Chapter 4

Development of Simulation Model using EPANET

4.1 General

Over recent years, there has been a significant increase in the number of software applications that have been released in the field of piped distribution network. It is becoming difficult for systems managers and designers to select a software package most adapted to local needs and circumstances. The various water software useful as distribution system models are Aqua Net, Archimede , Branch / Loop ,Cross ,EPANET 2.0, Eraclito, H_2O net/H_2O map, Helix delta-Q, Mike Net, Opti Designer ,Pipe 2000, Stanet Wadiso SA ,Water CAD 5.0 etc. (Schmid 2002) Water distribution system models such as EPANET (Rossman 1994) have become widely accepted both within the water utility industry and the general research arena for simulating both hydraulic and water quality behaviour in water distribution systems (USEPA 2005).

EPANET is a freely available computer program that performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks. EPANET has two capabilities to perform extended period simulation: hydraulic modelling and water quality modelling. EPANET is designed to be a research tool for different kinds of applications in distribution systems analysis like sampling program design, hydraulic model calibration, chlorine residual analysis, consumer exposure assessment etc. EPANET can be used to assess alternative management strategies for improving water quality throughout a system. (Rossman 2000)

For the simulation purpose, the water distribution network is represented in a hydraulic model as a series of links and nodes. Links represent pipes whereas nodes represent junctions, sources, tanks, and reservoirs, valves and pumps are represented as links. EPANET can be used for both steady-state and extended period simulation (EPS) hydraulic simulations. In addition, it is designed to be a research tool for modelling the movement and fate of drinking water constituents within distribution systems. The water quality routines in EPANET can be used to model concentrations of reactive and conservative substances, changes in age of water and travel time to a node, and the percentage of water reaching any node from any other node. (USEPA, 2005)

The various characteristics of hydraulic and water quality are to the prerequisite as input data for hydraulic and water quality simulation modelling.

4.2 Hydraulic Modelling

Building a network model, particularly if a large number of pipes are involved, is a complex process. The following categories of information are needed to construct a hydraulic model:

i. Characteristics of the pipe network components (pipes, pumps, tanks, valves).
ii. Water use (demands) assigned to nodes with temporal variations.
iii. Topographic information (elevations assigned to nodes).
iv. Control information that describes how the system is operated (e.g., mode of pump operation).
v. Solution parameters (e.g., time steps, tolerances as required by the solution techniques).

Full-featured and accurate hydraulic modelling is a prerequisite for doing effective water quality modelling. The network hydraulic model provides the foundation for modelling water quality in distribution systems. Three basic relations are used to calculate fluid flow in a pipe network i.e. conservation of mass, conservation of energy and pipe friction head loss. Three empirical equations commonly used are for pipe friction head loss are, (i) The Darcy-Weisbach, (ii) The Hazen-Williams, and (iii) The Manning equations. All three equations relate head or friction loss in pipes to the velocity, length of pipe, pipe diameter, and pipe roughness. A fundamental relationship that is important for hydraulic analysis is the Reynolds number Re, which is a function of the kinematic viscosity of water (resistance to flow), velocity, and pipe diameter.

$$R_e = \frac{vd}{\nu} \tag{4.1}$$

Where,

v = velocity of water, m/sec,

d = diameter of pipe, m

ν = kinematic viscosity of water (resistance to flow).

For the hydraulic model development, the Darcy Weisbach equation is generally considered to be theoretically more rigorous and widely used in India which is given by,

$$h_f = \frac{flv^2}{2gd}$$

(4.2)

Where,

h_f= head loss in pipes, m

f= friction factor

l= length of pipe, m

v= velocity at in pipe, m/s

g= acceleration due to gravity, m/s^2

d= diameter of pipe, m

Darcy-Weisbach formula uses different methods to compute the friction factor f depending on the flow regime:

(i) The Hagen–Poiseuille formula is used for laminar flow (R_e < 2,000).

(ii)The Swamee and Jain approximation to the Colebrook-White equation is used for fully turbulent flow (R_e > 4,000).

(iii) A cubic interpolation from the Moody Diagram is used for transitional flow (2,000 < R_e < 4,000).

Friction factor using Hagen – Poiseuille formula for R_e < 2,000 is given as:

$$f = \frac{64}{R_e}$$

(4.3)

Swamee and Jain approximation to the Colebrook - White equation for Re >4000 is given by

$$f = \frac{0.25}{\left(\ln\left(\frac{\mathcal{E}}{3.7d} + \frac{5.74}{{R_e}^{0.9}}\right)\right)^2}$$

(4.4)

Where, $\mathcal{E}$ = pipe roughness and d = pipe diameter.

Using the input data by running the EPANET the output obtained in EPANET is friction head loss using the Hazen-Williams, Darcy- Weisbach, or Chezy-Manning formulas, pressure and flow for extended period simulation (EPS). The hydraulic model can be utilized for water quality model by addition of other required input parameters.

4.3 Water Quality Modelling

In addition to the basic hydraulic model inputs, the water quality models require the additional data elements to simulate the behaviour in a distribution system. A water quality model requires the quality of all external inflows to the network and the water quality throughout the network be specified at the start of the simulation. Data on external inflows can be obtained from existing source monitoring records when simulating existing operations or could be set to desired values to investigate operational changes. Initial water quality values can be estimated based on field data. Alternatively, best estimates can be made for initial conditions. Then the model is run for a sufficiently long period of time under a repeating pattern of source and demand inputs so that the initial conditions, especially in storage tanks, do not influence the water quality predictions in the distribution system. The water age and source tracing options only require input from the hydraulic model.

4.3.1 Reaction Rate Data

For non-conservative substances, information is needed on how the constituents decay or grow over time. Modelling the fate of a residual disinfectant is one of the most common applications of network water quality models. Chlorine is most frequently used disinfectants in distribution systems and is reactive. There are two separate reaction mechanisms for chlorine decay, one involving reactions within the bulk fluid and other involving reactions with material on or released from the pipe wall (Vasconcelos et al. 1997). The most widely used approach for representing wall demand considers two interacting processes – transport of the disinfectant from the bulk flow to the wall and interaction with the wall (Rossman et al. 1994). Studies have suggested that this formulation may not adequately represent the actual wall demand processes and that further research is needed (Clark et al. 2005; Grayman et al. 2002; DiGiano & Zhang 2004 in USEPA 2005). There has been little study on the nature of the wall reaction in chlorinated systems. A limited amount of modelling of the growth of DBPs (most notably THMs) has been performed assuming an exponential growth approaching a maximum value corresponding to the THM formation potential. The governing equations for EPANET's water quality solver are based on the principles of conservation of mass coupled with reaction kinetics. The phenomena represented are (i) Advective transport of mass within pipes & mixing of mass at pipe junctions (ii) Mixing of mass at pipe junctions and storage tanks (iv) Bulk flow reactions within pipes and storage tanks (Rossman et al. 1993; Rossman and Boulos 1996). Bulk flow reaction is very important parameter for the analysis of residual chlorine for distribution network.

While a substance moves down a pipe or resides in storage it can undergo reaction with constituents in the water column called bulk flow reactions. The rate of reaction can generally be described as a power function of concentration:

$$R = kc^n \tag{4.5}$$

Where,

k = a reaction constant

n = the reaction order,

c = concentration (mass/volume) in pipe

The decay of many substances, such as chlorine, can be modelled adequately as a simple first-order reaction as given by

$$R = k_b c \tag{4.6}$$

This kinetic law takes the form of an equation which calculates the concentration of chlorine (Ct) in the water, throughout the transportation time, t. To calculate this, we need to know the chlorine concentration at the beginning of the transportation, C_o and bulk decay coefficient k_b.

$$Ct = Coe^{-k_b t} \tag{4.7}$$

Water quality models such as EPANET use the output of hydraulic models in conjunction with additional inputs as bulk decay coefficient (k_b)to predict the temporal and spatial distribution of a variety of constituents within a distribution system. These constituents include the fraction of water originating from a particular source, the age of water (e.g., duration since leaving the source), the concentration of a non-reactive constituent or tracer compound either added to or removed from the system (e.g., chloride or fluoride) and the concentration of a reactive compound including the concentration of a secondary disinfectant with additional input of its loss rate (e.g., chlorine or chloramines) and the concentration of disinfection by-products with their growth rate (e.g., THMs) as well as tracking contaminant propagation events.

In the present study the hydraulic and water quality modelling capabilities of EPANET software is used to simulate the hydraulic and water quality parameters for the different distribution networks and the real field problems. The EPANET simulation model is applied to check the effect of modes of water supply, traveling time and chlorine application strategy on residual chlorine using EPANET software. Initially to study the water quality simulation, a simple branch network is considered as an example problem.

4.4 Residual Chlorine Simulation in Branch Network (Example Problem)

The simple water distribution network is adopted for the study as shown in Fig. 4.1. The network modelled has 5 consumer nodes, 1 booster node, one source node R, and 5 links. Consumer nodes represent water demand locations for nearby areas while booster node represents locations of inline disinfectant addition. The node data includes the elevation and demand at various nodes which is considered to be steady state. The link data includes connectivity, length, diameter, and roughness information.

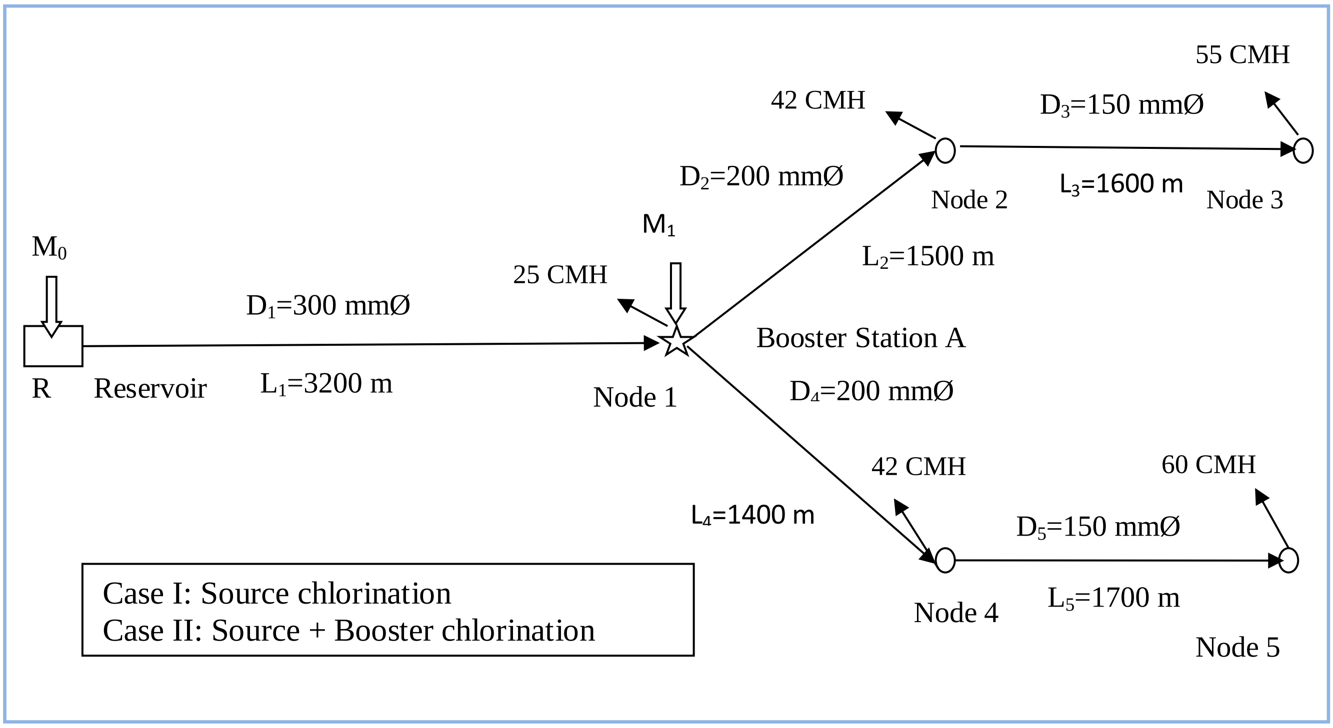


Fig 4.1: Distribution network used for study (Example Problem)

Simulation is carried out to check the effect of two different water supply scenarios. Case I represents the chlorine application only at source with continuous 2 hours water supply and split water supply of 1+1 hour for different periods. Case II uses the strategy of booster chlorination at critical location along with source chlorination. Simulation is also run to check the effect of supply hours and traveling time of chlorine on chlorine concentration at the farthest node.

4.4.1 Simulation Runs:

Simulation is carried out for two conditions: (1) When supply duration is less than travelling time up to farthest node 4 and 5 (2) When supply duration is greater than travelling time up to farthest node. Simulation is further extended for water quality modelling for two different water supply scenarios and two different cases of chlorine application for extended period of 5 days. Scenario I is having constant water supply of 2 hours i.e. from 6 a.m. to 8 a.m. and scenario II is having water supply of total 2 hours with two supply durations of 6 a.m. to 7 a.m. and 6 p.m. to 7 p.m.

The location and rate of chlorine injection of booster station is selected based on the trial and error methods to maintain the minimum chlorine concentration of 0.2 mg/L (minimum) to all the consumer nodes. Table 4.1 represents the data of injection rates of chlorine when supply hours (2 hour) is less than travelling time up to farthest node. The result shows the reduction in chlorine mass rate for case II and scenario II with respect to case I and scenario I. The mass injection time of chlorine is 2 hour that repeats every 24 h for scenario I while for scenario II, the mass injection time of chlorine is 1 hour which repeats every 12 hours. The disinfectant decay rate constant (k_b) is assumed to be 0.55 d^{-1} for all the links while wall decay coefficient is assumed to be negligible.

Table 4.1: Reduction in chlorine mass rate for different scenario, cases and mode of water supply (Example Problem)

Mode of water supply	Chlorine application strategies	Total Mass rate applied	Booster Location/Injection rate		% Reduction in chlorine mass rate with respect to case I Scenario I
			Source	M_1	
		(g/d)	(mg/min)	(mg/min)	
Scenario I (Continuous supply for 2 hour)	Case I	267.6	2230	-	-
	Case II	218.4	1300	520	18.39
Scenario II (Intermittent supply 1+1 hour)	Case I	204	1700	-	23.77
	Case II	182.4	1000	520	31.84

Case I - Only source chlorination;

Case II - Source and Booster Chlorination;

Scenario I - Continuous supply for 2 hour from 6 a.m. to 8 a.m.;

Scenario II - Total 2 hour water supply with two supply durations of 1 hour each from 6 a.m. to 7 a.m. and 6 p.m. to 7 p.m.

4.4.2 Simulation Results

The following results are obtained and observations are made for 2 hours water supply which is less than travelling time up to farthest end node.

(1) Effect of Source Chlorination: It is observed that the chlorine concentration is high in case I, scenario I, due to conventional strategy of supplying high mass rate of chlorine injection (267.6 g/d) at the source to maintain the minimum residual chlorine concentration of 0.2 mg/L at all the nodes. But for case I, scenario II results in reduction of mass rate of chlorine injection (204 g/d) which gives 23.77 % reduction in chlorine injection rate. The simulation results for the minimum, average and maximum chlorine concentration at each consumer node for case I, and scenario I is as shown in the Fig. 4.2(a). It is observed that concentration remains on higher side for the maximum and average concentration due to high dose of chlorine at source alone. The simulation results for the minimum, average and maximum chlorine concentration at each consumer node for case I, scenario II is shown in the Fig. 4.2(b). It is observed that concentration remains low for the maximum and average concentration due as compared to constant water supply and also more uniform distribution of chlorine is observed.

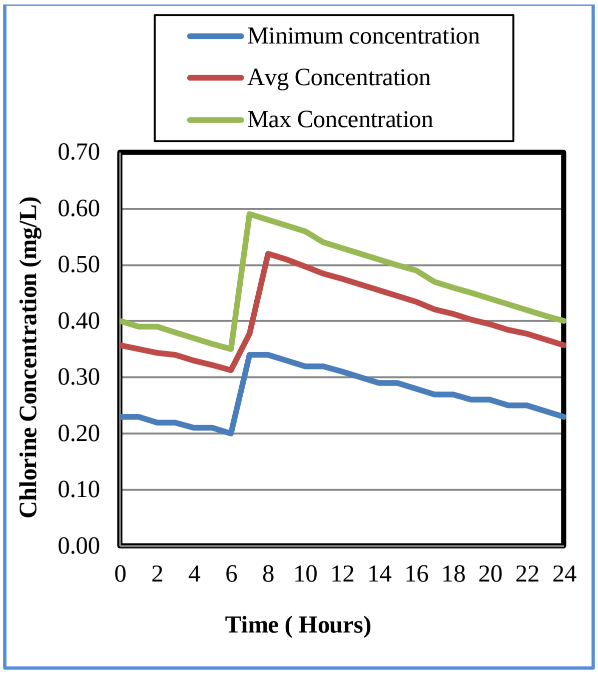


Fig. 4.2(a): Minimum , Average and maximum concentration of residual chlorine for case I, scenario I (Example Problem)

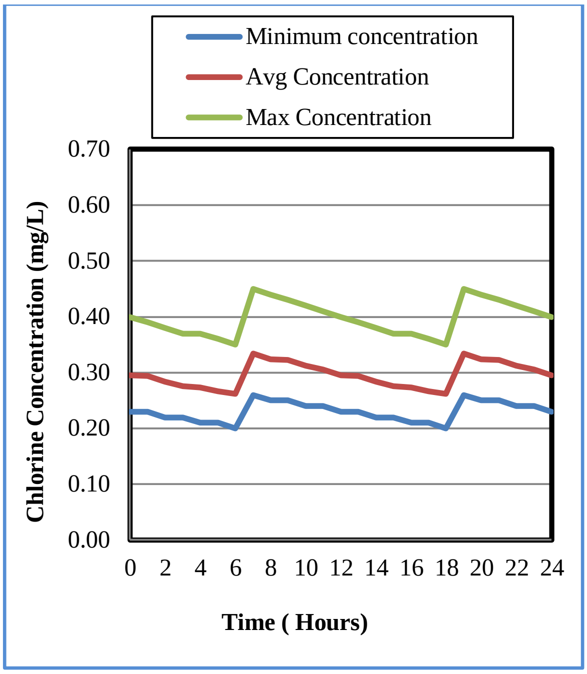


Fig. 4.2(b): Minimum , Average and maximum concentration of residual chlorine for case I scenario II (Example Problem)

Effect of booster chlorination: It is observed that the chlorine concentration is less in case II, scenario I and scenario II. Chlorine injection rate of (218.4 g/d) at the source and booster stations results in 18.39% reduction for maintenance of the minimum residual chlorine concentration of 0.2 mg/L at all the nodes. For the Booster chlorination with scenario II results in reduction of mass rate of chlorine injection (182.4 g/d) which gives 31.84 % reduction in chlorine injection rate. The simulation results for the minimum, average, and maximum chlorine concentration at each consumer node for scenario I for case II is shown in the Fig. 4.3(a). The simulation results for the minimum, average and maximum chlorine concentration at each consumer node for scenario II, case II is shown in the Fig. 4.3(b). It is observed that concentration remains low for the maximum, average and minimum concentration as compared to constant water supply. Also more uniform distribution of chlorine is observed as compared to uneven distribution of chlorine in case of only source chlorination.

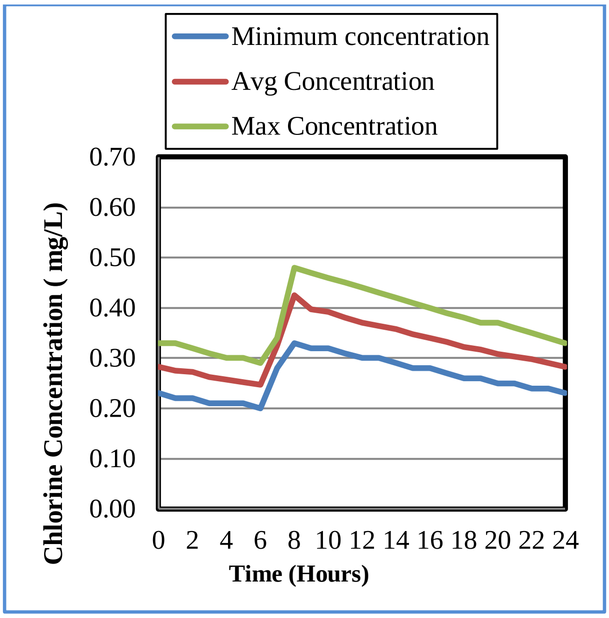


Fig. 4.3(a): Minimum , Average and maximum concentration of residual chlorine for case II, scenario I (Example Problem)

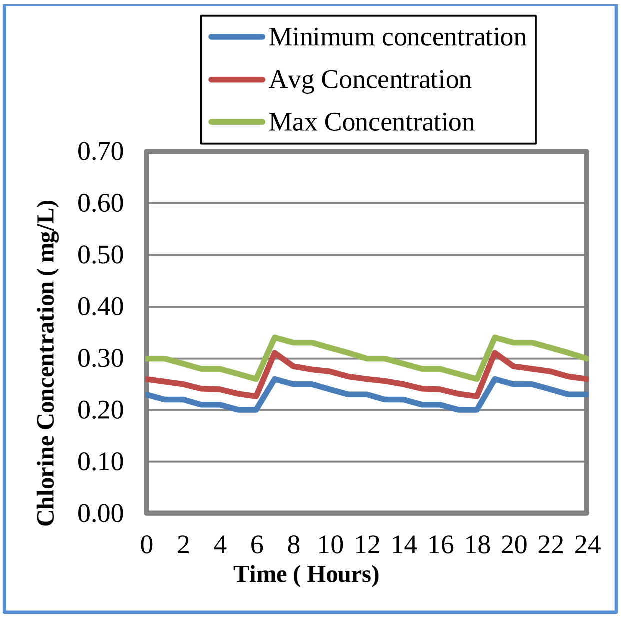


Fig. 4.3(b): Minimum , Average and maximum concentration of residual chlorine for case II, scenario II (Example Problem)

4.4.3 Discussions

It is observed that when the supply hours is kept as 2.5 hour which is more than travelling time of chlorine up to the farthest node , there is no reduction in chlorine mass injection rate either for constant or intermittent supply or conventional or booster chlorination approach. The main points observed from the water quality modelling analysis for 2 hour water supply are:

1. The conventional method of chlorination i.e case I and scenario I with constant 2 hour water supply needs higher mass rate of chlorine i.e. 267.6 g/d to maintain the minimum

concentration of 0.2 mg/L at the farthest consumer nodes, while the area nearer to the source are affected by the high residual chlorine which may result in harmful disinfection by products (DBP).

