BOOSTER DISINFECTION
IN
WATER DISTRIBUTION NETWORKS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ÇAĞLAYAN SERT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

JULY 2009

Approval of the thesis:

BOOSTER DISINFECTION
IN
WATER DISTRIBUTION NETWORKS

submitted by **ÇAĞLAYAN SERT** in partial fullfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen _____
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Güney Özcebe _____
Head of Department, **Civil Engineering**

Assoc. Prof. Dr. Ayşe Burcu Altan Sakarya _____
Supervisor, **Civil Engineering, METU**

Examining Committee Members:

Prof. Dr. Halil Önder _____
Civil Engineering, METU

Assoc. Prof. Dr. Ayşe Burcu Altan Sakarya _____
Civil Engineering, METU

Assoc. Prof. Dr. Nuray Tokyay _____
Civil Engineering, METU

Asst. Prof. Dr. Elçin Kentel _____
Civil Engineering, METU

Dr. Bergüzar Özbahçeci _____
Ministry of Transport and Communication

Date: _____

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name	:	Çağlayan Sert
Signature	:	

ABSTRACT

BOOSTER DISINFECTION
IN
WATER DISTRIBUTION NETWORKS

Sert, Çağlayan

M.S, Department of Civil Engineering

Supervisor: Assoc. Prof. Dr. Ayşe Burcu Altan Sakarya

July 2009, 124 pages

Disinfection of the municipal water systems is mostly achieved by means of chlorine addition at water treatment plants known as sources. Thus, there should be an adequate chlorine concentration at the source for an effective disinfection throughout the system by considering upper and lower limits of disinfectant. However, since the disinfectants are reactive and decays through the system, chlorine added at the source may not be enough to maintain desired disinfectant residuals which may lead to water quality problems in the water distribution system. Moreover, the disinfectants such as chlorine has also an effect to be carcinogen due to formation of disinfectant by-products. Thus, the system should balance the amount of disinfectant supplied while minimizing the health risk. In such a case, it is recommended that one or more booster disinfection stations can be located throughout the system. Such a method can provide more uniform distribution of the chlorine concentration while reducing the amount of the disinfectant used. In this thesis, optimum scheduling, and injection rates of the booster disinfection stations have been searched. The objective is to minimize the injected mass dosage rate subjected to the provision of adequate and more uniform residual concentration in the network. Determination of variable network hydraulics and chlorine concentrations is held out by EPANET network simulation sofware. A C++ code was developed to interface with EPANET by means of the EPANET Programmer's Toolkit for linear

optimization of the disinfectant mass dosage rate applied to the network.

Keywords: Booster Disinfection Stations, Water Distribution Network, Disinfectant Concentration, Chlorine Injection, EPANET

ÖZ

SU DAĞITIM ŞEBEKELERİNDE EK KLORLAMA UYGULANMASI

Sert, Çağlayan
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Ayşe Burcu Altan Sakarya

Temmuz 2009, 124 sayfa

Şehir içme suyu şebekelerinin dezenfektasyonu çoğunlukla ana su kaynağı olarak bilinen arıtma tesislerinden klor eklenmesi şeklinde yapılmaktadır. Bunun için bütün sistem çapında dezenfektant alt ve üst limitleri düşünülerek etkili bir dezenfektasyon sağlanabilmesi için artıma tesisinden yeterli miktarda klor konsantrasyonu sağlanması gerekmektedir. Ancak dezenfektanlar sistemde tepkimeye girdiğinden ve sönümlendiğinden arıtma tesisinden uygulanan klor, sistemde gerekli bakiye klor değerlerini sağlamakta yeterli olmayabilir ve bu durum su dağıtım şebekesinde su kalitesi problemlerine yol açmaktadır. Ayrıca klor gibi dezenfektanlar yan ürün oluşturduğundan kanserojen etkiye sahiptirler. Bundan dolayı sistemde sağlanan dezenfektanlar ve sağlık riski arasında bir denge kurulmalıdır. Bunun gibi durumlarda su dağıtım sistemine bir ya da daha fazla ek klor istasyonu kurulumu önerilmektedir. Bu yöntem sistemde kullanılan toplam dezenfektan miktarını azaltmakla birlikte sistem çapında daha düzgün bir klor konsantrasyon dağılımını sağlamaktadır. Bu tezde, söz konusu ek klor istasyonlarının en uygun planlanması ve enjeksiyon oranları incelenmiştir. Amaç, sisteme uygulanan klor dozaj miktarını en aza indirirken sistemde yeterli ve daha düzgün bir dağılıma sahip bakiye klor değerlerinin sağlanmasıdır. Değişken sistem hidroliği değerleri ve klor konsantrasyonları EPANET su şebekesi modelleme ve çözüm yazılımı ile elde edilmiştir. Su dağıtım şebekesine uygulanacak klor dozaj miktarının lineer olarak optimizasyonu

amacıyla EPANET'in programcılar için geliştirme aracı kullanılarak EPANET ile interaktif çalışan C++ dilinde bir bilgisayar programı hazırlanmıştır.

Anahtar Kelimeler: Ek Klor İstasyonları, Su Dağıtım Şebekesi, Dezenfektan Konsantrasyonu, Klor Enjeksiyonu, EPANET

To My Family

ACKNOWLEDGMENTS

First and foremost, I would like to thank to my research advisor Assoc. Prof Dr. Burcu Altan Sakarya for her kind guidance, constant support, encouragement and advice for this study.

I would like to extend my deepest gratitude to all members of Atılım University Civil Engineering Department for their both personal and academic support and their valuable time out.

I would like to send special thanks to my friend and colleague, Semih Özmen for his valuable help and comments for this research.

