Chapter 3

Development of Hydraulic and Water Quality Models

3.1 Introduction

Earlier the water distribution computer modelling, simulations were primarily used to solve design problems. As models were fairly cumbersome to use, operators preferred measuring pressures and flows in the field rather than working with a complicated computer program. But, the recent advances in software technology have made models more powerful and easier to use which results in more acceptances of computer simulations as a tool to aid the operation personnel in keeping the distribution system running smoothly. Using a model, the operator can simulate what is occurring at any location in the distribution system under a full range of possible conditions also to gather such a large amount of data in the field would be cost-prohibitive. A well calibrated model enables the operator to leverage relatively few field observations into a complete picture of what is occurring in the distribution system. Recent advancements in computation and instrumentation technologies have led to the availability of advanced tools that are already beginning to improve a utility's ability to effectively manage water quality in distribution systems. These computational advancements have led to the development of software models that can simulate the behaviour of distribution system networks. Models can be used to solve on-going problems, analyse proposed operational changes, and prepare for unusual events. By comparing model results with field operations, the operator can determine the causes of problems in the system and formulate solutions that will work correctly the first time, instead of resorting to trial-and-error changes in the actual system). The ease and speed provided by models can give the engineer the ability to explore many alternatives under a wide range of conditions, resulting in more cost-effective and robust designs. A model that has been assembled properly is an asset to the water utility and should therefore be maintained so that it is ready to be put to valuable use. The costs of modelling are incurred mostly in model development, and the benefits are realized later in the form of quicker calculations and better decisions (Walski 2003). A well calibrated water distribution model can be used to address some operational problems such as

- Solutions to low pressure problems and low fire flow
- Calculation of energy efficiency and optimum pump scheduling.
- Water distribution system flushing
- Sizing distribution system metering
- Investigation of contaminants events

- Leakage control
- Water quality investigations
- Maintaining an adequate disinfectant residual
- Impact of operations on water quality.

Realizing the benefits of simulation models in the field of water distribution system, nowadays water distribution system models have become widely accepted within the water utility industry as a mechanism for simulating the hydraulic and water quality behaviour in water distribution system networks. Current water distribution modelling software is powerful, sophisticated and user-friendly. The modelling research conducted by the USEPA has helped many drinking water utilities throughout the world alleviate public health threats due to the deterioration of water quality in drinking water networks. It helped provide a basic understanding as to how water quality can deteriorate due to the construction, design and operating philosophies associated with drinking water distribution systems. It has played a major role in the development and application of hydraulic/ water quality modelling in the United States and throughout the world (Clark 2015). The usability of these models was greatly improved in the 1990s with the introduction of the public domain EPANET model (Rossman 1994, 2000) and other windows-based commercial water distribution system models (USEPA 2005). The modelling research conducted by the USEPA has helped many drinking water utilities throughout the world alleviate public health threats due to the deterioration of water quality in drinking water networks. (Clark, 2015).

In the present study the EPANET modelling software is used to carry out the hydraulic and water quality modelling of DWDS.

3.1.1 Introduction to EPANET

Water distribution system models such as EPANET 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. EPANET was developed in 1993 with the functions of modelling chlorine decay and THM formation. (Rossman 1994).It is a freely available computer program that performs extended period simulation of hydraulic and water quality behaviour within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves and storage tanks or reservoirs. 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 help assess alternative management strategies for improving water quality throughout a system.

These can include:

- Plan and improve a system's hydraulic performance.
- Pipe, pump and valve placement and sizing.
- Fire flow analysis.
- Maintain and improve the quality of water delivered to consumers
- Study disinfectant loss and by-product formation.
- Altering source utilization within multi-source systems,
- Modifying pumping and tank filling/emptying schedules to reduce water age,
- Utilizing booster disinfection stations at key locations to maintain target residuals

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 either nodes or links depending on the specific software package. Fig 3.1 illustrates a simple link-node representation of a water distribution system.

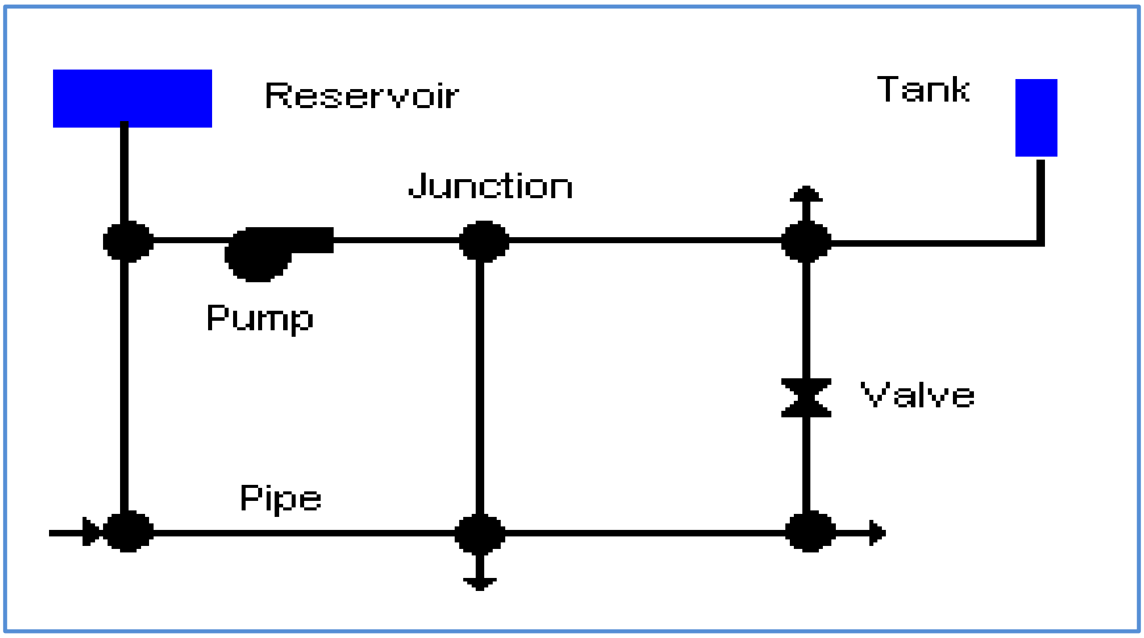

Fig 3.1: Simple link-node representation of a water distribution system (Source: Rossman, 2000).

