.174+975.61)8408.29	41	M_0+M_7+M_9	(9904.8+106.67+0)10011.47
19	M_0+M_3+M_5	(6349.23+1281.54+461.54)8092.31	42	M_0+M_7+M_{10}	(7282.94+431.37+264.71)7979.02
20	M_0+M_3+M_6	(6349.23+1281.54+1407.69)9038.46	43	M_0+M_8+M_9	(9904.8+63.77+0) 9968.57
21	M_0+M_3+M_7	(6878.33+1090.83+277.78)8246.94	44	M_0+M_8+M_{10}	(7282.94+257.9+264.71)7806.55
22	M_0+M_3+M_8	(6878.33+1090.83+166.07)8135.24	45	M_0+M_9+M_{10}	(10766.09+0+0)10766.09
23	M_0+M_3+M_9	(6878.33+2578.33+0)9456.67	**Minimum mass rate(mg/min)= 7601.78**		

Table 5.19: Optimization results for chlorine application (Case study 10: NH-2HD-LP)

Chlorine Mass rate applied at various locations for 2 hours duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine Case II	
	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)
Source	1291.9	10766	873.95	7282.94
BS_1 (M_1)	--	--	12.74	107.84
BS_2 (M_2)	--	--	25.20	210.00
Total Mass rate applied	1291.9	10766	912.09	7600.78
% Reduction in mass rate of chlorine compared to case I	--		29.4	

Fig. 5.25 gives the tank concentration of residual chlorine for case I and II for the last 24 hours of 10 days simulation. Fig. 5.26 and 5.27 shows the minimum, average and maximum concentration of chlorine for all nodes for Case I and case II. Fig. 5.28 and Fig. 5.29 show the average concentration and standard deviation for all nodes for case II. Fig. 5.30 shows the variation for case I and case II for all nodes for 240 hours simulation.

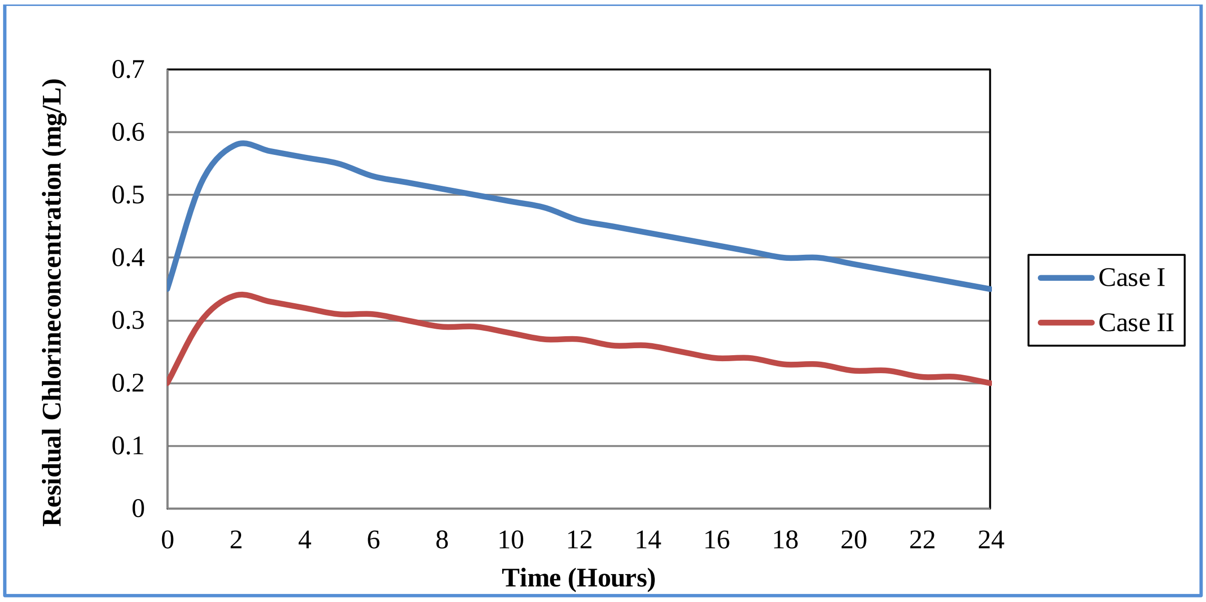


Fig. 5.25: Tank concentration of residual chlorine (Case I and Case II) for Case Study 10

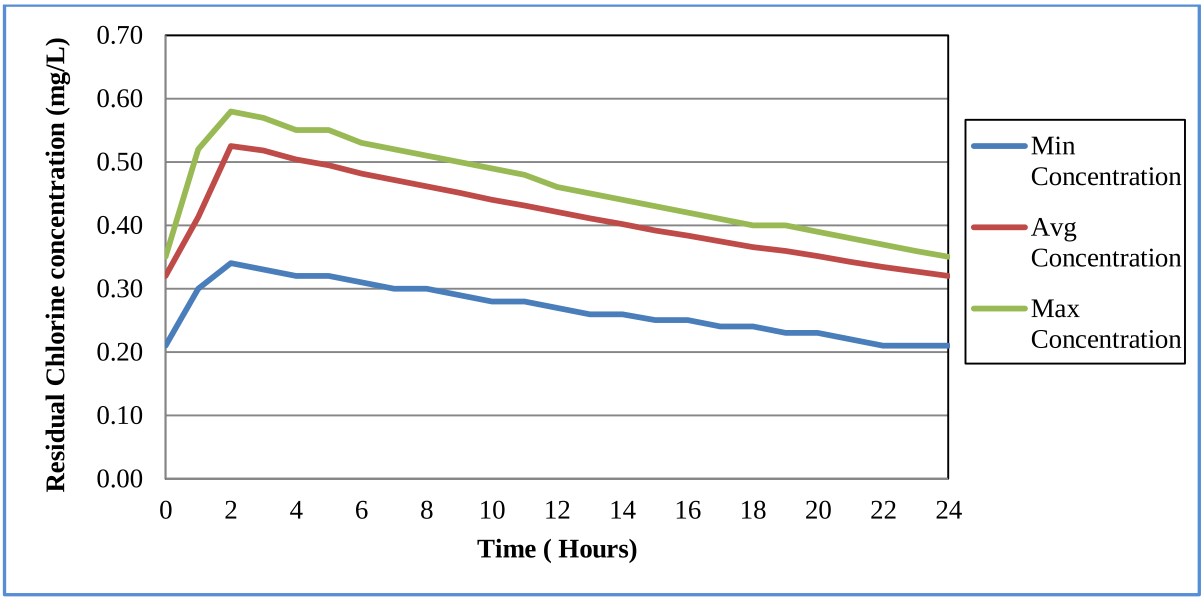


Fig. 5.26: Minimum, average and maximum concentration of residual chlorine for all nodes (Case I) for Case Study 10

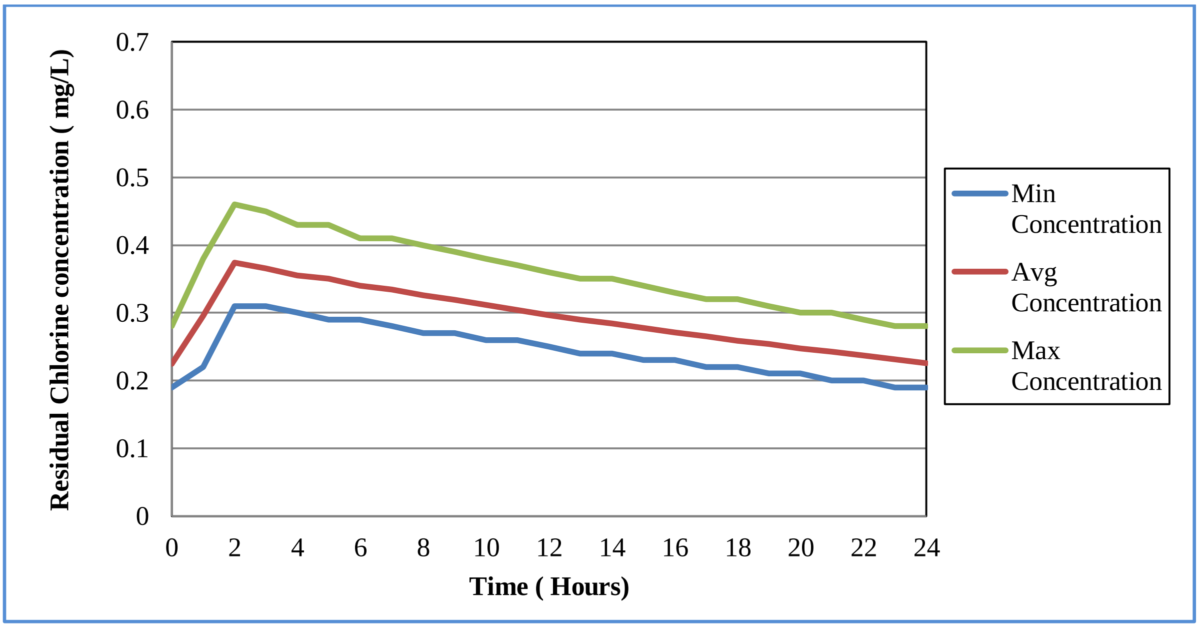


Fig. 5.27: Minimum, average and maximum concentration of residual chlorine for all nodes (Case II) for Case Study 10

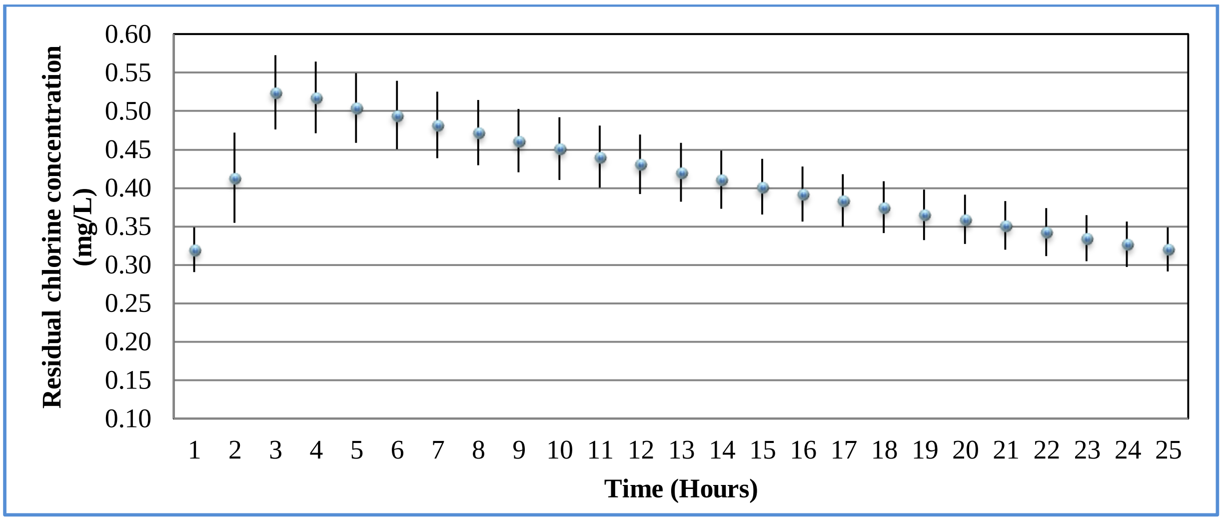


Fig. 5.28: Average residual chlorine concentration and standard deviation for all nodes (Case I) for Case Study 10

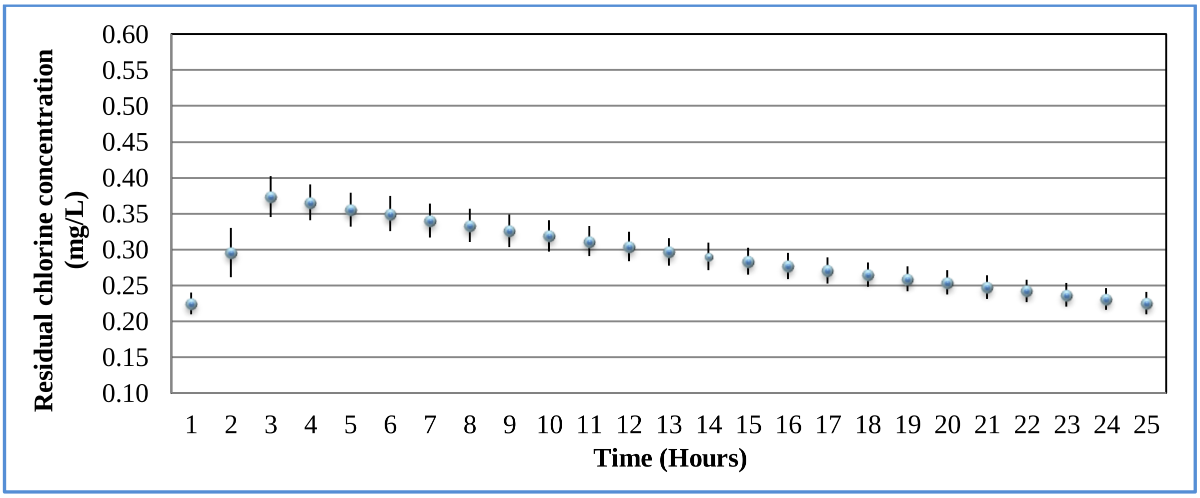


Fig. 5.29: Average residual chlorine concentration and standard deviation for all nodes (Case II) for Case Study 10