2. The conventional method of chlorination i.e case I and scenario II with total 2 hour water supply of 1+1 hour water supply needs less mass rate of chlorine i.e. 204 g/d to maintain the minimum concentration of 0.2 mg/L at the farthest consumer nodes, which results in 23.77 % reduction in mass rate of chlorine.
3. Application of booster chlorination at selected locations along with source chlorination and scenario I with constant 2 hour water supply needs less mass rate of chlorine i.e. 218.4 g/d to maintain the minimum concentration of 0.2 mg/L at the farthest consumer nodes. This enables 18.39 % reduction of chlorine application which reduces the average concentration of the chlorine concentration in the area nearer to the source while maintaining the minimum residual chlorine of 0.2 mg/L at the farthest point.
4. Application of booster chlorination at selected locations along with source chlorination and scenario II with total 2 hour water supply of 1+1 hour water supply needs less mass rate of chlorine i.e. 182.4 g/d to maintain the minimum concentration of 0.2 mg/L at the farthest consumer nodes, which results in overall reduction of 31.84 % reduction of chlorine application. It results in overall cost reduction of the chlorine. Reduction in mass rate of chlorine reduces the average concentration of the chlorine concentration in the area nearer to the source while maintaining the minimum residual chlorine of 0.2 mg/L at the farthest point.
5. The reduced mass rate of chlorine applied reduces the exposure of chlorine to organic and inorganic matter in water and indirectly to formation of harmful disinfection by products (DBP) while simultaneously maintains the minimum concentration.
6. Total 2 hour water supply with two water supply duration of 1+1 hour also results in reduction of total mass rate of chlorine as it reduces the contact time from 24 hours to 12 hours for chlorine reaction. Booster chlorination with two water supply duration helps in maintaining the even distribution of chlorine at all the nodes as compared to other cases.
7. Booster chlorination with 2 hour water supply duration of 1+1 hour provides effective chlorine management strategy by supplying uniform distribution of chlorine, minimizing cost and at the same time prevents the problems due to excess chlorination. Thus, for effective management of chlorine the system of water supply, travelling time of chlorine up to the farthest end and chlorine application strategies must be chosen properly to manage the desired residual chlorine at all the nodes.

Above example shows that the residual chlorine depends on network configuration, flow hydraulics, travelling time of chlorine, supply hours, source and booster chlorine injection rate. Therefore it is essential to study the real network for understanding the effect of all these parameters on real DWDS network. The real water distribution network of Vadodara city is used to understand the effect of travelling time of chlorine, effect of 24 X 7 water supply and intermittent water supply, Zoning on residual chlorine concentration and on various hydraulic parameters on the real distribution network. The first case study is carried out for the Cherry Hill-Brushy Plains portion of the South Central Connecticut Regional Water Authority (SCCRWA) distribution network which is taken for study by most of the researchers working for the distribution system modelling (Clark et al., 1994; Boccelli, 1998).

4.5 CASE STUDY 1: Water Quality Modelling using Booster Chlorination in Drinking Water Distribution System

A case study for water quality modelling is carried out using a model derived from the Cherry Hill-Brushy Plains portion of the South Central Connecticut Regional Water Authority (SCCRWA) distribution network (Boccelli, 1998). The network is shown in Fig. 4.4. The sample network has 34 consumer nodes, booster nodes (A to F), one source node No 1 representing a pump station, one storage tank (Node 26), and 47 links. Consumer nodes (nodes 2-25, 27-36) represent water demand locations while booster nodes (nodes A to F) represent locations of disinfectant addition. The link data includes connectivity, length, diameter, and roughness Information. The cylindrical tank, node 26, is modelled as a continuous flow stirred tank reactor. To simulate the actual field condition i.e. dynamic conditions, every consumer node is assigned a demand that is altered every hydraulic time step by a global demand multiplier as shown in Table 4.2. By using global demand multiplier we can vary the demand at each consumer node. As an example, node 12 has a base demand of 1. 2 L/s, a demand of 2.604 L/s at t = 10 h (1.2 L/s × 2.17), and a demand of 1.14 L/s at t = 11 h (1.20 L/s × 095). Case I represents the chlorine application near source (Pumping station) by booster station A. Case II uses the strategy of booster chlorination at critical locations (booster stations A to F) along with source chlorination. The locations of booster stations are selected based on the trial and error methods to maintain the chlorine concentration range of 0.2 mg/L (Lower bound) to 4 mg/L (Upper bound) at all the consumer Nodes except Tank. Table 4.3 shows the data of total mass rate of chlorine for different time period at Booster Locations (A to F) for both the cases. The mass injection time was set to 6 h to coincide with the four distinct periods of system hydraulics; thus the operation of each booster station is described by four separate constant mass injection intervals, each 6 h long, that repeat every 24 hours. The disinfectant decay rate constant k_b= 0.55 d^{-1} used while wall decay coefficient is assumed to be negligible.

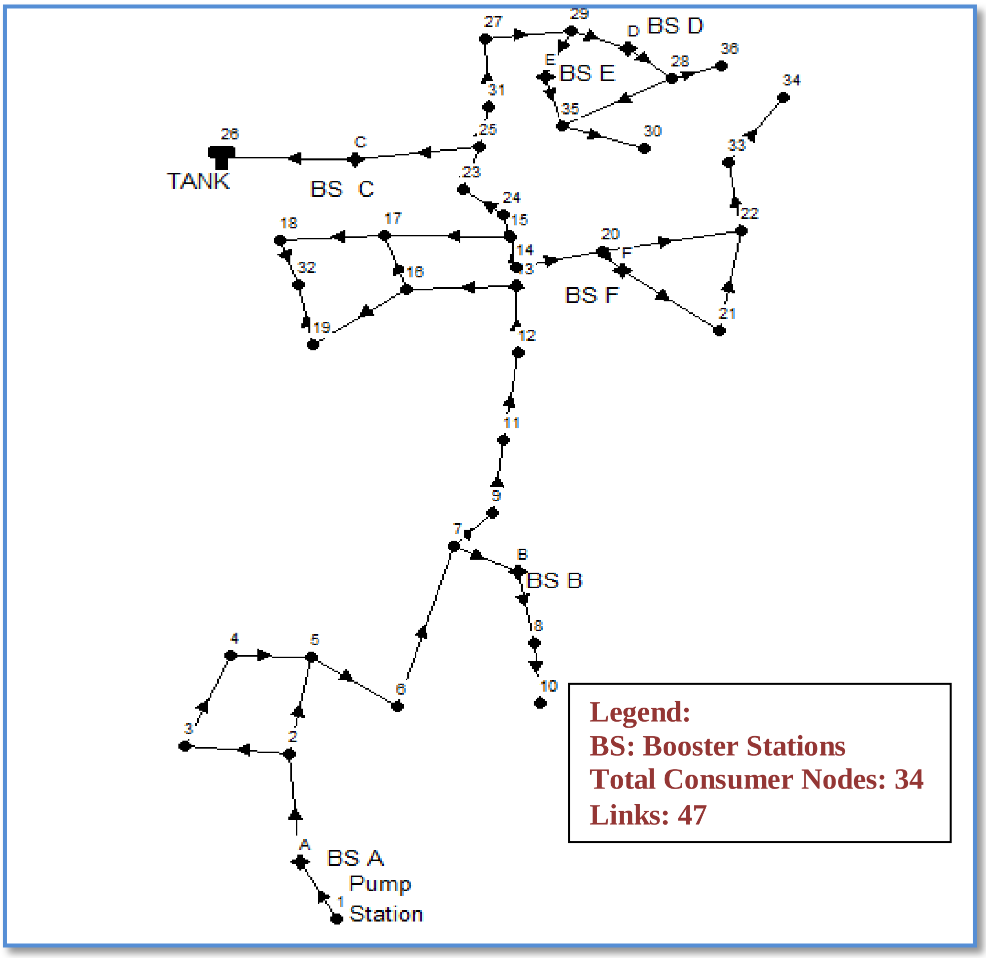


Fig 4.4: Sample Network of the Cherry Hill-Brushy Plains. (Case Study 1; Source: Clark et al. 1994)

Table 4.2: Consumer and Pump Demand Multipliers (Case Study 1)

Hour	Demand Multiplier	Source Multiplier	Hour	Demand Multiplier	Source Multiplier
0	1.2	0.9	12	0.9	0.9
1	1	0.9	13	0.64	1.2
2	0.9	0.9	14	1.4	1.2
3	0.9	0.9	15	0.65	1.2
4	0.82	0.9	16	0.33	1.2
5	1.2	0.9	17	0.77	0.55
6	1.3	0	18	0.38	0
7	0.65	0	19	0.66	0
8	0.65	0	20	1.25	0
9	1.3	0	21	1.48	0
10	2.17	0	22	1.3	0
11	0.95	0	23	1.2	0

Table 4.3: Injection rates of chlorine for booster stations (A to F) for Case Study 1

Cases	Total Mass rate (g/d)	Booster Period*	Booster Location/Injection rate					
			A (mg/min)	B (mg/min)	C (mg/min)	D (mg/min)	E (mg/min)	F (mg/min)
Case I (Only source chlorination)	4725	1	7500	-	-	-	-	-
		2	0	-	-	-	-	-
		3	5625	-	-	-	-	-
		4	0	-	-	-	-	-
Case II (Source + Booster Chlorination)	1332.74 (71.8% reduction in total chlorine)	1	650	25.6	0	9.2	20.5	160.4
		2	0	5.1	680	10.2	10.3	200.5
		3	1137.5	46.1	34	5.1	18.5	120.3
		4	0	0	442	6.1	20.5	100.3

***Booster Period 1= hours 0-6, 2=hours 7-12, 3= hours 13-18, 4=hours 19-24**

4.5.1 Simulation Results

Hydraulic Analysis: By running the EPANET software using input data of nodes, pipes for both the cases results in periodic network hydraulic behaviour as shown in Fig. 4.5. A negative flow rate indicates the tank is draining and a positive flow rate indicates the tank is filling. The 24-h cycle divide the hydraulic dynamics of the network into four distinct periods. During periods 1 (0-6 h) and 3 (12-18 h) the network hydraulics are controlled mainly by the source.

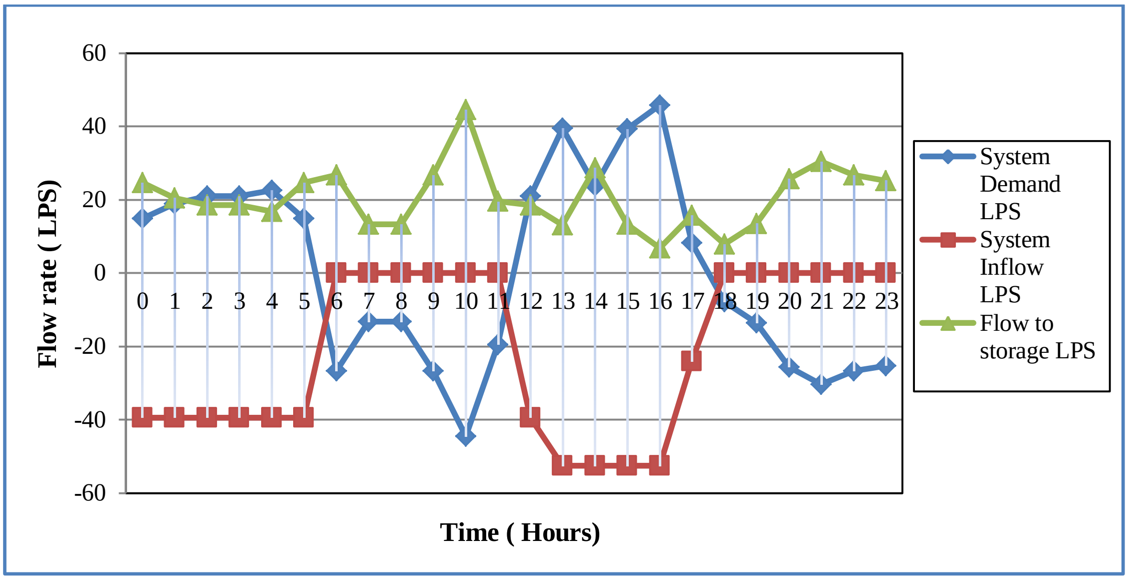


Fig. 4.5: Network Hydraulic Behaviour of Cases I & II (Case Study 1)

Water Quality Analysis: By incorporating the injection rates at different booster stations for different booster period, the resulting tank concentration of residual chlorine is obtained as shown in Fig 4.6. The simulation results for the average, maximum and minimum chlorine concentration at each consumer node for 24 hour is obtained and based on the results, the graphs of average concentration and standard deviation are shown in Fig 4.7(a) and 4.7(b) for case I and II respectively.

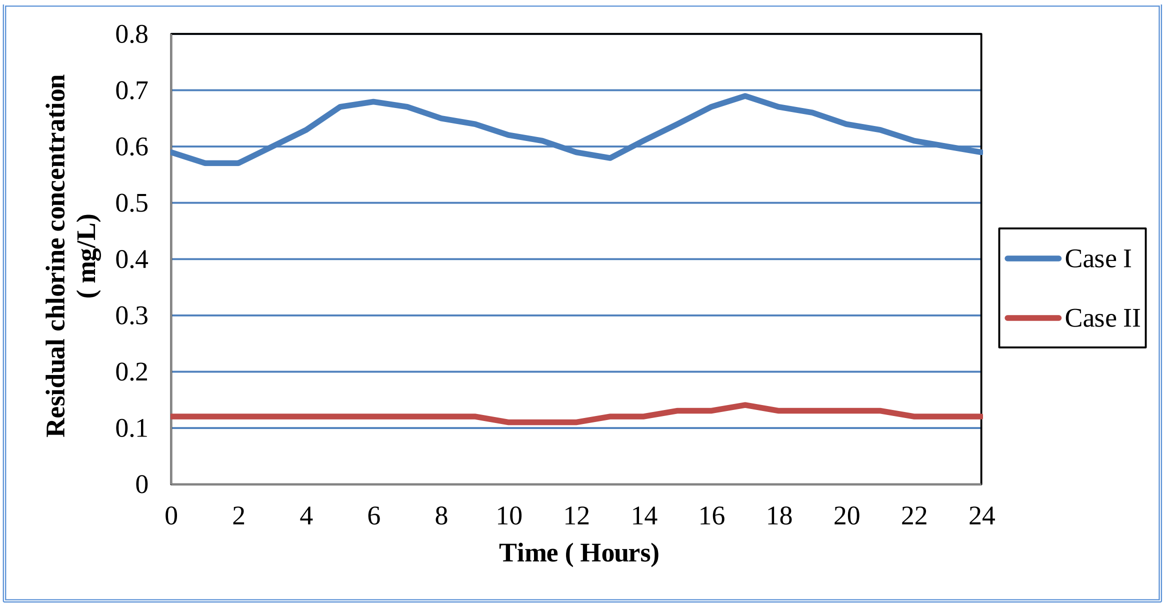


Fig. 4.6: Tank concentration of residual chlorine (Case I and II) for Case Study 1

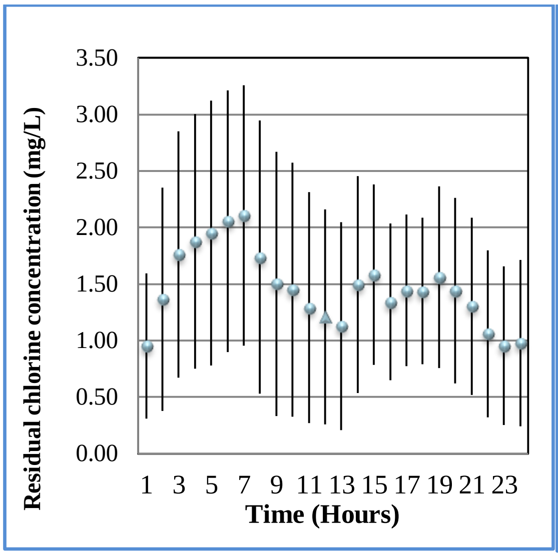


Fig. 4.7(a): Average residual chlorine concentration and standard deviation for all nodes (Case I) for Case study 1

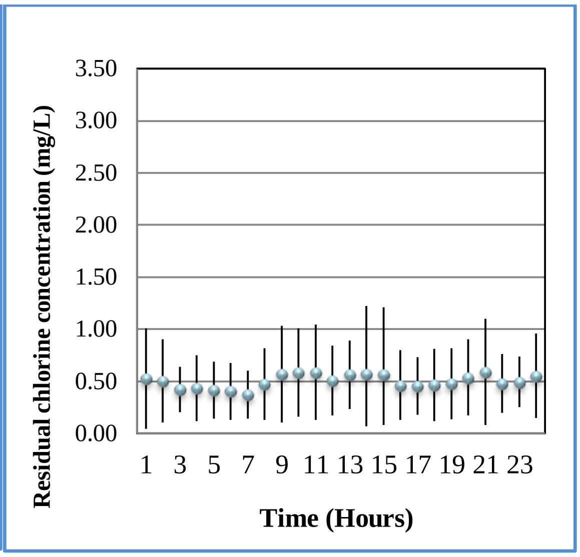


Fig. 4.7(b): Average residual chlorine concentration and standard deviation for all nodes (Case II) for Case study 1

4.5.2 Discussions

EPANET software is used for the water quality modelling of a sample network predict the chlorine concentration at the consumer nodes. The residual chlorine concentration obtained at each node is utilized to check the critical location of a node from chlorine concentration point of view. The critical locations having less chlorine residual used to select the location of booster station. The major observations obtained from the analysis of the results are:

(1) The Fig. 4.6 shows that the tank concentration in case II is much lower than case I. The lower concentration of chlorine at the tank does not affect the minimum concentration (0.2 mg/L) at all the consumer nodes.

(2) The conventional method of chlorination i.e. near the source by booster station A fails to maintain the minimum concentration at most of the consumer nodes even at 4725 g/d mass rate of chlorine.

(3) Application of booster chlorination with total mass rate of 1332.74 g/d successfully maintained the chlorine concentration within lower and upper limit of 0.2 mg/L and 4 mg/L.

(4) Total reduction of 71.8% is obtained in total mass rate of chlorine applied by booster chlorination at different stations. It results in overall cost reduction of the chlorine.

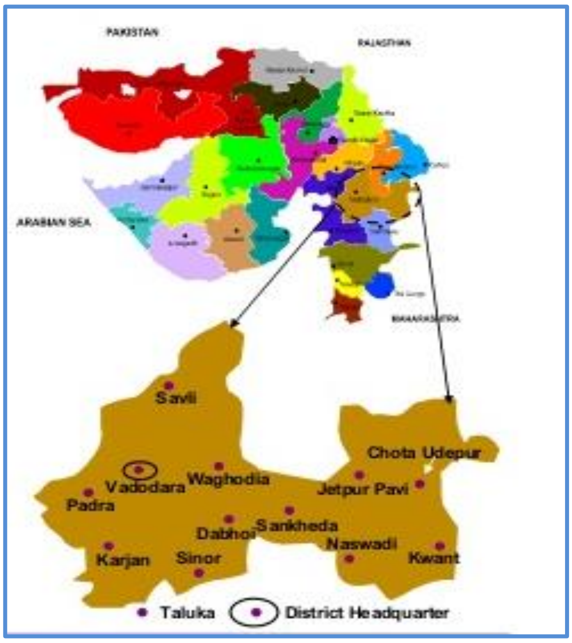
(5) As seen from the Fig 4.7(a) and 4.7(b) in case II, a pronounced drop in both the average concentration and standard deviation of concentration, implying more uniform spatial and temporal distribution of the disinfectant concentrations in the network. The overall standard deviation for case I is obtained as 0.982 while for case II is obtained as 0.388.

(6) Analysis can help to find the critical locations for sample collection and sensor placement for the monitoring of chlorine.

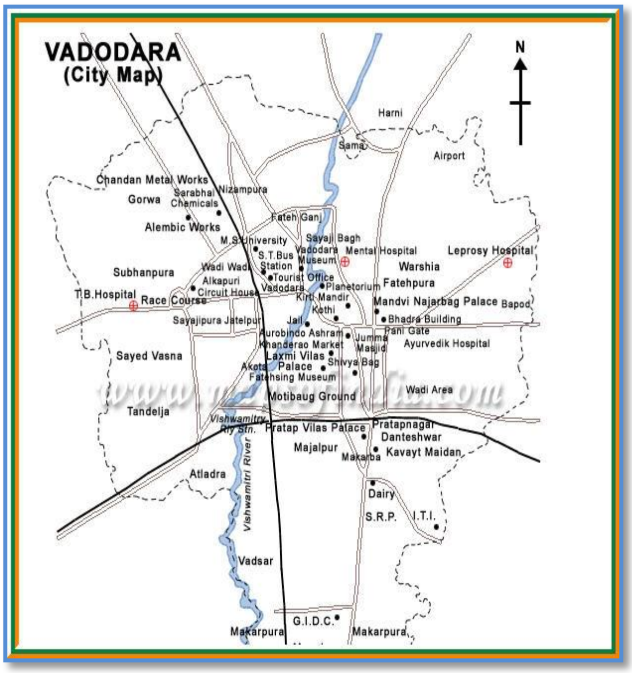
Thus it is observed that the booster chlorination may prove to be better option to maintain a desired level of chlorine than conventional method of chlorination at source. In this case study the number of booster stations are five along with source application of chlorine. From the installation, operation and maintenance point of view, the selection of number and location of booster stations play an important role in overall management of chlorine in DWDS

To further study the effect and feasibility of booster chlorination in real drinking water distribution system for Indian conditions, various distribution network of Vadodara city are adopted. The data required for the development of model related to existing water supply and details of different distribution network are collected for study areas from Vadodara Mahanagar Seva Sadan (VMSS) Vadodara. Fig. 4.8 shows the study area.