I would like to express my deepest gratitude to my family who were always present and supportive in my life.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLES

LIST OF SYMBOLS

ν	Flow velocity in pipe i
K_i	Overall first order decay coefficient
k_b	First order bulk reaction constant
k_f	Mass transfer coefficient
k_w	Pipe reaction constant
Q_j	Flow in pipe j
n_t	Number of scheduling time intervals of booster location
n_b	Number of booster disinfection stations
n_s	Number of source locations
u_i^j	Mass injection rate at booster node i and time period j
tr	Monitoring time
ir	Monitoring node
$\alpha_{ir,tr}^{i,j}$	Response coefficient at monitoring node ir at time tr
$C_{ir,tr}$	Concentration value at monitoring node ir at time tr
$\underline{C}$	Lower limit for the concentration value
$\overline{C}$	Upper limit for the concentration value
$\triangle t$	Booster mass injection time interval
$C_{ir,0}$	Initial concentration at monitoring node ir
$C_{ir,final}$	Final concentration at monitoring node ir
$\varepsilon_{ir,tr}^{rn}$	Impact coefficient of the initial concentration of the node rn to the node ir at time tr
A	Response coefficient matrix
U	Booster mass injection matrix
q	Discharge matrix
C	Nodal concentration matrix
C^0	Initial concentration matrix
E	Impact coefficient matrix
T_c	Sampling time horizon

CHAPTER 1

INTRODUCTION

1.1 Problem Definition

The disinfectant concentration added to the system is effected by the system hydraulics which are time varying and complicated. Nodal demands, discharge in pipes and residence times change continuously within a day. Thus, the water quality in municipal water system varies significantly with time throughout the network. The variability of the disinfectant residual brought up water quality problems such as taste and odor as well as potential health risk. Municipal water system should be properly designed so that the minimum and maximum levels for the disinfectant residuals are satisfied to provide acceptable drinking water to the consumers. The minimum and the maximum limits for the disinfectant residual are given by the Safe Drinking Water Act and its amendments (SDWAA). The minimum limit for the residual concentration is about biological regrowth and the maximum limit is about taste and odor. Higher concentrations of the disinfectant, which is mostly chlorine, can lead to formation of the disinfectant by-products (DBPs). Some of the DBPs are potential carcinogens and could result in serious health problems [1]. Various methodologies have been developed for the provision of the adequate residual concentration along the network while considering water quality requirements.

Conventionally, disinfection in the municipal water distribution networks are mostly achieved by means of chlorine addition at the entrance of the network, known as sources at the water treatment plants. The disinfectant mass dosage applied at the source should be increased in order to provide adequate residual concentrations at the far nodal points of the network. However, this application may result in higher residuals in other locations of the distribution system and non-uniform distribution of the chlorine

within the network. Conventional application of the disinfection is a practical method but it is not a proper strategy to maintain adequate disinfectant residuals.

As a new strategy for the residual maintenance, the booster disinfection stations are being applied. The disinfectant is applied from the located booster disinfection stations to the network. By use of booster stations, residual maintenance difficulties are overcomed without imposing excessive chlorine concentrations to the consumers. Application of booster disinfectors also reduces the amount of chlorine to be applied to the network. Thus, reduced amount of disinfectant also decrease risk of formation of the disinfectant by-products. Booster disinfection locations are mostly placed near the places in which the disinfectant residual maintenance is a problem. Strategically located and proper scheduled booster disinfection stations not only minimize the total disinfectant mass required for the residual maintenance throughout the network but also provide more uniform distribution of the chlorine without showing significant variations.

The main concern for the implementation of the booster disinfection stations is the high cost of building and maintenance of the stations. Scheduling of operation of the booster stations, total mass of disinfectant to be applied and the number of booster stations and their locations should be simultaneously considered in the municipal water distribution network design. Thus, there is a need for optimized solution for the number of booster stations while maintaining the required disinfectant residual concentrations within the water distribution network.

1.2 Related Work

Optimization of the water distribution network systems has been started in late 1960s for mostly design purposes such as optimal dimensioning of the network components by means of cost minimization [2]. Optimization of the hydraulic component size was the main concern for these studies. Then, the operational components such as pumps and valves were included into the optimization problems [3]. Sizing of network components and setting the operational decisions were started to be considered simultaneously.

The problem of water quality optimization in municipal water distribution systems was started to be studied in late 1980s with facility optimization models [4]. Then, development of the computer softwares for water distribution network simulation allowed extended period analysis for both network hydraulics and water quality.

Booster disinfection in water distribution networks is introduced as a optimal schedul-

ing problem in late 1990s. Boccelli et al. [5] presented an optimal scheduling model for the booster disinfection at known locations of the booster stations, by considering two objectives: 1) maintaining the disinfectant residual between minimum and maximum values at designated consumer nodes for all monitoring times and, 2) minimization of the total disinfectant mass applied to the network. The network application model presented in the study reveals that the booster disinfection can reduce the total disinfectant used when compared to the conventional method of disinfection.

Tryby et al. [6] extended the formulation presented by Boccelli [5] by addition of booster disinfection operation types into problem. The formulation is a mixed integer linear programming and branch and bound algorithm is used for the solution.

Propato and Uber [7] developed a linear-least squares formulation for the booster disinfection in which the individual contributions of the consumer demand nodes are included in the formulations as their weights on residual concentrations.

Lansey et al. [8] introduce an optimization model for the booster disinfection stations by including additional constraints to the problem. The model take the effect of initial concentrations into account to avoid long water quality simulations. Concentrations at the beginning and end of the design time period considered to be same in the formulation.

1.3 Research Objective

The goal of this research is to investigate the efficiency of the application of booster disinfection stations on minimizing the disinfectant mass dosage applied to the network while maintaining the required residual concentrations. In the analysis different types of booster stations and their operational effects on the water distribution network are also investigated. Booster disinfection station locations are selected with accordance to the network behavior by trial and error. Number of stations are kept in minimum while considering the zones in which the residual maintenance difficulties exist. The main objectives are:

(1) Minimize the total disinfectant mass applied to the water distribution network.

(2) Maintaining required consumer disinfectant residuals and provision of as uniform as possible distribution of the residuals throughout the network.

1.4 Thesis Outline

This thesis consists of four main parts. Firstly, in Chapter 2, the background information about the water quality modelling in water distribution systems are illustrated. In this part, the disinfectant, i.e. chlorine, decay kinetics are also briefly discussed. Additionally, a general information about the booster disinfection stations and their functionality are introduced.

Then the mathematical problem formulation and the optimization model is defined in Chapter 3. The objective function, bounds and the assumptions used in the solution are explained.

In Chapter 4, the solution procedure for the problem and the network model application is expressed. The computer code and user interface is shown with details in this chapter.

In Chapter 5, the results and outcomes of the model application is given. Besides this, analysis of the assumptions used in the formulation are also discussed in this chapter.

Finally, the conclusions drawn from this research and the future work considerations are explained in Chapter 6.

CHAPTER 2

BACKGROUND

2.1 Hydraulic Modelling

A hydraulic model refers to the computer simulation software which solves the network equations characterizing the considered water distribution network. Properties of pipes, junctions, pumps, valves, tanks and the user demands constitutes the network characteristics. The planning and operation studies about the network are highly dependent on these features of the network components.