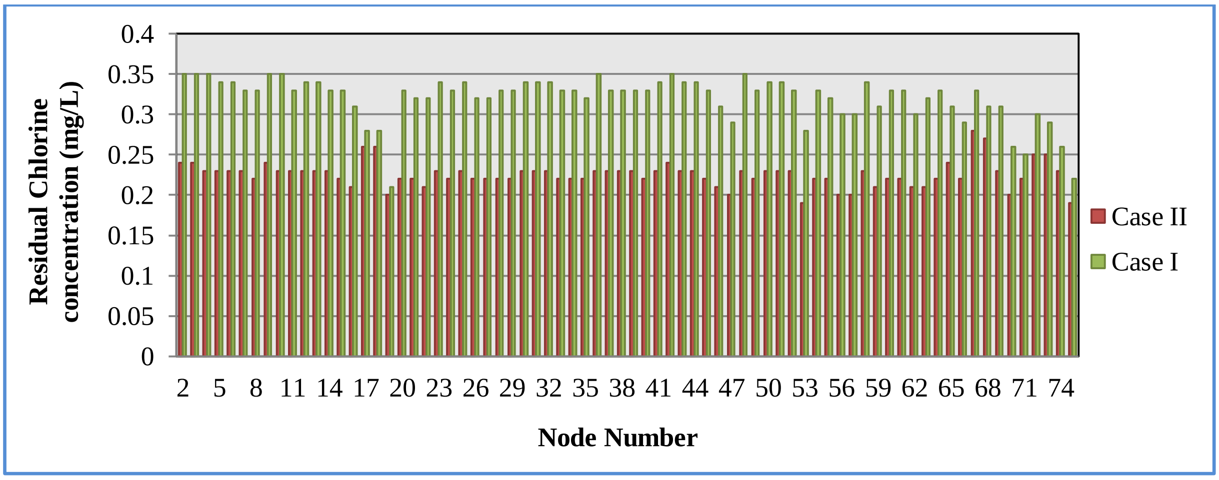


Fig. 5.30: Variation of residual chlorine concentration at each node after 240 hours for EPS for Case Study 10

The standard deviation for all nodes for case I is obtained as 0.073 whereas for case II is 0.049.

5.11.2. Discussions

As seen from table 5.18, the combination of booster stations BS_1 and BS_2 along with source chlorination gives the minimum mass rate of the chlorine to be applied amongst all the options. The mass rate required for source chlorination is 1291.9 g/d against the mass rate required to be applied for combination of one booster station with source chlorination is obtained as 912.09 g/d in case of booster station BS_1 and BS_2 along with source application which gives reduction of total mass rate of chlorine as 29.4% as compared to conventional chlorination. Tryby et al.(2002) observed the reduction of 37.6% reduction using booster chlorination strategy using three booster stations for Eastern United States DWDS. The indirect benefit of reduction in in chlorine mass rate is reduction in formation of harmful disinfection by products (DBP) due to reduced chlorine mass rate application at booster stations is achieved. The selection of optimal location of booster stations using optimization method gives the less number of booster stations which results in overall economy for any project. Therefore the combination of source along with two booster stations is considered to reduce the trial and to avoid extra cost of installation of booster station. The mass rate of chlorine to be applied at booster stations obtained after optimization is applied on DWDS network using EPANET software, which shows that the constraints of minimum residual chlorine of 0.2 mg/L is satisfied at all the locations. Also the introduction of booster stations along with source application of chlorine shows uniform distribution of chlorine as compared to only source chlorination (Fig. 5.26 to 5.30). This reduced mass rate of chorine yields the indirect benefit of reduced formation of harmful disinfection by products at the same time overall economy is achieved due to less consumption of cost of chlorine. The selection of optimal location of booster stations simultaneously with optimization of mass rate results in more economical option for the installation, operation and maintenance cost of booster station. This model can guide the water supply authority, who may select the number and location of booster stations and scheduling of mass rate of chlorine for the particular DWDS based on their requirements. By adopting booster chlorination strategy the water supply authority can maintain lower average residual chlorine throughout the DWDS and more uniform distribution of residual chlorine as compared to conventional chlorination. Thus, the development of coupled model using simulation model such as EPANET and optimization method like linear programming(LP) in excel for optimal location and optimization of chlorine mass rate serve as an important decision making tool for managing, scheduling and selection of number of booster chlorination stations for any drinking water distribution system (DWDS).

The above Studies 6,7,8,9 and 10 indicate that linear programming method using solver function in excel or MATLAB can be successfully applied in conjunction with method of linear superposition based on water quality simulation. The results shows that the large network of Manjalpur DWDS for 1 hour and 2 hour water supply the booster stations proves to be better option as compared to conventional source chlorination. Whereas the small network like North Harni the booster stations can be justified only during deficit flow conditions. The summary of the result for both the distribution network obtained using linear programming optimization method is presented in Table 5.20.

Table 5.20: Summary Table for different flow conditions and water supply hours (NH and MJ using LP Optimization Method)

Distribution Network	Case Study	Flow rate considered (m^3/hr)	Supply Duration (hours)	Total Demand (m^3/d)	Chlorine application strategy	Chlorine consumption (g/d)	Chlorine consumption ratio (g/m^3)	% reduction as compared to conventional chlorination
Manjalpur	6 (MJ-1H)	9452	1	9452	Conventional (Case I)	5500.00	0.58	-
	6(MJ-1H-LP)	9452	1	9452	Source with two booster stations (Case II)	3821.81	0.40	30.51
	7(MJ-2H-LP)	4726	2	9452	Conventional (Case I)	5500.00	0.58	-
	7(MJ-2H-LP)	4726	2	9452	Source with two booster stations (Case II)	3666.47	0.39	33.34
North Harni	8(NH-1H-LP)	4061	1	4061	Conventional (Case I)	1980.00	0.49	-
	8(NH-1H-LP)	4061	1	4061	Source with two booster stations (Case II)	1688.00	0.42	14.76
	9(NH-2H-LP)	2031	2	4061	Conventional (Case I)	1523.80	0.38	-
	9(NH-2H-LP)	2031	2	4061	Source with two booster stations (Case II)	1457.18	0.36	4.37
	10(NH-2HD-LP)	1015	2	2031	Conventional (Case I)	1291.90	0.64	-
	10 (NH-2HD-LP)	1015	2	2031	Source with two booster stations (Case II)	912.09	0.45	29.40

Summary Table 5.20 shows that the overall percentage reduction in chlorine mass rate with two booster stations is obtained as around 30% for large network like Manjalpur and small network of North Harni for deficit flow conditions. The chlorine consumption ratio for different case studies varies from 0.38 to 0.64 for case I, whereas the ratio varies from 0.36 to 0.45 for case II.

As seen from the above case studies (6 to 10) it is very laborious to select the optimum location of booster chlorination station by running the various combinations of many trial runs for booster stations in excel using linear programming optimization method. In case of large network with many potential booster locations and control nodes, optimization problem needs better solution techniques for optimal location and scheduling of booster stations. New evolutionary algorithms such as particle swarm optimization method (PSO) are applied for coupled simulation optimization problems. Therefore, PSO optimization technique is applied to the same networks used for LP to get and compare the results of the optimal location and scheduling of booster chlorination stations.

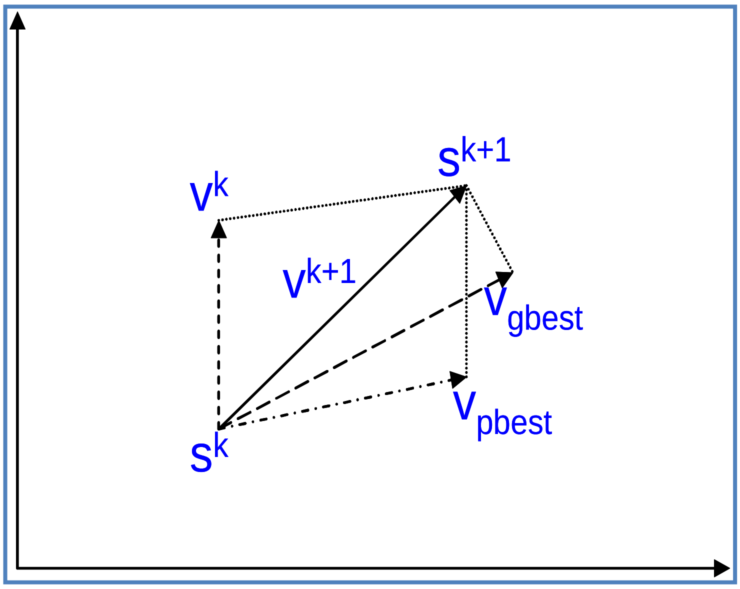
5.12 Particle Swarm Optimization (PSO) for Chlorine Management in DWDS

The Modern method of optimization such as Particle Swarm Optimization (PSO) is utilized for the optimization of scheduling of mass rate of chlorine and optimal location of booster stations. Particle swarm optimization abbreviated as PSO, is a populated search method for optimization, and was developed from attempts to simulate the flocking behaviour of a colony or swarm of insects, such as ants, termites, bees, and wasps; a flock of birds; or a school of fish. The PSO algorithm was originally proposed by Kennedy and Eberhart in 1995. A swarm of particles (analogous to a population in a GA) containing both local and collective knowledge is ’flown’ through the parameter space in search of the optimal solution (Kennedy and Eberhart, 1995 and Kennedy, 1997). The word particle denotes a bee in a colony or a bird in a flock. Each individual or particle in a swarm behaves in a distributed way using its own intelligence and the collective or group intelligence of the swarm. As such, if one particle discovers a good path to food, the rest of the swarm will also be able to follow the good path instantly even if their location is far away in the swarm. Optimization methods based on swarm intelligence are called behaviourally inspired algorithms as opposed to the genetic algorithms, which are called evolution-based procedures. The term “Swarm Intelligence” is used to describe algorithms and distributed problem solvers inspired by the collective behaviour of insect colonies and other animal societies. Under this prism, PSO is developed for solving optimization problems. In the context of multivariable optimization, the swarm is assumed to be of specified or fixed size with each particle located initially at random locations in the multidimensional design space. Each particle is assumed to have two characteristics: a position and a velocity. Each particle wanders around in the design space and remembers the best position (in terms of the food source or objective function value) it has discovered. The particles communicate information or good positions to each other and adjust their individual positions and velocities based on the information received on the good positions. Each particle keeps track of its coordinates in the solution space which are associated with the best solution (fitness) that has achieved so far by that particle. This value is called personal best, pbest. Another best value that is tracked by the PSO is the best value obtained so far by any particle in the neighborhood of that particle, called gbest. Each particle accelerates towards its pbest and the gbest locations, with a random weighted acceleration. Each particle tries to modify its position using the information such as the current positions, the current velocities, the distance between the current position and pbest and the distance between the current position and the gbest.

Thus the PSO algorithm consists of just three steps, which are repeated until some stopping condition is met:

i. Evaluate the fitness of each particle
ii. Update individual and global best fitnesses and positions
iii. Update velocity and position of each particle

By using PSO, it will be easier to handle non-linearity and non-convexity of the problem domain; the search does not depend on initial population, but overcomes the chances of trapping to local optima, faced by conventional non-linear optimization techniques. PSO is recognized as an evolutionary technique under the domain of computational intelligence (Clerc & Kennedy 2002). It has been proved to be an efficient method for many global optimization problems and in some cases it does not suffer the difficulties encountered by other EC techniques (Eberhart & Kennedy 1995; Parsopoulos & Vrahatis 2002). Fig. 5.31 shows the concept of modification of searching point by PSO.