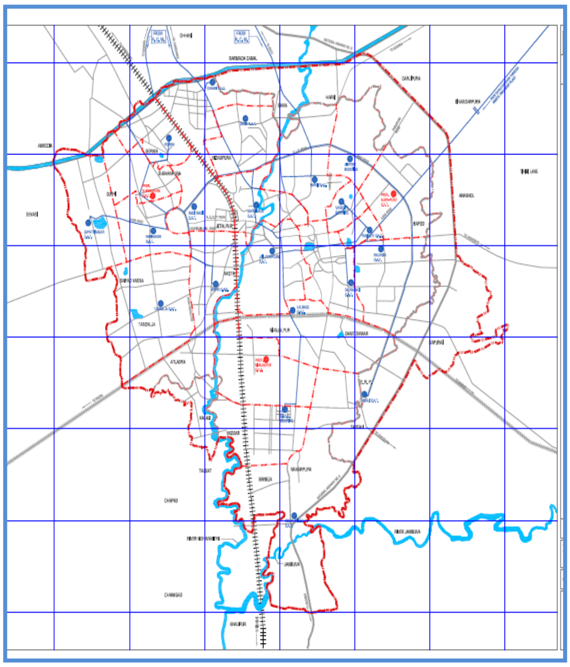
India



Gujarat



Vadodara City



Vadodara DWDS networks

Fig. 4.8: Study Area of Vadodara City DWDS

4.6 Vadodara City at a Glance

Vadodara is an important industrial City of Gujarat, situated on the broad gauge railway track on the Mumbai - Delhi and Mumbai - Ahmedabad routes. Located in the fertile plains between the rivers Narmada and Mahi and on the banks of River Vishwamitri, Vadodara lies on the 22° 17’ 59” N Latitude and 73° 15’ 18” E Longitude. The topography of the City is generally flat with a gentle slope from the Northeast to Southwest, following the basin of Vishwamitri. Vishwamitri - a meandering river, bifurcate the City centrally in two halves. The City is also dotted with many pretty lakes, which form part of the catchment of Vishwamitri and another tributary known as Jambuva River, which flows on the southern outskirts of the City and merges with the River Vishwamitri. The general ground level of the City varies from 20 m to 40 m above mean sea level. The climate of the City is moderately dry and arid, with the maximum temperature range of 35-40°C during summer and 15-30°C during winter. It has an average annual rainfall of 900 mm which is spread over 3 to 4 months.

4.6.1 Sources of Water for Vadodara City

The old Vadodara town had a piped water supply since 1894. At present the the main sources of water for the Vadodara city are the Sayaji Sarovar (Ajwa) on the northeast , Radial collector wells (RCW) in Mahi river on the northwest of the city. The other sources of water are tube wells and Khanpur water treatment plant (WTP).The construction of this WTP has solved the low pressure & quantity problems in western areas of the city. Table 4.4 gives the summary of the source and quantity of the water supply source of Vadodara city.

Table 4.4: Source and quantity of water supply (VMSS; https://vmc.gov.in)

Source of Water	Quantity of water
Ajwa / Nimeta	145 MLD
Radial Collector Wells	250 MLD
Tube wells	25 MLD
Khanpur WTP	37 MLD
Total	457 MLD

4.6.2. Scenario of Water Distribution Services of Vadodara City

To distribute water with good pressure in the different areas, they have been divided into 4 major zones area wise. At each distribution station, normally there is a Ground Service Reservoir (GSR) and an Over Head Tank (OHT). Water is pumped to the OHT during the supply hours and the supply is made through the OHT. Each zone was given a supply twice daily for duration of 30 to 45 minutes during each supply time. The total water supply from each reservoir lasts for about 6 to 8 hours in a day. Water is given once daily for about 40 to 70 minutes. Pressures are maintained such that water reaches to at least ground and sometimes at first floors in City area. Consumers in the upper floors fetch water from the ground floors. In the extended areas and TP schemes, almost all the premises have a sump below ground level. In some areas, the water is received quite below the ground level and ditches are made to collect the water from the pipeline. The total length of the distribution line is 1100 km which supplies 210 LPCD water without losses.

At present the distribution network consists of Elevated Service Reservoirs (ESRs) & Ground Service Reservoir (GSRs) & Boosting Stations for the adequate supply of water to the city.
The service reservoirs (ESR & GSR) in the city are provided integration with different supply sources (Mahi river & Ajwa reservoir) through Feeder grid, which results in uninterrupted & consistent water supply. The Distribution Network is made up of mainly DI/CI mains with rubber or lead joints. The minimum size of pipeline in the system is 75 mm (3-inch) and the maximum size is 750 mm (30-inch). The main distribution line in Vadodara City normally consists of sizes from 750 mm to 450 mm. No consumer connections are to be given from main distribution line. The sub main distribution consists from 450 mm to 250-mm size. Presently the consumer connections are given from 100-mm and 150-mm size pipeline only.
Each OHT has two or more outlets and each outlet serves more than one zone. Normally there are minimum two zones and maximum of six zones in the command area, however in some cases the supply zones are more than ten. Table 4.5 gives the information about the present and future population with water demand with available water source. Table 4.6 gives the command area of each zone of water tank.

Table 4.5: Present and future water demand (VMSS; https://vmc.gov.in)

Forecast Population & Demand of water YEAR	**Population in Lac**	**Demand @ 180 lpcd with 15% UFW MLD**	**Demand @ 212 lpcd with 30% UFW MLD**	**Source available MLD**	**Gap in Demand MLD**
2012	18	324	381	420	-
2022	24.6	442.8	522	495	-
2031	30	540	636	495	141
2040	36.2	651	768	495	273

Table 4.6: Population forecasting and command area for each tank and Zone (VMSS; https://vmc.gov.in)

Zone	Sr.no.	Tank name	Population (2011)	Population (2040)	Command area (km^2)
South Zone	1	Gajarawadi	58226	113610	4.37
	2	Kapurai	58842	114812	6.62
	3	Nalanda	52231	101912	3.31
	4	Bapod	23553	45956	1.31
	5	Tarsali	52484	102406	7.55
	6	Manjalpur	43857	85573	6.57
	7	GIDC	29593	57741	5.13
	8	South GIDC	61103	119223	12.11
East Zone	1	Panigate	81515	159051	3.74
	2	Warashia	10191	19885	1.06
	3	Ajwa	122052	238146	5.53
	4	Airport	47651	92976	5.38
	5	Sayajipura	87680	171080	5.26
	6	North Harni	28158	54941	3.18
North Zone	1	Lalbaug	91641	178809	8.01
	2	Jail	58611	114361	4.37
	3	Sayajibaug	44208	86258	3.08
	4	Vhicalpool	9947	19408	0.49
	5	Harni	64676	126195	4.28
	6	Sama	64312	125485	7.19
	7	Extra	28358	55332	3.16
	8	Chhani village	59327	115758	6.61
	9	Chhani jakat	39800	77657	4.43
West Zone	1	Subhanpura	55896	109064	3.71
	2	Gorwa	48259	94162	2.77
	3	Wadiwadi	57450	112096	3.27
	4	Harinagar	54652	106636	5.54
	5	Gayatrinagar	57415	112027	6.77
	6	Kalali	70382	137328	7.07
	7	Tandalja	56274	109801	6.69
	8	Akota	48150	93950	5.28
Total			1666494	3251639	153.84

4.7 Drinking Water Distribution Networks used for Case Studies

The hydraulic and water quality models are developed for the different distribution networks and the real field problems of Vadodara city using EPANET software. The EPANET simulation model is applied to check the effect of modes of water supply (Continuous / 24 X 7 water supply or intermittent water supply), traveling time and chlorine application strategy (i.e. source /booster chlorination) on residual chlorine. The different Drinking water Distribution networks of Vadodara city used for the case study is Subhanpura, Channi, North Harni and Manjalpur which are marked in the Fig. 4.9.

Following assumptions are made for all the case studies for hydraulic and water quality modelling

Hydraulic Modelling:

(1) For computation of head loss Darcy Weishbach formula (Equation 2.4) is used

(2) Friction factor is obtained using Swamee and Jain formula (Equation 2.6.) is used

(3) The value of equivalent pipe roughness is considered as 0.035 mm for ductile iron pipe and 0.26 mm for CI pipes. As the network is adopted as demand driven network, the variation in roughness value will result in variation of residual pressure and will not affect the velocity in the pipe. As the main objective of the study is to simulate the residual chlorine concentration which is independent of roughness value.

(4) Minor losses are not considered in the analysis because the network flow is driven by node demand and hence velocities are not affected by the minor losses. The main objective of the study is to compute residual chlorine which is dependent on velocities and not on pressure.

(5) For flat topography the uniform elevations of 100 m is assumed at all nodes.

Water Quality Modelling:

(1) First order chlorine decay equation (Feben &Taras 1951; Johnson 1978; Clark 1994; Rossman et al. 1994; Hua et al. 1999; Boccelli et al., 2003) is used for computing residual chlorine at various nodes.

(2) Value of bulk decay coefficient k_b is adopted as $0.55d^{-1}$ (Rossman et al., 1994) for all the case study except for Subhanpura DWDS for which the chlorine decay coefficient is obtained using field investigations. The wall decay coefficient is neglected.

(3) Flow is steady state for each demand pattern during supply of water.

(4) The cylindrical tank at node is modelled as a continuous flow stirred tank reactor.

(5) At booster station node the flow is taken first and then booster dose is applied.

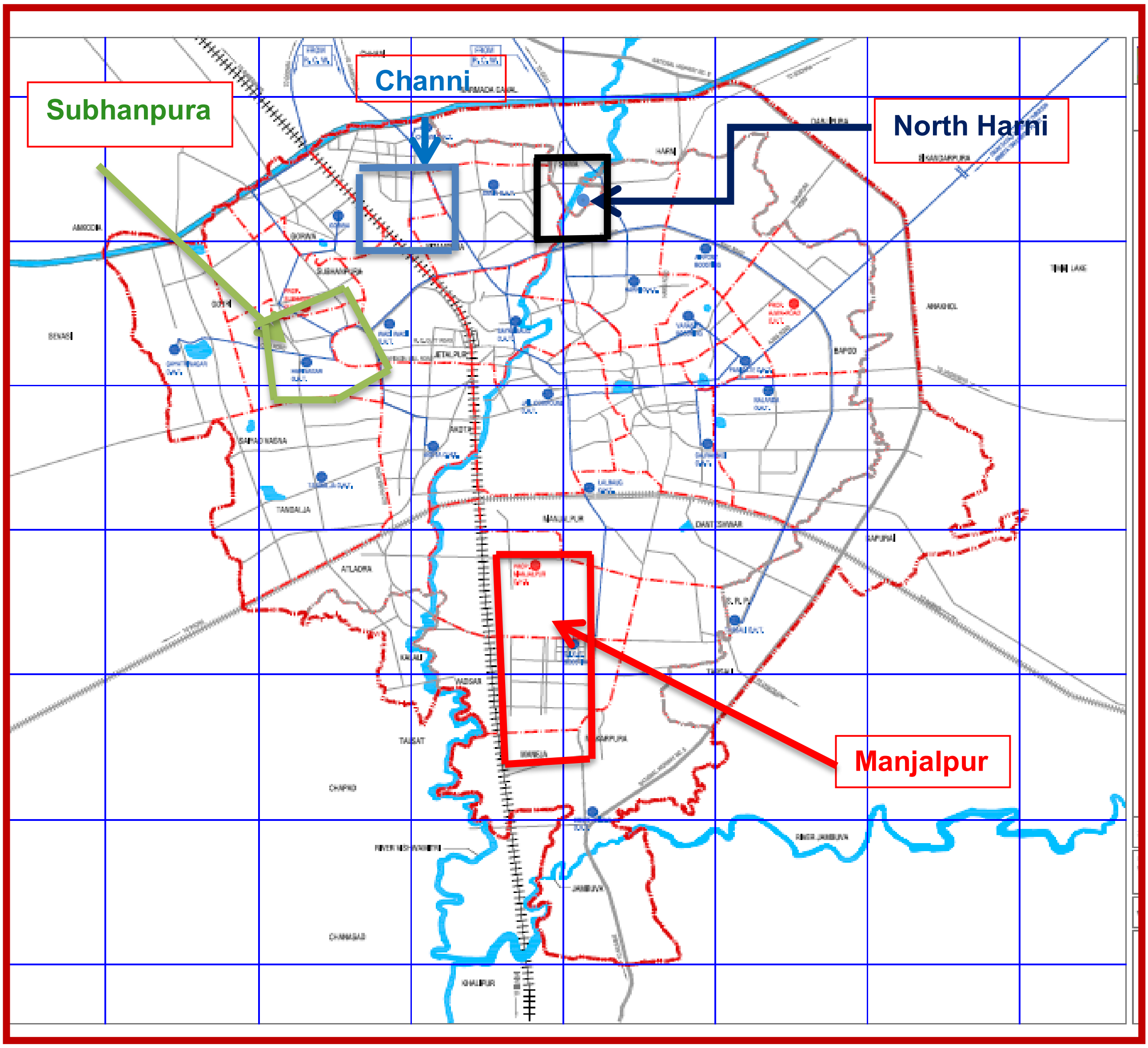


Fig. 4.9: Drinking water distribution networks of Vadodara city selected for study.

4.8 CASE STUDY 2: Hydraulic and Water Quality Analysis of Zoning System of Subhanpura Drinking Water Distribution System.

In major part of Vadodara, Gujarat, India, the intermittent water supply is adopted for different zones of area. This case study presents hydraulic analysis in terms of head and pressure at different locations as well as water quality in terms of residual chlorine and THM concentration throughout the network with the help of constructed network using EPANET software. The information is collected for study area from Vadodara Mahanagar Seva Sadan, Vadodara. The details of all the nodes, link, connectivity of Subhanpura Drinking Water Distribution System network is shown in Fig. 4.10.

The distribution network supply the drinking water to the total command area of 3.71 Km^2 with the population of 55896 for year 2011 and projected population of 109064 for year 2040. The existing rectangular ESR is having capacity of 1.8 ML and existing capacity of Ground surface reservoir is 7.2 ML making total existing capacity of 9 ML. The average water consumption is 42.38 Lac Gallon. The network modelled has 375 consumer nodes, one source node R_1, four pumps to supply the water in different zones at different durations, one storage tank (Node T_1), and 482 links. The link data includes connectivity, length, diameter, and roughness information. As pipes are of cast iron material, the equivalent roughness of the pipes is taken as 0.26 mm. The whole area is divided into four zones with different water supply durations. The Water quality Simulation is carried for all four zones with one hour duration with intermittent water supply using EPANET software. For intermittent system the supply hours for different zones are Zone I (Morning 6:00 am- to 7:00 am) & Zone 2 (8.00 am-9:00 am). For Evening the water is supplied from 6:00 pm to 7:00 pm (Zone 3) & 8:00 pm- 9:00 pm (Zone 4).

Water quality analysis results are used to check the effect of zoning for intermittent water supply on pressure and the residual chlorine concentration at various locations of distribution network through hydraulic and water quality simulation as per water supply schedule. For the analysis of various parameters such as pressure, residual chlorine and disinfection by-products i.e Tri halomethanes (THM) at the farthest nodes of each zone are identified. The nodes J 447, J 235, J 82 and J 116 are considered as the critical nodes for the analysis. To carry out the water quality modelling the bulk decay coefficient is very important input parameter. Therefore the field measurements are taken for the investigation of bulk decay coefficients.

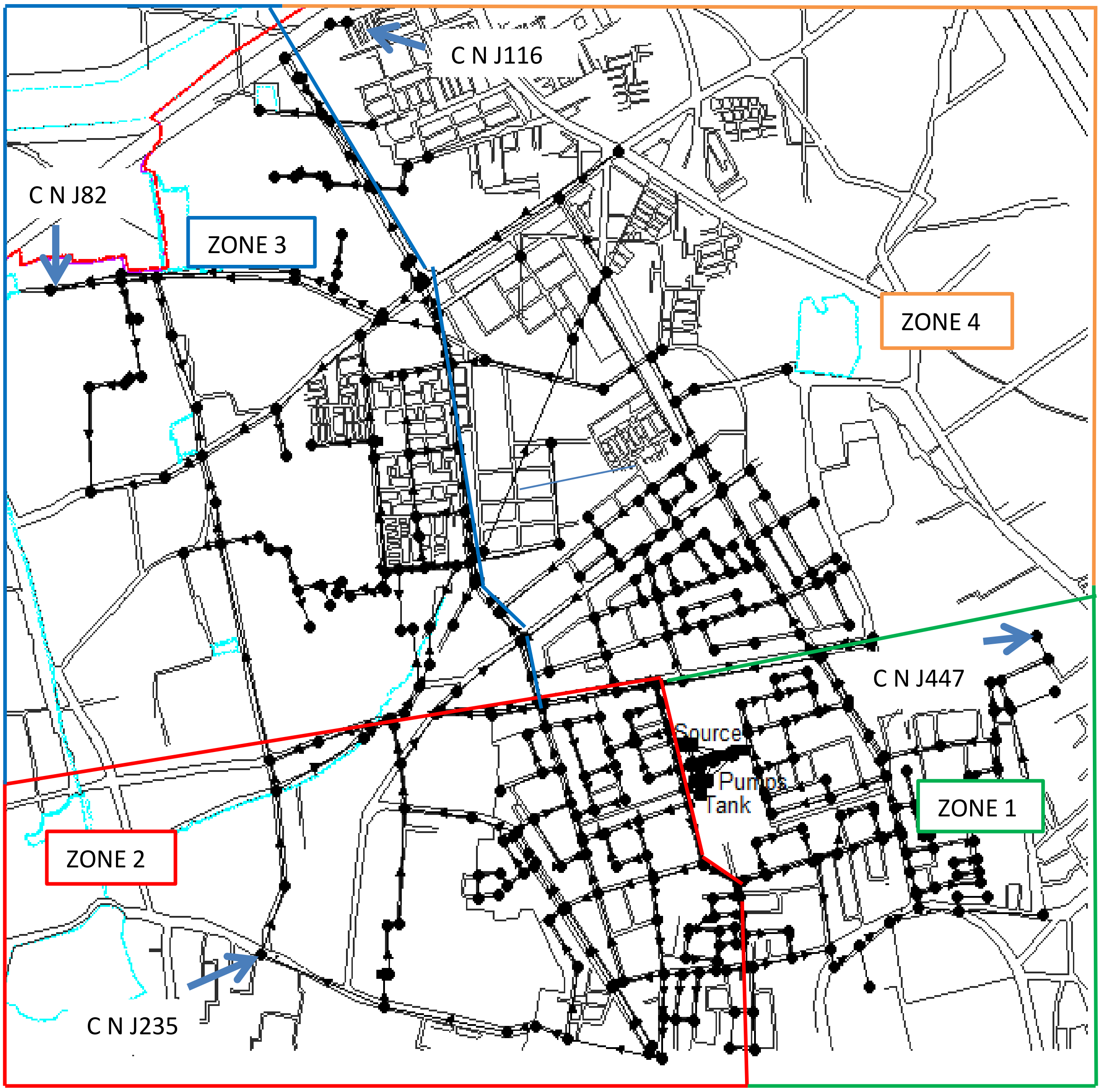


Fig. 4.10: Subhanpura Drinking Water Distribution System Network. (Case study 2)

4.8.1 Investigation of Bulk Decay Coefficients

The Laboratory analysis is done for the residual chlorine by starch Iodide method (APHA standard method for examination of water and wastewater, 2012) to investigate the value of bulk decay coefficient. The value is obtained by conducting the field experiment using bottle test at three different locations of networks. The sample 1, 2 and 3 are collected form Zone 3, Zone 1 and Zone 2. The graphs in Fig. 4.11(a), (b) and (c) show the decay of chlorine at different time interval to obtain the bulk decay coefficient for sample 1, 2 and 3 respectively. The average value of bulk decay coefficient k_b is obtained as 0.268 d^{-1}. Table 4.7 gives the summary of bulk chlorine decay coefficient with average value

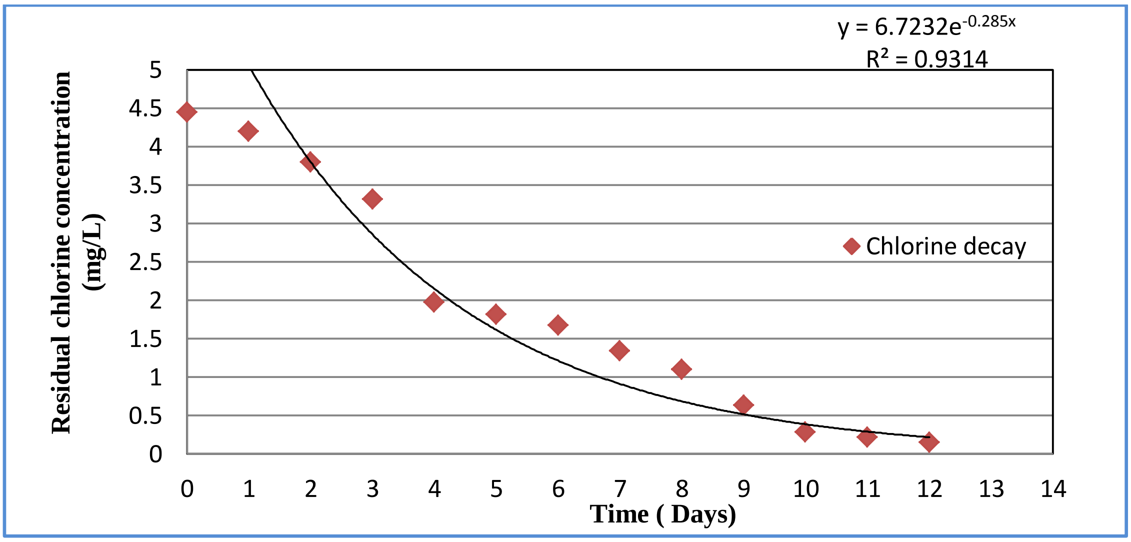


Fig 4.11(a): Determination of bulk chlorine decay coefficient for sample 1(Case study 2)

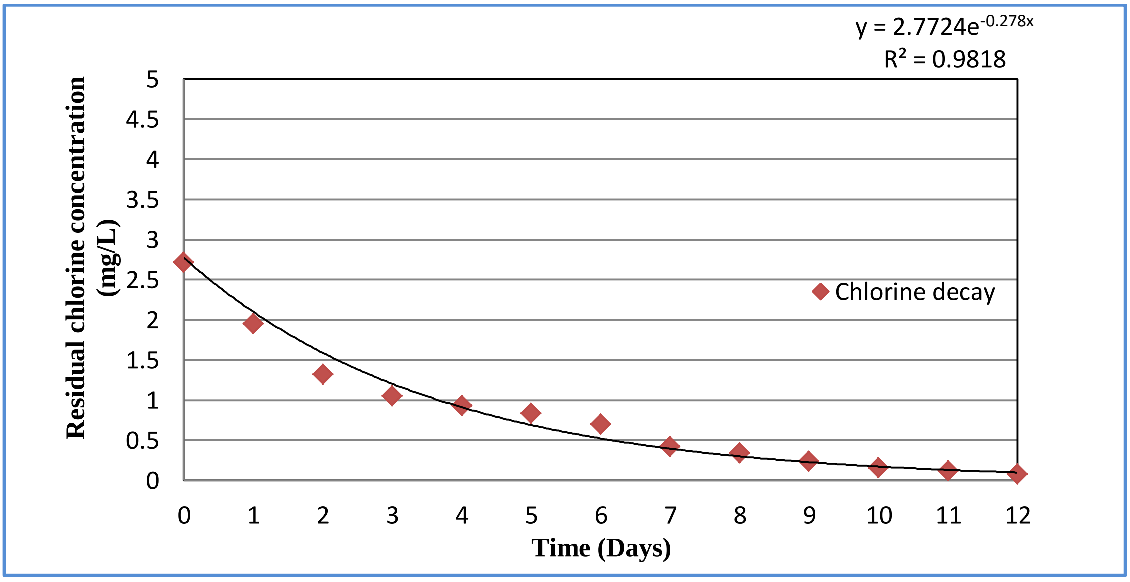


Fig. 4.11(b): Determination of bulk chlorine decay coefficient for sample 2(Case study 2)