A water distribution network model includes (1) the network data file which consists of physical data as geometry and operational values such as nodal user demands or pump characteristics, and (2) the computer simulation software which handles the mathematical network equations.

The network system solution could be steady or quasi-steady (extended period simulation). Both analysis require accurate mathematical representation of the water distribution network. The extended period simulation (EPS) of a network is thought to be proper by considering the aim of this research since the residence time of the disinfectant within the network could take several days and the decay kinetics are highly dependent on the variable system hydraulics.

EPANET, a network simulation program, is used for dynamic hydraulic modelling [9]. The method used in the EPANET solution for system hydraulics is called hybrid node-loop approach. There are two equation sets to be satisfied in the solution of the hydraulics.

First set of equations to be satisfied is the headloss equations, given for a pipe from node i to j :

$$H_i - H_j = h_{ij} = rQ_{ij}^n + mQ_{ij}^2 \tag{2.1}$$

where, H, is the nodal head, h_{ij}, headloss in the pipe located between node i and node j, r, resistance coefficient, Q_{ij}, flow rate in pipe between nodes i and j, n, flow exponent, and m, minor loss coefficient. The value of the resistance coefficient changes according to the friction headloss formula used such as Swamie and Jain or Hagen-Poiseuille.

Second set of equation is the flow continuity about all nodes as:

$$\sum_j Q_{ij} - D_i = 0 \quad for \;\; i = 1, ...N \tag{2.2}$$

where, D_i ,is the flow demand at node i and by sign convention, flow into a node is positive. By using Equations 2.1 and 2.2, solution for all heads H_i and flows Q_{ij} are searched.

2.2 Water Quality Modelling

Water quality variation within the water distribution network directly depends on the network hydraulics. Investigation of the water quality parameters along the network requires simulating the disinfectant transport and knowledge of the chemistry of the dissolved disinfectant in water along pipes throughout the network. In terms of water quality modelling, the disinfectant kinetics are important to observe residual concentrations required for the network.

Chlorine is a commonly used disinfectant in the municipal water distribution networks. Chlorine undergoes multiple reactions and decays as it travels through the pipes within the network. Dissolved chlorine reacts with natural organic matter (NOM) in the bulk water, and with the pipe wall material[10]. Thus, the chlorine residual concentration decreases depending on the residence time of the disinfectant in the network. Additionally, the holding time of the chlorine in the storage facilities such as tanks is also a major factor for the decrease of residual concentration and corresponding increase in the DBPs.

The chlorine concentration dissipation results from (i) its reaction with natural organic material (NOM) in bulk water, (ii) its reactions with biofilms attached to the pipe wall, (iii) its consumption due to the corrosion reactions and (iv) mass transport of chlorine between bulk flow and pipe wall.

2.2.1 Chemistry of Disinfectant in Water

Chlorine is added to bulk water and it dissolves. It yields HOCl, so called free chlorine, from the following equation [11]:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \tag{2.3}$$

HOCl reacts with the NOM and the pipe material resulting in consumed chlorine as follows:

$$HOCl + Cl_{demand} \rightarrow products \tag{2.4}$$

Consumed disinfectant increases vulnerability of the water distribution network to contamination.

2.2.2 Chlorine Decay Kinetics in Water Distribution Networks

Along the water distribution network, chlorine travels in pipes between nodes. Water is conveyed with accordance to the designated pressures. Disinfectant concentration in the network changes with the variable system hydraulics with certain decay kinetics. For a single pipe with known hydraulic conditions, the mass-conservation equation during a hydraulic time step is given as:

$$\frac{\partial C_i}{\partial t} = -\nu_i \frac{\partial C_i}{\partial x} - K_i C_i \tag{2.5}$$

where, C_i is the disinfectant concentration in pipe i at a distance x along the pipe at time t, ν_i is the flow velocity in pipe i and K_i is an overall decay constant.

Several reactions which the disinfectant encounters is expressed as overall first order decay coefficient K_i above. Actually, K_i includes both bulk water and wall reactions of the disinfectant transport through the pipe. The open form of the mass transfer equation for chlorine consumption is defined in Equation 2.6 as:

$$\frac{\partial C_i}{\partial t} = -\nu_i \frac{\partial C_i}{\partial x} - k_b C_i - k_f (C_i - C_w) \tag{2.6}$$

where, k_b is the first order bulk reaction constant, k_f is the mass transfer coefficient and C_w is the chlorine concentration at pipe wall. The general definition for the overall reaction rate, K_i is given by Rossman et al.[12] is defined in Equation 2.7 as:

$$K_i = k_b + \frac{k_w k_f}{r_{hi} k_w + k_f} \tag{2.7}$$

where, k_w is the pipe wall reaction constant and r_{hi} is the hydraulic radius of the pipe.

Figure 2.1: Pipe Chlorine Model

By assuming first order reaction kinetics in bulk water and at the pipe wall, consider a single pipe as shown in Figure 2.1 for the chlorine modelling. The downstream concentration, C_d can be expressed as a linear function of the upstream concentration, C^u at a given time, t as in Equation 2.8;

$$C_d(t) = b(t)\, C^u(t - \tau(t)) \tag{2.8}$$

where, $b(t)$ represents the decay of chlorine through the pipe and $\tau(t)$ is the travel time of chlorine between upstream and downstream nodes. The decay of the chlorine is defined as in Equation 2.9;

$$b(t) = exp(-K_i \tau(t)) \tag{2.9}$$

In Equation 2.9 the value of the K_i , is the overall reaction rate defined in Equation 2.7.

EPANET network simulation model is used for the decay kinetics and water quality modelling. Dynamic water quality solver of the EPANET combines the conservation of mass equations with reaction kinetics of the disinfectant to estimate the residual concentrations at all locations of the municipal water distribution system [9].

2.3 Booster Disinfectors

Chlorine consumption with several reactions illustrated in above equations reveals the need for disinfectant addition to meet minimum residual levels at consumer nodes. In conventional method of disinfectant injection to the network, the only control and addition point of the disinfectant is the source. In order to meet minimum disinfectant residual requirement at a far point of the network, the chlorine injection is achieved

only from source point with high concentrations. Thus, conventional addition of the disinfectant, i.e. from the source, results in non-uniform distribution of the disinfectant since high residual concentrations occur at some places along the network to meet minimum residuals at far locations.

Such a problem puts the booster disinfection method of application into practice to solve residual maintenance all over the network while providing more uniform distribution of the residuals. As shown in Figure 2.2, in this application of booster disinfection, "booster location(s)" are placed along the network in specified locations and disinfectant is added into pipe flow to maintain disinfectant residual within desired values in the water distribution network.