Where,

s^k : current searching point.

s^{k+1}: modified searching point.

v^k: current velocity.

v^{k+1}: modified velocity.

v_{pbest} : velocity based on pbest.

v_{gbest} : velocity based on gbest

Fig. 5.31: Concept of modification of a searching point by PSO

5.12.1 Computational Implementation of PSO

Suppose that the search space is D-dimensional, then ith particle (set of parameter values) of the swarm can be represented by a D-dimensional vector, Xi = (xi1, xi2, …, xiD)^T. The velocity of this particle can be represented by defining another D-dimensional vector Vi = (vi1, vi2, … viD)^T. The best previously visited position of the ith particle is denoted as Pi = (pi1, pi2, …, piD)^T. Defining the *g* as the index of best particle (having best fitness function value) in the swarm and denoting the iteration number as superscript, then the swarm is manipulated as following two equations (Shi and Eberhart, 1998):

$$v_{id}^{n+1} = \chi\, w\, v^n_{id} + C_1 r^n_1 [p^n_{id} - x^n_{id}] + C_2 r^n_2 [p^n_{gd} - x^n_{id}] \qquad d=1,2\ldots D \quad ; i= 1,2,3,4\ldots N \quad (5.10)$$

$$x^{n+1}_{id} = x^n_{id} + V^n_{id} \qquad d=1,2\ldots D \quad ;i=1,2,3,4\ldots N \qquad (5.11)$$

Where,

n = iteration number, D = number of parameters, xid and vid = value and velocity of parameter d of ith particle, χ = constriction factor, w = inertia weight, r_1 and r_2 = independent and uniformly distributed random numbers, C_1 = cognitive parameter, the weight of a particle's own experience, C_2 = social parameter, the weight of the combined experience of the swarm, pid = parameter value corresponding to the best solution ever personally visited by the given particle, and pgd = parameter value corresponding to the best solution ever visited by any particle (the current global best).

Examination of equation 5.10 and 5.11 reveals three components for updating a particle: (a) the previous velocity, (b) the current local best, and (c) the current global best. The particle will retain some fraction (w) of its previous velocity while moving in the general direction of the global (p_g) and local (p_i) best solutions. These directions are randomly weighted (r_1 and r_2) and scaled by their respective cognitive (C_1) and social (C_2) parameters. Following steps illustrate the particle swarm optimization iterative procedure.

1) Initialize Particle Swarm

The initial swarm is assigned in a random positions x_d and velocities v_d for each particle in d^{th} dimension where x_d represent the value of d^{th} decision variable.

2) Evaluate optimization function

For each particle, the desired optimization function is evaluated. The optimization function may be minimization or maximization.

3) Modify particle's best value

For each particle, the previously visited best position (p_i) is remembered. If the current value of particle is better than that given by existing p_i, then the current location is set to p_i.

4) Modify overall best value

The fitness value of current best position is also compared with overall best value of the swarm given by p_g. If current best value is better than that of gbest, then the current position is set to p_g.

5) Move each particle to new position.

The velocity and position of each particle are updated by using equation 5.10 and 5.11.

6) If termination criteria satisfied, stop.

Else, go to step 2.

The PSO method appears to follow the five basic principles of swarm intelligence, as defined by Eberhart et al. (1996): (i) Proximity, i.e., the swarm must be able to perform simple space and time computations; (ii) Quality, i.e., the swarm should be able to respond to quality factors in the environment; (iii) Diverse response, i.e., the swarm should not commit its activities along excessively narrow channel; (iv) Stability, i.e., the swarm should not change its behaviour every time the environment alters; and (v) Adaptability, i.e., the swarm must be able to change its behaviour, when the computational cost is not prohibitive. The movement of swarm is effectively controlled by various parameters used in equation 5.10.

The role of the inertia weight *w*, is considered critical for the PSO's convergence behaviour. The inertia weight is employed to control the impact of the previous history of velocities on the current one. Accordingly, the parameter w regulates the trade-off between the global (wide-ranging) and local (nearby) exploration abilities of the swarm. A large inertia weight facilitates global exploration (searching new areas), while a small one tends to facilitate local exploration, i.e., fine-tuning the current search area. A suitable value for the inertia weight w usually provides balance between global and local exploration abilities and consequently results in a reduction of the number of iterations required to locate the optimum solution. Initially, the inertia weight was constant. However, experimental results indicated that it is better to initially set the inertia to a large value, in order to promote global exploration of the search space, and gradually decrease it to get more refined solutions. Thus, an initial value around 1.2 and a gradual decline towards 0 can be considered as a good choice for w (Shi and Eberhart 1998).

The parameters C_1 and C_2 are not critical for PSO's convergence. However, proper fine-tuning may result in faster convergence and alleviation of local minima. An extended study of the acceleration parameter in the first version of PSO is given in (Kennedy 1998). As default values, $C_1 = C_2 = 2$ were proposed, but experimental results indicate that $C_1 = C_2 = 0.5$ might provide even better results. Recent work reports that it might even be better to choose a larger cognitive parameter, C_1, than a social parameter, C_2, such that $C_1 + C_2 \leq 4$. The parameters r_1 and r_2 are used to maintain the diversity of the population, and they are uniformly distributed in the range [0, 1]. Clerc & Kennedy (2002) introduced a constriction factor χ into PSO to control the convergence properties of the particles. The constriction factor χ controls on the magnitude of the velocities, different from the one with the inertia weight (Parsopoulos & Vrahatis 2002). Its value ranges from 0.7 to 1.0.

PSO shares many common points with GA. Both the algorithms starts with a group of randomly generated population, both have fitness values to evaluate the population. Both update the population and search for the optimum with random techniques. Both systems do not guarantee unique global optimal but by their very nature give near global optimal solutions. However, PSO does not have genetic operators like cross over and mutation. Particles update themselves with internal velocity. They also have memory, which is important to the algorithm. Compared to GAs, the information sharing mechanism in PSO is completely different. In GAs, chromosomes share information with each other. So the whole population moves like one group towards an optimal area. In PSO, only global best (or local best) gives out the information to others. It is a one way information sharing mechanism. The evolution only looks for the best solution. Compared with GAs, all the particles tend to converge to the best solution quickly even in the local version in most cases. Since its introduction, the PSO algorithm has been studied rather intensively and has been applied to a wide variety of applications.

Fig. 5.32 shows the flow chart of the PSO model development procedure.

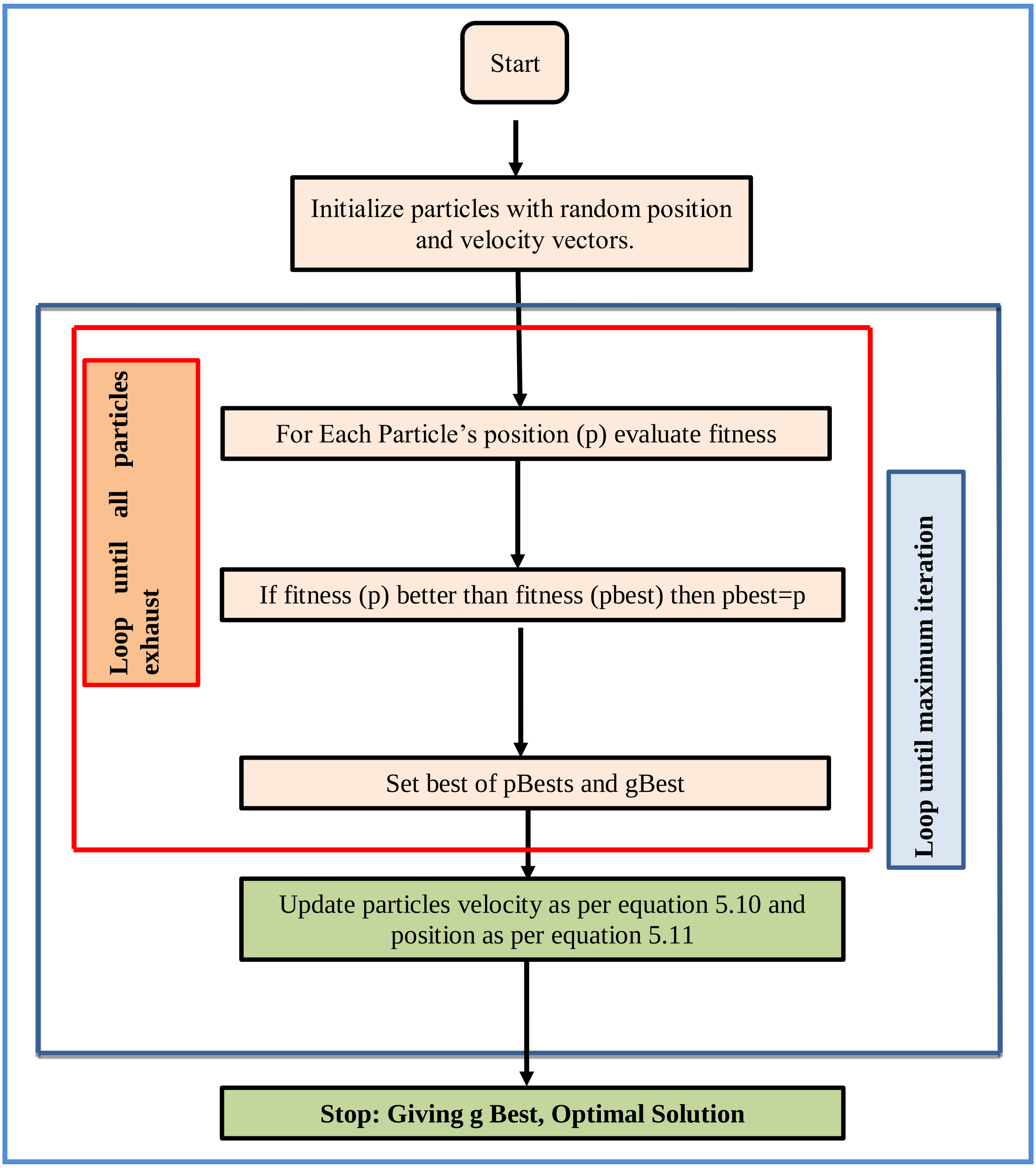


Fig. 5.32: Flow Chart for PSO Model.

The PSO can be applied to the water quality management area if we couple it with the water quality simulation model such as EPANET for effective management of chlorine disinfection within DWDS. Initially the optimization model was developed for the fixed source application with two variables of booster stations obtained as optimum location using LP as mentioned in case study 10 i.e. (NH-2HD-LP). Next optimization model was developed for all three (source + two booster stations) variable for the North Harni DWDS with deficit flow condition.

5.13 Case Study 11: Coupled Simulation Optimization Model using PSO for North Harni DWDS Network with Deficit Flow Condition (NH-2HD-PSO)

The same North Harni distribution network as shown in Fig. 5.24 is used for the minimization of mass injections of chlorine considering two cases with two decision variables and three decision variables using PSO method. Initially, consider the minimization of the total chlorine mass rate applied at known booster locations obtained as optimal location (M_0+M_1+M_2) using LP. Case I represents source chlorination (M_0)only , Case II is considered for M_0 (Constant) & M_1 ,M_2 variable, while Case III is considered for three decision variables as M_0, M_1, M_2. For the simulation of residual chlorine the method is adopted using EPANET software in which the unit dose of chlorine is applied at booster stations and residual chlorine is found at control nodes and find out the constant using principle of linear superposition (Boccelli, 1998) as mentioned in previous case studies with LP.The minimum residual chlorine concentration to satisfy lower bound constraints (0.2 mg/L as per IS 10500, 2012) as well as the maximum concentration is considered as 2 mg/L as upper bound constrained of residual chlorine at all the locations of DWDS. For optimization of booster chlorination doses the ten critical nodes i.e. Node no 2, 9, 11,19, 27, 37, 47, 57, 70 and 75 are identified as critical nodes 1 to 10 respectively as mentioned in case study 10 covering all the directions at farthest locations. The decision variables in booster chlorination optimization model are location of booster station, chlorine injection rate at source, booster chlorine injection rate, etc. A particle in hyper space is characterized by its position coordinates which indicate values of decision variables in feasible region. The fitness value of position of each particle is determined based on the objective function and constraints. The group of such particles moves in the hyperspace and their positions are evaluated for fitness. Finally a position of such particle giving best fitness suggests the solution of decision variableThe optimization problem is formulated in MATLAB using PSO optimization technique as.

Objective function is to

Minimize:

$$\sum_{i=1}^{n} Mi \tag{5.12}$$

Subject to Constraints:

$$C_j = \sum_{j=1}^{m} \sum_{i=1}^{n} K_{i,j} M_i \geq 0.2$$

(5.13)

Non negativity constraints,

$$M_i \geq 0$$

(5.14)

Where,

i = injection Nodes

j = critical Nodes

m = total numbers of critical nodes

m = total number of Injection nodes

C_j = chlorine concentration at junction node 1 to 10 corresponding to critical nodes number 2,9,11,19, 27, 37, 47, 57, 70 and 75 respectively, mg/L.

$K_{i,j}$= impulse response coefficients corresponding to injection nodes i.e. source, BS_1 and BS_2 for critical nodes 1 to 10.

M_i = Mass rate injected at injection corresponding to injection location at source, booster station 1, booster station 2 respectively, mg/min.

For case II and III with source application of chlorine along with chlorine injected from 2 booster nodes, the values of impulse response coefficient is obtained from the results of residual chlorine at node nodes 2, 9, 11, 19, 27, 37, 47, 57, 70 and 75 using EPANET software by running the extended period simulation separately when chlorine is applied at source alone (M_0), only at booster station 1(M_1), only at booster Station 2(M_2). The summary of the values of impulse response coefficients at critical nodes is given in Table 5.21.