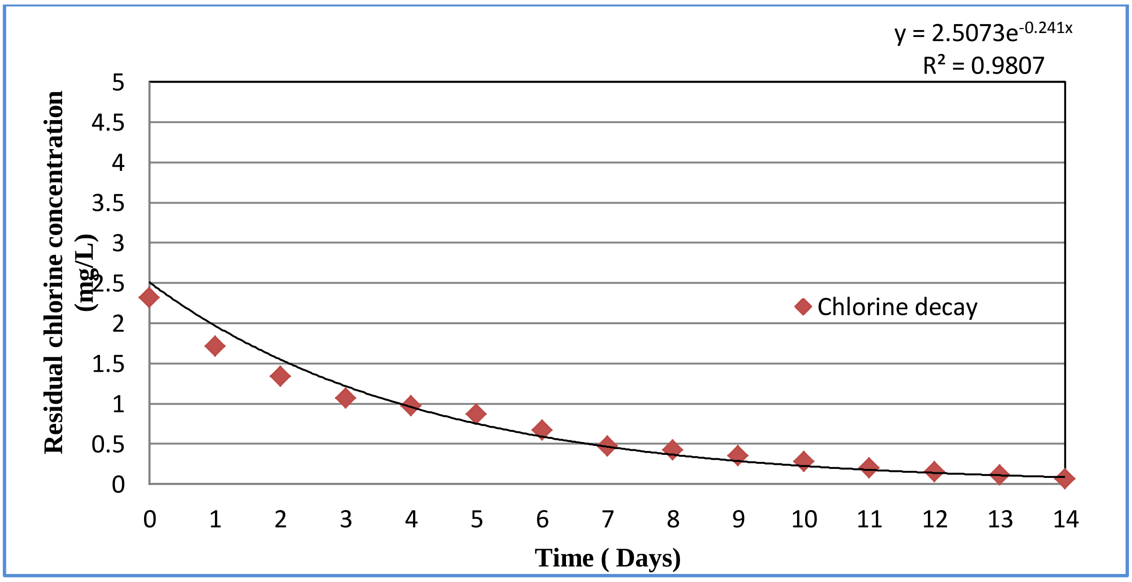


Fig. 4.11(c): Determination of bulk chlorine decay coefficient for sample 3(Case study 2)

Table 4.7: Determination of Chlorine Decay Coefficient (Case study 2)

Sample No	Collection Date	Sample collection site	Bulk chlorine decay coefficient (d^{-1})
1	17-09-2014	Harikrishna Society, Subhanpura	0.285
2	12-11-2014	Subhanpura water tank, Subhanpura	0.278
3	19-11-2014	Mayur park Society, Subhanpura	0.241
		Average Value	0.268

Hydraulic and water quality simulation is carried out for intermittent water supply for extended simulation for period of 10 days. The analysis of simulation result is as under.

4.8.2 Simulation Results

Hydraulic Analysis: The resulting water head in the tank is obtained as shown in Fig 4.12 for intermittent water supply for last 24 hour cycle of extended period simulation (EPS) of 10 days i.e. from 216 hour to 240 hour. The pumping rate is selected in such a way that there is no much variation in the water level in tank for both the scenario. Fig 4.13 represents the system flow balance for the network during intermittent water supply for EPS results for last 24 hours (i.e. 216 to 240 hour) for the extended period simulation. The peak hours for the hydraulic analysis is taken as 222.5 hour for the water supply hours for Zone 1 (Morning 6 a.m. to 7 a.m.) , 224.5 hours for Zone 2 (8.00 am-9:00 am) for extended period simulation. The peak hours for the Evening schedule of 234.5 hours (6:00 pm to 7:00 pm Zone 3) & 236.5 hours (8:00 pm- 9:00 pm for Zone 4).

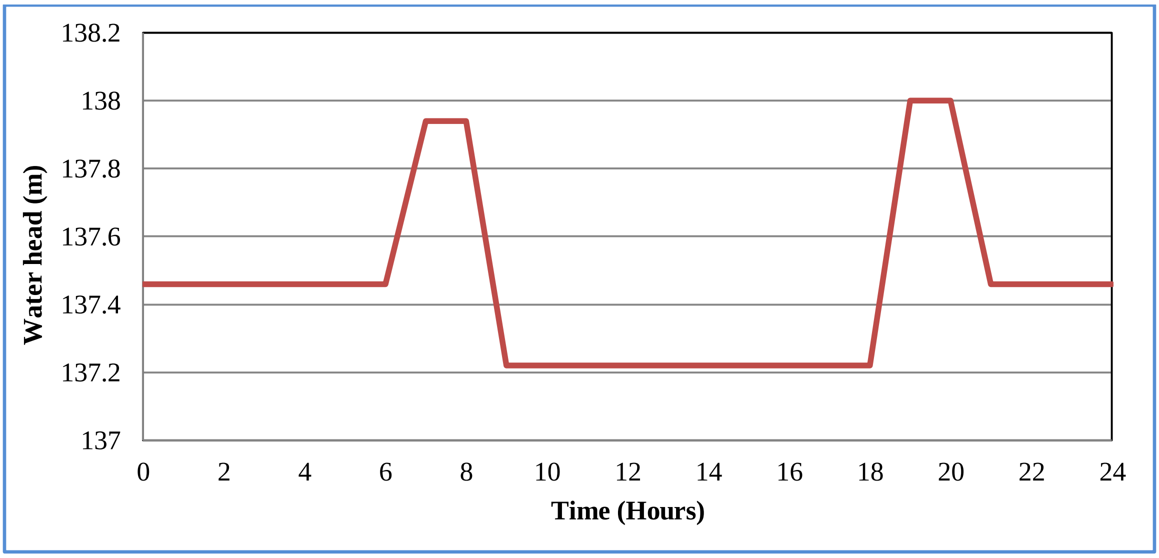


Fig. 4.12: Water head in tank (EPS of ten days for last 24 hours) for Case Study 2.

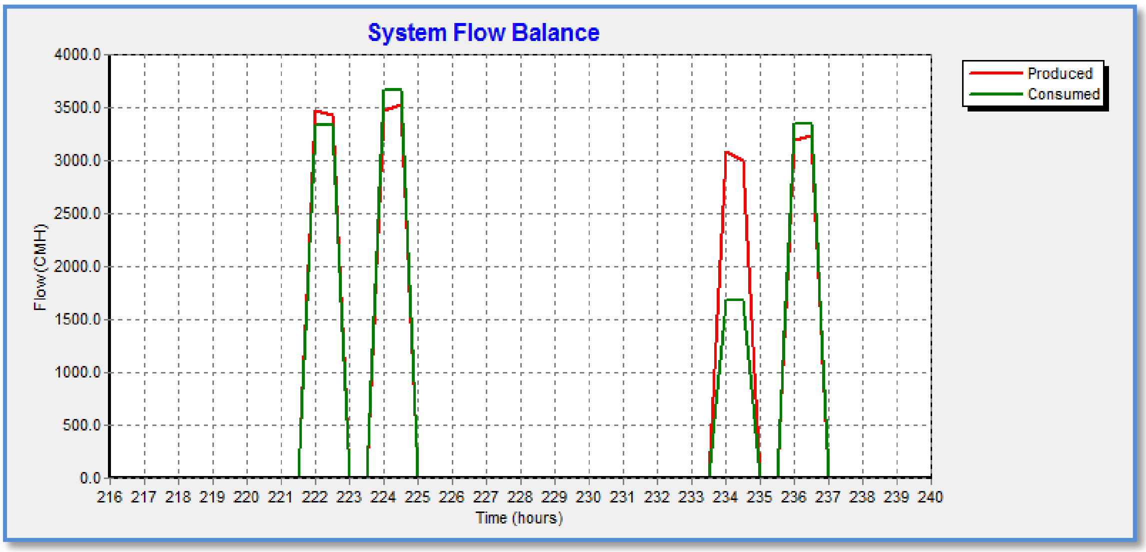


Fig. 4.13: System flow balance (EPS of ten days for last 24 hours) for Case Study 2.

The water quality analysis is also carried out for the extended period simulation of 10 days (i.e. 240 hours). The results of the last 24 hours are considered for the analysis purpose.

Water Quality Analysis: At source 2 mg/L of chlorine is supplied. The chlorine is supplied during the pump operation in scheduling as per the time scheduling for each Zone. For analysis of Tri halomethanes (THM), it is assumed that most of the THMs are formed within the source before being pumped to the distribution system as the maximum residence time of chlorine is in reservoir only. The initial concentration of THMs at the source is assumed as 25 μg/L with the assumed growth rate as 0.18 μg/L from literature (Ahn et al. 2012). Fig. 4.14 shows the tank concentration of residual chlorine during last 24 hours of extended period simulation which varies from 1.53 mg/L to 1.69 mg/L. Fig. 4.15 provides the details of minimum, average and maximum concentration of residual chlorine for last 24 hours of extended period simulation for all nodes.

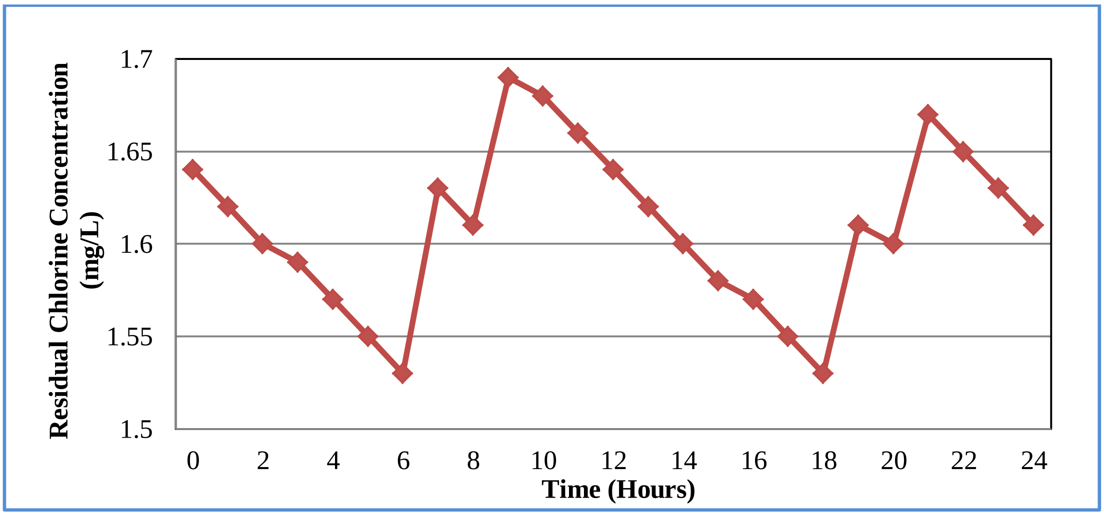


Fig. 4.14: Tank concentration of residual chlorine (EPS of ten days for last 24 hours) for Case Study 2

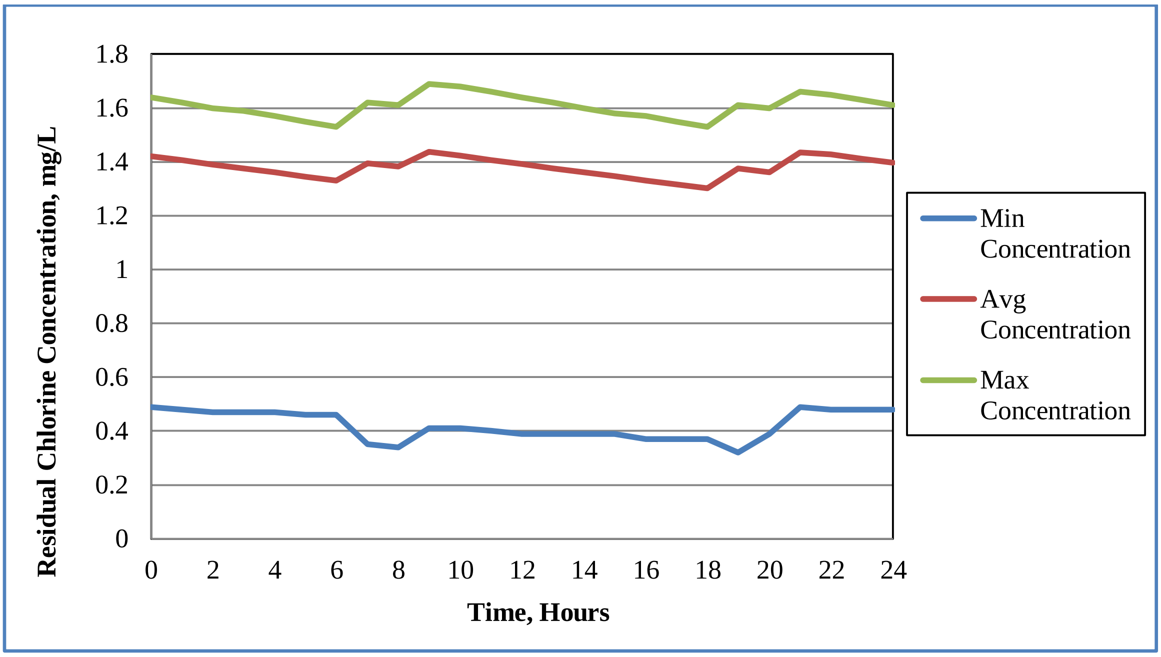


Fig. 4.15: Minimum, average and maximum concentration of residual chlorine for all nodes (EPS of ten days for last 24 hours) for Case Study 2

The peak hour in water quality analysis is taken as 222.5 hour for the water supply hours for Zone 1 (Morning 6 a.m. to 7 a.m.), 224.5 hours for Zone 2 (8.00 am-9:00 am) for extended period simulation, as starting point of application of chlorine is critical in intermittent supply as long residence time of chlorine will result in chlorine decay during non-supply hours. The peak hours for the Evening schedule of 234.5 hours (6:00 pm to 7:00 pm Zone 3) & 236.5 hours (8:00 pm- 9:00 pm for Zone 4). Table 4.8 shows the variations in pressure, chlorine and THM for the last 24 hours of simulation for extended period.

Table 4.8: Variations in pressure, chlorine and THM (EPS of 10 days for last 24 hours) for Case Study 2

Time (Day 10)	Node J116 (Zone 4)			Node J82 (Zone 3)			Node J235 (Zone 2)			Node J447 (Zone 1)		
	Pressure m	Chlorine mg/L	THM µg/L	Pressure m	Chlorine mg/L	THM µg/L	Pressure m	Chlorine mg/L	THM µg/L	Pressure m	Chlorine mg/L	THM µg/L
216:00:00	37.46	1.2	30.37	37.46	0.72	34.14	37.46	1.41	28.87	37.46	1.23	30.18
217:00:00	37.46	1.19	30.47	37.46	0.71	34.21	37.46	1.4	28.98	37.46	1.22	30.28
218:00:00	37.46	1.17	30.57	37.46	0.7	34.28	37.46	1.38	29.08	37.46	1.21	30.38
219:00:00	37.46	1.16	30.67	37.46	0.7	34.35	37.46	1.37	29.19	37.46	1.19	30.47
220:00:00	37.46	1.15	30.76	37.46	0.69	34.42	37.46	1.35	29.3	37.46	1.18	30.57
221:00:00	37.46	1.13	30.86	37.46	0.68	34.49	37.46	1.34	29.4	37.46	1.17	30.67
222:00:00	36.28	1.12	30.95	36.28	0.67	34.55	34.91	1.32	29.51	30.23	1.15	30.76
223:00:00	37.94	1.11	31.04	37.94	0.67	34.68	37.94	1.24	30.14	37.94	1.46	28.56
224:00:00	36.38	1.1	31.14	36.37	0.66	34.74	32.13	1.23	30.24	36.32	1.46	28.67
225:00:00	37.22	1.08	31.23	37.22	0.44	36.85	37.22	1.17	30.68	37.22	1.44	28.78
226:00:00	37.22	1.07	31.32	37.22	0.43	36.9	37.22	1.16	30.77	37.22	1.42	28.89
227:00:00	37.22	1.06	31.41	37.22	0.42	36.94	37.22	1.14	30.87	37.22	1.41	29
228:00:00	37.22	1.05	31.5	37.22	0.42	36.99	37.22	1.13	30.96	37.22	1.39	29.11
229:00:00	37.22	1.04	31.59	37.22	0.41	37.04	37.22	1.12	31.06	37.22	1.38	29.22
230:00:00	37.22	1.03	31.68	37.22	0.41	37.09	37.22	1.1	31.15	37.22	1.36	29.32
231:00:00	37.22	1.01	31.77	37.22	0.41	37.14	37.22	1.09	31.24	37.22	1.35	29.43
232:00:00	37.22	1	31.86	37.22	0.4	37.19	37.22	1.08	31.33	37.22	1.33	29.53
233:00:00	37.22	0.99	31.94	37.22	0.39	37.23	37.22	1.07	31.42	37.22	1.32	29.64
234:00:00	34.4	0.98	32.03	34.31	0.39	37.28	36.55	1.06	31.51	36.64	1.3	29.74
235:00:00	38	0.97	32.12	38	0.66	34.8	38	1.37	29.21	38	1.29	29.85
236:00:00	33.09	0.96	32.2	33.29	0.49	36.35	36.41	1.36	29.3	35.58	1.27	29.95
237:00:00	37.46	1.21	30.34	37.46	0.73	34.06	37.46	1.43	28.79	37.46	1.26	30.05
238:00:00	37.46	1.2	30.35	37.46	0.72	34.13	37.46	1.42	28.83	37.46	1.25	30.15
239:00:00	37.46	1.19	30.45	37.46	0.71	34.2	37.46	1.4	28.94	37.46	1.23	30.25
240:00:00	37.46	1.18	30.54	37.46	0.71	34.27	37.46	1.39	29.05	37.46	1.22	30.35

4.8.3 Discussions

Extended period simulation for 10 days was carried out for Subhanpura Drinking Water Distribution Network to check the effect of zoning and mode of water supply on various hydraulic and water quality parameters like residual chlorine and THM concentration at various locations of Drinking Water Distribution System. The graphs of hydraulic analysis for water head (Fig. 4.12) shows that during pumping hour's water head increases and water level remains at uniform level during non-pumping hours. System flow balance (Fig. 4.13) shows that both the flow i.e. produced and consumed are balanced during pumping hours.

For maintaining 0.2 mg/L residual chlorine at all the locations, 2 mg/L of chlorine is supplied at the source during water supply hours for different zones. It is observed from the water quality analysis that the chlorine concentration variation in tank is in the range of 1.53 mg/L to 1.69 mg/L for last 24 hours of extended period simulation of 10 days. Fig. 4.14 shows that the residual chlorine concentration increases during pumping hours and decreases during non-pumping hours. Fig. 4.15 represents the minimum, average and maximum residual chlorine concentration for which shows that the minimum concentration at all nodes range between 0.26 mg/L to 0.49 mg/L, average concentration ranges from 1.3 mg/L to 1.44 mg/L and maximum concentration is in the range of 1.53 to 1.69 mg/L. As mentioned in Table 8.2, the results of hydraulic and water quality parameters suggest that all the locations receive the residual chlorine concentration more than specified limit i.e. 0.2 mg/L. This is due to zoning in which the travelling time of chlorine is reduced and due to less travelling time of chlorine it will reach to the farthest node before duration of water supply hours.

The formation of THM is in the range of 28.5 µg/L to 37.5 µg/L for critical nodes for last 24 hours of extended period simulation. In India the limit of THM is not specified . In USA, the standard for THMs is 0.1 mg/L (100 µg/L) to 0.08 mg/L (80 µg/L). The THM value in the present study is found within limit. As zonation is done in the DWDS all the parameters are found within the specified limit.

The further case study is carried out to check the effect of continuous and intermittent water supply on hydraulic and water quality analysis.

4.9 CASE STUDY 3: Hydraulic and Water Quality Analysis of Channi Drinking Water Distribution System for Continuous and Intermittent Water Supply

24 X 7 water supply system is proposed for the Channi Drinking Water Distribution System network, Vadodara, Gujarat, India is selected for the case study of hydraulic and water quality

analysis. The Channi distribution network supply the drinking water to the total command area of 4.43 Km^2 with the population of 39800 for year 2011 and projected population of 77657 for year 2040 having total pipe length of 16118.7m. The existing ESR is having capacity of 1.8 ML and existing capacity of Ground surface reservoir is 6.8 ML making total existing capacity of 8.6 ML. Network is constructed in EPANET based on the information collected for study area from Vadodara Mahanagar Seva Sadan, Vadodara.

Two scenarios of modes of water supply are simulated to study its effect on various hydraulic parameters like pressure, head and discharge. Scenario 1 represents the 24 X 7 continuous supply and scenario 2 uses the intermittent supply of total 4 hours in a day divided into two zones for the same network. For intermittent supply Upper zone receives water supply during 6 a.m. to 8 a.m. and 4 p.m. to 6 p.m., while the water supply hours for lower zone are 8 a.m. to 10 a.m. and 6 p.m. to 8 p.m. Further the simulation is extended to check the effect of mode of water supply on residual concentration during peak hour is studied.

The effect of different modes of water supply on various hydraulic parameters like discharge, head, and pressure is obtained across the network by the result of hydraulic simulation. Water quality analysis results are used to check the effect of mode of water supply on the residual chlorine concentration at various locations of distribution network through water quality simulation. The demand at various nodes is considered to be dynamic in nature as shown in Fig. 4.16 and Fig. 4.17 for 24 X 7 and intermittent water supply respectively.