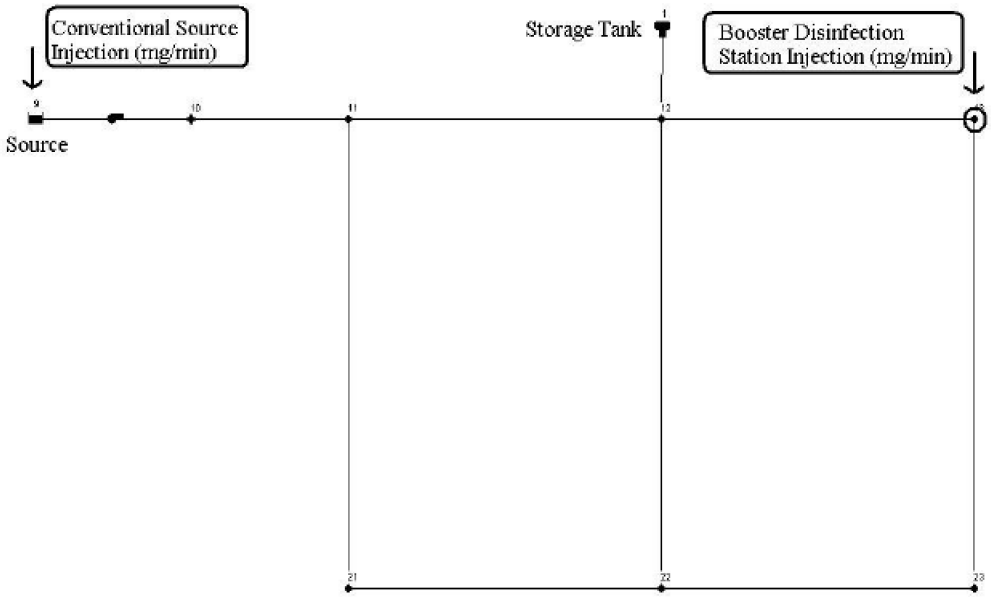


Figure 2.2: Simple Scheme for a Booster Disinfector

Booster stations are simply injecting necessary disinfectant dosage from the node on which it is placed in addition to the source chlorination. To understand the methodology, consider the mass balance through a booster node as shown in Figure 2.3. Node i, completely mixes input flows with the disinfectant dosage, $u_i(t)$, injected at the booster station. Thus the resultant concentration $C_{j,out}$ assigned to all flows leaving the node i , will be:

$$C_{j,out}(t) = \frac{1}{Q_{j,out}(t)} \sum_{j=1}^{N} Q_j(t) C_j(t) + \frac{1}{Q_{j,out}(t)} u_i(t) \tag{2.10}$$

where, Q_j = flow in pipe j (L^3/T) and $j = 1, 2, ...N$, N is the number pipes con-

necting the node i, C_j= disinfectant concentration entering or leaving node i (M/L^3), and u_i= mass dosage rate of the booster station (M/T). The first term in the Equation 2.10 represents the input concentration contributions into node i. The second term on the right is the concentration addition due to booster mass dosage u_i.

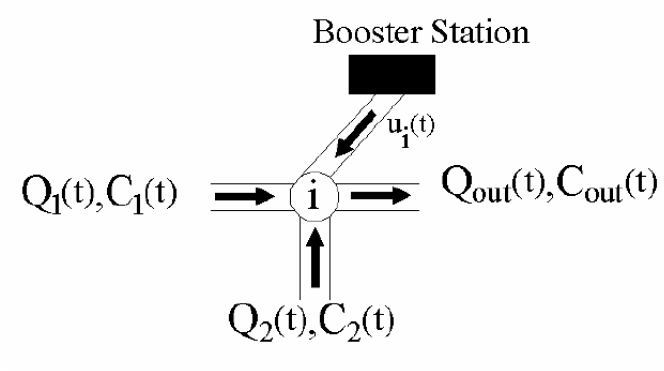


Figure 2.3: Booster Station Operation Analogy

At the earlier stage representation of the booster chlorination for the water quality simulation models was difficult and approximate since disinfectant material could only be injected to the network by adding a negative demand, i.e. inflow, with specified concentration. This behavior was limiting the actual behavior of the booster disinfection stations. Then, new computer simulation models for different types of booster station operations are developed. Recent models could allow the designers to simulate the booster disinfection stations which closely represents the actual operation.

Operational characteristics of the booster stations should also be known well in water quality modelling of the municipal water distribution network with booster disinfectors. Booster disinfection stations operate differently by considering their feeder mechanism to the network. Regulation strategy for the desired disinfectant dosage through booster disinfection stations is the main factor which determines type. Booster disinfectors are of three main types according to their operation principles: (1) mass booster, (2) flow paced booster, and (3) set point booster.

2.3.1 Mass Booster

Mass type of booster representation is used for a disinfectant feeder which is set to add fix mass dosage to the node regardless of the flow or concentration into the node as shown in Figure 2.4. The concentration out of the booster injection node given as:

$$C_o = \frac{\sum Q_i C_i + M}{\sum Q_i} \tag{2.11}$$

where,

C_o = concentration at and out of node i (M/L^3)

Q_i = flow into the node i (L^3/T)

C_i = concentration into the node i (M/L^3)

M = mass rate injected into the node i (M/T)

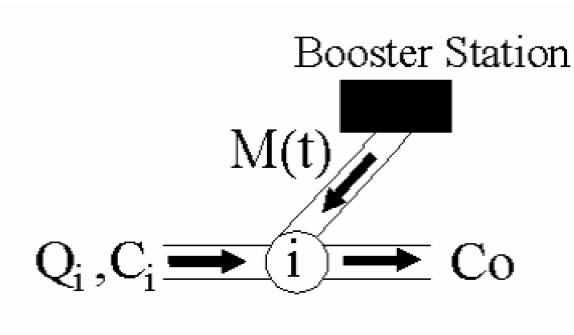


Figure 2.4: Mass Booster Operation Analogy

2.3.2 Flow Paced Booster

Flow paced or flow proportional booster type adds a variable mass dosage to the input node to rise the input concentrations to a set concentration value. In other words flow paced booster adds a fixed concentration to the mixing of all inflows into the injection node as shown in Figure 2.5. Resulting concentration out of the booster node is given as:

$$C_o = \frac{\sum Q_i C_i}{\sum Q_i} + C_f \tag{2.12}$$

where,

Cf = increase in the concentration at node i (M/L^3).