Table 5.21: Values of impulse response coefficients at critical nodes for case II and III (Case Study 11: NH-2HD-PSO)

Critical Node Number	Values of Constants Kij, with application of Chlorine mass rate at critical nodes (mg/L) / (mg/min)			
	Node No in Network	Only at Source, M_0	Only at Booster BS_2 , M_1	Only at Booster BS_2 , M_2
1	Node 2	0.00003312	0	0
2	Node 11	0.00003150	0	0
3	Node 19	0.00001858	0.00060000	0

4	Node 27	0.00002908	0	0
5	Node 37	0.00003150	0	0
6	Node 40	0.00003069	0	0
7	Node 47	0.00002746	0	0
8	Node 57	0.00002746	0	0
9	Node 70	0.00002423	0	0.0001401
10	Node 75	0.00002019	0	0.0002521

To convert the constrained problem into unconstrained optimization problem the penalty function is introduced for each constrained violation. If a constraint is violated at any point, the objective function is panelized by an amount depending on the extent of constraint violation. Penalty terms vary in the way the penalty is assigned. Those penalty methods which cannot deal with infeasible points at all and even penalize feasible points that are close to the constraint boundary called interior penalty methods. Those penalty methods which penalize infeasible points but do not penalize feasible points are known as exterior penalty methods. Methods which penalize both infeasible and feasible points are known as the mixed penalty methods. (Deb 2009; Raju 2009). For the current study the exterior penalty method is used to penalize the objective function as mentioned below. If a constraint is violated at any point the penalty function is assigned as

$$\sum_{j=1}^{n} P_1 \times (0.2 - Cj) + \sum_{j=1}^{n} P_2 \times (Cj - 2) \tag{5.15}$$

Where,

P_1= penalty term for lower bound

P_2= penalty term for upper bound

C_j= chlorine concentration at junction node 1 to 10 corresponding to critical nodes number 2,9,11,19, 27, 37, 47, 57, 70 and 75 respectively, mg/L.

After obtaining the value of Penalty function the fitness function is updated by fitness function f= M_0+M_1+M_2+ penalty function.

Fig. 5.33 shows the simulation model using EPANET was developed to couple with optimization model. The simulation model was developed using EPANET and later couple with optimization model using PSO.The coupled simulation and optimization model is as shown in Fig. 5.34.

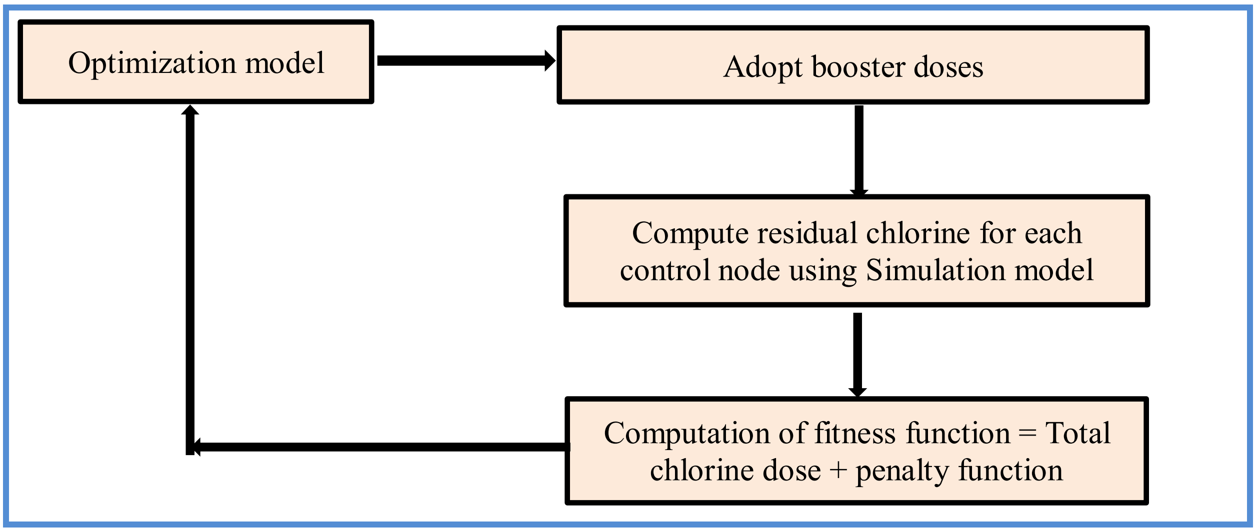


Fig. 5.33: Simulation Model for coupling with optimization Model.

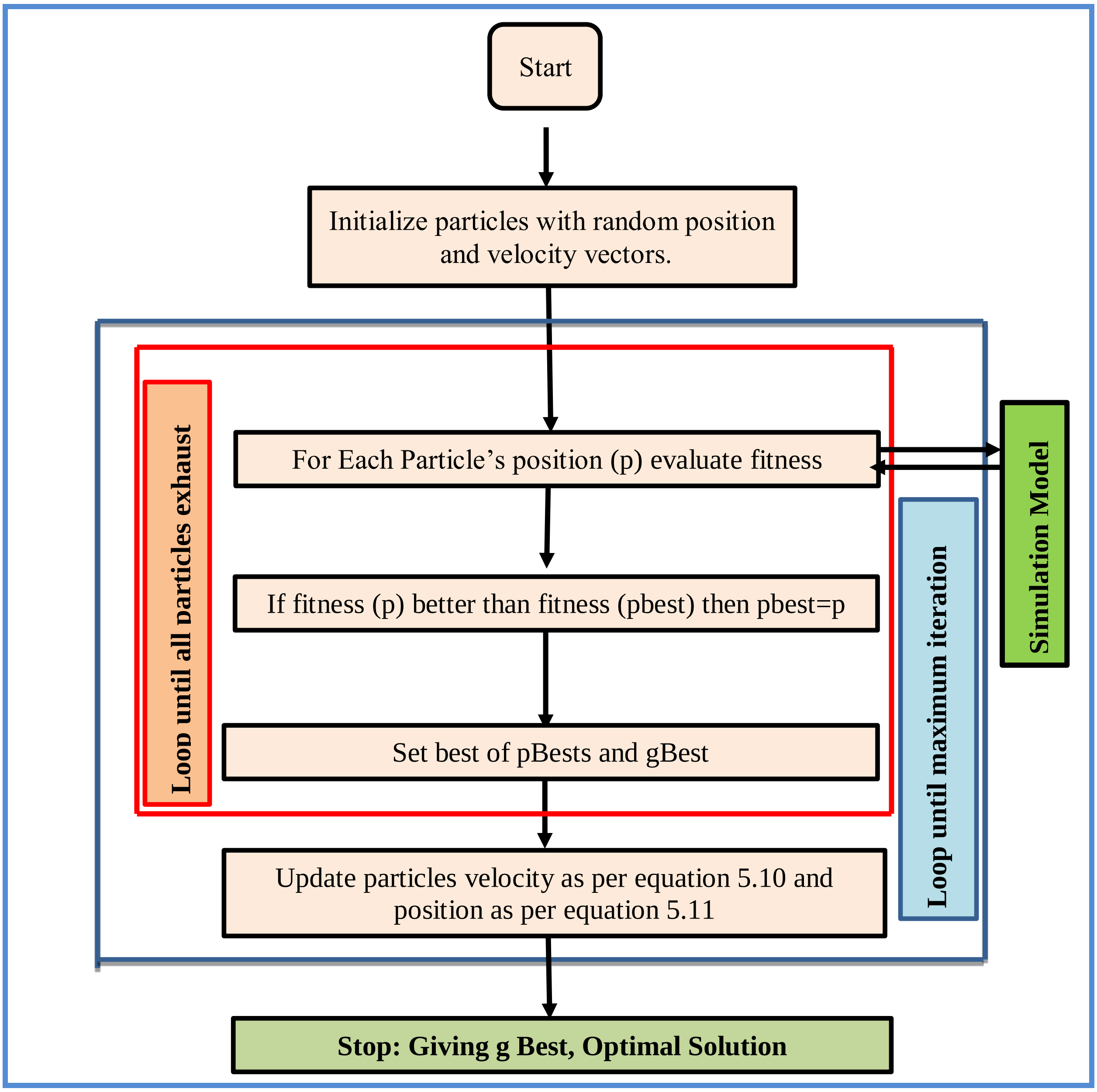


Fig. 5.34: Coupled Simulation-Optimization Model installed in MATLAB

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The PSO can be applied to the water quality management area if we couple it with the water quality simulation model such as EPANET for effective management of chlorine disinfection within DWDS. Initially the optimization model was developed for the fixed source application with two variables of booster stations obtained as optimum location using LP as mentioned in case study 10 i.e. (NH-2HD-LP). Next optimization model was developed for all three (source+ two booster stations) variable for the North Harni DWDS with deficit flow condition.

The constraint such as lower bound of residual chlorine concentration is set at 0.2 mg/L (as per IS-10500, 2012) and upper bound as 2 mg/L at all the critical nodes which are converted into unconstrained problem using penalty function by introducing penalty terms. Once the model is implemented in MATLAB, the function gives the optimum solution of minimum mass rate of chlorine to be applied to satisfy the constraints of residual chlorine at all the critical nodes as well as throughout the distribution network. Here the optimization method using PSO is applied to North Harni Distribution System for case II in which two decision variables (M_1 and M_2) are taken by keeping the source mass rate of chlorine at source as constant i.e. 7282.94 mg/min. In case III three decision variables are taken i.e. M_o, M_1 and M_2.
The computation of fitness at each control nodes using PSO in MATLAB is organized for case I as follows:

- Objective function: Minimize M_1+ M_2 subject to $0.2 \leq Cj \leq 2$
- Fitness function = f = 7282.94 + M_1 + M_2 + Penalty Function, Mo=7282.94 mg/min
- Penalty function for lower bound violation= P_1 x (0.2-Cj), P_1= 10500
- Penalty function for upper bound violation= P_2 x (Cj-2), P_2= 10500

The PSO code was developed in MATLAB for both the cases and after running the PSO pregame in MATLAB following results is obtained.

5.13.1 Optimization Results

Table 5.22 gives the results of fitness function after running PSO in MATLAB for two decision variables. The first part of the table gives the infeasible solution with penalty value while the final position which gives the optimum solution with total penalty value 0. The final fitness value obtained is 7601.2 mg/min.

Table 5.22: Fitness Function value for different Mass rate application of Chlorine (Case Study 11: NH-2HD-PSO)

Mass rate M_0= 7282.94 mg/min, M_1= 3500 mg/min , M_2=400 mg/min			Mass rate M_0= 7282.94 mg/min, M_1= 107.84 mg/min , M_2=210 mg/min	
Node No	**Residual Chlorine (mg/l)**	**Penalty**	**Residual Chlorine (mg/l)**	**Penalty**
1	0.24	0	0.24	0
2	0.23	0	0.23	0
3	2.21	2205	0.2	0
4	0.22	0	0.22	0
5	0.23	0	0.23	0
6	0.22	0	0.22	0
7	0.2	0	0.2	0
8	0.2	0	0.2	0
9	0.19	105	0.2	0
10	0.17	315	0.2	0
Total Penalty		**2625**	**Total Penalty**	**0**
Total Fitness		**13508**	**Total Fitness**	**7601.2**

PSO programming is done for the objective function in MATLAB to find the next updated velocity and new position of the particles at each iteration. The variation and updates of the fitness function for different iteration is shown in Fig. 5.35 and 5.36 for two decision variables and three decision variables respectively. The position of the particle at different iterations for two decision variables is shown in Fig 5.37.