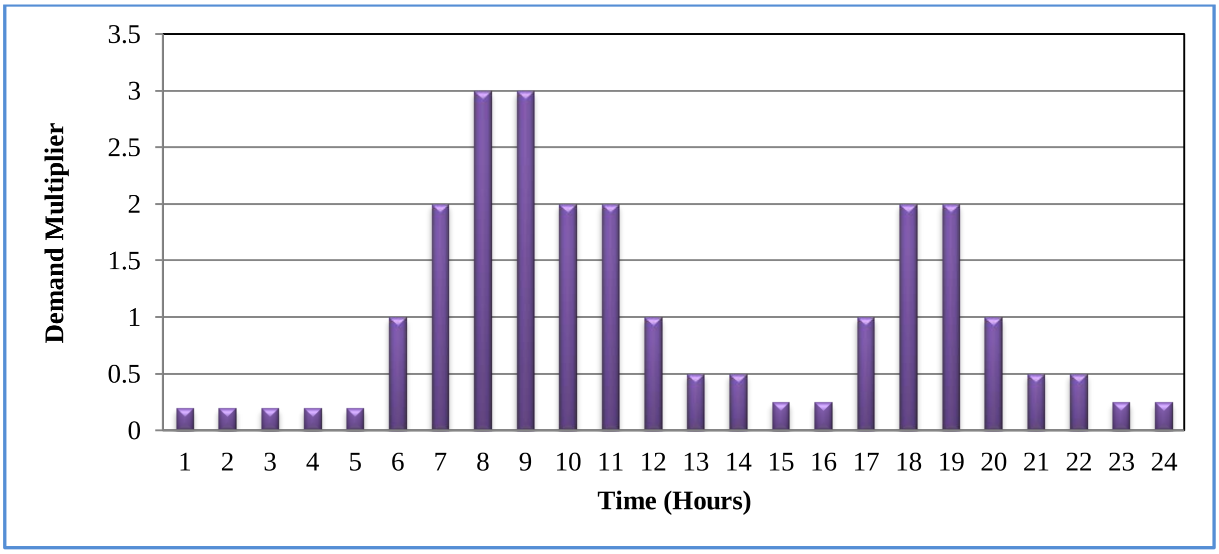


Fig. 4.16: Variation in demand for 24 X 7 continuous water supply (Case Study 3)

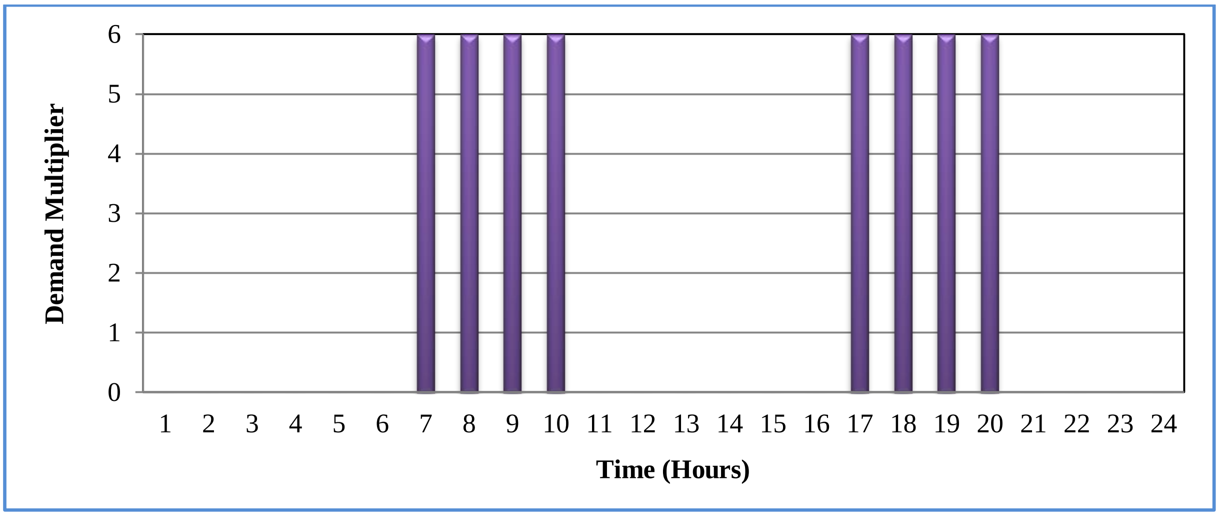


Fig. 4.17: Demand for Intermittent water supply of 4 hours in a day (Case Study 3)

The network modelled has 75 consumer nodes, one source node R_1, one pumping station, one storage tank (Node T_1), and 81 links. The link data includes connectivity, length, diameter, and roughness information. The water distribution network for the study area is shown in Fig. 4.18.

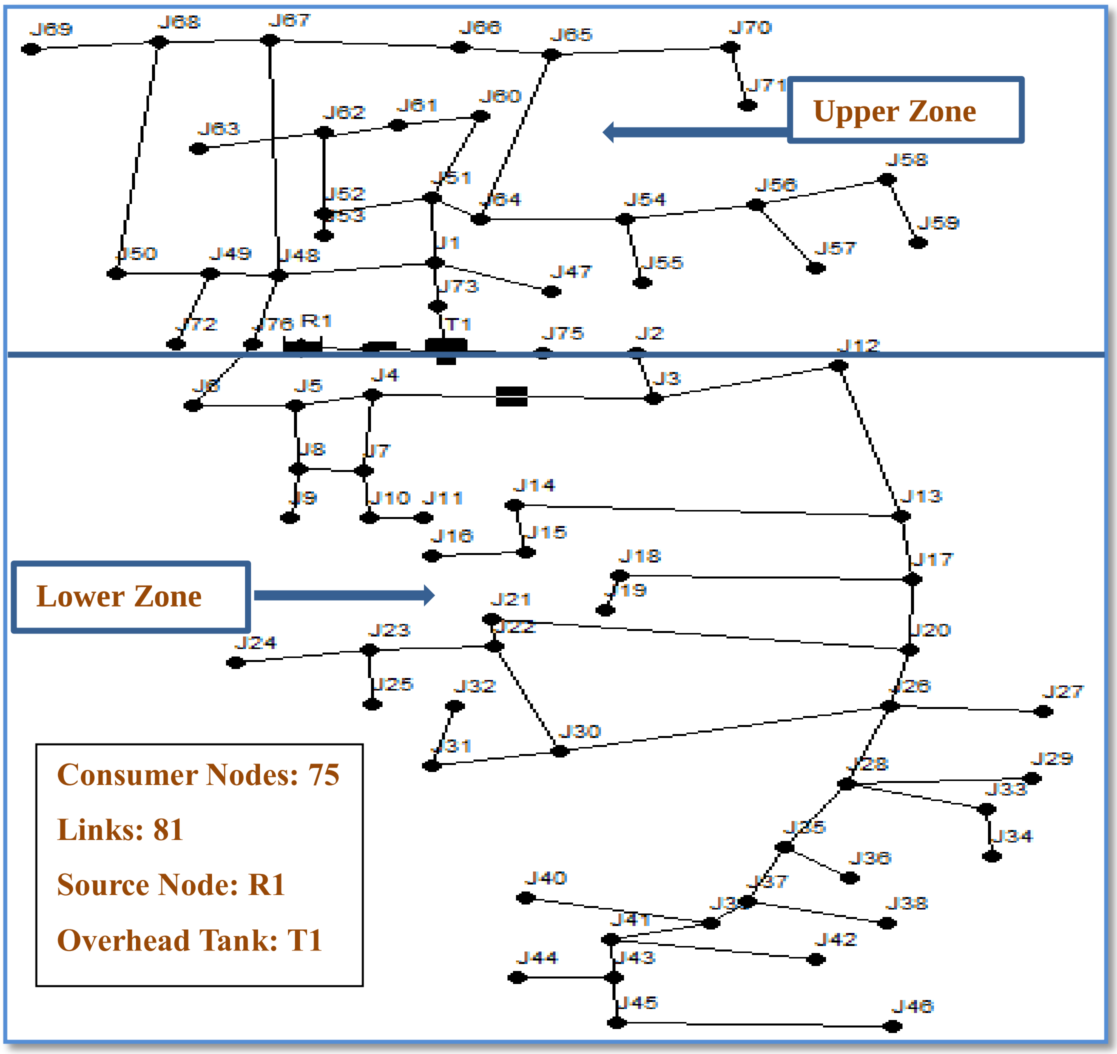


Fig. 4.18: Channi Drinking Water Distribution Network (Case Study 3)

Simulation is carried out for two scenarios of water supply for extended simulation for period of 10 days. Simulation is further extended for water quality modelling to check the effect of mode of water supply on residual chlorine concentration. The analysis of result is as under.

4.9.1 Simulation Results

Hydraulic Analysis: The resulting head in the tank is obtained as shown in Fig 4.19 for two scenario of water supply i.e. 24 X 7 water supply and intermittent water supply for last 24 hour cycle of extended period simulation of 10 days i.e. from 216 hour to 240 hour. The pumping rate is selected in such a way that there is no much variation in the water level in tank for both the scenario. Fig 4.20 and 4.21 represents the system flow balance for scenario 1 and 2 respectively for 216 to 240 hour. The least pressure is obtained at Junction 46, which is 14.69 m for 24 X 7 water supply where as it is 6.31 m for intermittent supply. Fig 4.22 a and 4.22 b represents the contour plot of pressure for the whole network at peak hour of 8 a.m. to 9 a.m. for scenario 1 and 2 respectively. It is observed from the contour plot that there is a wide variation in the pressure for intermittent supply as compared to 24 X 7 water supply.

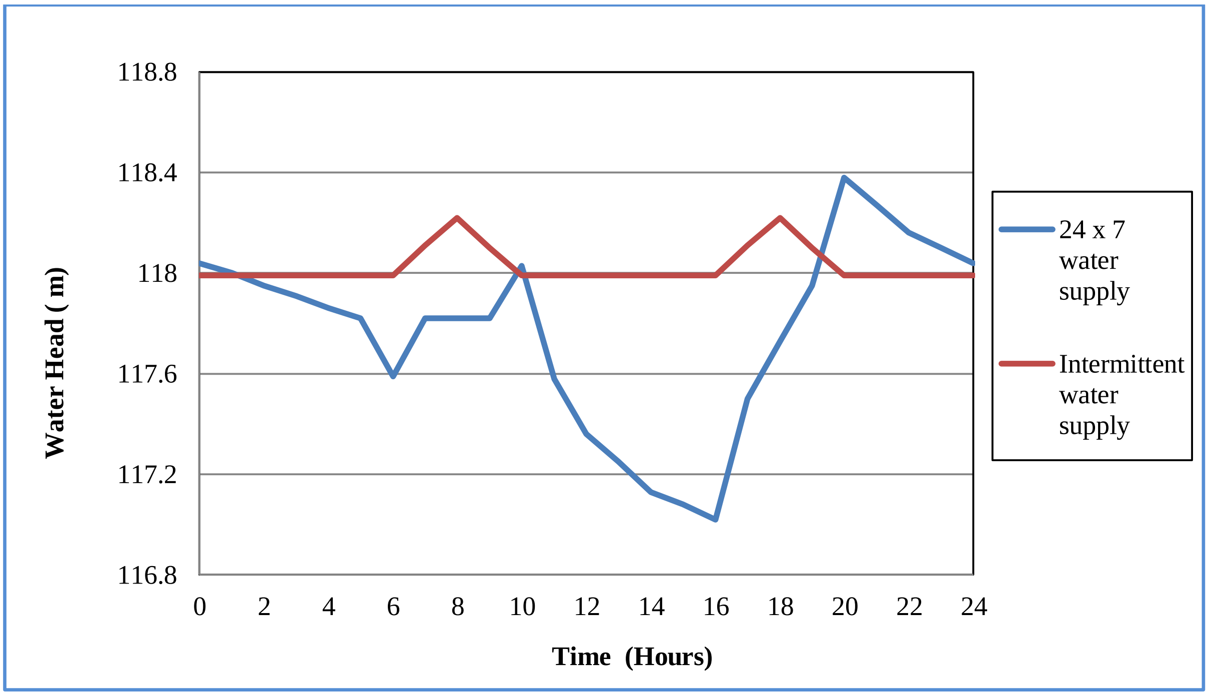


Fig. 4.19: Water Head in tank for scenario 1 and 2. (Case Study 3)

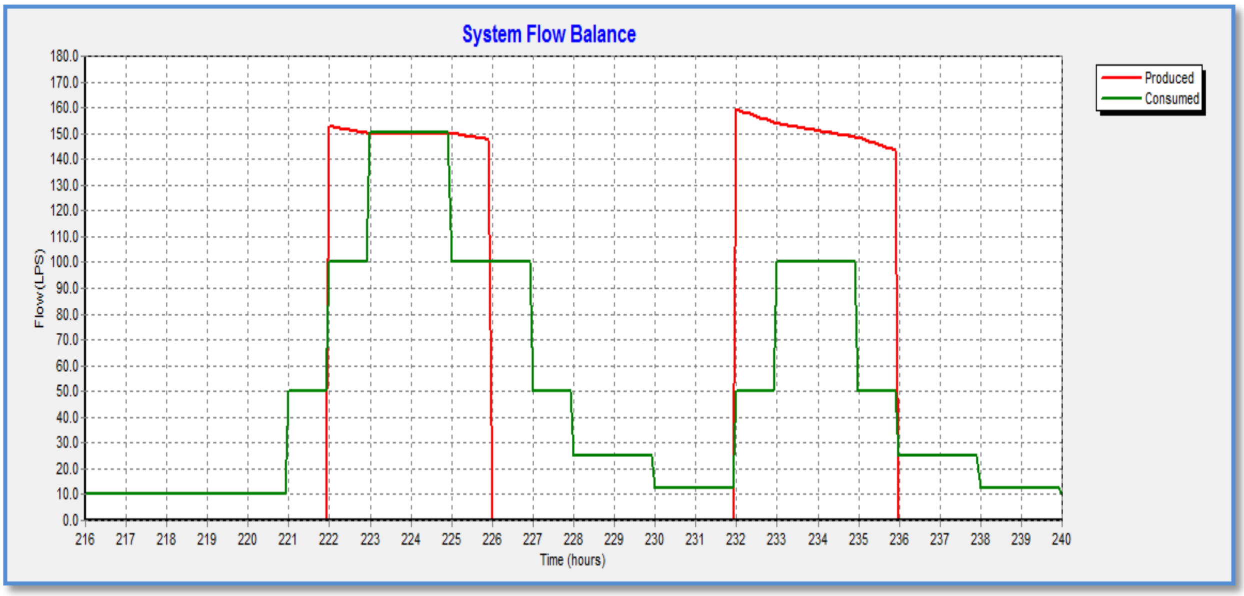


Fig. 4.20: System flow balance of scenario 1 for 24 X 7 water supply (Case study 3)

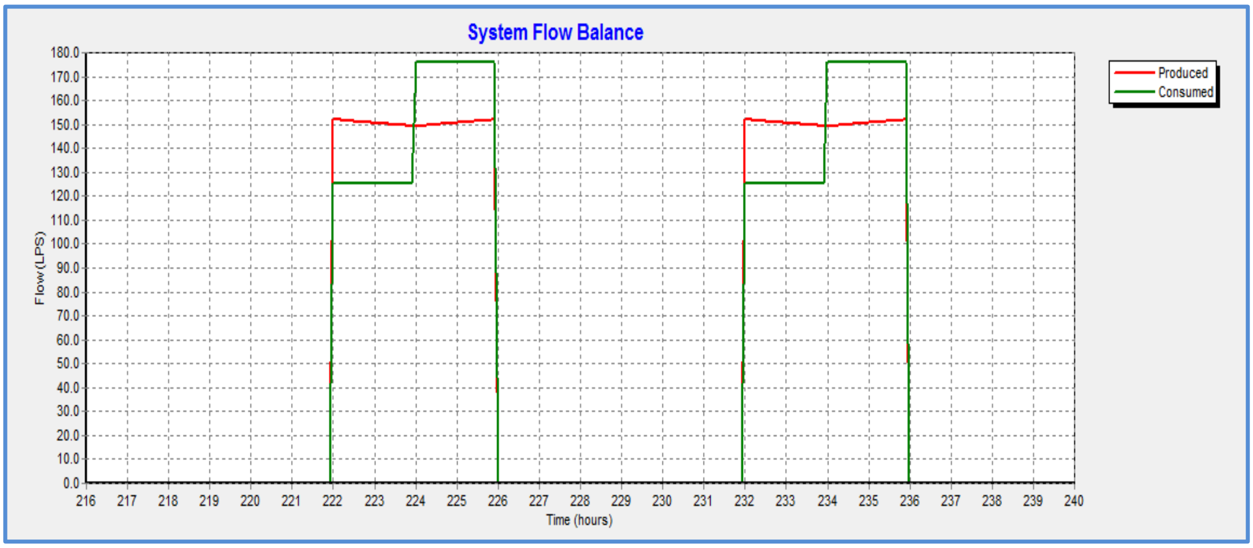


Fig. 4.21: System flow balance of scenario 2 for intermittent water supply of 4 hours (Case study 3)

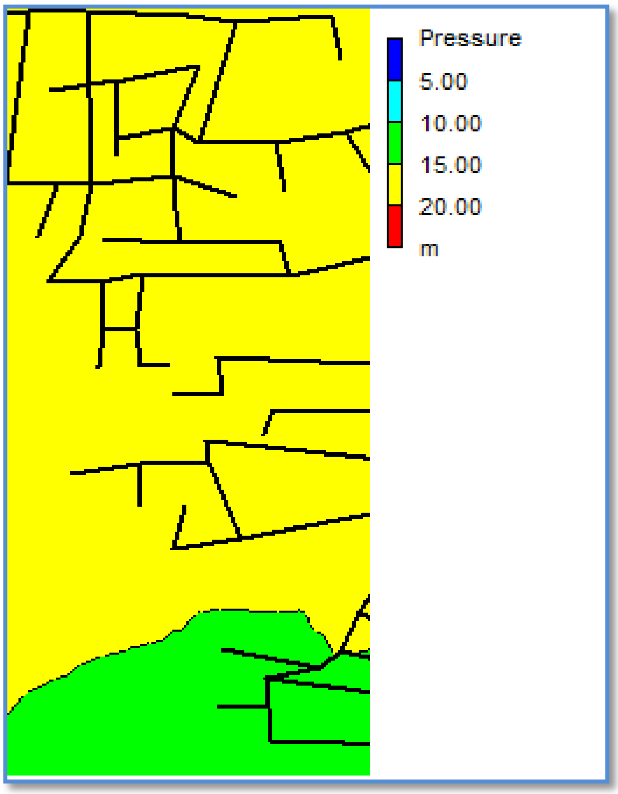
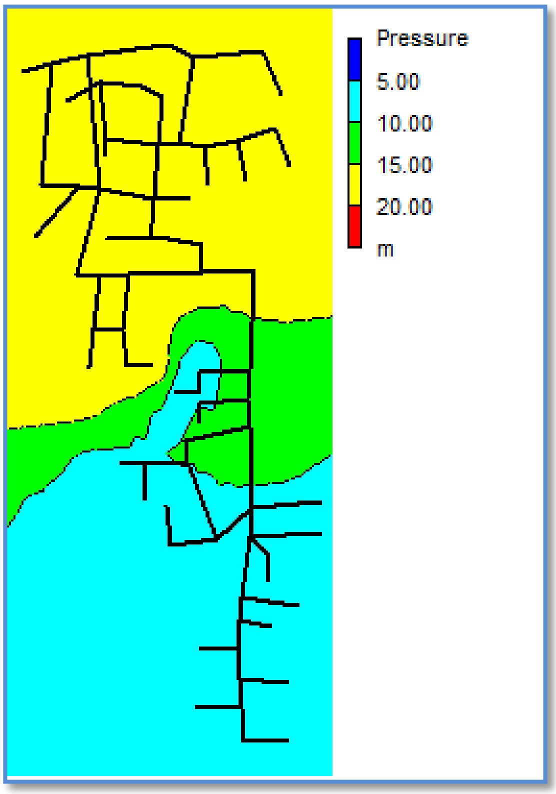


Fig 4.22 (a) Contour plot of pressure peak hour of 8 a.m. to 9 a.m. for scenario 1 (Case Study 3)



4. 22 (b) Contour plot of pressure peak hour of 8 a.m. to 9 a.m. for scenario 2 (Case Study 3)

Water Quality Analysis: Water quality simulation is carried out for two cases i.e. scenario 1 with 24 X 7 continuous water supply and scenario II for intermittent water supply for extended simulation for period of 10 days. The results are used to check the effect of mode of water supply on residual chlorine concentration at various locations of Drinking Water Distribution System.

To maintain 0.2 mg/L of residual chlorine up to the farthest node during peak hours needs more mass rate of chlorine is to be applied in case II i.e. 4700 mg/min as against 4000 mg/min in 24 X 7 water supply. Thus reduction of 14.89% in chlorine mass rate application is obtained in case of 24 X 7 water supply as compared to intermittent water supply. Tank concentration of residual chlorine is obtained as shown in Fig. 4.23 for scenario 1 and 2. It is observed that the chlorine concentration variation in tank is in the range of 0.33 mg/L to 0.42 mg/L for scenario 1 and 0.36 mg/L to 0.45 mg/L for scenario 2. The peak hour in water quality analysis for 24 X 7 water supply is taken as 224 and 225 hour (8 a.m. to 10 a.m.) as the demand is maximum during this period. The peak hour for intermittent water supply is taken as 222 hour (6 a.m.) , as starting point of application of chlorine is critical in intermittent supply as long residence time of chlorine will result in chlorine decay during non-supply hours. Fig. 4.24 and 4.25 represent the minimum, average and maximum residual chlorine concentration for the scenario I and scenario II respectively for all the nodes.

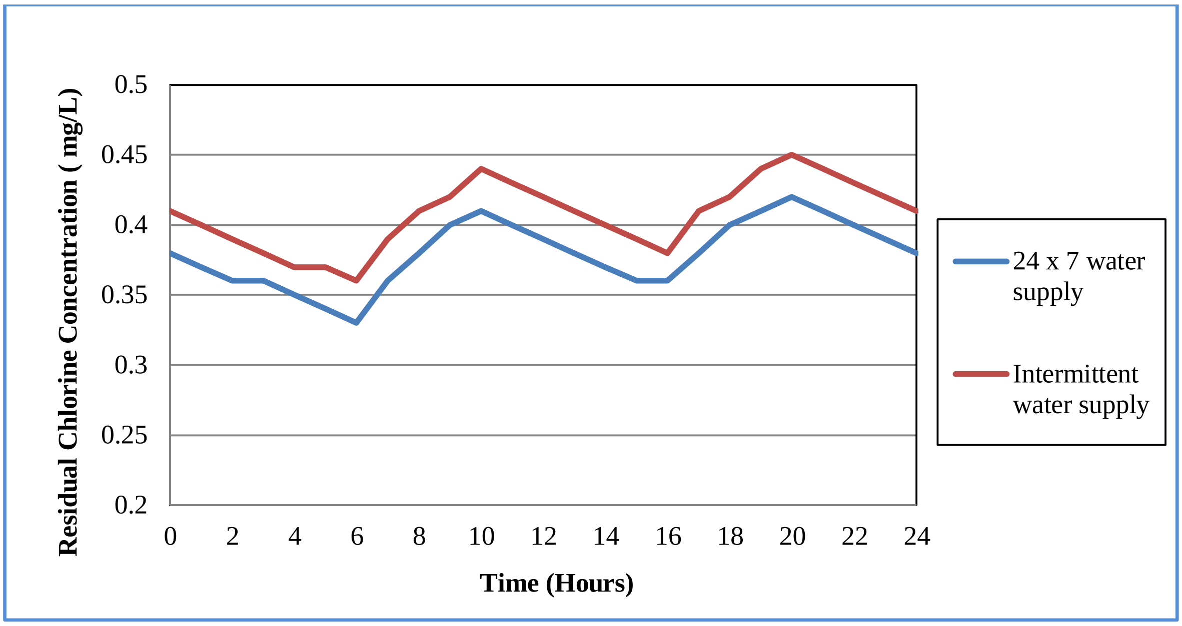


Fig. 4.23: Tank concentration of residual chlorine (Scenario 1 and 2) for Case Study 3.