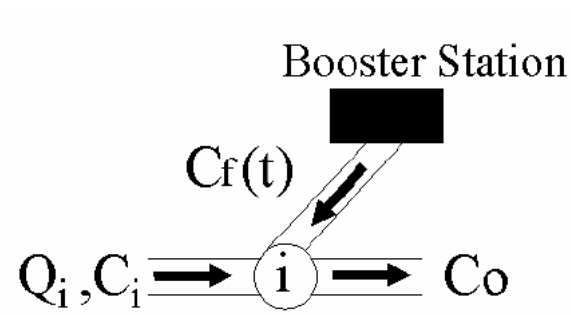


Figure 2.5: Flow Paced Booster Operation Analogy

2.3.3 Set Point Booster

Set point type of booster stations are used for the controlling feed rate. This type of booster stations adds necessary amount of the disinfectant to set the concentration of any flow leaving the node to a desired value, as long as the concentration of the inflows to the node is below the set-point at the booster location. Thus the outflow concentration could be written as:

$$C_o = \begin{cases} C & C_m < C \\ C_m & C_m \geq C \end{cases} \tag{2.13}$$

where,

C_o = concentration at and out of node i (M/L^3)

$C_m = \sum Q_i C_i / \sum Q_i$, concentration without any injection, due to mixing alone (M/L^3)

C = outflow concentration setpoint (M/L^3).

2.4 Disinfectant Mixing in Storage Tank

Chlorine residual dynamics in water storage tanks should also be considered in the water quality analysis. Contribution of large amount of water into and out of tank and its disinfectant concentration effects the nodal disinfectant residuals significantly throughout the water distribution network. The concentration of the disinfectant within a day varies because the chlorine inflows to the storage tank and then outflows from the tank while exposing continuous mixing with large amount of water in storage. The behavior of the mixing should be defined. The simplest form of mixing is used in this study as "Complete Mixing Model".

This model assumes, all water entering the tank instantaneously and completely mixes with the water already in the tank. In water quality analysis, the tank mixing options are provided in the simulation software EPANET [9].

2.5 Network Model and Linear Superposition Principle

By considering the dynamics for system hydraulics, water quality modelling as chlorine concentration through pipes, nodes and within the tanks, general disinfection model expression for the water distribution network is derived in this section. Boccelli et al. [5] have shown that the output concentrations obtained in dynamic hydraulics of the

water distribution network can be described using linear system theory by assuming first order decay kinetics of the chlorine. The output concentrations at points in the network are linear superposition of the responses to individual injection mass dosages. The following illustration makes this finding more clear. Consider three nodes; named 1, 2 and 3 as shown in Figure 2.6. Disinfectant addition is held out from nodes 1 and 2 as u_1 and u_2 which are injected mass dosage rates (M/T). Assume the residence times of disinfectant from node 1 to 3 is t_{13} and the residence time between node 2 to 3 is t_{23}. The discharges from node 1 to junction and node 2 to junction are Q_1 and Q_2, respectively.

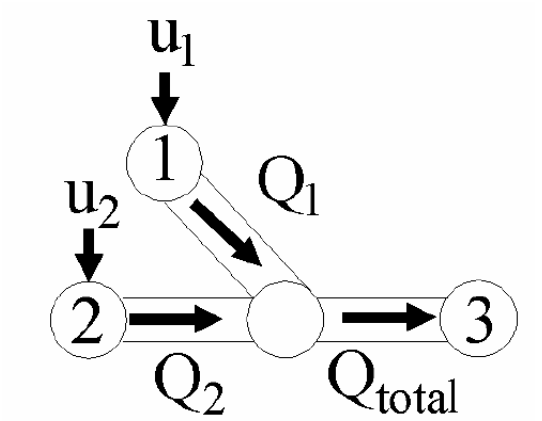


Figure 2.6: Linear superposition of individual output concentrations

The concentration for the nodes 1 and 2 could be calculated by their fraction of mass rates u_i , to the discharges Q_i, as $C_i = {}^{u_i}/_{Q_i}$. The decay of the disinfectant through the links 1 to 3 and 2 to 3 is modelled by assuming first order decay kinetics defined in Equation 2.8 with a decay constant of b . Thus the concentration entering to the node 3 from node 1 becomes, ${}^{(C_1 e^{-bt_{13}} Q_1)}/_{(Q_1+Q_2)}$ and similarly the concentration coming from the node 2 to 3 is, ${}^{(C_2 e^{-bt_{23}} Q_2)}/_{(Q_1+Q_2)}$. As a result the total concentration entering node 3 will be, $C_3 = {}^{(C_1 e^{-bt_{13}} Q_1 + C_2 e^{-bt_{23}} Q_2)}/_{(Q_1+Q_2)}$.

Linear superposition implies the effect of any individual mass rate u_i, on concentration C_i, is linear in u_i with $\alpha = {}^{\partial C}/_{\partial u}$ which is called response coefficients [13]. Response coefficients define the effect of dosage u_i, on the concentration C_i at monitoring node i . In the previous illustration shown in Figure 2.6, the response coefficients are $\alpha_{13} = {}^{C_3}/_{u_1}$ and the $\alpha_{23} = {}^{C_3}/_{u_2}$. These are the effects of the injection mass dosages u_1 at node 1 and u_2 at node 2 to the concentration of node 3, C_3. Linear superposition of individual responses allows the summation of each booster location effect along the monitoring nodes

in which the chlorine concentrations to be checked. Thus, if the two individual responses of the nodal injections are known and available, no further water quality simulations are needed to determine combined response of those. The separate individual responses are just added to obtained combined response to the third node. The combined response corresponding to any multiple of the known injections could be directly obtained by multiplying the separate responses before adding them. For instance, if the individual injections in above illustration in Figure 2.6, u_1, u_2 are doubled, combined response at node 3 is simply obtained by doubling of the individual responses, then adding them. However,the linear superposition of the injections is valid in certain assumptions which will be defined and clarified in Chapter 3.3 under Assumptions subsection.

CHAPTER 3

OPTIMAL BOOSTER DISINFECTION SCHEDULING

Water quality analysis requires detailed knowledge about the variations within the water distribution network such as water demands, pipe flows (both discharge and direction), and storage volumes in tanks because of their direct and subsequent effect on disinfectant concentrations. Booster disinfection facility operation and scheduling are also affecting the concentrations in municipal water distribution networks.