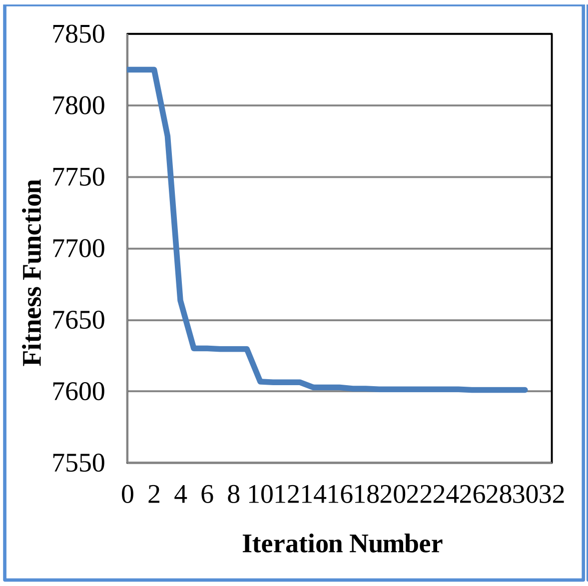


Fig. 5.35: Variation in fitness function after each iteration for two decision variables (Case Study 11)

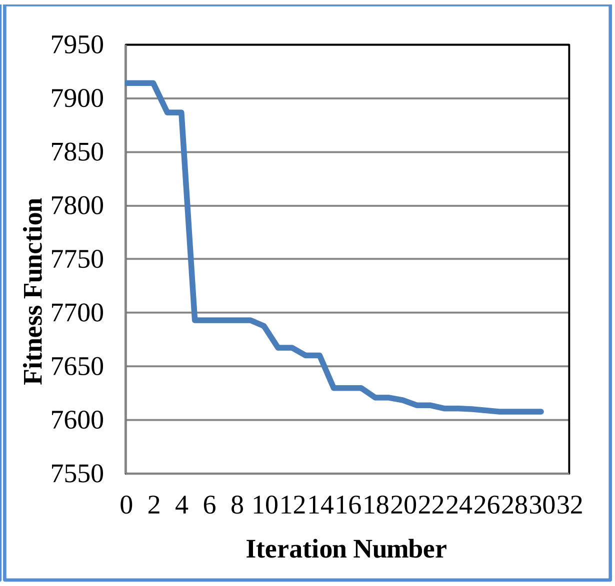
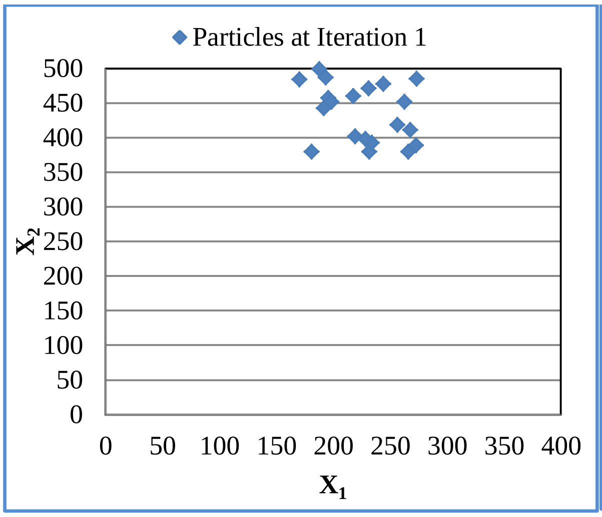
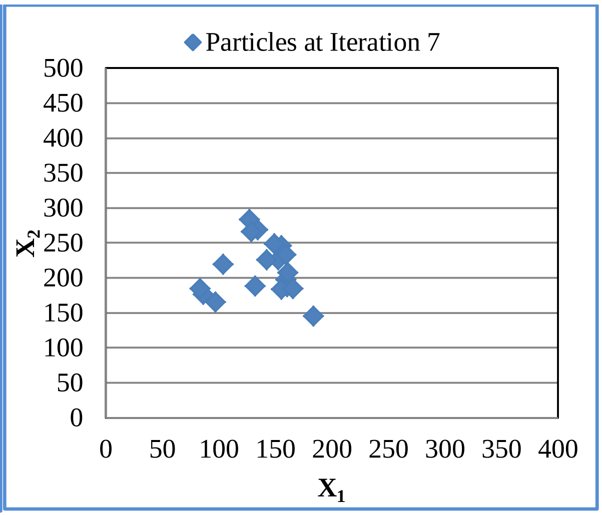
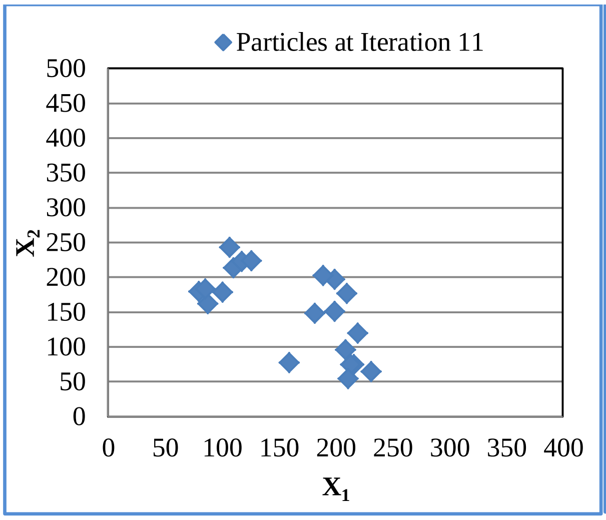
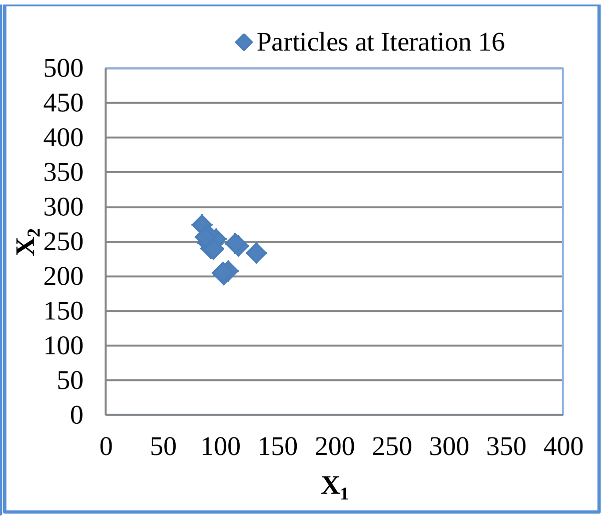


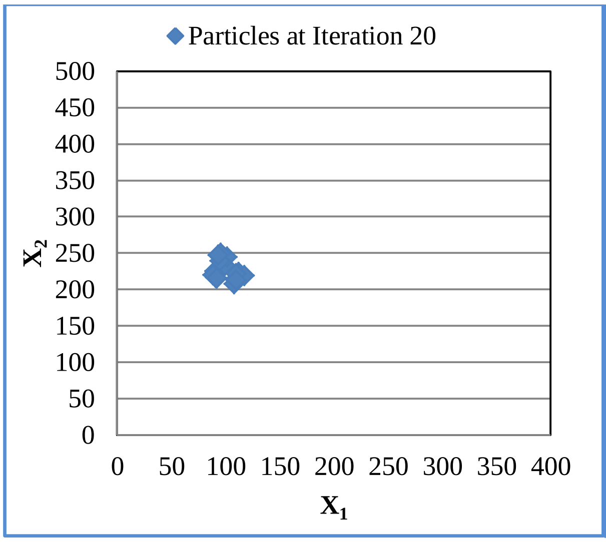
Fig. 5.36: Variation in fitness function after each iteration for three decision variables (Case Study 11)

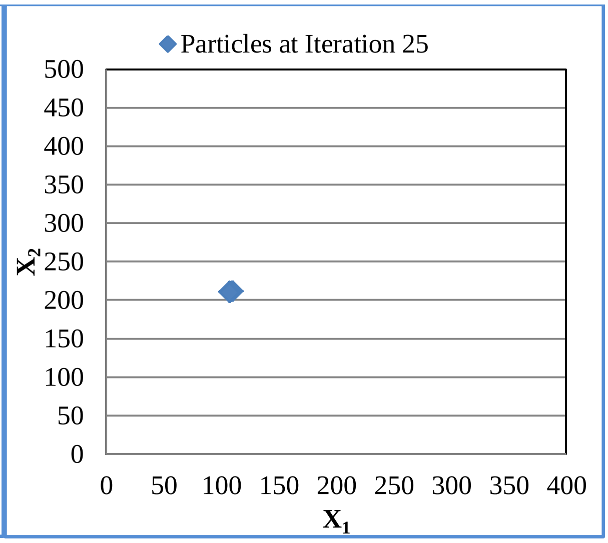

Particles at Iteration 1
X_2
X_1
0 50 100 150 200 250 300 350 400
500 450 400 350 300 250 200 150 100 50 0


Particles at Iteration 7
X_2
X_1
0 50 100 150 200 250 300 350 400
500 450 400 350 300 250 200 150 100 50 0


Particles at Iteration 11
X_2
X_1
0 50 100 150 200 250 300 350 400
500 450 400 350 300 250 200 150 100 50 0


Particles at Iteration 16
X_2
X_1
0 50 100 150 200 250 300 350 400
500 450 400 350 300 250 200 150 100 50 0


Particles at Iteration 20
X_2
X_1
0 50 100 150 200 250 300 350 400
500 450 400 350 300 250 200 150 100 50 0


Particles at Iteration 25
X_2
X_1
0 50 100 150 200 250 300 350 400
500 450 400 350 300 250 200 150 100 50 0

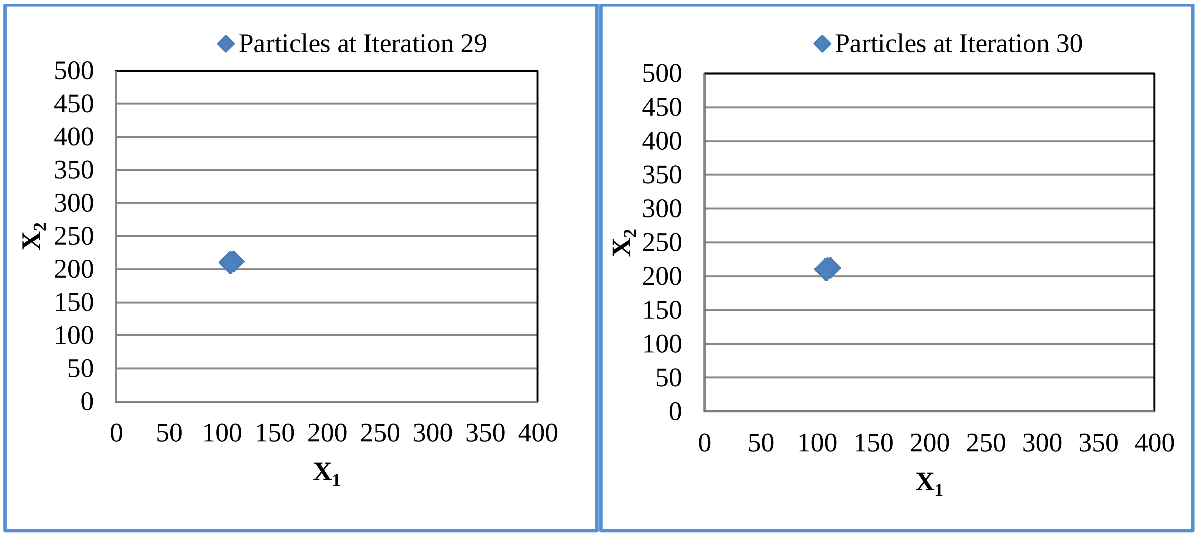


Fig. 5.37: Particle's position for two decision variables after different iteration (Case Study 11).

5.13.2 Sensitivity Analysis for PSO Parameters

Sensitivity analysis was carried out to find out the best value of iteration number, Number of swarms, values of C_1 and C_2 for both the cases. Table 5.23 and 5.24 gives the result of sensitivity analysis for two and three decision variables respectively.

Table 5.23: Sensitivity analysis for PSO parameters (Two decision variables) for Case Study 11: NH-2HD-PSO)

Iteration for N=20, C_1 ,C_2 =1				
Max Iteration	**Fitness value**	**M_1**	**M_2**	**M_3**
20	7601.61	7282.94	107.83	210.62
30	7601.04	7282.94	107.81	210.07
50	7601.03	7282.94	107.81	210.07
No of swarms for iteration 30, C_1,C_2=1				
No of swarms	**Fitness value**	**M_1**	**M_2**	**M_3**
20	7601.06	7282.94	107.81	210.07
30	7601.13	7282.94	107.88	210.05
Change in C_1 ,C_2 for N=20, Itmax=30				
C_1 C_2	**Fitness value**	**M_1**	**M_2**	**M_3**
1	7601.06	7282.94	107.81	210.07
2	7606.08	7282.94	112.16	209.64
3	7620.58	7282.94	119.88	217.53

Table 5.24: Sensitivity analysis for three decision variables (Case Study 11: NH-2HD-PSO)

Iteration for N=20, C_1 ,C_2 =1				
Max Iteration	**Fitness value**	**M_1**	**M_2**	**M_3**
20	7604.22	7283.55	108.27	212.41
30	7604.96	7283.62	111.29	210.05
50	7602.30	7283.32	108.01	210.96
No of swarms for iteration 30, C_1,C_2=1				
No of swarms	**Fitness value**	**M_1**	**M_2**	**M_3**
20	7604.96	7283.62	111.29	210.05
30	7608.66	7286.74	109.85	212.06
Change in C_1 ,C_2 for N=20, Itmax=30				
C_1 C_2	**Fitness value**	**M_1**	**M_2**	**M_3**
1	7604.96	7283.62	111.29	210.05
2	7609.02	7287.75	107.92	213.34
3	7676.24	7284.65	170.9	220.69

The results obtained after applying the PSO in MATLAB for case II and III given in Table 5.25 which shows the total mass rate to be applied to satisfy all the constraint at critical nodes. The mass rate of chlorine to be applied at source along with two booster stations with two decision variables, for case II and two booster stations along with source application with three decision variables for Case III after using the PSO optimization is tabulated in Table No 5.25. The mass rate of chlorine to be applied at booster stations obtained after optimization is applied on DWDS network using EPANET software to check 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 1291.9 g/d, while booster chlorination for case II required 912.10 g/d and for case III it comes to be 912.28 g/d to satisfy the constraints of 0.2 mg/L residual chlorine at all the locations in DWDS network. The result of sensitivity analysis for PSO parameters shows that the best fitness function is obtained after 50 iteration, 20 numbers of swarms with C_1 and C_2 = 1 for two decision variables and three decision variables.