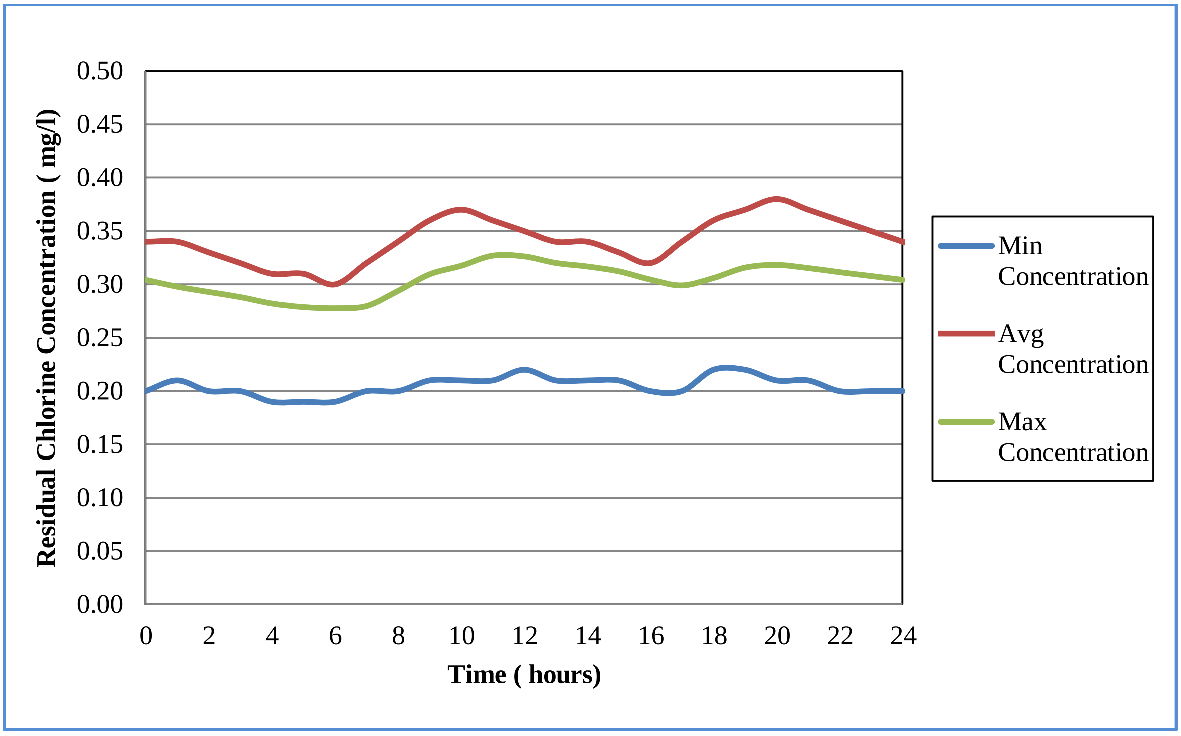


Fig. 4.24: Minimum, average and maximum concentration of residual chlorine (Scenario I) for Case Study 3.

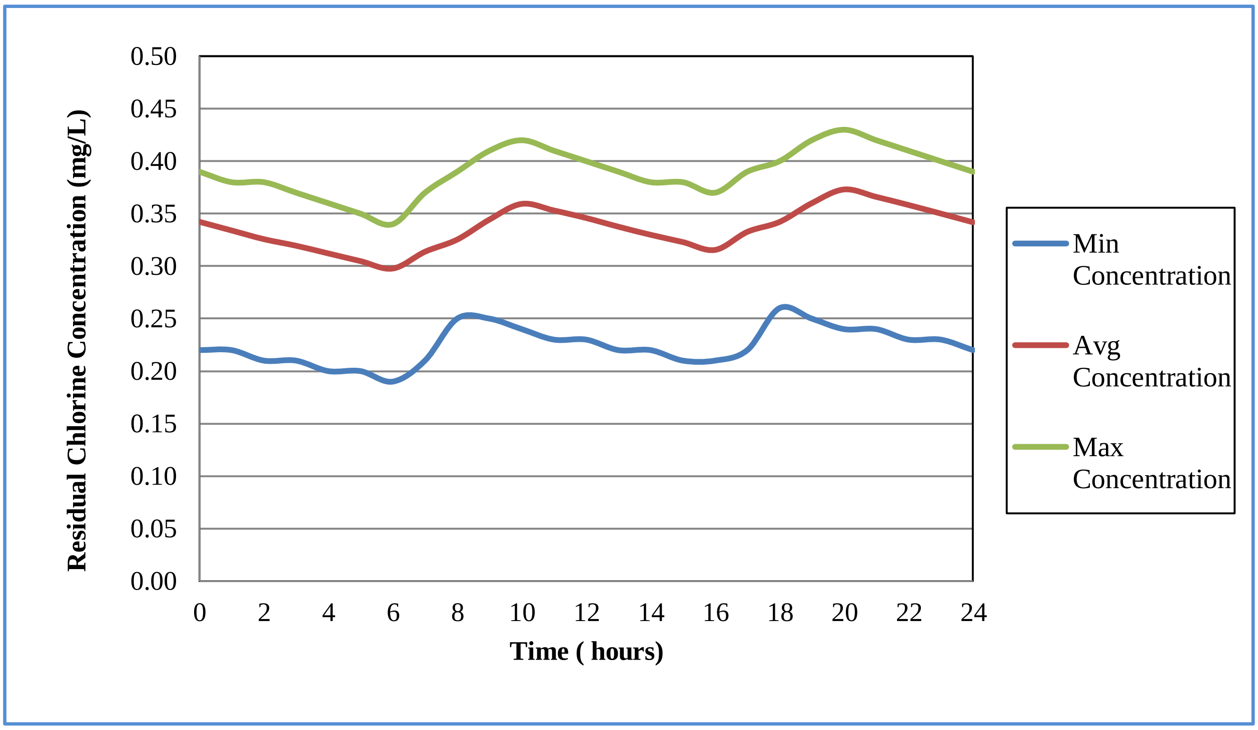


Fig. 4.25: Minimum, average and maximum concentration of residual chlorine (Scenario II) for Case study 3

Fig. 4.26 shows minimum residual chlorine concentration for selected nodes for peak hour of 222 hour (6 a.m. to 7 a.m.) for scenario 1 and 2. It is observed from critical nodes can be identified from simulation study which can be useful for the location of sensor placement for the critical nodes for monitoring of residual chlorine.

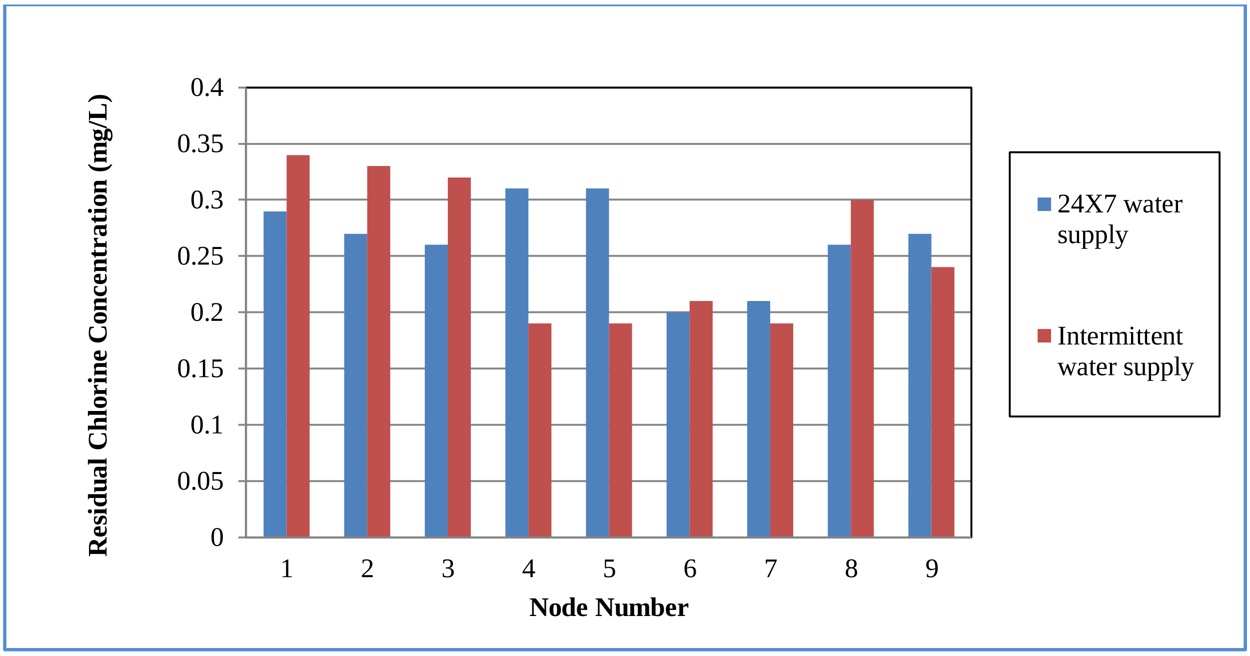


Fig. 4.26: Minimum residual chlorine concentration for selected nodes (6 a.m. to 7 a.m. for scenario 1 and 2) for Case Study 3

Observation of the Fig 4.25 shows that, for 24 X 7 water supply system for time duration between 4 hours to 6 hours the minimum concentration drops below minimum specified limit of 0.2 mg/L due to less flow conditions which may be critical from contamination point of view. Fig. 4.25 shows that for intermittent water supply the critical time from chlorine point of view is 6 hour as after stagnation the water supply will resume and maximum decay in residual chlorine would take place. The variation of residual chlorine concentration with respect to time for all the nodes is divided into 3 categories i.e. range having concentration greater than 0.35 mg/L , range of residual chlorine with concentration range of 0.2 to 0.35 mg/L and critical range having residual chlorine less than 0.2 mg/L, and as shown in Table 4.9 .

Table 4.9: Distribution of residual chlorine at different nodes (Case Study 3)

Time (Hour)	Number of Nodes with the range of residual chlorine (mg/L)					
	Scenario I			Scenario II		
	>0.35 mg/L	(0.2-0.35 mg/L)	Critical < 0.2 mg/L	>0.35 mg/L	(0.2-0.35 mg/L)	Critical < 0.2 mg/L
0	0	75	0	41	34	0
1	0	75	0	34	41	0
2	0	75	0	25	50	0
3	0	75	0	10	65	0
4	0	73	2	3	72	0
5	0	73	2	0	75	0
6	0	74	1	0	72	3
7	0	75	0	3	72	0
8	0	75	0	19	56	0
9	1	74	0	32	43	0
10	3	72	0	46	29	0
11	19	56	0	44	31	0
12	0	75	0	43	32	0
13	0	75	0	35	40	0
14	0	75	0	35	40	0
15	0	75	0	20	55	0
16	0	75	0	7	68	0
17	0	75	0	17	58	0
18	1	74	0	25	50	0
19	3	72	0	48	27	0
20	10	65	0	58	17	0
21	3	72	0	54	21	0
22	7	68	0	47	28	0
23	0	75	0	46	29	0
24	0	75	0	40	35	0

As seen from table 4.9, with 24 X 7 water supply system most of the nodes are coming under the range of 0.2 mg/L to 0.35 mg/L residual chlorine which indicate the uniform distribution of chlorine at all the nodes in different direction as compared to intermittent water supply. The excess chlorine may result in harmful disinfection by products as observed in intermittent water supply. The critical nodes are observed during low flow conditions in 24 X 7 water supply against the starting period of application of chlorine in intermittent water supply. The critical conditions may be avoided by slightly increasing the mass rate of chlorine considering the critical time period for both the cases.

4.9.2 Discussions

Channi Drinking Water Distribution Network which is proposed for 24 X 7 continuous water supply is simulated for extended period of 10 days with the help of EPANET software to check the effect of mode of water supply on various hydraulic parameters and on residual chlorine concentration. The main observations drawn from the hydraulic and water quality Modelling analysis are:

(1) More variations in water level of tank are observed in case of 24 X 7 water supply as compared to intermittent water supply due to fluctuation of demand in 24 hr supply.

(2) Uniform pressure is achieved in case of 24 X 7 as compared to intermittent supply which indicates that 24 X 7 water supply system is more effective in maintaining uniform pressure at various locations than intermittent supply.

(3) As higher mass rate of chlorine is applied to maintain 0.2 mg/L residual chlorine at all the locations during peak hours for intermittent water supply the tank concentration of residual chlorine for intermittent supply is slightly more than 24 X 7 water supply.

(4) Higher range of minimum, average and maximum residual chlorine concentration is observed at various locations in intermittent water supply as compared to 24 X 7 water supply. This is due to higher mass rate of application of chlorine at source in case Scenario II

(5) To maintain 0.2 mg/L of residual chlorine within the network up to the farthest node, more mass rate of chlorine is required to be applied in Scenario II which shows reduction of 14.89% in application of chlorine mass rate for Scenario I.

(6) Most of the nodes in Scenario I are coming under range of residual chlorine of 0.2 to 0.35 mg/L which indicates the more uniform distribution of chlorine as compared to Scenario II in which most of the nodes falls under the category of excess range of chlorine having residual chlorine concentration greater than 0.35 mg/L.

(7) Minimum flow condition in the pipe for 24 X 7 continuous water supply may result in less velocity of flow which increases the travelling time of the chlorine give rise to critical condition from residual chlorine point of view which can be improved by increasing the dose at source by using water quality Modelling software like EPANET.

(8) The critical time period for intermittent water supply is the time elapsed between two supply hours as the chlorine decay would take place during stagnation of water during non-supply hours. Simulation study can be useful to identify the critical nodes and location for sensor placement for monitoring of residual chlorine for such critical nodes.

(9) More uniform distribution of chlorine is achieved in 24 X 7 water supply system against intermittent supply.

Thus, for effective management of pressure and residual chlorine at all the locations of distribution network, 24 X 7 water supply system proves to be better option than intermittent water supply for any drinking water distribution systems. But in India most of the cities have intermittent water supply. To manage the minimum residual chlorine in intermittent water supply is a crucial task. Therefore to check the effect of booster stations on residual chlorine concentration the case study was carried for North Harni DWDS with intermittent water supply of one hour.

4.10 CASE STUDY 4: Evaluating Booster Chlorination Strategies for North Harni Drinking Water Distribution System Using EPANET

The proposed North Harni Drinking Water Distribution System covering part of northern area of Vadodara is selected for the case study of water quality modelling. The water distribution network for the study area is shown in Fig. 4.27. 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. Initially the capacity of the USR and OHT was designed to supply the flow of 4062 m3/h. Recently the capacity of newly constructed USR is 9.88 ML and OHT is 2.47 ML making total water storage capacity as 12.35 ML. The network has 74 consumer nodes, three booster nodes (A, B and C), one source node R_1, one pumping station, one storage tank (Node 1), and 87 links. Consumer nodes (nodes 2-75) represent water demand locations for nearby areas while booster nodes (nodes A to C) represent locations of inline disinfectant addition. The demand at various nodes is considered to be steady state and satisfied by supplying the water in one hour a day. The link data includes connectivity, length, diameter, and roughness information. 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 critical locations (Booster stations A, B and C) 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. Table 4.10 represents the data of total mass rate of chlorine for different time period at booster locations (A to C) for both the cases. The mass injection time of chlorine is 2 hour that repeats every 24 hours. The disinfectant decay rate constant k_b is assumed to be 0.55 d^{-1} for the all the links while wall decay coefficient is assumed to be negligible.

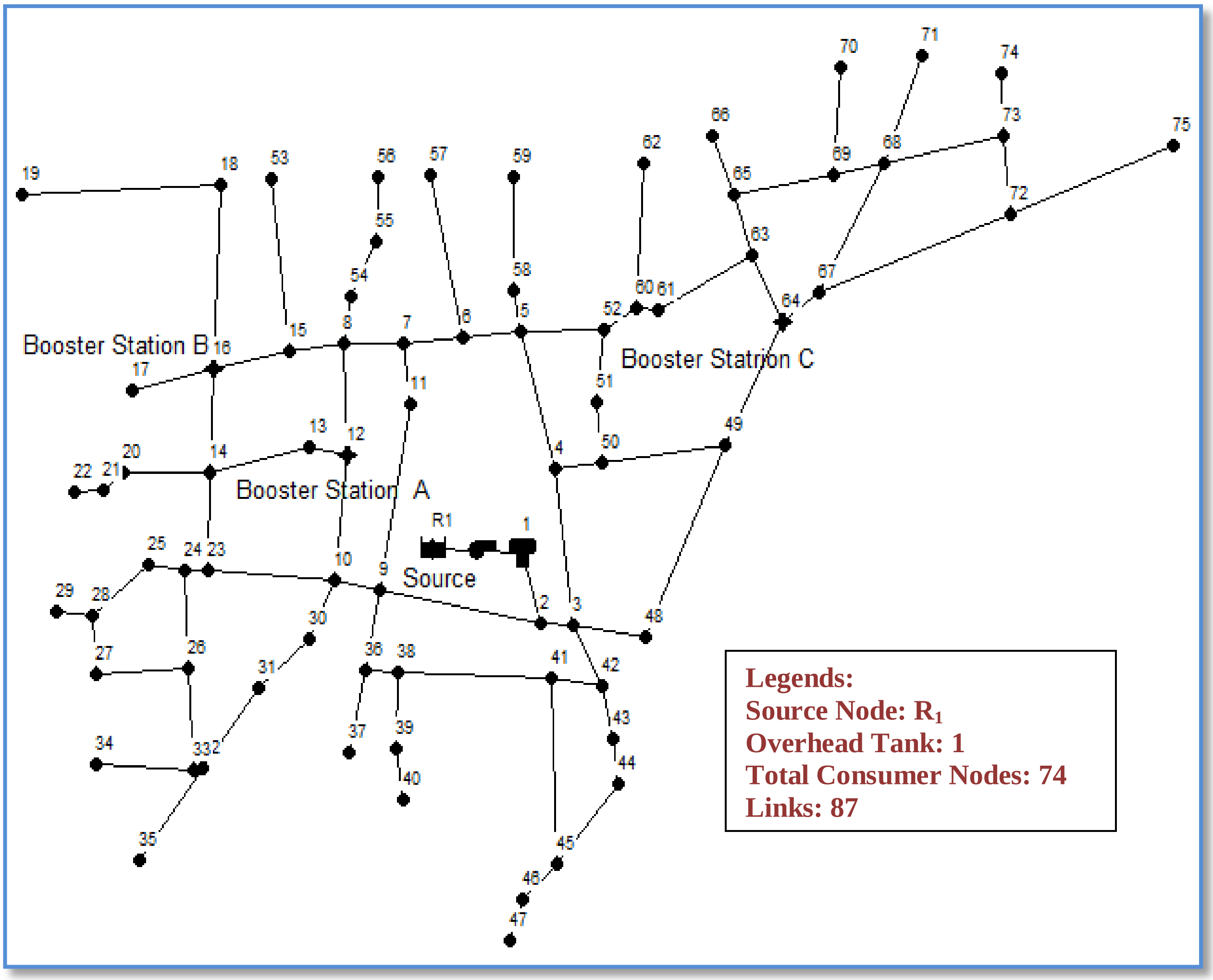


Fig. 4.27: North Harni Distribution Network (Case Study 4)

Table 4.10: Injection rates of chlorine for booster stations (Case Study 4)

Cases	Total Mass rate (g/d)	Booster Period (Hours)	Source &Booster Locations/Injection rate (mg/min)			
			Source	A	B	C
Case I (Only source chlorination)	2240	1	34000	-	-	-
Case II (Source +Booster Chlorination)	1662 (18.52 % reduction in total mass rate of chlorine	1	26200	650	250	600

4.10.1 Simulation Results

Simulation is carried out for extended period with a cycle of one hour of pumping in a day and the pressure available at the end of 10 days simulation is computed for each demand junctions as shown in Table 4.11.

Simulation is further extended for water quality modelling for two different cases under two different chlorination strategies. The results shown are for last 24 hour of EPS of 10 days (i.e. 216 to 240 hours). The resulting tank concentration of chlorine for case I and II is obtained as shown in Fig 4.28. It is observed that the concentration suddenly increases in the tank after starting of pump. After one hour, the chlorination concentration gradually reduces. The simulation results for the minimum, average and maximum chlorine concentration at each consumer node for case I as shown in the Fig 4.29. It is observed that concentration remains on higher side Case 1 in each time step. Consequently the average chlorine concentration is found to be between 0.26 to 0.45 mg/L for the Case 1. The residual chlorine concentration obtained at each node is utilized to check the critical location of a node from chlorine concentration point of view. The critical locations having less chlorine residual for conventional chlorination method were used to select the location of Booster station. The simulation results are obtained for Case 2 and compared with Case 1. The initial and maximum concentration at Tank in Case 2 is lower than that in Case 1 because of lower rate of injection at source in Case 2 (Fig. 4.34). Using booster chlorination strategy adopted in Case 2, the average concentration was brought down within 0.20 mg/L and 0.36 mg/L (Fig. 4.39**).** However, in both the cases the minimum chlorine concentration is maintained at 0.2 mg/L.