In EPANET, the hydraulic head lost by water flowing in a pipe due to friction with the pipe walls can be computed using one of three different formulas i.e. Hazen-Williams formula, Darcy-Weisbach formula and Chezy-Manning formula. The solution for heads and flows at a particular point in time involves solving simultaneously the conservation of flow equation for each junction and the head loss relationship across each link in the network. This process, known as “hydraulically balancing” the network, requires using an iterative technique to solve the nonlinear equations involved. EPANET employs the "Gradient Algorithm" for this purpose

The governing equations for EPANET's water quality solver are based on the principles of conservation of mass coupled with reaction kinetics. EPANET effectively uses first order chlorine decay for prediction of residual chlorine in drinking water distribution system. It uses a Lagrangian time-based approach to track the fate of discrete parcels of water as they move along pipes and mix together at junctions between fixed-length time steps.

To understand the inherent calculation principles of all the hydraulic and water quality parameters simple simulation models are formulated to find out the hydraulic parameters like pressure and head and residual chlorine concentration at each nodes for conventional chlorination and booster chlorination.

3.2 General Formulation for Hydraulic Model

A sample network of simple drinking water distribution system (DWDS) is developed for the development of formula for the prediction of pressure at various nodes using Darcy Wieshbach head loss equation. The results of hydraulic parameters obtained using formula are compared with the results of EPANET software for the same Network. Fig 3.2 shows the sample network used for development of equations.

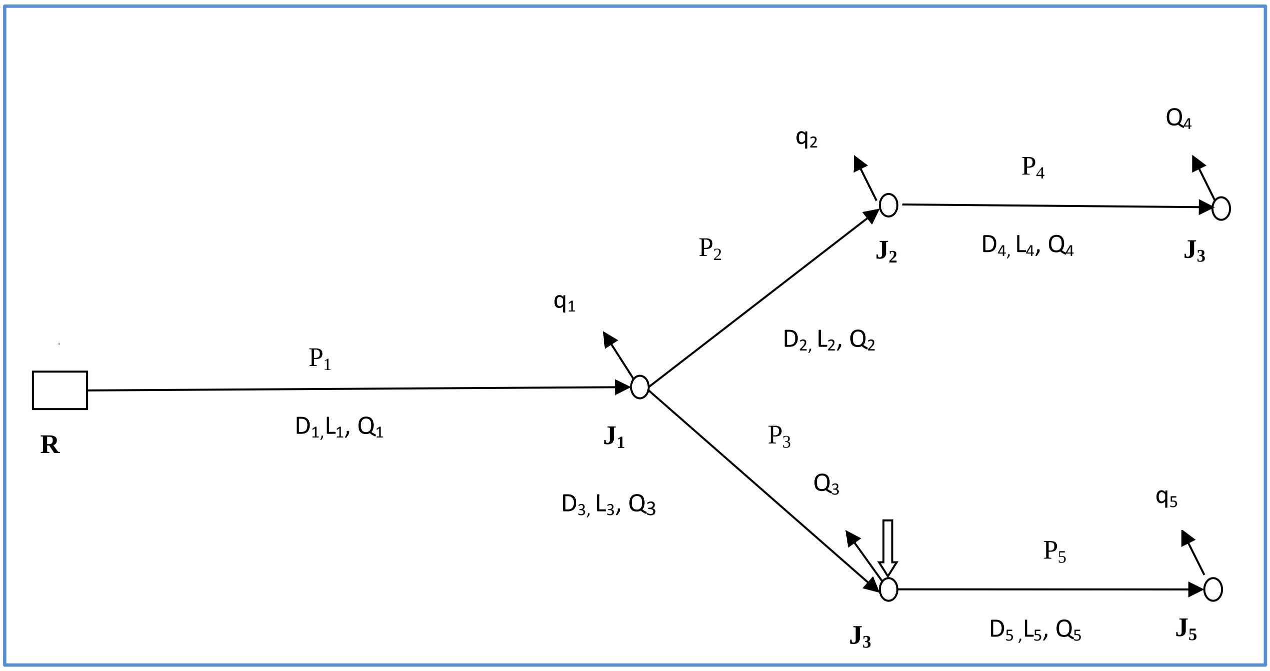

Fig 3.2: Sample network for calculation of hydraulic parameters at each node (Example 1).

The sample network consists of a source reservoir (e.g., a treatment plant or clear water reservoir) from which water is supplied into a two-loop pipe network. The ID labels for the various components are shown in the Fig. 3.2. The characteristics of nodes in the network and the properties of the pipes are shown in Table 3.1.

Following notations are used to denote the various components of distribution network in Fig. 3.2,

R= source

J_1,J_2,J_3,J_4,J_5 = junction Node 1,2,3,4,5 respectively.

P_1, P_2, P_3, P_4, P_5 = pipe 1,2,3,4,5 respectively.

D_1,D_2,D_3,D_4,D_5 = diameter of Pipe P_1, P_2, P_3, P_4, P_5 respectively, m

L_1,L_2,L_3,L_4,L_5 = length of Pipe P_1, P_2, P_3, P_4, P_5 respectively, m

q_1, q_2, q_3, q_4,q_5 = demand at node 1,2,3,4,5 respectively, m^3/h

Q_1,Q_2,Q_3,Q_4,Q_5 = flow in Pipe P_1, P_2, P_3, P_4, P_5 respectively, m^3/h

V_1,V_2,V_3,V_4,V_5 = velocity of flow in Pipe P_1, P_2, P_3, P_4, P_5 respectively, m/s

The properties of each node and link is presented in the Table 3.1

Table 3.1: Sample network node and link properties (Example 1)

Node Notation	Elevation (m)	Demand (m^3/h)	Pipe Notation	Diameter (mm)	Length (m)	Roughness Ɛ, (mm)
R	130	00	--	--	--	--
J_1	100	12	P_1	300	8000	0.26
J_2	100	14	P_2	200	4000	0.26
J_3	100	14	P_3	200	5000	0.26
J_4	100	26	P_4	150	9000	0.26
J_5	100	26	P_5	150	8000	0.26

To find out the various hydraulic parameters such as head and pressure at each junction the following formulation is done in excel using the Darcy Weisbach equation which is generally considered to be theoretically more rigorous and widely used in India which is given by,

$$h_L = \frac{flv^2}{2gd} \tag{3.1}$$

Where,

h_L= head loss in pipes, m

f= friction factor

l= length of pipe, m

v= velocity in pipe, m/s

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

d= diameter of pipe, m

With the Darcy-Weisbach formula EPANET 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:

$$f = \frac{64}{R_e} \tag{3.2}$$

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

$$f = \frac{0.25}{\left(\mathrm{Ln}\left(\frac{\varepsilon}{3.7d} + \frac{5.74}{R_e^{0.9}}\right)\right)^2} \tag{3.3}$$

Where,

ε = pipe roughness and

d = pipe diameter.