Table 5.25: Chlorine mass rate to be applied at various locations after using Optimization (Case Study 11: NH-2HD-PSO)

Chlorine Mass rate applied at various locations for 2 hours duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine			
			Case II (Two decision variables)		Case III (Three decision variables)	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate
	(g/d)	(mg/min)	(g/d)	(mg/min)	(g/d)	(mg/min)
Source, (M_0)	1291.9	10766	873.95	7282.94	873.99	7283.32
Booster BS_1(M_1)	--	--	12.94	107.81	12.96	108.01
Booster BS_2 (M_2)	--	--	25.21	210.07	25.32	210.96
Total Mass rate applied	1291.9	10766	912.10	7600.81	912.28	7602.30
% Reduction in mass rate of chlorine compared to case I	--		29.4		29.4	

5.13.3 Discussions

Principle of Linear Superposition is successfully used for the development of optimization model 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. Optimal Scheduling of chlorine mass rate the optimization is carried by PSO method (i) By keeping source concentration constant and finding mass rate to be applied at Booster station (two decision variables). (ii) By finding the mass rate to be applied at source as well as at booster stations (three decision variables). For PSO the constrained optimization problem was transformed into unconstrained problem by introducing the penalty function for the each violation of the constraint of residual chlorine at each control node between 0.2 to 2 mg/L.

The results obtained suggest that the Network using conventional chlorination (Case I) requires application of 1291.9 g/d 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 PSO optimization technique using MATLAB suggests that for case II with two decision variables (M_0 i.e.7282.94mg/min+ M_1, M_2), at various locations in network satisfied the constraint with application of chlorine mass rate as 912.10 g/d which gives reduction of total mass rate of chlorine as 29.4%. For case III with three decision variables (M_0, M_1, M_2), requires 912.28 g/d which gives 29.4% reduction in total mass rate of chlorine. More uniform distribution of chlorine is observed when booster stations are adopted as compared to only source chlorination. The reduced chlorine mass rate application at Booster stations or choice of less number of booster stations results in overall economy for any project at the same time results in reduced harmful disinfection by products. Water supply authority may select the number of booster stations and scheduling of mass rate of chlorine based on the requirement of a particular DWDS. Adopting Booster chlorination strategy maintains lower average residual chlorine throughout the DWDS and results in more uniform distribution of residual chlorine as compared to conventional chlorination.The results obtained using PSO is exactly matching with the optimization result obtained using LP.The coupling of the simulation results of EPANET with LP and PSO optimization method may serve as an important Decision Support Model (DSM) for managing optimum mass rate application at Booster Stations.

In the above case study the optimum location are taken from the results obtained using earlier linear programming (LP) optimization method. As mentioned earlier for the optimum locations the linear programming needs many trial runs and tedious. Therefore to get the optimal location of booster stations, the optimization model was developed using PSO in MATLAB. The coupled simulation optimization model to get the optimum location of booster stations was applied with combinations of five booster stations for the same network of North Harni and for Manjalpur DWDS for one hour water supply and two hours water supply. Also for the deficit flow conditions for North Harni DWDS the coupled model is used to get the optimum locations of booster stations.

5.14 Case Study 12: Optimal Location and Scheduling of North Harni DWDS Network using PSO for Deficit flow conditions (NH-2HD-PSO-OL)

The same network of North Harni DWDS with deficient flow conditions as mentioned in Fig 5.24 is used for the development of model for optimum location and scheduling of booster stations using PSO for five booster stations (BS_1 to BS_5). For the Optimum location of booster station, the program is prepared in MATLAB with the values of the impulse coefficient obtained by simulation results using EPANET for five booster stations as given in Table 5.16. The PSO code was generated in MATLAB for the optimum location of booster stations. After running the PSO program the optimum location of booster stations with the scheduling of the doses of chlorine is obtained. The optimum location is obtained at BS_1 and BS_2 along with the source chlorination which exactly matches with the optimum location obtained by linear programming. Table 5.26 gives the chlorine mass rate application for optimum locations of booster stations using PSO. Sensitivity analysis for the the various parameters of PSO are shown in Table 5.27.

Table 5.26: Chlorine mass rate at optimum locations after using PSO Optimization (Case Study 12: NH-2HD-PSO-OL)

Chlorine Mass rate applied at various locations for 2 hours duration	Only Source Chlorination Case I		Optimum location of Booster Chlorination along with source application of chlorine Case II	
	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)
Source, (M_0)	1291.9	10766.1	874	7283.3
Booster BS_1(M_1)	--	--	12.9	107.8
Booster BS_2 (M_2)	--	--	25.2	210.1
Total Mass rate applied	1291.9	10766.1	912.1	7601.2
% Reduction in mass rate of chlorine compared to case I	--		29.4	

Table 5.27: Sensitivity analysis for the various parameters of PSO (Case Study 12: NH-2HD-PSO-OL)

Iteration for No of swarm (N)=20, C_1, C_2 = 1				
Max Iteration	**Fitness value**	**M_0**	**M_1**	**M_2**
20	7605.30	7283.31	107.81	214.16
30	7604.49	7283.38	111.08	210.03
50	7601.18	7283.33	107.79	210.05
No of swarms for iteration (Itmax) =30, C_1, C2 = 1				
No of swarms	**Fitness value**	**M_0**	**M_1**	**M_2**
20	7604.49	7283.38	111.08	210.03
30	7604.16	7283.33	110.73	210.10
Change in C_1 ,C_2 for N=20, Itmax=30				
C_1,C_2	**Fitness value**	**M_0**	**M_1**	**M_2**
1	7604.49	7283.38	111.08	210.03
2	7603.75	7284.51	108.59	210.65
3	7610.21	7285.80	114.50	209.91

5.14.1Discussions:

The optimum locations obtained by PSO are same as obtained by linear programming optimization method. But using PSO the trial runs are reduced as compared to linear programming. The % reduction obtained using booster stations is 29.4% which is similar as obtained by linear programming optimization methods. The sensitivity analysis of the PSO parameters suggests that the various PSO parameters have minor impact on the optimum solution. The best solution is obtained for the swarm number of 20 with C_1 and C_2 as 1 and maximum iteration 50.

5.15 Case Study 13: Optimal Location and Scheduling of Booster Stations using PSO for North Harni DWDS Network with One and two hours water supply (NH-1H-PSO-OL & NH-2H-PSO-OL)

The network as mentioned in Fig 5.15 is used for the development of model for optimum location and scheduling of booster stations using PSO. For the optimum location of booster station the program is prepared in MATLAB with the values of the impulse coefficient obtained as mentioned in Table 5.10 by simulation results using EPANET for five booster stations.

The program is developed in MATLAB for the optimal location and scheduling of the booster stations. After running the program the optimum location and mass rate of chlorine to be applied to the booster stations along with the source chlorination is given in Table 5.28 and 5.30 for one hour and two hours water supply respectively. The result shows the optimum location of booster stations with the scheduling of the doses of chlorine. The optimum location is obtained at BS_4 and BS_5 along with the source chlorination which exactly matches with the optimum location obtained by linear programming.

Table 5.28: Chlorine mass rate at various locations after using PSO Optimization (Case Study 13: NH-1H-PSO-OL)

Chlorine Mass rate applied at various locations for 1 hour duration	Only Source Chlorination Case I		Optimum location of Booster Chlorination along with source application of chlorine Case II	
	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)
Source, (M_0)	1980	33000	1583.15	26385.84
Booster BS_4(M_4)	--	--	40.21	670.24
Booster BS_5 (M_5)			64.44	1073.94
Total Mass rate applied	1980	33000	1687.88	28130.02
%Reduction in mass rate of chlorine compared to case I	--		14.77	

The sensitivity analysis for various parameters of PSO is carried out for the number of iteration, number of swarms and change in C_1 and C_2 which is shown in following Table 5.29. Fig. 5.38 shows the graph of variation of fitness function at different iteration.

Table 5.29: Sensitivity analysis for various PSO parameters (Case Study 13: NH-1H-PSO- OL)

Iteration for N=20, C_1 ,C_2 =1				
Max Iteration	**Fitness value**	**Mo**	**M_4**	**M_5**
20	28280.21	26458.56	748.45	1073.20
30	28162.93	26385.12	696.66	1080.91
40	28126.94	26385.42	668.54	1072.97
50	28216.82	26385.25	758.57	1072.99
No of swarms for iteration 30, C_1,C_2=1				
No of swarms	**Fitness value**	**Mo**	**M_4**	**M_5**
20	28162.93	26385.12	696.67	1080.91
30	28130.02	26385.84	670.24	1073.94
40	28223.06	26384.87	764.15	1073.03
50	28127.23	26385.24	668.99	1072.99
Change in C_1 ,C_2 for N=20, Itmax=40				
C_1 C_2	**Fitness value**	**Mo**	**M_4**	**M_5**
1	28126.94	26385.42	668.54	1072.97
2	28216.82	26383.97	758.57	1072.99
3	28382.48	26614.05	695.62	1072.81

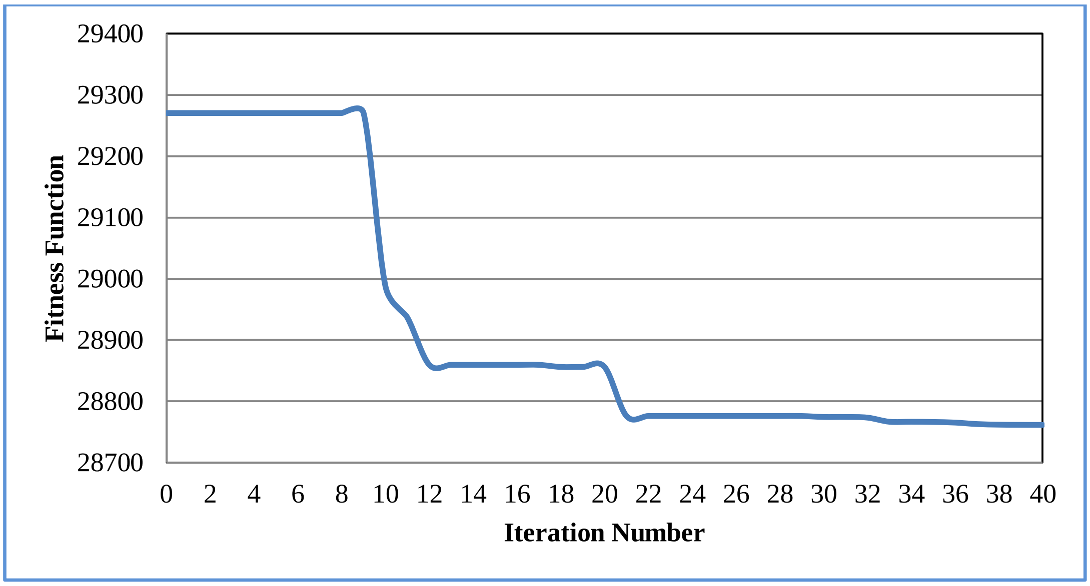


Fig. 5.38: Variation in fitness functions at different Iteration (Case Study 13: NH-1H-PSO-OL)

Table 5.30: Chlorine mass rate at various locations after using PSO Optimization (Case Study 13: NH-2H-PSO-OL)

Chlorine Mass rate applied at various locations for 2 hours duration	Only Source Chlorination Case I		Optimum location of Booster Chlorination along with source application of chlorine Case II	
	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)	Total Mass rate (g/d)	Chlorine Injection rate (mg/min)
Source, (M_0)	1523.76	12698	1414.29	11785.73
Booster BS_1(M_1)	--	--	14.17	118.12
Booster BS_5 (M_5)	--	--	15.13	126.1
Total Mass rate applied	1523.76	12698	1443.59	12029.95
%Reduction in mass rate of chlorine compared to case I	--		5.26	

5.15.1 Discussions:

The optimum locations obtained by PSO are same as obtained by linear programming optimization method. But using PSO the trial runs are reduced as compared to linear programming. The % reduction obtained using booster stations is 14.77% and 5.26% for water supply duration of one and two hours respectively. These results are similar as obtained by linear programming optimization methods. The sensitivity analysis of the PSO parameters suggests that the various PSO parameters have minor impact on the optimum solution. The best solution is obtained for the swarm number of 30 with C_1 and C_2 as 1 and maximum iteration 30 for one hour water supply.

Similarly the coupled simulation optimization model was applied to Manjalpur DWDS to locate the optimum location and scheduling of booster stations.