The main purpose of the booster disinfection facility is to provide water with proper quality to the consumers with minimum variation. If the disinfectant injected to the network, i.e. chlorine, does not decay over the time when it travels, every demand node and consumer would receive water with required quality and exposed to a concentration within the limits. However, chlorine is depleted over the time and required concentrations could not be provided along certain places of water distribution networks. Decay of the disinfectant results in residual variation both in space and time. Thus proper scheduling of the booster disinfection facility which applies minimum mass dosage injection to overcome this variation is necessary.

3.1 Model Formulation

The objective of the optimal scheduling of the booster disinfection stations is provision of the minimum disinfectant residuals all over the network while minimizing the disinfectant mass applied. The number of the booster stations and the mass dosage applied are the parameters which are related to the cost of constructing and operating of the facility. Here the decision variables are the location of booster disinfection stations and their injection rates for a typical daily operation.

There are two formulations applied in this research. In the first formulation the existing conditions and actual concentration values of the water distribution network is not considered. The optimal analysis achieved as if the network is operated from the beginning with known physical components and operation characteristics. Thus, it is more theoretical. In the second formulation, the initial concentrations existing in the actual network is taken into account. The final concentrations at the end of typical day is forced to be equal to the initial concentration in this formulation.

3.1.1 Formulation 1

Consider a water distribution network where there are ir consumer nodes and n_b number of possible booster locations, n_s number of source locations and n_t dosage schedule time intervals within typical daily operation of booster with step size of Δt. All consumer demand nodes are considered as monitoring locations in this research. In other words, the disinfectant limits will be checked for all consumer demand nodes. The aim of the optimal scheduling of booster station is the minimization of the total mass of chlorine supplied to the system. Thus,

Minimize total mass injected:

$$= \sum_{j=1}^{n_t} \sum_{i=1}^{n_b+n_s} (u_i^j)\Delta t \tag{3.1}$$

Subject to the constraints for the required residual concentration provision:

$$\underline{C} \leq C_{ir,tr} = \sum_{j=1}^{n_t} \sum_{i=1}^{n_b+n_s} \alpha_{ir,tr}^{i,j} u_i^j \leq \overline{C} \tag{3.2}$$

for all ir response locations and tr monitoring times.

Also additional mathematical constraints for the non-negativity of the injections should be introduced:

$$u_i^j \geq 0 \tag{3.3}$$

In Equation 3.1, the decision variable is the injection mass rates, u_i^j. Where, u_i^j= mass injection rate (M/T) at booster or source location i, at time j and Δt = time step duration (T). Their product gives the total mass dosage supplied to the water distribution network from location i and at time j (M). The total mass dosage injected to the water distribution network is the summation over the time period of n_t and the number of booster stations and sources, $n_b + n_s$.

In Equation 3.2 the constraints for the problem are defined. The nodal concentrations, $C_{ir,tr}$ (M/L^3) should be between in upper and lower limits $\overline{C}$ and $\underline{C}$, for all response nodes ir and monitoring time tr . As illustrated in Chapter 2.5, in Figure 2.6, the effect of the individual injections to the response nodes could be represented as linear functions of the injections, u. Thus if, u_i^j units of chlorine is added from location i, at time j; the total response at the monitoring node ir will be $\alpha_{ir,tr}^{i,j} u_i^j$. Here the $\alpha_{ir,tr}^{i,j} = {}^{\partial C_{ir,tr}}/_{\partial u_i^j}$ is the response coefficient $[(M/L^3)/(M/T)]$, which refers to the chlorine change at the monitoring location ir, at monitoring time tr corresponding to the unit injection at the booster or a source location i, at time j. As a result by means of a simple summation shown in Equation 3.2, the concentration values at all monitoring nodes for all times corresponding to each booster location and injection period are available.

3.1.2 Formulation 2

In this formulation additional constraint for the initial concentrations, $C_{ir,0}$ is introduced to the above formulation. This approach of solution includes the existing disinfectant amount within the water distribution networks into the optimization problem. The initial concentrations of the water distribution network are included in this formulation as decision variables by forcing the initial concentration of the nodes to be equal to the final boosted concentration as;

$$C_{ir,0} = C_{ir,final} \tag{3.4}$$

Determination of response coefficients, $\alpha_{ir,tr}^{i,j}$ for the booster and source injections along the water distribution network, requires the cyclical steady state conditions [5], which will be further discussed in Part 3.3.3 in detail. Then the total simulation time need for the system to reach steady state conditions is thought to be reduced [8] by forcing this equality in Equation 3.4.

Since the effect of initial concentrations are also added to the problem as a decision variable, the impact coefficients corresponding to the initial concentrations, ε; similar to regular response coefficients, α of the disinfectant sources should be introduced in the formulation as,

$$\underline{C} \leq C_{ir,tr} = \sum_{j=1}^{n_t} \sum_{i=1}^{n_b+n_s} \alpha_{ir,tr}^{i,j} u_i^j + \sum_{rn=1}^{NNODES} \varepsilon_{ir,tr}^{rn} C_{rn,0} \leq \overline{C} \tag{3.5}$$

where, $\varepsilon_{ir,tr}^{rn}$ is the impact coefficient of the initial concentration at $time = 0$ of the node rn, to the node ir, at time tr. The value of $C_{rn,0}$ is introduced as decision variable to be solved similar to periodic injections, u_i^j in the problem. The effect of the initial concentrations are also linear and the impact coefficients $\varepsilon_{ir,tr}^{rn}$, could be presented as the linear functions of the initial concentrations, $C_{rn,0}$.

3.2 Problem Solution

The relationship of $C_{ir,tr} = \sum_{j=1}^{n_t} \sum_{i=1}^{n_b+n_s} \alpha_{ir,tr}^{i,j} u_i^j$ in Equation 3.2 in the first formulation and $C_{ir,tr} = \sum_{j=1}^{n_t} \sum_{i=1}^{n_b+n_s} \alpha_{ir,tr}^{i,j} u_i^j + \sum_{rn=1}^{NNODES} \varepsilon_{ir,tr}^{rn} C_{rn,0}$ relation in Equation 3.5 in formulation 2 are linear and with equation of the objective function 3.1 becomes a linear programming (LP) problem. The constraints are simple upper and lower constraints. However, complexity of the problem arises with the scheduling time horizon, n_t and the number of booster stations, n_b.