Here value of pipe roughness ε is taken as 0.26 mm for Cast Iron Pipe.

Table 3.2 shows the Calculations of various hydraulic parameters using above equations.

Table 3.2: Results of hydraulic parameters (Example 1)

Pipe	U/S Node	D/S Node	Discharge CMH	Discharge m^3/s	Diameter m	Length m	Velocity m/s	Reynold's Number	Head Loss m	Friction Factor (Cole brook)	Pressure at D/S Node m
P_1	R	J_1	92	0.0256	0.3	8000	0.362	108461.15	3.85	0.022	26.15
P_2	J_1	J_2	40	0.0111	0.2	4000	0.354	70735.53	3.07	0.024	23.08
P_3	J_1	J_3	40	0.0111	0.15	9000	0.354	70735.53	3.84	0.024	22.31
P_4	J_2	J_4	26	0.0072	0.2	5000	0.409	61304.13	13.08	0.026	9.997
P_5	J_3	J_5	26	0.0072	0.15	8000	0.409	61304.13	11.63	0.026	10.68

The same network was prepared in EPANET simulation model and the results of the hydraulic parameters obtained using EPANET exactly matches with the results obtained by the calculation done using Excel. The modelled network in EPANET is shown in Fig. 3.3.

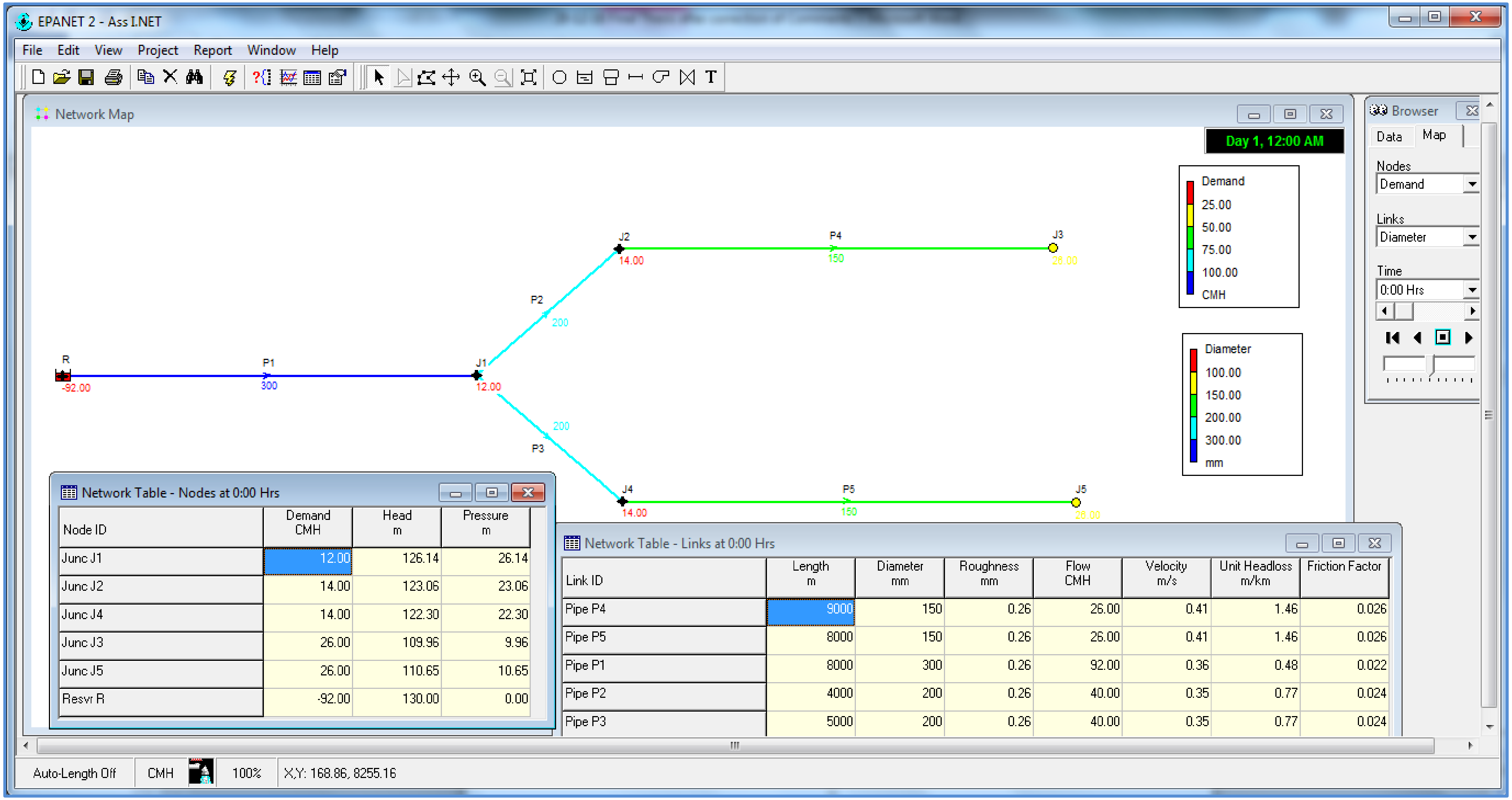

Fig 3.3: Modelled sample network using EPANET simulation Model.

After conducting the hydraulic simulation, the water quality simulation is done for water quality modelling of sample network. The explicit equations are formulated in terms of flow and chlorine mass rate for quick computation of the residual chlorine concentration at various nodes. Two cases are considered for the water quality modelling to analyse the residual chlorine at each node. Case I applies the chlorine by conventional method i.e. chlorine application at source only. Case II considered the booster chlorination strategy in which the chlorine is applied at various booster stations along with source chlorination. The explicit equations for both the cases are developed using Excel.

3.3 General Formulation for Water Quality Model

A sample network of simple drinking water distribution system is developed for the generalization of different equations to obtain the residual chlorine concentration at different nodes. Fig 3.4 shows the sample network used for development of equations. The two cases are considered for the application of chorine i.e. case I having conventional chlorination in which the chlorine is applied at only source R. Case II represents the Booster chlorination with chlorine applied at source as well as at nodes 1, 2, and 3. The supply hours of water is kept as 2 hours i.e. intermittent water supply to represent the general mode of water supply in Indian city. The water remains stagnant for rest of the 22 hours during which the decay in chlorine takes place. The initial quality of water at all the nodes is kept as 0.2 mg/L to avoid the contamination of water at various locations.