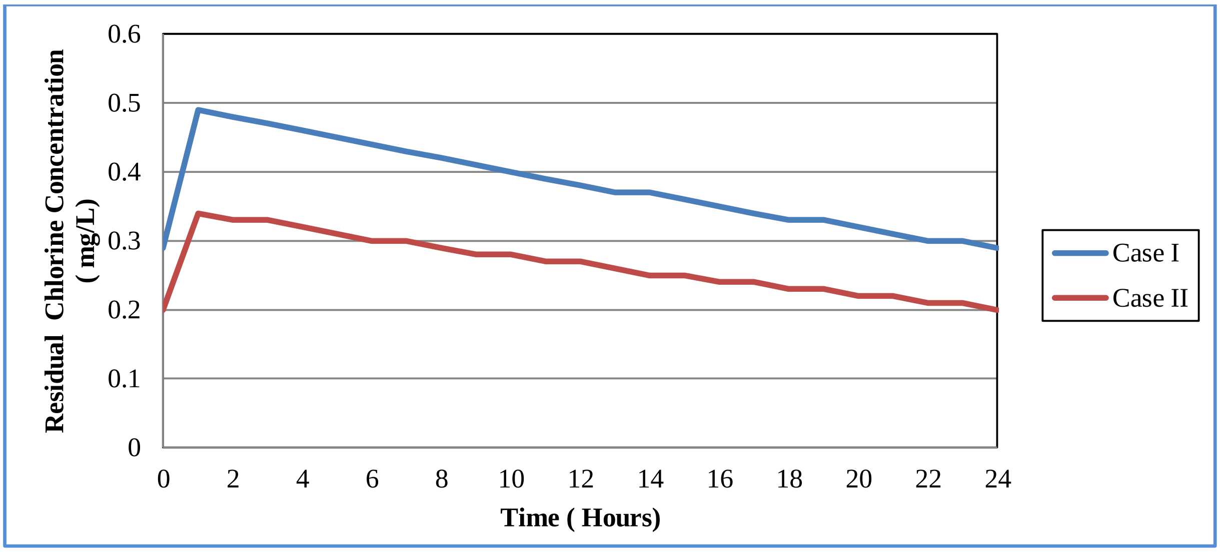


Fig. 4.28: Tank concentration of residual chlorine (Case I and II) for Case Study 4

Table 4.11: Pressure at all nodes after 10 days extended period simulation (Case Study 4)

Node ID	Pressure (m)	Node ID	Pressure (m)	Node ID	Pressure (m)	Node ID	Pressure (m)	Node ID	Pressure (m)	Node ID	Pressure (m)	Node ID	Pressure (m)
Junc 2	19.18	Junc 13	6.38	Junc 24	7.8	Junc 35	5.73	Junc 46	12.24	Junc 57	9.54	Junc 68	4.92
Junc 3	17.19	Junc 14	6.01	Junc 25	6.93	Junc 36	9.36	Junc 47	12.17	Junc 58	11.45	Junc 69	4.88
Junc 4	13.48	Junc 15	6.26	Junc 26	5.76	Junc 37	8.85	Junc 48	16.69	Junc 59	11.26	Junc 70	4.47
Junc 5	11.81	Junc 16	5.75	Junc 27	5.55	Junc 38	9.21	Junc 49	11.68	Junc 60	9.79	Junc 71	4.81
Junc 6	9.97	Junc 17	5.48	Junc 28	5.86	Junc 39	7.37	Junc 50	11.9	Junc 61	9.58	Junc 72	5.88
Junc 7	8.72	Junc 18	4.13	Junc 29	5.25	Junc 40	6.6	Junc 51	10.6	Junc 62	8.54	Junc 73	4.56
Junc 8	7.1	Junc 19	3.24	Junc 30	9.72	Junc 41	12.83	Junc 52	10.38	Junc 63	8.31	Junc 74	4.39
Junc 9	11.88	Junc 20	4.33	Junc 31	8.45	Junc 42	14.31	Junc 53	5.58	Junc 64	8.82	Junc 75	5.51
Junc 10	10.85	Junc 21	4.17	Junc 32	6.66	Junc 43	13.88	Junc 54	5.41	Junc 65	7.23		
Junc 11	8.96	Junc 22	4.08	Junc 33	6.06	Junc 44	13.62	Junc 55	4.57	Junc 66	7.06		
Junc 12	7.38	Junc 23	7.98	Junc 34	3.83	Junc 45	12.39	Junc 56	4.37	Junc 67	7.42		

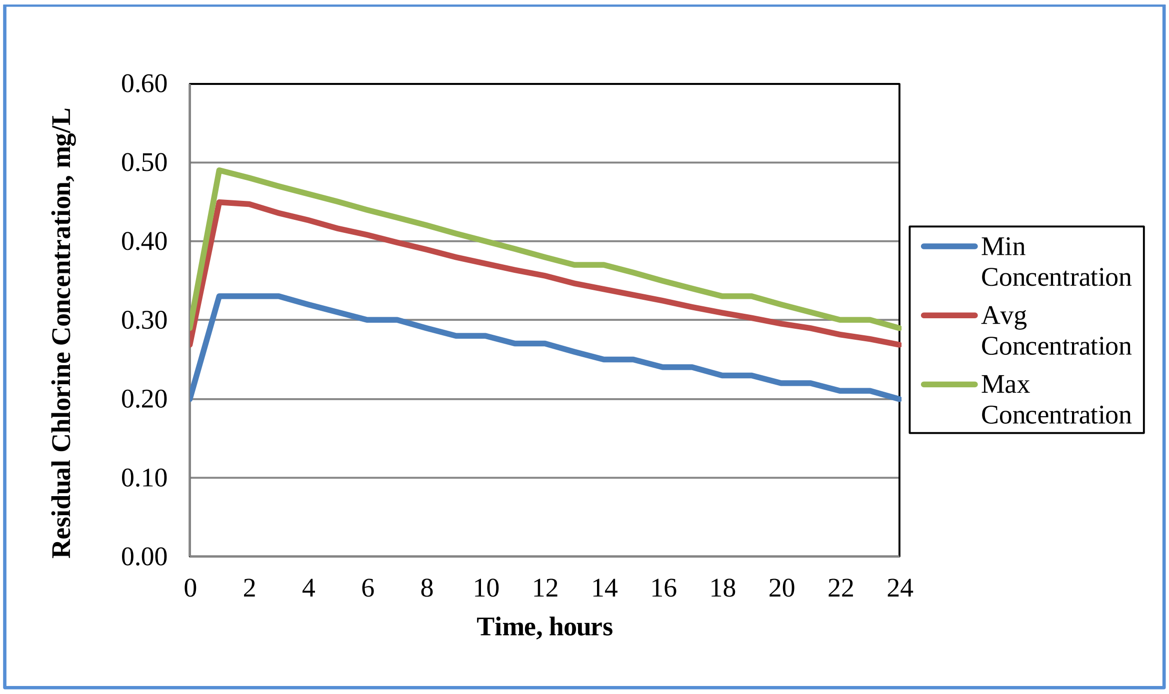


Fig. 4.29: Minimum, average and maximum concentration of residual chlorine (Case I) for Case Study 4

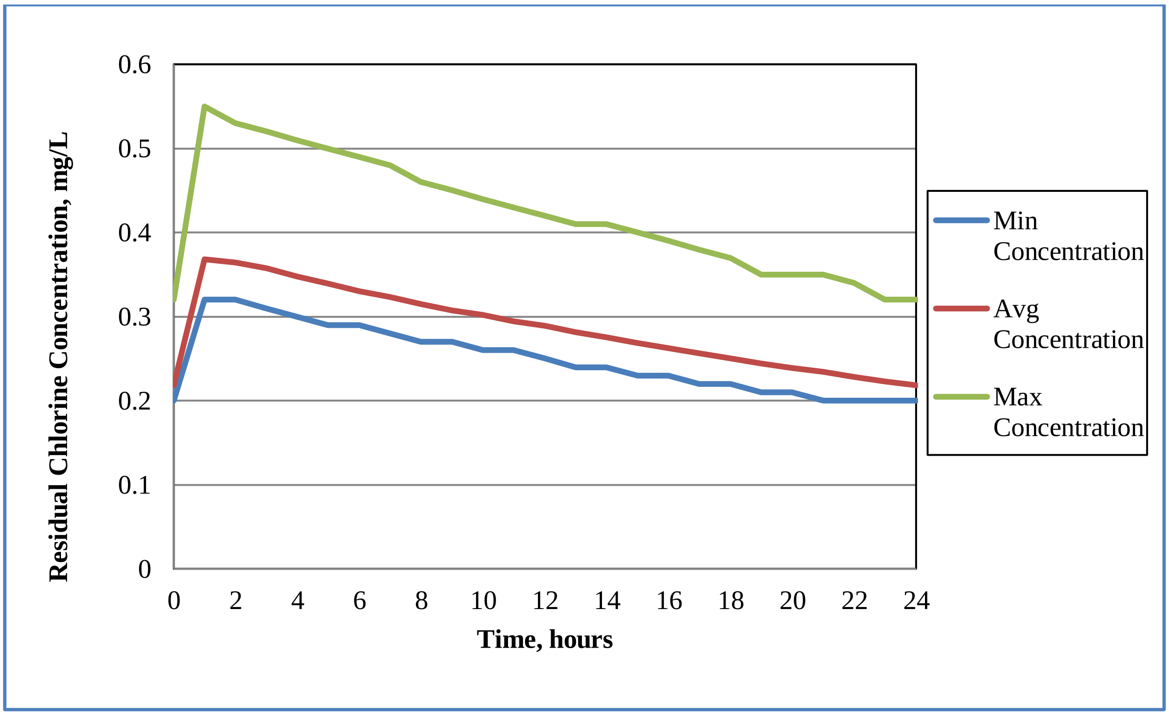


Fig. 4.30: Minimum, average and maximum concentration of residual chlorine (Case II) for Case Study 4

The average concentration with standard deviation for case I and II are shown in Fig. 4.31 and Fig. 4.32 respectively. The variation of chlorine concentration at each node for both the cases is shown in Fig. 4.33.

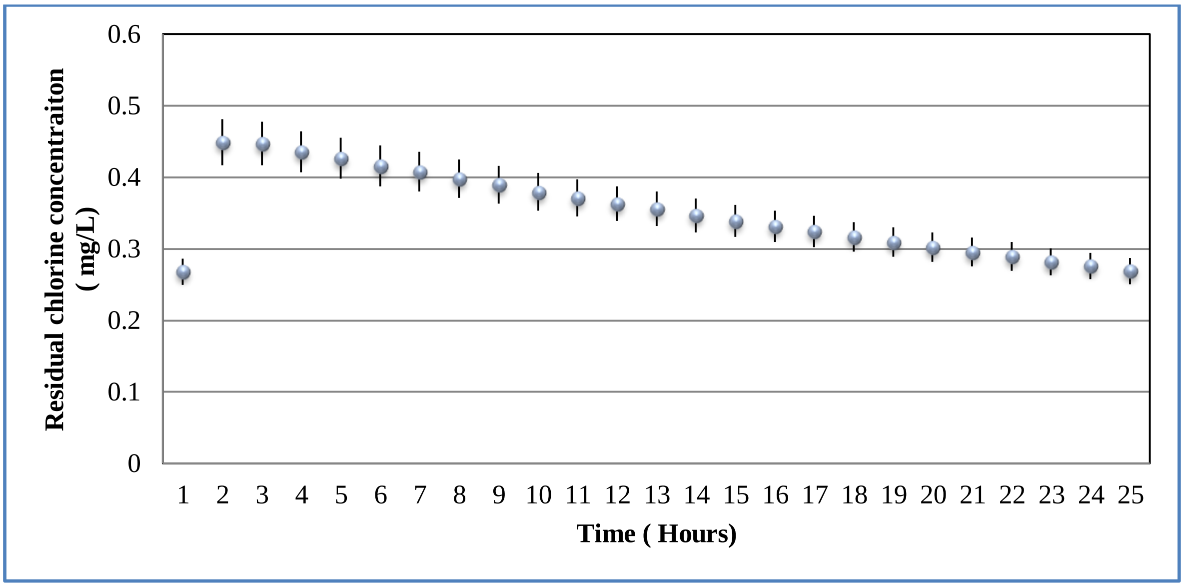


Fig. 4.31: Average residual chlorine concentration and standard deviation for all nodes (Case I) for Case Study 4

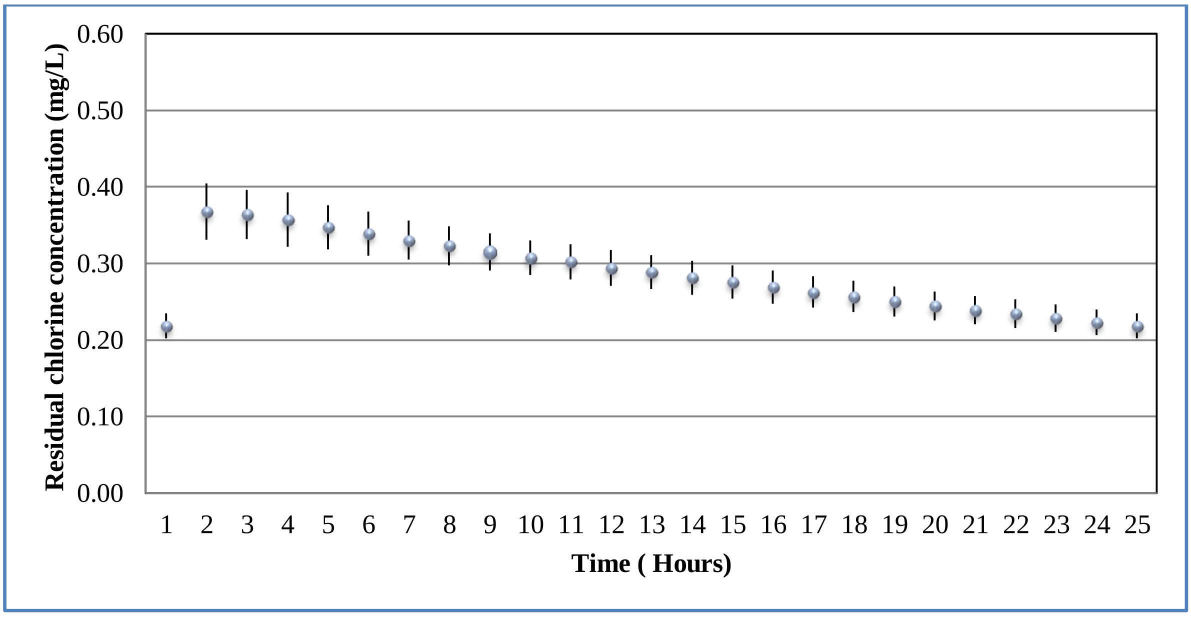


Fig. 4.32: Average concentration and standard deviation for all nodes (Case II) for Case Study 4

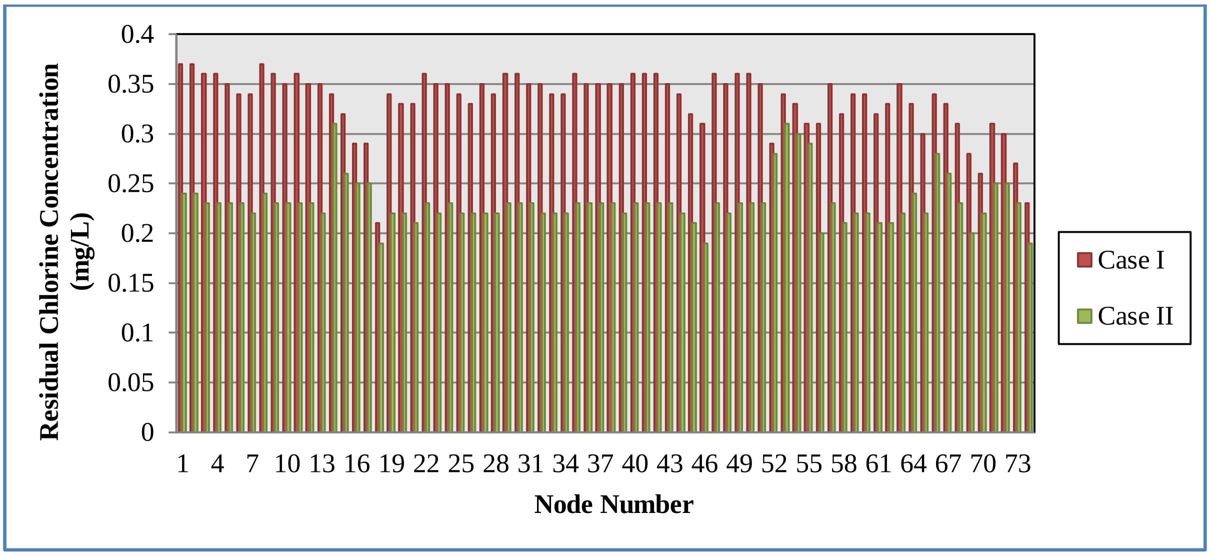


Fig 4.33: Variation of residual chlorine concentration at each node (Case I and Case II) for Case Study 4

4.10.2 Discussions

It is observed from Fig. 4.29 to 4.33 that the applications of booster chlorination at selected locations along with source chlorination enable reduction of chlorine application at source; consequently, the average chlorine concentration in the network is reduced. In case I, total mass rate of application is 34000 mg/min while case II needs 26200 mg/min at source, 650 mg/min, 250 mg/min and 600 mg/min at three booster locations, which give total reduction of 18.52 %. Also the statistical data shows that the average concentration is 0.35 mg/L and 0.28 mg/L as well as standard deviation of 0.061 and 0.053 for case I and Case II respectively The reduced concentration of chlorine reduces the exposure of chlorine to organic and inorganic matter in water and indirectly reduced the harmful disinfection by products (DBP) while maintains the minimum concentration. Booster chlorination strategy provides effective chlorine management by minimising cost and at the same time prevents the problems due to excess chlorination. Selection of booster chlorination stations using trial and error method is tedious and not giving exact solution. To avoid such trial and error method different optimization techniques can be used to maintain uniform residual chlorine and to minimize the total chlorine mass rate.

For selecting the best chlorine application strategy for the existing network the model is run for the two cases i.e. conventional chlorination at source only and, source and booster chlorination. The main conclusions drawn from the water quality modelling analysis are:

(1) Tank concentration and residual chlorine concentration show gradual decay during non-injection period.

(2) The conventional method of chlorination i.e. near the source needs higher mass rate of chlorine to maintain the minimum concentration of 0.2 mg/L at most of the consumer nodes.

(3) Application of Booster chlorination at selected locations along with source chlorination enable reduction of chlorine application at source. Consequently, the average chlorine concentration in the network is considerably reduced.

(4) Total reduction of 18.52 % is obtained in total mass rate of chlorine applied by Booster chlorination at different stations. The reduction in the chlorine mass rate will result in overall cost reduction of the chlorine.

(5) The reduced concentration of chlorine reduces the exposure of chlorine to organic and inorganic matter in water and indirectly to formation of harmful disinfection by products (DBP) while simultaneously maintains the minimum concentration.

(6) Water quality simulations provide effective chlorine management strategy by minimising cost and at the same time prevent the problems due to excess chlorination.

(7) Simulation of residual chlorine also helps to find the critical locations for sample collection and sensor placement for the monitoring of chlorine in the drinking water distribution systems.

Thus, Booster chlorination strategy may prove to be better option than conventional method of source chlorination for drinking water distribution systems. Further to check the feasibility of selecting booster stations for the large network of Manjalpur is selected

4.11 CASE STUDY 5: Alternative Chlorine Management Strategy Using Booster Chlorination for Manjalpur Drinking Water Distribution System

The existing water distribution system network of Manjalpur, covering part of southern area of Vadodara is selected for the case study of water quality modelling. The distribution network, supply the drinking water to the total command area of 6.57 km^2, the population of 43,857 persons. The USR is having capacity of 7.2 ML and OHT can store 1.8 ML making the total water storage capacity of 9 ML. The water distribution network for the study area is shown in Fig. 4.34. The network modelled has 153 consumer nodes, 5 booster nodes (A, B ,C, D , E), 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 A to E) represent locations of inline disinfectant addition. The demand at various nodes is considered to be steady state and satisfied by supplying the water in one hour a day. The link data includes connectivity, length, diameter, and roughness information.

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 critical locations (Booster stations A, B, C, D, E) 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. Table 4.12 represents the data of total mass rate of chlorine for different time period at Booster Locations (A to E) for both the cases. The mass injection time of chlorine is 1 hour that repeats every 24 hours.

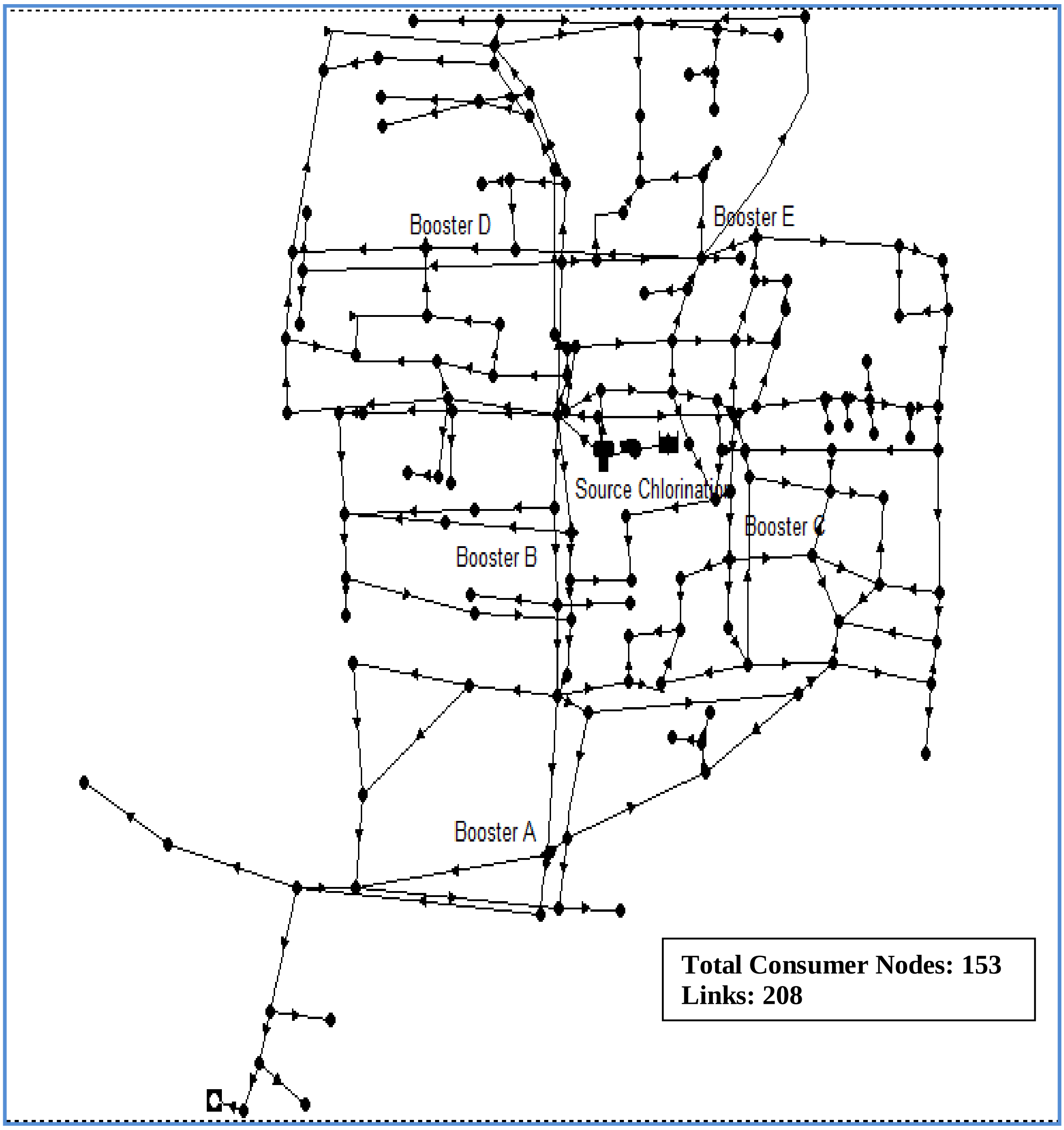


Fig. 4.34: Manjalpur Distribution Network (Case Study 5)

Table 4.12: Injection rates of chlorine for booster stations (Case Study 5)

Cases	Total Mass rate (mg/min)	Booster Period (Hours)	Source & Booster Locations/Injection rate (mg/min)					
			Source	A	B	C	D	E
Case I (Only source chlorination)	5671	1	94520	-	-	-	-	-
Case II (Source + Booster Chlorination)	3842 (32.25% reduction in total mass rate of chlorine)	1	55136	5300	1000	1000	400	1200

4.11.1 Simulation Results

Simulation is carried out for extended period with a cycle of one hour of pumping in a day and the elevation of HGL or heads are computed for each demand junctions. The residual pressure obtained at the each node is obtained in the range of 11 to 33m.