Since the solution consists of the finite time scheduling period, the problem size of the linear programming could be determined. Consider a network with ir consumer nodes called monitoring or response nodes, n_b possible booster locations with j different injection intervals. Then the number of water quality simulation required for the determination of response coefficients α is $n_b \times j$. Similarly, the number of water quality simulations for the impact coefficients ε, due to initial concentration effect will be equal to j. Single simulation for the initial quality is enough for the impact coefficients ε. As a numerical example suppose a network with $ir = 30$ nodes and there are two possible booster disinfection station locations as $n_b = 2$. Along each booster location disinfectant is added to the distribution system for a typical daily scheduling with total of 24 h for every 1 h interval. Then the response of these 2 booster stations to the 30 consumer response nodes can be determined by running the distribution system for each injection period separately, thus 24 times for each booster location, i.e 24x2 = 48 times.

In addition to the number of simulations required, the concentration at the consumer nodes (i.e. response nodes) are also to be checked in the LP problem as a constraint to satisfy necessary disinfectant residuals at water user nodes. As a result at every consumer node ir, the concentration is checked at every monitoring time interval tr.

3.2.1 Mathematical LP formulation

3.2.1.1 LP for Formulation-1

Consider a case shown in Figure 3.1 in which a disinfectant concentration of $C_{i,j_1} = {}^{u_i^j}/_{q_i^j}$ is injected at a booster station i.

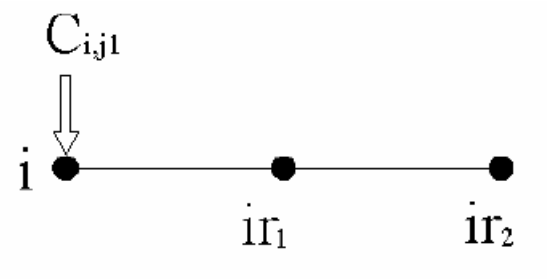


Figure 3.1: Illustration of Response for a Single Booster Station

The resultant of the injected mass dosage at booster location u_i^j, to the monitoring consumer nodes ir_1 and ir_2 at time j_1 are C_{ir_1,j_1} and C_{ir_2,j_1} respectively. The response coefficients corresponding to these mass dosage injections to the monitoring nodes are, $\alpha_{ir_1,tr}^{i,j_1}$ and $\alpha_{ir_2,tr}^{i,j_1}$. There will be 24 different injections for a typical daily operation of the booster station while selecting the injection time interval as 1 h. Thus in vector notation the periodic injections for one booster disinfection station will be:

$$U = \left[u_1^1, u_1^2, ..., u_1^{23}, u_1^{24}\right] \tag{3.6}$$

Similarly if there are two booster locations specified in the formulation the vector form of 3.6 becomes:

$$U = \left[u_1^1, u_1^2, ..., u_1^{23}, u_1^{24}, u_2^1, u_2^2, ..., u_2^{23}, u_2^{24}\right] \tag{3.7}$$

Consider also a water distribution network in which concentration of consumer demand nodes, so called monitoring nodes are checked in every 1 h interval resulting in $tr = 1, 2, ...23, 24$. As a result for every injection of the booster station say u_1^1, there are 24 different response coefficients at a monitoring node ir_1 in vector notation as:

$$A^{1,1}_{ir_1,tr} = \begin{bmatrix} \alpha^{1,1}_{ir_1,1} \\ \alpha^{1,1}_{ir_1,2} \\ . \\ . \\ . \\ \alpha^{1,1}_{ir_1,24} \end{bmatrix} \tag{3.8}$$

Then response coefficient vector form for two monitoring consumer nodes ; $ir_1$and ir_2 for the first injection u^1_1 at the booster disinfection station will be:

$$A^{1,1}_{ir,tr} = \begin{bmatrix} \alpha^{1,1}_{ir_1,1} \\ \alpha^{1,1}_{ir_1,2} \\ . \\ . \\ \alpha^{1,1}_{ir_1,24} \\ \alpha^{1,1}_{ir_2,1} \\ \alpha^{1,1}_{ir_2,2} \\ . \\ . \\ \alpha^{1,1}_{ir_2,24} \end{bmatrix} \tag{3.9}$$

The final matrix form of the response coefficients $\alpha^{i,j}_{ir,tr}$ for all injections, u^j_i at the booster location(s) to all monitoring nodes $ir = 1, 2, ..., number\, of\, nodes\, in\, network$ for all times, $tr = 1, 2, ..., 24$ will be:

$$
A = \begin{bmatrix}
\alpha^{i=1,j=1}_{ir_1,tr=1} & .. & \alpha^{1,24}_{ir_1,1} & \alpha^{i=2,j=1}_{ir_1,1} & .. & \alpha^{2,24}_{ir_1,1} & .. & \alpha^{n_b,23}_{ir_1,1} & \alpha^{n_b,24}_{ir_1,1} \\
\alpha^{1,1}_{ir_1,2} & .. & \alpha^{1,24}_{ir_1,2} & \alpha^{2,1}_{ir_1,2} & .. & \alpha^{2,24}_{ir_1,2} & .. & \alpha^{n_b,23}_{ir_1,2} & \alpha^{n_b,24}_{ir_1,2} \\
. & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & . \\
\alpha^{1,1}_{ir_1,23} & .. & \alpha^{1,24}_{ir_1,23} & \alpha^{2,1}_{ir_1,23} & .. & \alpha^{2,24}_{ir_1,23} & .. & \alpha^{n_b,23}_{ir_1,23} & \alpha^{n_b,24}_{ir_1,23} \\
\alpha^{1,1}_{ir_1,24} & .. & \alpha^{1,24}_{ir_1,24} & \alpha^{2,1}_{ir_1,24} & .. & \alpha^{2,24}_{ir_1,24} & .. & \alpha^{n_b,23}_{ir_1,24} & \alpha^{n_b,24}_{ir_1,24} \\
\alpha^{1,1}_{ir_2,1} & .. & \alpha^{1,24}_{ir_2,1} & \alpha^{2,1}_{ir_2,1} & .. & \alpha^{2,24}_{ir_2,1} & .. & \alpha^{n_b,23}_{ir_2,1} & \alpha^{n_b,24}_{ir_2,1} \\
\alpha^{1,1}_{ir_2,2} & .. & \alpha^{1,24}_{ir_2,2} & \alpha^{2,1}_{ir_2,2} & .. & \alpha^{2,24}_{ir_2,2} & .. & \alpha^{n_b,23}_{ir_2,2} & \alpha^{n_b,24}_{ir_2,2} \\
. & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & . \\
\alpha^{1,1}_{ir_2,23} & .. & \alpha^{1,24}_{ir_2,23} & \alpha^{2,1}_{ir_2,23} & .. & \alpha^{2,24}_{ir_2,23} & .. & \alpha^{n_b,23}_{ir_2,23} & \alpha^{n_b,24}_{ir_2,23} \\
\alpha^{1,1}_{ir_2,24} & .. & \alpha^{1,24}_{ir_2,24} & \alpha^{2,1}_{ir_2,24} & .. & \alpha^{2,24}_{ir_2,24} & .. & \alpha^{n_b,23}_{ir_2,24} & \alpha^{n_b,24}_{ir_2,24} \\
. & . & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . & . \\
\alpha^{1,1}_{ir_N,24} & .. & \alpha^{1,24}_{ir_N,24} & \alpha^{2,1}_{ir_N,24} & .. & \alpha^{2,24}_{ir_N,24} & .. & \alpha^{n_b,23}_{ir_N,24} & \alpha^{n_b,24}_{ir_N,24}
\end{bmatrix} \tag{3.10}
$$