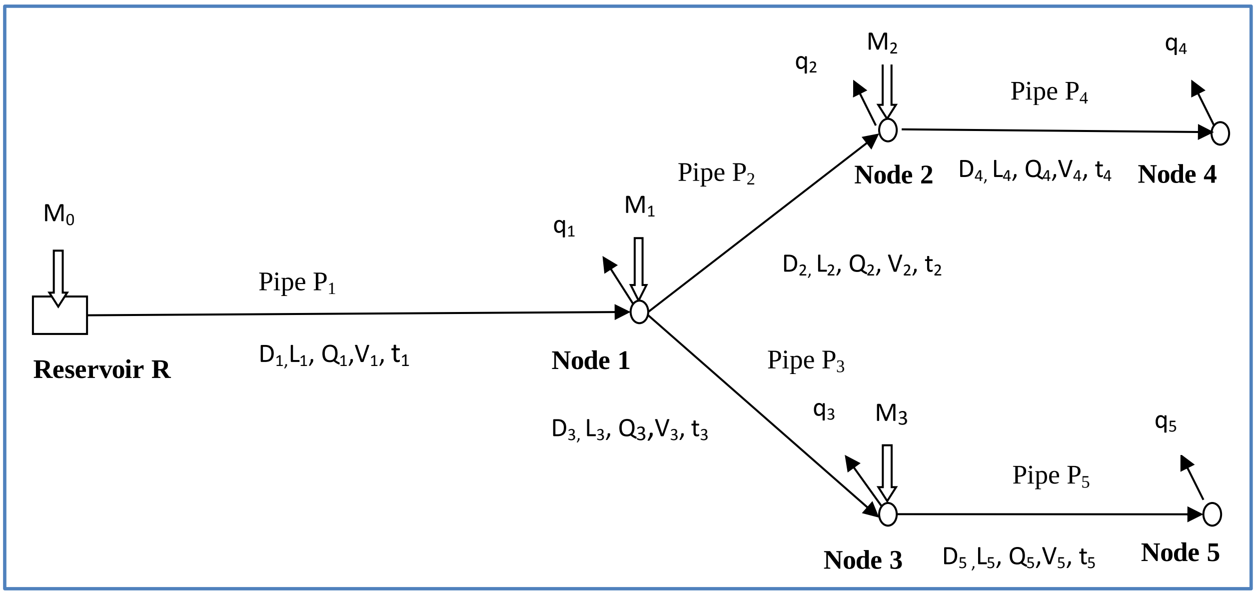

Fig 3.4: Sample network for calculation of chlorine concentration at each node

Following notations are used for the different components s of distribution network in Fig. 3.2

M_0= mass rate of chlorine applied at source i.e. Reservoir R

M_1=mass rate of chlorine injected at node 1, mg/min

M_2=mass rate of chlorine injected at node 2, mg/min

M_3=mass rate of chlorine injected at node 3, mg/min

D_1,D_2,D_3,D_4,D_5= diameter of Pipe P_1, P_2, P_3, P_4, P_5 respectively, m

L_1,L_2,L_3,L_4,L_5= length of Pipe P_1, P_2, P_3, P_4, P_5 respectively, m

q_1, q_2, q_3, q_4,q_5 = demand at node 1,2,3,4,5 respectively, m^3/h

Q_1,Q_2,Q_3,Q_4,Q_5= flow in Pipe P_1, P_2, P_3, P_4, P_5 respectively, m^3/h

V_1,V_2,V_3,V_4,V_5= velocity of flow in Pipe P_1, P_2, P_3, P_4, P_5 respectively, m/s

t_1,t_2,t_3,t_4,t_5= travelling time of chlorine to reach up to each node 1,2,3,4,5 respectively from preceding node , days

T_1,T_2,T_3,T_4,T_5= travelling time of chlorine to reach up to node 1,2,3,4,5 respectively from the source i.e. reservoir , days

C_0 ,C_{1i}, C_{2i}, C_{3i}, C_{4i}, C_{5i}= concentration of chlorine at reservoir R, and inlet of node 1, 2, 3, 4, 5 respectively, mg/L

C_{1o}, C_{2o}, C_{3o}, C_{4o}, C_{5o} = concentration of chlorine at outlet of node 1, 2, 3, 4, 5 respectively, mg/L

X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9 = constants.

3.3.1 Computation of Residual Chlorine

Explicit equations are developed to find out the residual chlorine concentration at inlet and outlet of the nodes 1, 2, 3, 4 and 5 for total 2 hours of water supply for two different strategies of application of chorine i.e. case I having conventional chlorination in which the chlorine mass rate of M_0 is applied at only source R and Case II is Booster chlorination with chlorine applied at source M_0 as well as at nodes 1, 2 and 3 i.e. M_1, M_2 and M_3 respectively. .

Following assumptions are made for developing the explicit equations for the computations of Residual Chlorine for Example problem.

(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,

$$C = C_0 e^{-k_b t} \tag{3.4}$$

Where,

C = concentration of chlorine in the water, mg/L

t = travelling time, days.

C_0 =chlorine concentration at the beginning of the transportation, mg/L

k_b = bulk decay coefficient, d^{-1}.

(2) Value of bulk decay coefficient k_b is taken as 0.55 d^{-1} (Rossman 1994)

(3) Flow is steady state for each demand pattern during supply of water for 2 hours.

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

(5) Initial concentration at starting of the day i.e. 0 hour = 0.2 mg/L.

Computation for Node 1

Case I (Conventional Chlorination)

Mass rate of chlorine, M_0 (mg/min) is added at source

$$C_{1i} = C_0 e^{-kt_1}$$

Where,

$$t_1 = \frac{L_1}{V_1} = \frac{L_1}{\frac{Q_1}{A_1}} = \frac{L_1 \pi {D_1}^2}{4Q_1}$$

$$C_0 = \frac{M_0}{Q_1}$$

$$C_1 = \frac{M_0}{Q_1}\ e^{-kL_1\pi {D_1}^2}/4Q_1$$

Taking Constant X_1

$$X_1 = \frac{1}{Q1}\ e^{-kL_1\pi {D_1}^2}/4Q_1$$

$C_{1i}=M_0\ X_1$ (3.5)

Concentration at the end of travelling time, t_1

$$t_1 = \frac{L_1 \pi {D_1}^2}{4Q_1}$$

$C_{1i}=C_{10}=M_0\ X_1$

(3.5 A)

Case II (Booster Chlorination)