Simulation is further extended for water quality modelling for two different cases under two different chlorination strategies for extended period of 10 days simulation. The resulting tank concentration of residual chlorine is obtained as shown in Fig. 4.35 for case I and case II. It is observed that the chlorine concentration is high in case I due to conventional strategy of supplying high concentration of 0.6 mg/L (94520 mg/min) at the source to maintain the minimum residual chlorine concentration of 0.2 mg/L at all the nodes.

Though the high concentration is applied at the source node, it fails to maintain the minimum residual concentration of 0.2 mg/L at some of the farthest point. In case of Booster Chlorination approach the tank concentration is low due to less amount of chlorine application at the source i.e. 0.35 mg/L along with the application of chlorine at Booster stations (A to E). The simulation results for the minimum, average and maximum chlorine concentration at each consumer node for one hour is obtained for case I as shown in the Fig. 4.36. It is observed that concentration remains on higher side for the maximum and average concentration due to high dose of chlorine at source alone while the locations farther from source in Case 1 receives less residual chlorine even at the application rate of 0.6 mg/L (94520 mg/min) at source for one hour.

The residual chlorine concentration obtained at each node is utilized to check the critical location of a node from chlorine concentration point of view. The critical locations having less chlorine residual for conventional chlorination method were used to select the location of Booster station. The simulation results are obtained for Case 2 and compared with Case 1.

The initial and maximum concentration at Tank in Case 2 is lower than that in Case 1 because of lower rate of injection at source in Case 2 (Fig. 4.37). Using booster chlorination strategy adopted in Case 2, the average concentration was brought down within the desirable range of residual chlorine i.e. 0.2 mg/L However, in case II, the minimum chlorine concentration is maintained at 0.2 mg/L after one hour while it fails to maintain the minimum required chlorine in case of conventional chlorination at some of the farthest point. Fig. 4.38 shows the contour plot for the concentration of residual chlorine for the case I and Fig. 4.39 shows for case II. Fig. 4.38 and 4.39 indicate that there is uniform distribution of average concentration of chlorine obtained in case of Booster application as compared to uneven distribution of chlorine in case of only source chlorination.

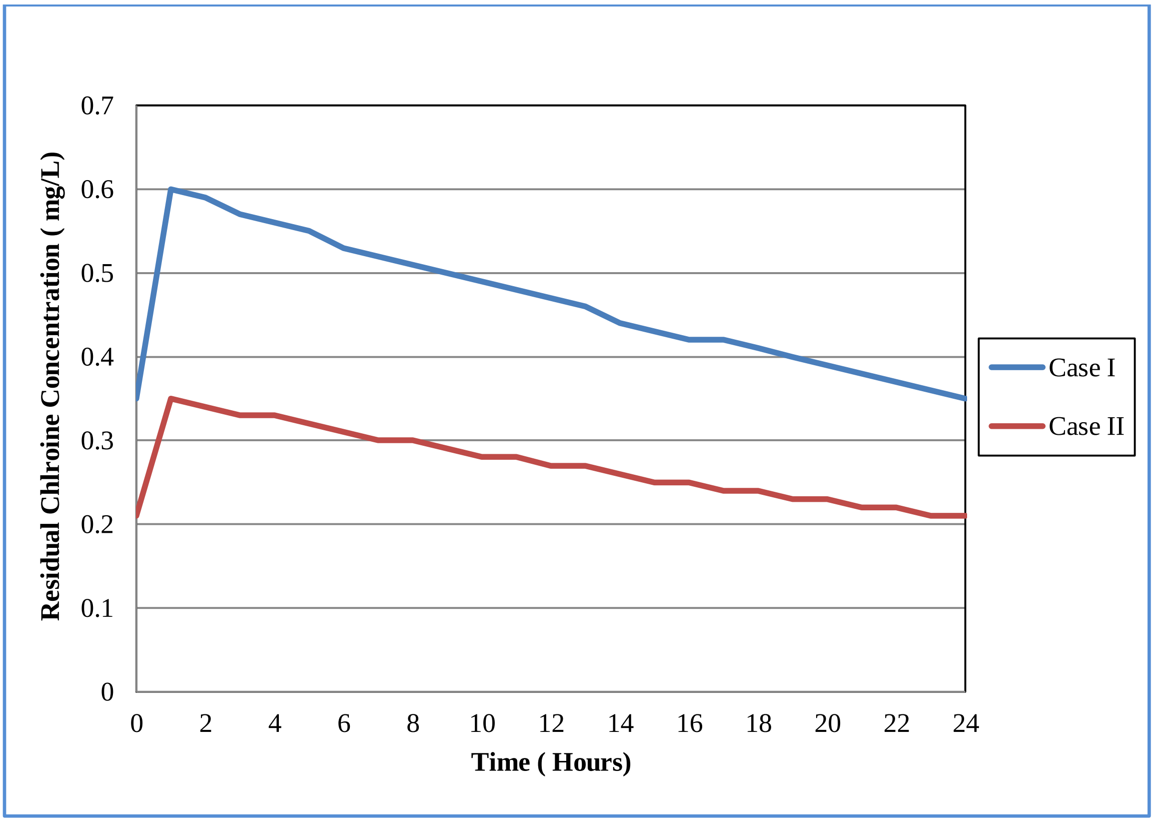


Fig. 4.35: Tank concentration of residual chlorine (Case I and Case II) for Case Study 5

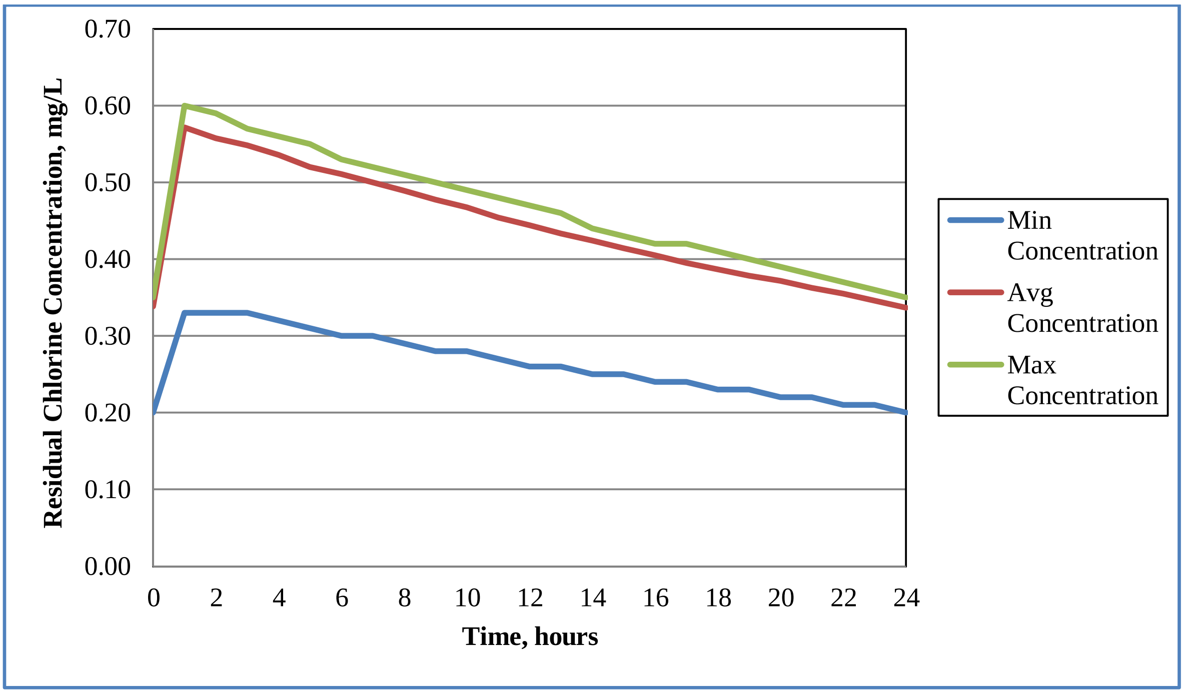


Fig. 4.36: Minimum, average and maximum concentration of residual chlorine (Case I) for Case Study 5

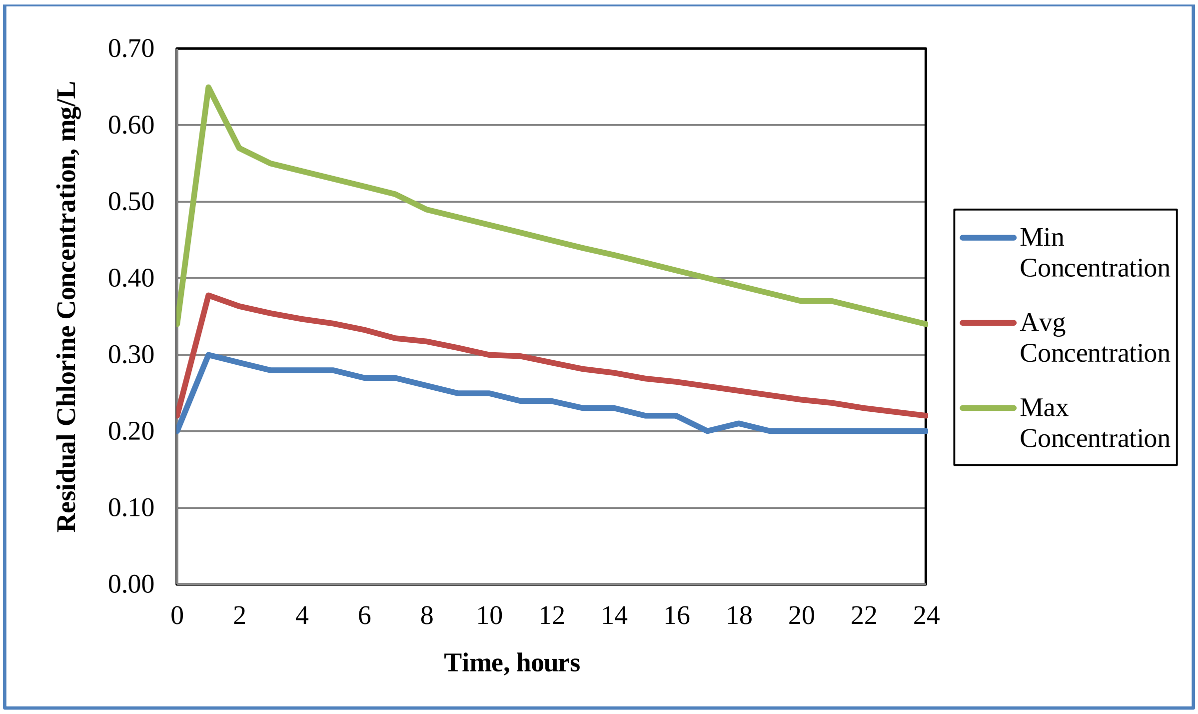


Fig. 4.37: Minimum, average and maximum concentration of residual chlorine (Case II) for Case Study 5

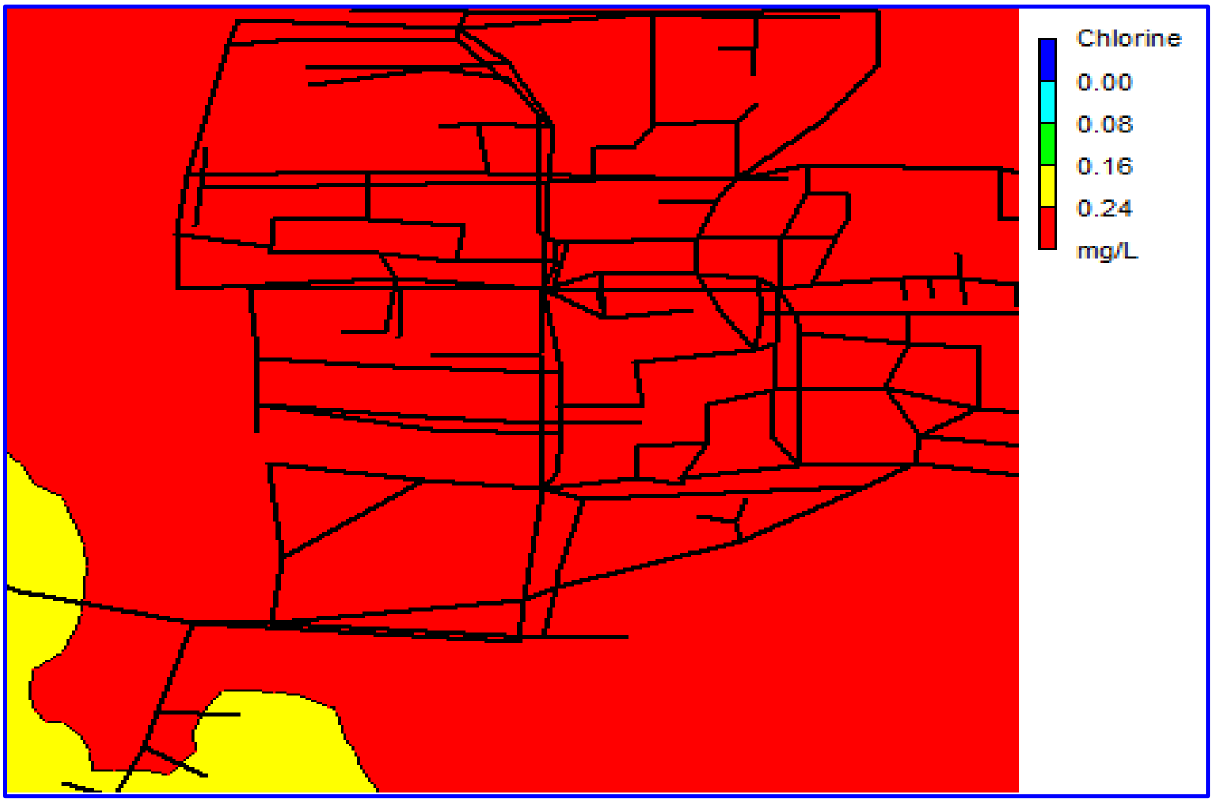


Fig. 4.38: Contour Plot of Residual Chlorine (Case I) for Case Study 5

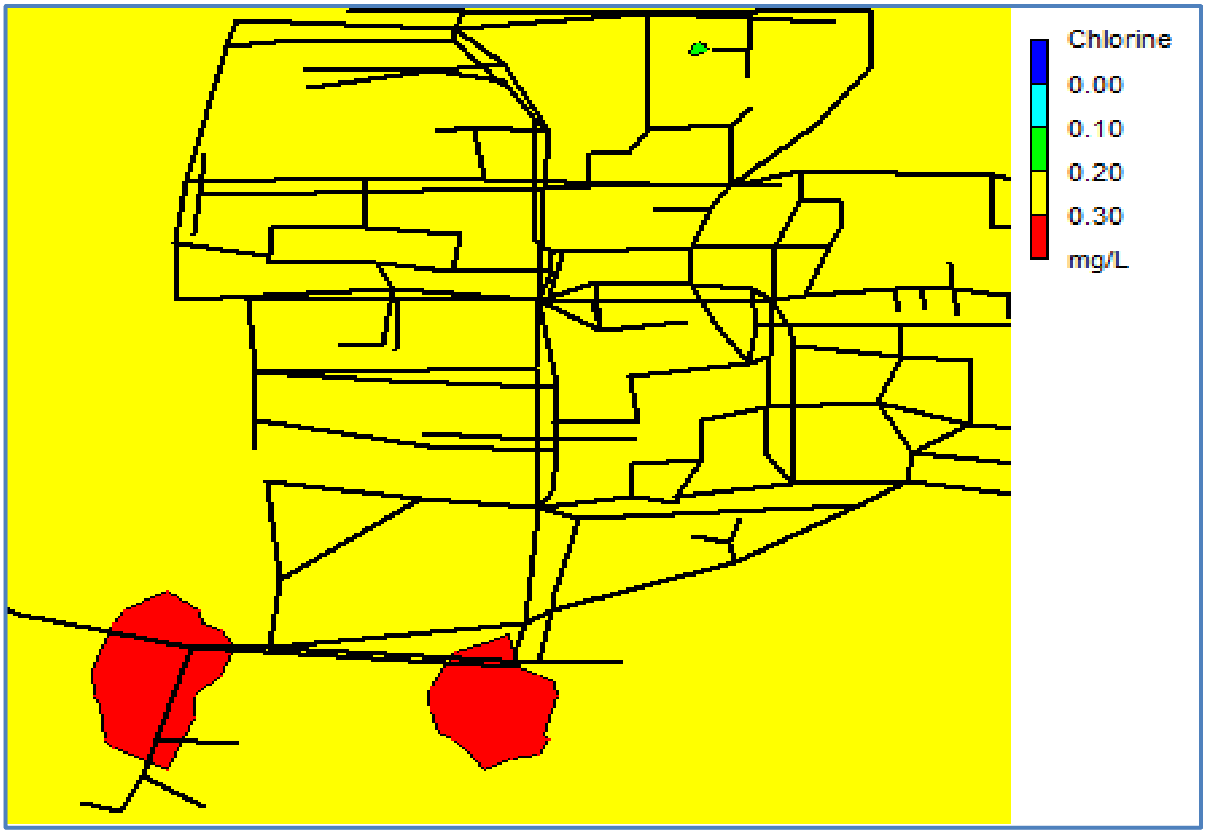


Fig. 4.39: Contour Plot of Residual Chlorine (Case II) for Case Study 5

4.11.2 Discussions

For effective management of the chlorine dose the two chlorine application strategies for the existing network the model are run i.e. conventional chlorination at source only and, source and booster chlorination. The main observations drawn from the water quality modelling analysis are:

(1) Tank concentration and residual chlorine concentration show gradual decay during non-injection period. The tank concentration in case I is higher than case II due to higher dose of application of chlorine at source as compared to case II

(2) The conventional chlorination method of chlorination i.e. near the source needs higher mass rate of chlorine i.e. 5671 g/d fails to maintain the minimum concentration of 0.2 mg/L at some of the farthest consumer nodes while the area nearer to the source are affected by the high residual chlorine which may result in harmful disinfection by products (DBP).

(3) Application of Booster chlorination at selected locations (A to E) along with source chlorination enable reduction of chlorine application at source. Consequently, the total mass rate including booster stations comes to 3842 g/d which reduces the average concentration of the chlorine concentration in the area nearer to the source while maintaining the minimum residual chlorine of 0.2 mg/L at the farthest point.

(4) Total reduction of 32.25 % is obtained in total mass rate of chlorine applied by Booster chlorination at different stations. It results in overall cost reduction of the chlorine.

(5) The reduced concentration of chlorine reduces the exposure of chlorine to organic and inorganic matter in water and indirectly to formation of harmful disinfection by products (DBP) while simultaneously maintains the minimum concentration.

(6) Booster chlorination helps in maintaining the even distribution of chlorine at all the nodes as compared to source chlorination only. The overall standard deviation obtained for case I is 0.084 while for case II is 0.051.

(7) Booster Chlorination provides effective chlorine management strategy by supplying uniform distribution of chlorine, minimizing cost and at the same time prevents the problems due to excess chlorination. The simulation of residual chlorine also helps to find the critical locations for sample collection and sensor placement for the monitoring of chlorine in the drinking water distribution systems.

Thus, for effective management of chlorine the booster chlorination strategy may prove to be better option than conventional method of source chlorination alone for drinking water distribution systems.

4.12. Inferences

The hydraulic and water quality models are developed for the different distribution networks and the real field problems of Vadodara city using EPANET software. The EPANET simulation model is applied to check the effect of modes of water supply (Continuous / 24 X 7 water supply or intermittent water supply), traveling time and chlorine application strategy (i.e. Source /Booster Chlorination)on residual chlorine. Case study of Channi DWDS suggests that for effective management of chlorine 24 X 7 water supply is better option than intermittent water supply. Case study of North Harni DWDS shows that the travelling time of the chlorine has major impact on the residual chlorine concentration for the farthest node in intermittent water supply. The more reduction in the chlorine mass rate is observed for large network such as Manjalpur DWDS for booster chlorination as compared to small DWDS network. Simulation of residual chlorine also helps to find the critical locations for sample collection and sensor placement for the monitoring of chlorine in the drinking water distribution systems. Booster chlorination strategy provides effective chlorine management by minimising cost and at the same time prevents the problems due to excess chlorination. Instead of trial and error method for selection of booster stations, the use of optimization methods can help to select the optimal location and scheduling of mass rate of chlorine for DWDS network. Therefore, the coupling of the simulation models with optimization technique is tried to develop the decision support models for managing chlorine disinfection for DWDS using booster chlorination stations.