5.16 Case Study 14: Optimal Location and Scheduling of Booster Stations using PSO for Manjalpur DWDS with One Hour and Two Hours Water Supply (MJ-1H-PSO-OL & MJ-2H-PSO-OL)

The same network as mentioned in Fig 5.3 is used for the development of model for optimum location and scheduling of booster stations using PSO. In MATLAB the program is developed for the optimal location and scheduling of the booster station as using the values of impulse response coefficients mentioned in Table 5.3 and 5.7 for 1 hour and 2 hour water supply respectively. After running the PSO program in the MATLAB for 1 hour and 2 hour water supply the results are obtained which are presented in Table 5.31 and 5.33, which shows the chlorine mass rate to be applied at optimum locations of booster stations. Table 5.32 shows the sensitivity analysis for the PSO parameters for one hour water supply duration.

Table 5.31: Chlorine mass rate at optimum locations after using PSO Optimization (Case Study 14: MJ-1H-PSO-OL)

Chlorine Mass rate applied at various locations for 1 hour duration	**Only Source Chlorination Case I**		**Optimum location of Booster Chlorination along with source application of chlorine Case II**	
	Total Mass rate (g/d)	**Chlorine Injection rate (mg/min)**	**Total Mass rate (g/d)**	**Chlorine Injection rate (mg/min)**
Source, (M_0)	5500	91666.67	3409.7	56828.4
Booster $BS_1(M_1)$	--	--	302.1	5035.4
Booster BS_5 (M_5)	--	--	109.5	1824.6
Total Mass rate applied	5500	91666.67	3821.3	63688.4
%Reduction in mass rate of chlorine compared to case I	--		30.52	

Table 5.32: Sensitivity analysis for PSO parameters (Case Study 14: MJ-1H-PSO-OL)

Iteration for N=20, C_1 ,C_2 =1				
Max Iteration	**Fitness value**	**Mo**	**M1**	**M5**
20	64396.18	57955.44	4872.76	1567.98
30	64327.32	57884.55	4882.10	1557.07
40	64336.87	57668.08	4913.80	1565.79
50	64339.49	57656.96	4916.31	1567.42
No of swarms for iteration 30, C_1,C_2=1				
No of swarms	**Fitness value**	**Mo**	**M1**	**M5**
20	64971.17	56722.58	5319.69	1923.03
30	63688.33	56828.39	5035.39	1824.56
40	64407.19	56924.41	5028.68	1622.56
50	64404.55	56862.26	5030.71	1626.35
Change in C_1 ,C_2 for N=30, Itmax=30				
C_1 C_2	**Fitness value**	**Mo**	**M1**	**M5**
1	64352.49	57493.83	4938.51	1578.80
2	64359.44	57601.90	4921.19	1569.18
3	64334.10	57869.99	4886.71	1562.61

Table 5.33: Chlorine mass rate at optimum locations after using PSO Optimization (Case Study 14: MJ-2H-PSO-OL)

Chlorine Mass rate applied at various locations for 2 hours duration	**Only Source Chlorination Case I**		**Optimum location of Booster Chlorination along with source application of chlorine Case II**	
	Total Mass rate (g/d)	**Chlorine Injection rate (mg/min)**	**Total Mass rate (g/d)**	**Chlorine Injection rate (mg/min)**
Source, (M_0)	5500	45833	3270.96	27258.02
Booster $BS_1(M_1)$	--	--	343.62	2863.54
Booster BS_5 (M_5)	--	--	51.25	427.10
Total Mass rate applied	5500	45833	3665.84	30548.67
%Reduction in mass rate of chlorine compared to case I	--		33.35	

5.16.1 Discussions:

The optimum locations obtained by PSO are same as obtained by linear programming optimization method. But using PSO the trial runs are reduced as compared to linear programming. The % reduction obtained using booster stations is 30.53% and 33.35% for water supply duration of one and two hours respectively. These results are similar as obtained by linear programming optimization methods. The sensitivity analysis of the PSO parameters suggests that the various PSO parameters have minor impact on the optimum solution. The best solution is obtained for the swarm number of 30 with C_1 and C_2 as 1 and maximum iteration 30 for one hour water supply. Table 5.34 to 5.38 shows the summary of chlorine mass rate applied at optimum locations of booster stations for North Harni and Manjalpur DWDS with different water supply scenario.

Table 5.34: Chlorine mass rate to be applied at optimum locations of booster stations (MJ-1H-LP & MJ-1H-PSO-OL, Fig 5.3)

Chlorine Mass rate applied at various locations for 1 hour duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine using LP		Booster Chlorination along with source application of chlorine using PSO	
			With two Booster stations		With two Booster stations	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate
	(g/d)	(mg/min)	(g/d)	(mg/min)	(g/d)	(mg/min)
Source, (M_0)	5500	91666.67	3410.33	56838.91	3409.7	56828.4
Booster BS_1 (M_1)	--	--	302.06	5034.19	302.1	5035.4
Booster BS_5 (M_5)	--	--	109.42	1823.71	109.5	1824.6
Total Mass rate applied,	5500	91666.67	2281.85	63696.81	3821.3	63688.4
% Reduction as compared to case I	--		30.51		30.52	

Table 5.35: Chlorine mass rate to be applied at optimum locations of booster stations (MJ-2H-LP & MJ-2H-PSO-OL, Fig 5.3)

Chlorine Mass rate applied at various locations for 2 hours duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine using LP		Booster Chlorination along with source application of chlorine using PSO	
			With two Booster stations		With two Booster stations	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate
	(g/d)	(mg/min)	(g/d)	(mg/min)	(g/d)	(mg/min)
Source, (M_0)	5500	45833	3271.96	2766.29	3270.96	27258.02
Booster BS_1 (M_1)	--	--	343.52	2862.70	343.62	2863.54
Booster BS_5 (M_5)	--	--	50.99	424.92	51.25	427.10
Total Mass rate applied,	5500	45833	3666.47	30553.92	3665.84	30548.67
% Reduction as compared to case I	--		33.34		33.35	

Table 5.36: Chlorine mass rate to be applied at optimum locations of booster stations (NH-1H-LP & NH-1H-PSO-OL, Fig. 5.15)

Chlorine Mass rate applied at various locations for 1 hour duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine using LP		Booster Chlorination along with source application of chlorine using PSO	
			With two Booster stations		With two Booster stations	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate
	(g/d)	(mg/min)	(g/d)	(mg/min)	(g/d)	(mg/min)
Source, (M_0)	1980	33000	1584	26400	1583.15	26385.84
Booster BS_4 (M_4)	--	--	40	666.67	40.21	670.24
Booster BS_5 (M_5)	--	--	64	1066.67	64.44	1073.94
Total Mass rate applied,	1980	33000	1688	28133.33	1687.88	28130.02
% Reduction as compared to case I	--		14.75		14.77	

Table 5.37: Chlorine mass rate to be applied at optimum locations of booster stations (NH-2H-LP & NH-2H-PSO-OL, Fig. 5.15)

Chlorine Mass rate applied at various locations for 1 hour duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine using LP		Booster Chlorination along with source application of chlorine using PSO	
			With two Booster stations		With two Booster stations	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate
	(g/d)	(mg/min)	(g/d)	(mg/min)	(g/d)	(mg/min)
Source, (M_0)	1523.8	12698	1440	12000	1414.29	11785.73
Booster BS_4 (M_4)	--	--	10.47	87.27	14.17	118.12
Booster BS_5 (M_5)	--	--	6.71	55.94	15.13	126.1
Total Mass rate applied,	1523.8	12698	1457.18	12143.22	1443.59	12029.95
% Reduction as compared to case I	--		4.35		5.26	

Table 5.38: Chlorine mass rate to be applied at various locations (NH-2HD-LP, NH-2HD-PSO & NH-2HD-PSO-OL, Fig.5.24)

Chlorine Mass rate applied at various locations for 1 hour duration	Only Source Chlorination Case I		Booster Chlorination along with source application of chlorine using LP		Booster Chlorination along with source application of chlorine using PSO				Booster Chlorination along with source application of chlorine using PSO	
			With two Booster stations		Case II (Two decision variables)		Case III (Three decision variables)		With two Booster stations	
	Total Mass rate	Chlorine Injection rate	Total Mass rate	Chlorine Injection rate	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)	(g/day)	(mg/min)	(g/day)	(mg/min)
Source, (M_0)	1291.9	10766	873.95	7282.94	873.95	7282.94	873.99	7283.32	874.0	7283.33
Booster BS_1 (M_1)	--	--	12.74	107.84	12.94	107.81	12.96	108.01	12.9	107.79
Booster BS_2 (M_2)	--	--	25.20	210	25.21	210.07	25.32	210.96	25.2	210.05
Total Mass rate applied,	1291.9	10766	912.09	7600.78	912.10	7600.81	912.28	7602.30	912.1	7601.17
% Reduction as compared to case I	--		29.4		29.4		29.4		29.4	

5.17 General Discussions

The optimum location of booster station and scheduling of the mass rate of chlorine as suggested by the LP optimization and PSO Optimization method using Excel and MATLAB suggest that considerable reduction (29 to 34%) in mass rate of chlorine is achieved as compared to conventional approach of application of chlorine at source alone for Manjalpur (one hour and two hours water supply) and North Harni DWDS network (for deficit flow conditions with two hours water supply). For North Harni DWDS with one hour water supply is % reduction is 14.77 while for the two hours water supply the reduction is very less (4-5%). As the North Harni DWDS network is small when we increase the water supply hours to two hours the travelling time to the farthest node is less than 2 hours, which doesn't need the installation of booster station. The results obtained using PSO is exactly matching with the optimization result obtained using LP. As observed from the graphs of minimum, average and maximum chlorine concentration as well as for the graph of average and standard deviations shows that booster chlorination allows lower average residual chlorine throughout the DWDS which results in more uniform distribution of residual chlorine as compared to conventional chlorination. The reduced chlorine mass rate application at booster stations and optimum location of booster stations provides choice of less number of booster stations results in overall economy for any project at the same time results in reduced harmful disinfection by products. Water supply authority may select the number of booster stations and scheduling of mass rate of chlorine based on the requirement of a particular DWDS. For any drinking water distribution system, the coupled simulation model using EPANET software and optimization method such as LP or PSO using Excel or MATLAB for optimization of chlorine mass rate and optimum location of booster station serve as an important Decision Support Model(DSM) for managing, scheduling and selection of number and optimum location of booster chlorination stations.

The values of impulse response coefficient obtained using EPANET simulation model can be used for the development of impact matrix which can be used to estimate the impact of chlorine injection at various locations on residual chlorine at critical nodes. For the rapid estimation of the impact of chlorine injection at various locations on residual chlorine at critical nodes is established by developing an impact matrix using the values of impulse response coefficients used for the optimization model development at 22 critical nodes for North Harni DWDS and Manjalpur DWDS with 25 critical nodes.

5.18 Impact Matrix for Booster Chlorination

The Impact Effort Matrix is a grid that helps you assess solutions for their relative impact given the effort required. It provides a quick way to filter out solutions that might not be worth the effort. Here an impact matrix is developed for the quick assessment of impact of the injection of chlorine at source/booster station and its probable impact at particular critical nodes using the values of impulse response coefficients. Table 5.39 and 5.40 gives the impact matrix for the booster chlorination for North Harni DWDS network with deficit flow conditions with two hours water supply and Manjalpur DWDS network with two hours water supply duration respectively.

Table 5.39: Impact Matrix for booster chlorination station (North Harni DWDS for 2 hour duration with deficit flow condition)

Sr no	Node /BS	Source	BS_1	BS_2	BS_3	BS_4	BS_5	BS_6	BS_7	BS_8	BS_9	BS_{10}
1	**Node 2**	0.00003312	0	0	0	0	0	0	0	0	0	0
2	**Node 11**	0.00003150	0	0	0	0.00010	0	0	0	0	0	0
3	**Node 19**	0.00001858	0.0006	0	0.00002801	0.00005	0.0001	0.00003279	0.00015	0.0002509	0	0
4	**Node 27**	0.00002908	0	0	0	0.00010	0.0003	0.0001311	0	0	0	0
5	**Node 37**	0.00003150	0	0	0	0.00010	0	0	0	0	0	0
6	**Node 40**	0.00003069	0	0	0.00004669	0.00005	0	0	0	0	0	0
7	**Node 47**	0.00002746	0	0	0.00005602	0	0	0	0	0	0	0
8	**Node 57**	0.00002746	0	0	0.00005602	0	0	0	0	0	0	0
9	**Node 70**	0.00002423	0	0.0001401	0.00005602	0	0	0	0	0	0.0002	0.0001000
10	**Node 75**	0.00002019	0	0.0002521	0.00005602	0	0	0	0	0	0	0.0002000
11	**Node 5**	0.39000000	0	0	0.00005602	0	0	0	0	0	0	0
12	**Node 13**	0.00003150	0	0	0	0.00010	0	0.0001311	0	0	0	0
13	**Node 22**	0.00002908	0	0	0	0.00010	0.0002	0.0001311	0	0	0	0
14	**Node 33**	0.00003069	0	0	0	0.00010	0	0.0001311	0	0	0	0
15	**Node 35**	0.00002988	0	0	0	0.00010	0	0.0001311	0	0	0	0
16	**Node 40**	0.00003069	0	0	0.00004669	0.00005	0	0	0	0	0	0
17	**Node 48**	0.00003231	0	0	0.00005602	0	0	0	0	0	0	0
18	**Node 49**	0.00003069	0	0	0.00005602	0	0	0	0	0.0003405	0	0
19	**Node 53**	0.00002585	0	0	0.00003735	0	0	0	0	0	0	0
20	**Node 62**	0.00002827	0	0	0.00005602	0	0	0	0	0	0.0004	0
21	**Node 67**	0.00003069	0	0.000252101	0.00005602	0	0	0	0	0	0	0.00025
22	**Node 74**	0.00002342	0	0.000252101	0.00005602	0	0	0	0	0	0	0.00020

By using above impact matrix for booster chlorination the following rapid assessment can be done as:

- Farthest Node 19 indicates smallest value for source chlorination. This node is the most critical node for source chlorination.
- The injection rate required at source to maintain residual chlorine of 0.2 mg/L may be determined as 0.2/0.00001858 = 10764.26 mg/min
- Booster station BS_1 has only impact on critical node no 19 which is most critical for source chlorination.
- Booster station 1 and 2 covers those critical nodes which are critical for source chlorination; hence these are preferred over other locations for booster chlorination.
- In case of local contamination at node 22, the additional chlorine can be given by increasing rate at source or by supplying chlorine from booster stations 4, 5 or 6. The injection at booster station no 5 has higher impact than source, BS_4 and BS_6.
- The impact matrix developed can be used to estimate the impact of chlorine injection at various locations on residual chlorine at critical nodes as well as other nodes.