(1) Concentration after addition of and M_1 at J_1 given by

$$J_1 = \frac{M_1}{Q_2 + Q_3} + 0.2$$

(2) Concentration at the inlet and outlet of the node 1 after end of Total Travelling time

$$T_1 = t_1 \;,\; C_{1i} = M_0 X_1$$

$$C_{1o} = M_0 X_1 + \frac{M_1}{Q_2 + Q_3}$$

(3.5 B)

Computation for Node 2

$$C_{2i} = C_{1o}\, e^{-kt}{}_2$$

Substituting

$$C_{10} = M_0 X_1 + \frac{M_1}{Q_2 + Q_3}$$

$$\therefore\; C_{2i} = \left(M_0 X_1 + \frac{M_1}{Q_2 + Q_3}\right) e^{-kL_2 \pi D_2{}^2} / 4Q_2$$

Substituting Constant X_2

$$X_2 = e^{-kL_2 \pi D_2{}^2} / 4Q_2$$

$$\therefore\; C_{2i} = \left(M_0 X_1 + \frac{M_1}{Q_2 + Q_3}\right) X_2$$

$$\therefore\; C_{2i} = M_o X_1 X_2 \;+ \frac{M_1 X_2}{Q_2 + Q_3}$$

Taking Constant X_3

$$X_3 = \frac{X_2}{Q_2 + Q_3}$$

$$C_{2i} = M_o X_1 X_2 \;+\; M_1 X_3$$

(3.6)

Case I (Conventional Chlorination)

(1) Concentration at the end of total travelling time from source, $T_2 = t_1 + t_2$

$$C_{2i} = C_{20} = M_o X_1 X_2 \;+\; M_1 X_3$$

(3.6 A)

Case II (Booster Chlorination)

(1) Concentration after addition of M_2 at Node 2 is given by

$$\frac{M_2}{Q_4}$$

(2) Concentration after addition of M_1 at node 1 and M_2 at Node 2 after travelling time

$$t_2 = \frac{L_2 \pi {D_2}^2}{4Q_2}$$

$$\frac{M_2}{Q_4} + M_1X_3 + 0.2$$

(3) Concentration at the inlet and outlet of node 2 after end of total travelling time from source $T_2 = t_1 + t_2$,

$$C_{2i} = M_oX_1X_2 \; + \; M_1X_3$$

$$C_{20} = M_0X_1X_2 \; + \; M_1X_3 + \frac{M2}{Q4}$$

(3.6 B)

Computation for Node 4

$$C_{4i} = C_{20}\, e^{-kt_3}$$

Substituting C_{20}

$$C_{20} = M_0X_1X_2 \; + \; M_1X_3 + \frac{M_2}{Q_4}$$

$$\therefore C_{4i} = \left(M_oX_1X_2 \; + \; M_1X_3 + \frac{M_2}{Q4}\right) e^{-kL_4\pi {D_4}^2}/4Q_4$$

Taking Constant X_4

$$X_4 = e^{-kL_4\pi {D_4}^2}/4Q_4$$

$$\therefore C_{4i} = M_oX_1X_2X_4 \; + \; M_1X_3X_4 \; + \frac{M_2X_4}{Q_4}$$

Taking Constant X_5

$$X_5 = \frac{X_4}{Q_4}$$

$$\therefore C_{4i} = M_oX_1X_2X_4 \; + \; M_1X_3X_4 \; + \; M_2X_5$$

(3.7)

Case I (Conventional Chlorination)

(1) Concentration at inlet and outlet of node 4 after the end of total travelling time from source, $T_4 = t_1 + t_2 + t_4$

$$C_{4i} = C_{4o} = M_0X_1X_2X_4 \; + \; M_1X_3X_4 \; + \; M_2X_5$$

(3.7 A)

Case II (Booster Chlorination)

(1) Concentration after addition of M_2 at node 2 after travelling time, t_4

$$t_4 = \frac{L_4 \pi {D_4}^2}{4Q_4}$$

$M_2X_5 + 0.2$

(2) Concentration after addition of M_1 at node 1 and M_2 at Node 2 after travelling time, $t_2 + t_4$,

$M_1X_3X_4 + M_2X_5 + 0.2$

(3) Concentration at inlet and outlet of node J_3 after the end of Total Travelling time from source $T_3 = t_1 + t_2 + t_4$,

$$C_{4i} = C_{4o} = M_0X_1X_2X_4 + M_1X_3X_4 + M_2X_5$$

(3.7 B)

If T_3 > water supply duration then Mo will not reach to the node and concentration will be

$$C_{4i} = C_{4o} = M_1X_3X_4 + M_2X_5$$

(3.7 C)

Computation for Node 3

$$C_{3i} = C_{10}\, e^{-kt_3}$$

Substituting C_{1o}

$$C_{1o} = M_0X_1 + \frac{M_1}{Q_2 + Q_3}$$

$$C_{3i} = \left(M_0X_1 + \frac{M_1}{Q_2 + Q_3}\right) e^{-kL_3\pi D_3^2}/4Q_3$$

Taking constant $X_6 = e^{-kL_3\pi D_3^2}/4Q_3$

$$C_{3i} = M_oX_1X_6 + \frac{M_1X_6}{Q_2 + Q_3}$$

Taking constant X_7

$$X_7 = \frac{X_6}{Q_2 + Q_3}$$

$$C_{4i} = M_oX_1X_6 + M_1X_7$$

(3.8)

For Case I (Conventional Chlorination)

Concentration at the end of Total Travelling time from source, T_4

$$T_4 = t_1 + t_3$$

$$C_{4i} = C_{40} = M_oX_1X_6 + M_1X_7$$

(3.8 A)

For Case II (Booster Chlorination)

(1) Concentration after addition of M_3 at node 3

$$\frac{M_3}{Q_5} + 0.2$$

(2) Concentration after addition of M_1 at Node 1 and M_3 at Node 3 after TT t_3

$$t_3 = \frac{L_3 \pi D_3{}^2}{4Q_3}$$

$$\frac{M_3}{Q_5} + M_1 X_7 + 0.2$$

(3) Concentration at inlet and outlet of node 3 after the end of Total Travelling time from source $T_3 = t_1 + t_3$

$$C_{3i} = M_o X_1 X_6 + M_1 X_7$$

$$C_{3o} = M_o X_1 X_6 + M_1 X_7 + \frac{M3}{Q5}$$

(3.8 B)

Computation for Node 5

$$C_{5i} = C_{3o}\, e^{-kt_5}$$

Substituting C_{4o}

$$C_{4o} = M_o X_1 X_6 + M_1 X_7 + \frac{M3}{Q5}$$

$$C_{5i} = \left(M_o X_1 X_6 + M_1 X_7 + \frac{M_3}{Q_5}\right) e^{-kL_5 \pi D_5^2}/4Q_5$$

Taking constant $X_8 = e^{-kL_5 \pi D_5^2}/4Q_5$

$$\therefore C_{5i} = M_o X_1 X_6 X_8 + M_1 X_7 X_8 + \frac{M_3 X_8}{Q_5}$$

Taking constant X_9

$$X_9 = \frac{X_8}{Q_5}$$

$$\therefore C_{5i} = M_o X_1 X_6 X_8 + M_1 X_7 X_8 + M_3 X_9$$

(3.9)

For Case I (Conventional Chlorination)

Concentration at the end of total travelling time from source, $T_5 = t_3 + t_5$

$$C_{5i} = C_{5o} = M_o X_1 X_6 X_8 + M_1 X_7 X_8 + M_3 X_9$$

(3.9 A)

For Case II (Booster Chlorination)

(1) Concentration after addition of M_3 at node 3 at the end of travelling time,

$$t_5 = \frac{L_5 \pi D_5{}^2}{4Q_5}$$

$$M_3 X_9 + 0.2$$

(2) Concentration after addition of M_1 at Node 1 and M_3 at node 3 at the end of travelling time, $t_3 + t_5$ is given by,

$$M_1X_7X_8 + M_3X_9 + 0.2$$

(3) Concentration at inlet and outlet of node J_5 after the end of Total Travelling time from source, $T_5 = t_1 + t_2 + t_3$

$$C_{5i} = C_{5o} = M_o X_1 X_6 X_8 + M_1X_7X_8 + M_3X_9$$

(3.9 B)

If T_5 > water supply duration then M_1 will not reach to the node and concentration will be

$$C_5 = M_1X_7X_8 + M_3X_9 \quad (3.9\ C)$$

Table 3.3 gives the summary of various explicit equations developed to calculate the residual chlorine concentration at various nodes at different travelling time for case I (Conventional chlorination) and Case II (Booster chlorination).

Table 3.3: Concentration of residual chlorine at various nodes at the end of different travelling time for two cases

Node Number	Cases	Concentration of residual chlorine at the end of different travelling time		
		Residual chlorine concentration at different duration	**Inlet of Node**	**Outlet of Node**
1	Case I	Concentration at the end of travelling time t_1	$C_{1i}=M_0 X_1$	$C_{1o}=M_0 X_1$
1	Case II	Concentration after addition of and M_1 at J_1	$\frac{M_1}{Q_2+Q_3}+0.2$	
		Concentration at the end of travelling time t_1 which is equal to Total Travelling time T_1	$C_{1i}=M_0 X_1$	$C_{1o}=M_0 X_1+\frac{M_1}{Q_2+Q_3}$
2	Case I	Concentration at the end of total travelling time from source, $T_2 = t_1+t_2$	$C_{2i}=M_oX_1X_2$	$C_{20}=M_oX_1X_2$
2	Case II	Concentration after addition of M_2 at Node 2	$\frac{M_2}{Q_4}$	
		Concentration after addition of M_1 at node 1 and M_2 at Node 2 after travelling time t_2	$\frac{M_2}{Q_4}+M_1X_3+0.2$	
		Concentration at the inlet and outlet of node 2 after end of total travelling time from source $T_2=t_1+t_2$,	$C_{2i}=M_oX_1X_2+M_1X_3$	$C_{20}=M_0X_1X_2+M_1X_3+\frac{M_2}{Q_4}$
4	Case I	Concentration at inlet and outlet of node 4 after the end of total travelling time from source $T_4=t_2+t_2+t_4$	$C_{4i}=M_0X_1X_2X_4$	$C_{4o}=M_0X_1X_2X_4$
4	Case II	Concentration after addition of M_2 at node 2 after travelling time, t_4	$M_2X_5+0.2$	
		Concentration after addition of M_1 at node 1 and M_2 at Node 2 after travelling time, t_2+t_4	$M_1X_3X_4+M_2X_5+0.2$	

		Concentration at inlet and outlet of node J_3 after the end of total t travelling time from source $T_3 = t_1 + t_2 + t_4$	$C_{4i} = M_0X_1X_2X_4 + M_1X_3X_4 + M_2X_5$	$C_{4o} = M_0X_1X_2X_4 + M_1X_3X_4 + M_2X_5$
		If T_3 > water supply duration then M_o will not reach to the node and concentration will be $C_{4i} = C_{4o} = M_1X_3X_4 + M_2X_5$		
3	Case I	Concentration at the end of total travelling time from source $T_3 = t_1 + t_3$	$C_{3i} = M_o X_1 X_6$	$C_{30} = M_o X_1 X_6$
3	Case II	Concentration after addition of M_3 at node 3 ,	$\frac{M_3}{Q_5} + 0.2$	
		Concentration after addition of M_1 at Node 1 and M_3 at Node 3 after travelling time t_3	$\frac{M_3}{Q_5} + M_1X_7 + 0.2$	
		Concentration at inlet and outlet of node 3 after the end of total travelling time from source, $T_3 = t_1 + t_3$	$C_{3i} = M_o X_1X_6 + M_1X_7$	$C_{3o} = M_o X_1X_6 + M_1X_7 + \frac{M3}{Q5}$
5	Case I	Concentration at the end of Total travelling time from source, $T_5 = t_3 + t_5$	$C_{5i} = M_o X_1 X_6 X_8$	$C_{5o} = M_o X_1 X_6 X_8$
5	Case II	Concentration after addition of M_3 at node 3 at the end of travelling time, t_5	$M_3X_9 + 0.2$	
		Concentration after addition of M_1 at Node 1 and M_3 at node 3 at the end of travelling time , $t_3 + t_5$	$M_1X_7X_8 + M_3X_9 + 0.2$	
		Concentration at inlet and outlet of node J_5 after the end of Total travelling time from source, $T_5 = t_1 + t_3 + t_5$	$C_{5i} = M_o X_1 X_6 X_8 + M_1X_7X_8 + M_3X_9$	$C_{5o} = M_o X_1 X_6 X_8 + M_1X_7X_8 + M_3X_9$
		If T_5 > Water supply duration then M_0 will not reach to the node and concentration will be $C_{5i} = C_{5o} = M_1X_7X_8 + M_3X_9$		

If the distribution network consists of many loops and branches, the development of explicit equations for computing residual chlorine is cumbersome. In such cases, computer based methods such as EPANET software can be used. The explicit equations developed as mentioned in Table 3.3 are used to compute the residual chlorine for example problem and compared the results with EPANET software

3.3.2 Model Computations for Example Problem

Equations developed as mentioned in Table 3.3 are used for the example network as shown in Fig 3.5 with input data of water demand at different nodes and pipe diameter and length for links. Initial concentration of chlorine at all the nodes is assumed to be 0.2 mg/L. The mass rate of chlorine supplied at all the nodes for both the cases is shown in Table 3.4.