Table 5.40: Impact Matrix for booster chlorination station (Manjalpur DWDS for 2 hour duration)

Sr no	Node /BS	Source	BS_1	BS_2	BS_3	BS_4	BS_5
1	**Node 14**	0.000007455	0.000026415	0.000008	0	0	0
2	**Node 38**	0.000007273	0	0	0	0.00003	0.00002
3	**Node 46**	0.000007455	0	0	0	0	0
4	**Node 47**	0.000007273	0	0	0.00005	0	0.000004
5	**Node 49**	0.000007273	0	0	0	0	0.000022
6	**Node 51**	0.000004364	0.000028302	0.000004	0	0	0
7	**Node 57**	0.000004364	0.000050943	0.000004	0	0	0
8	**Node 59**	0.000004364	0.000037736	0.000004	0	0	0
9	**Node 70**	0.000007455	0	0.000008	0	0	0
10	**Node 74**	0.000007455	0.000026415	0.000008	0	0	0
11	**Node 102**	0.000007455	0	0	0	0.000052	0
12	**Node 118**	0.000007636	0	0.000184	0	0	0
13	**Node 122**	0.000007636	0	0	0	0	0
14	**Node 123**	0.000007455	0	0	0	0.000026	0
15	**Node 126**	0.000007455	0	0	0	0.000036	0
16	**Node 128**	0.000007455	0	0	0	0.000014	0.000074
17	**Node 5**	0.000007273	0	0	0	0	0.000022
18	**Node 13**	0.000006182	0	0	0	0.000014	0.000074
19	**Node 154**	0.000007455	0	0.000002	0.000076	0	0
20	**Node 105**	0.000007455	0	0	0	0	0
21	**Node 120**	0.000007636	0	0	0	0	0
22	**Node 134**	0.000006909	0	0	0	0	0.000022
23	**Node 142**	0.000007091	0	0.00003	0	0	0
24	**Node 80**	0.000007636	0	0	0	0	0
25	**Node 94**	0.000007455	0	0	0	0	0

By using above impact matrix for booster chlorination the following rapid assessment can be done as:

- Node 51, 57, 59 indicates smallest value for source chlorination. These nodes are the most critical node for source chlorination
- The injection rate required at source to maintain residual chlorine of 0.2 mg/L may be determined as 0.2/0.000004364 = 45833.33 mg/min
- Booster station BS_3 has only effect on residual chlorine of nodes 47 and 154. Hence it suggests that the addition of chorine at this booster has very less impact on most of the nodes and hence it is not selected for the optimum location by LP or PSO optimization.
- Booster station 1 and 5 covers most of the critical nodes except node-46,70, 102, 118, 122, 123, 126, 154, 105, 120, 142, 80 and 94 . As the addition of chlorine mass rate at BS_1 had marked impact on the critical nodes 51, 57 and 59 which are most critical nodes for the source chlorination the optimum location comes to be BS_1 and BS_5 along with source chlorination. Hence these are preferred over other locations for optimal location of booster chlorination.
- In case of local contamination at node 57 the additional chlorine can be given by increasing rate at source or by supplying chlorine from booster stations 1 and 2. The injection at booster station no 1 has higher impact than source and BS_2.
- The impact matrix developed can be used to estimate the impact of chlorine injection at various locations on residual chlorine at critical as well as other nodes.

As seen from the all case studies (6 to 14) the installation of booster chlorination results in overall reduction in mass rate of chlorine, at the same time results in uniform distribution of chlorine in DWDS. But from operation and maintenance point of view it is essential to carry out the economic feasibility of installing booster stations. Hence the cost analysis is carried out for the two case studies for the optimum location of booster stations

5.19 Cost Analysis for the Optimum Locations of Booster Chlorination Station.

The cost analysis for the booster chlorination station is very important aspect to check the economic feasibility of installing booster stations. Ostfeld & Salomon (2006) proposed the two models i.e. (1) Min Cost—for minimizing the costs of pumping and design and operation of chlorine boosters, and (2) Max Protection—for maximizing the system protection by maximizing the injected chlorine dose. The Min Cost model addresses the problem of simultaneously optimizing the operation of existing pumping and booster chlorination injection units, as well as the design of new disinfection booster chlorination stations—locations and size—under extended period simulation, while delivering required water quantities at acceptable pressures and residual chlorine concentrations. Ohar & Ostfeld (2014) formulated the model and aimed at setting the required chlorination dose of the boosters for delivering water at acceptable residual chlorine and TTHM concentrations for minimizing the overall cost of booster placement, construction, and operation under extended period hydraulic simulation conditions. The overall optimization model objective is to minimize the booster chlorination operational injection cost (BCI) plus booster chlorination capital cost (BCD) plus constraint penalty incurred on constraints violation. For the present study, the cost analysis for the optimum location of the booster chlorination station is carried out to check the feasibility of installing extra booster stations given in Table 5.41 for North Harni DWDS network for deficit flow condition with 2 hours water supply and Table 5.42 for Manjalpur DWDS network with two hours water supply. The Tables give the cost of solution of chlorine as well as pumping cost per year.

Table 5.41: Cost analysis for the optimum solution of booster chlorination station (NH-2HD)

Booster Station	Mass rate of chlorine	Concentration of chlorine in Container used	Flow of chlorine		Head available	Power required	Solution cost	Pumping cost
	mg/min	mg/L	l/min	m^3/sec	m	KW	Rs. per year	Rs. per year
BS_1	107.84	100	1.0784	1.79733E-05	18.95	0.01	283403.52	40.65
BS_2	210	100	2.1	0.000035	18.95	0.01	551880.00	79.16
						Total cost	835283.52	119.81

Table 5.42: Cost analysis for the optimum solution of booster chlorination station (MJ-1H)

Booster Station	Mass rate of chlorine	Concentration of chlorine in Container used	Flow of chlorine		Head available	Power required	Solution cost	Pumping cost
	mg/min	mg/L	l/min	m^3/sec	m	KW	Rs. per year	Rs. per year
BS_1	5035.4	100	50.35	0.000839	18.9500	0.26	13233031.20	1898.16
BS_5	1824.6	100	18.25	0.000304	18.9500	0.09	4795048.80	687.81
						Total cost	18028080.00	2585.97

As observed from above Table 5.41 and Table 5.42, the major cost in installing, operating and managing the booster chlorination station is the cost of chlorine. The cost of pumping is negligible. Hence the objective function to minimize the dose can reduce the overall cost of booster chlorination station. The optimal scheduling and location of the booster station gives the overall economical solution for the selection of booster station used for the effective management of chlorine disinfection in DWDS. Using all the case studies, the Decision Support Model (DSM) is developed for the management of chlorine disinfection is shown in Fig. 5.39.

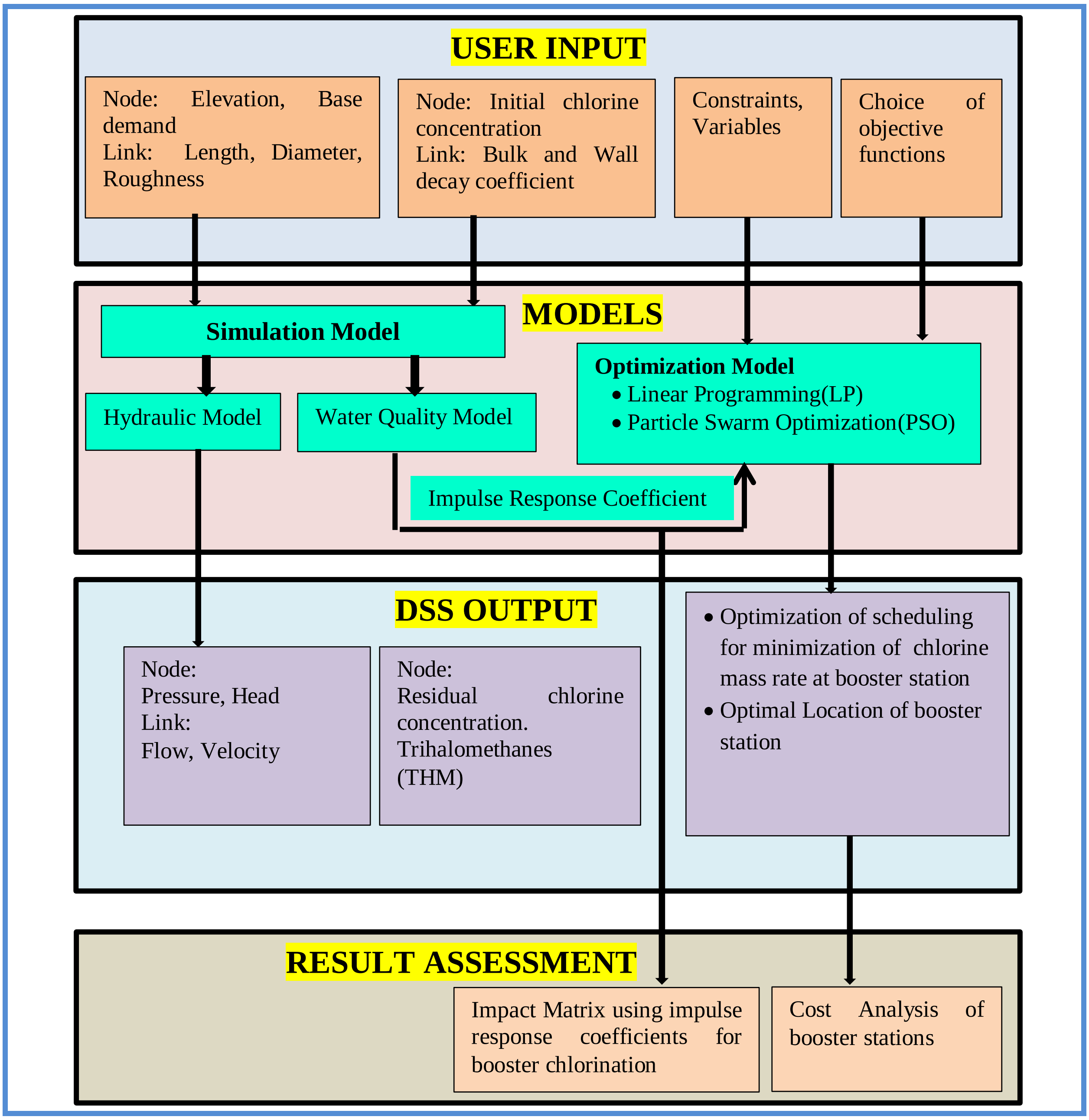


Fig. 5.39: Decision Support Model (DSM) for management of chlorine disinfection in DWDS

5.20 Inferences

This chapter gives the development of coupled simulation and optimization method for the optimum location and scheduling of mass rate of chlorine and location of booster stations. The two optimization methods are used i.e. linear programming (LP) and particle swarm optimization (PSO) method. Both the optimization results give the similar results. For the optimum locations of booster stations, linear programming method needs more trial runs as compared to PSO optimization method. The results of coupled simulation optimization model suggest that for any Drinking water distribution system (DWDS), the coupling of simulation results using simulation model such as EPANET software and optimization method like PSO or linear programming using tools such as excel and MATLAB serve as an important decision support models for managing, scheduling, selection of number and location of booster chlorination stations and overall management of chlorine.

For the rapid estimation of the impact of chlorine injection at various locations on residual chlorine at critical nodes an impact matrix may be the useful tool. The cost analysis for the booster station suggest that if we install the booster stations the major cost of operation is the cost of chlorine which can be minimized using the coupled simulation optimization model.