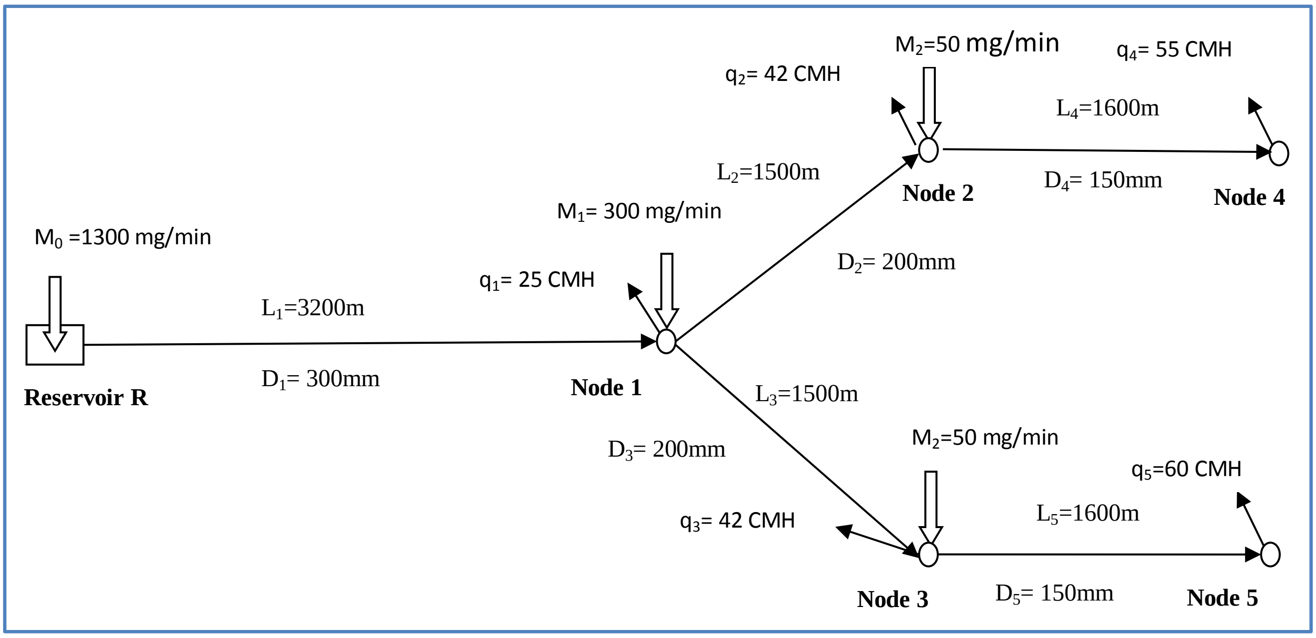

Fig 3.5: Computation of residual chlorine concentration at each node for Case II (Example network)

Table 3.4: Mass rate of chlorine applied at various locations (Example Network)

Cases	Total Mass rate applied (g/d)	Chlorine Application Period (Hours)	Source and Booster Locations/Injection rate at			
			Source (M_0)	Node 1(M_1)	Node 2 (M_2)	Node 3 (M_2)
			mg/min	mg/min	mg/min	mg/min
Case I (Only source chlorination)	267.6	2	2230			--
Case II (Source and Booster Chlorination)	204 (23.78% reduction in total mass rate of chlorine)	2	1300	300	50	50

3.3.3 Analysis and Discussions of Results

Graphs of residual chlorine concentration at different time period is generated using the data of residual chlorine concentration at each node calculated using explicit equations as mentioned in Table 3.3. Fig 3.6 and Fig 3.7 gives the residual chlorine concentration obtained from equations for farthest node 4 for case I and Case II respectively , having travelling time greater than 2 hours i.e. water supply duration. Fig 3.8 and Fig 3.9 gives residual chlorine concentration obtained from equations for farthest node 5 for case I and Case II respectively having travelling time less than 2 hours i.e water supply duration. The simulation is done on EPANET software for the same network to check the results obtained using equations. The results obtained by using the equations are exactly matching with the results obtained by EPANET software.

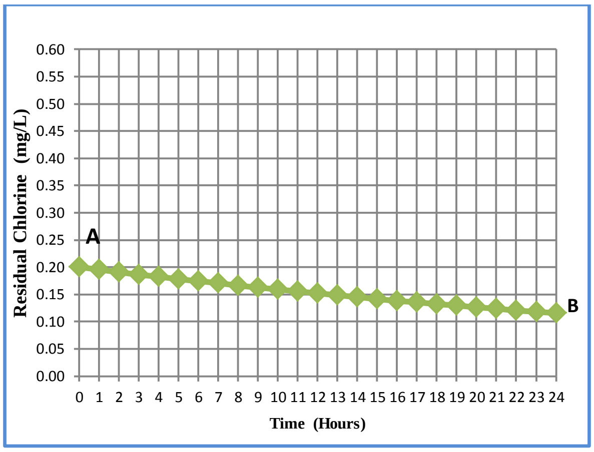

Fig. 3.6: Residual chlorine concentration at Node 4 for Case I.

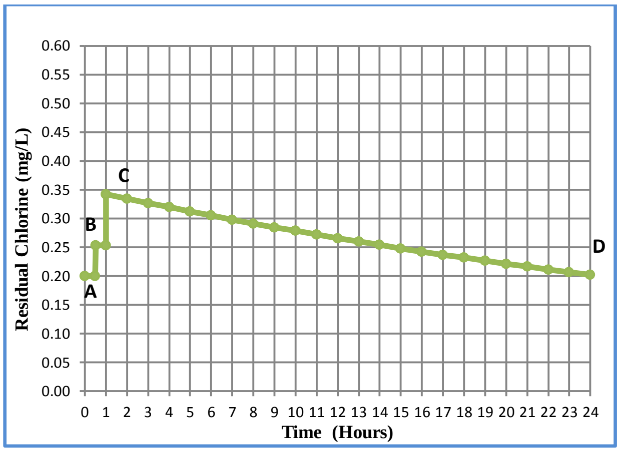

Fig. 3.7: Residual chlorine concentration at Node 4 for Case II.

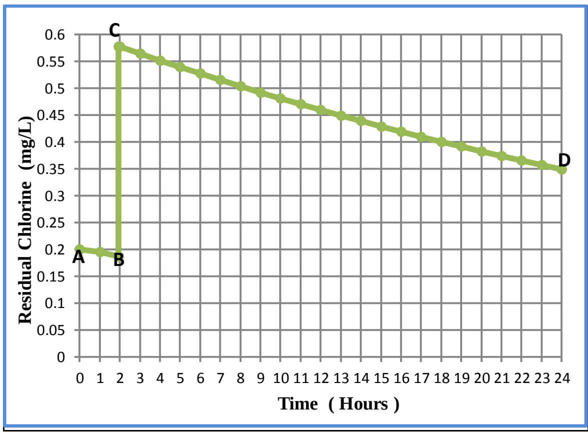

Fig. 3.8: Residual chlorine concentration at Node 5 for Case I.

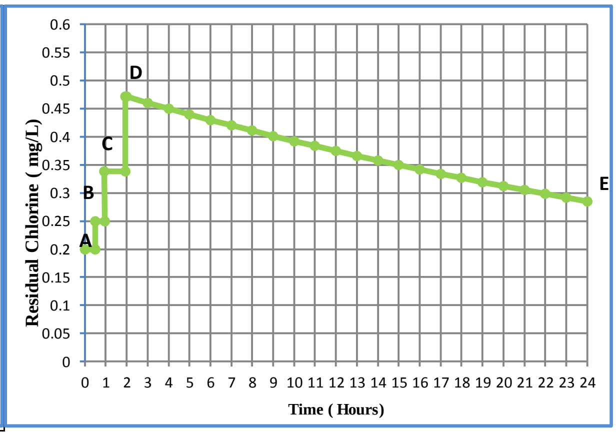

Fig. 3.9: Residual chlorine concentration at Node 5 for Case II

The results obtained using the explicit equations are exactly matching with results generated using EPANET software. In all the above figures point A indicates initial concentration of chlorine at 0 hours i.e. 0.2 mg/L. The observations for both the farthest nodes Node 4 and Node 5 for case I and Case II is as under.

As observed from Fig. 3.6 (case I i.e. conventional chlorination at node 4), the concentration after 24 hours (Point B) is less than 0.2 mg/L as the travelling time of chlorine is greater than water supply hour of 2 hours and chlorine decay of 0.2 mg/L takes place. If we add more concentration at source then also there will not be any effect on final concentration as the travelling time is greater than supply hours. In such cases the Booster chlorination helps to attain the required minimum concentration of chlorine.

As shown in Fig. 3.7(case II i.e. booster chlorination at node 4), point B shows the effect of addition of M_2 at node 2 which will reach first to node 4 after travelling time of t_4. Peak of point C is the effect of M_1 added at node 1 which will reach after travelling time of t_4+t_2. As travelling time of chlorine is more than 2 hours the effect of M_o is not felt at node 4. After 2 hours the chlorine decay will take place for rest of 22 hours of stagnant period and point D gives the final concentration of chlorine at node 4 after 24 hours. As compared to case I due to addition of booster doses at node 1 and 2, chlorine concentration of 0.2 mg/L is achieved after 24 hours which was not possible in case I due to less supply hours than travelling time.

In Fig. 3.8 (case I i.e. conventional chlorination at node 5), point B shows the initial decay of initial chlorine concentration of 0.2 mg/L. The peak (point C) is observed due to addition of M_0 at source and it will reach to node 5 as its travelling time is less than 2 hours. After 2 hours the decay of chlorine will takes place for 22 hours of stagnant period and point D shows the final concentration after 24 hours.

As shown in Fig. 3.9 (for case II i.e. booster chlorination at node 5), point B shows the effect of addition of M_3 at node 3 which will reach first to node 5 after travelling time of t_5. Point C is the effect of M_1 added at node 1 which will reach after travelling time of t_3+t_5. As travelling time of chlorine is less than 2 hours for node 5, the effect of M_o is observed at node 5 which gives the peak at point D. After 2 hours the chlorine decay will take place for rest of 22 hours of stagnant period and point E gives the final concentration of chlorine at node 5 after 24 hours. As time of travelling at node 5 is less than supply hours there is no major effect of booster chlorination is observed on final concentration of chlorine. Thus Booster chlorination is effective only for the farthest nodes, if the travelling time of chlorine is greater than supply hours as observed for node 4.

The major points observed from the results and comparisons of results with EPANET software are:

(1) For conventional chlorination method if the travelling time of chlorine is greater than supply hours of water, the residual chlorine cannot reach to the farthest node like Node

4 after 24 hours. In case I even though high mass rate of chlorine (2230 mg/min) is supplied chlorine will not reach to node 4 after 24 hours as its travelling time is greater than supply duration of 2 hours.

(2) Provision of Booster chlorination is only effective in such conditions where farthest nodes are not receiving minimum desired residual chlorine concentration due to greater travelling time than supply hours.

(3) Application of Booster chlorination strategy helps to maintain the residual chlorine of 0.2 mg/L at node 4 having travelling time greater than 2 hours water supply after 24` hours at the same time gives 23.78% reduction in total mass rate of chlorine application.

Explicit equations based on first order chlorine decay can provide very useful decision making tool to justify the chlorine mass injection rate and selection of booster chlorination strategy. For effective management of residual chlorine at all the locations of distribution network, booster chlorination strategies proves to be better option than conventional source chlorination if travelling time of chlorine is greater than water supply hours for intermittent water supply at farthest point for any drinking water distribution systems.. The results suggest that the booster chlorination strategies proves to be better options over conventional chlorination method if travelling time of the chlorine is greater than the water supply hours for the farthest node. For the large distribution networks consisting of many farthest critical nodes justify the use of booster chlorination stations using simulation model such as EPANET.

3.4 Inferences

A simple sample network is utilized to formulate the hydraulic model using excel for prediction of hydraulic parameters like pressure and head at each junction. The result obtained by using EPANET software is exactly matching with the pressure obtained using formulation.

For formulation of simulation model for water quality modelling a simple sample network is developed to generate explicit equations in terms of flow and chlorine mass rate for quick computation of the residual chlorine concentration at various nodes. EPANET software gives the same results as the result obtained for sample problem with intermittent water supply and two chlorine application strategies using formulation. This computation tool is also useful to decide the effect of booster chlorination on residual chlorine concentration. To have the better understanding regarding the application of booster chlorination strategies the simulation of real drinking water distribution system is essential and requires the use of simulation model.