where $n_b + n_s$, is the total number of booster disinfection stations and source locations, and ir_N is the total number of consumer monitoring nodes along which the disinfectant residual concentrations will be controlled. For a further understanding, consider the element highlighted as red which is $\alpha^{2,24}_{ir_2,2}$ in above matrix. This response coefficients refers to the response of booster $i = 2$, due to its injection u_2^{24} occurs at time $j = 24$ to the monitoring node ir_2 at time $tr = 2$.

Obtained vector notation along Equations 3.6 and 3.10 in finite time interval is adequate for the solution of formulation-1 in Equations 3.1 and 3.2. By rewriting the objective function and the constraint in vector notation for the formulation 1 gives the LP problem as;

Objective function:

$$
Minimize\ Z = \sum_{j=1}^{n_t} (U^T) \tag{3.11}
$$

Subject to constraints:

$$
\underline{C} \leq C = A\,U^T \leq \overline{C} \tag{3.12}
$$

$$U^T \geq 0$$

Where, U^T is the column vector of the individual booster injections u_j^i, A is the response coefficient matrix shown in 3.10, C is the column vector of concentration values at consumer demand nodes for all times tr, $\underline{C}$ and $\overline{C}$ are the column vectors of constant limit concentration values as bound constraints.

3.2.1.2 LP for Formulation-2

By considering formulation-2, the only change occurs in the LP formulation in Equation 3.12 due to intrusion of the initial quality effects as impact coefficients, ε. As explained previously the initial concentrations $C_{ir,0}$, are introduced as decision variables to the problem. The problem will try to solve for the initial concentrations for all consumer response nodes. Thus number of initial quality values, $C_{ir,0}$ to be solved in the LP problem is equal to the total number of consumer nodes exists in the water distribution network i.e. ir_N. In vector notation the initial concentrations described as;

$$C^0 = [C_{ir_1,0}, C_{ir_2,0}, ..., C_{ir_{N-1},0}, C_{ir_N,0}] \tag{3.13}$$

Similar to the response coefficients, the impact coefficient matrix of the initial concentration, $\varepsilon_{ir,tr}^{rn}$ should also be developed for the LP solution. Consider an effect of the initial concentration of the node $rn = ir_1$ to all consumer nodes, $ir = 1$ to ir_N and for all times $tr = 1, 2, ..., 24$. Then the vector form of impact coefficients $\varepsilon_{ir,tr}^{rn=1}$ will be,

$$E_{ir,tr}^{ir_1} = \begin{bmatrix} \varepsilon_{ir_1,1}^{ir_1} \\ \varepsilon_{ir_1,2}^{ir_1} \\ . \\ \varepsilon_{ir_1,24}^{ir_1} \\ \varepsilon_{ir_2,1}^{ir_1} \\ \varepsilon_{ir_2,2}^{ir_1} \\ . \\ \varepsilon_{ir_N,24}^{ir_1} \end{bmatrix} \tag{3.14}$$

Then the general form of the impact coefficient, $\varepsilon_{ir,tr}^{rn}$ matrix defining the initial concentration effect of all nodes, $rn = 1, 2, ..., ir_N$ to other consumer monitoring nodes $ir = 1, 2, ..., ir_N$ for all times $tr = 1, 2, ..., 24$ is:

$$E = \begin{bmatrix} \varepsilon^{rn=1}_{\substack{ir=1\\tr=1}} & \varepsilon^{2}_{1,1} & \varepsilon^{3}_{1,1} & . & . & \varepsilon^{rn=ir_N}_{1,1} \\ \varepsilon^{1}_{1,2} & \varepsilon^{2}_{1,2} & \varepsilon^{3}_{1,2} & . & . & \varepsilon^{ir_N}_{1,2} \\ \varepsilon^{1}_{1,3} & \varepsilon^{2}_{1,3} & \varepsilon^{3}_{1,3} & . & . & \varepsilon^{ir_N}_{1,3} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ \varepsilon^{1}_{1,24} & \varepsilon^{2}_{1,24} & \varepsilon^{3}_{1,24} & . & . & \varepsilon^{ir_N}_{1,24} \\ \varepsilon^{1}_{\substack{ir=2\\tr=1}} & \varepsilon^{2}_{2,1} & \varepsilon^{3}_{2,1} & . & . & \varepsilon^{ir_N}_{2,1} \\ \varepsilon^{1}_{2,2} & \varepsilon^{2}_{2,2} & \varepsilon^{3}_{2,2} & . & . & \varepsilon^{ir_N}_{2,2} \\ . & . & . & . & . & . \\ \varepsilon^{1}_{2,24} & \varepsilon^{2}_{2,24} & \varepsilon^{3}_{2,24} & . & . & \varepsilon^{ir_N}_{2,24} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ \varepsilon^{1}_{ir_N,24} & \varepsilon^{2}_{ir_N,24} & \varepsilon^{3}_{ir_N,24} & . & . & \varepsilon^{ir_N}_{ir_N,24} \end{bmatrix} \tag{3.15}$$

Each element of the above matrix defines the effects of the initial concentration of a certain node rn, to the other nodes, $ir = 1, 2, ..., ir_N$ for all times, tr. Consider the element highlighted in red which is $\varepsilon^{3}_{2,24}$. This impact coefficient refers to the initial concentration effect of the node $rn = 3$, to the node $ir = 2$ at the time $tr = 24$. Similar to the formulation-1, the objective function and the constraints for the formulation-2 by adding the impact coefficients could be rewritten in vector form as;

Objective function:

$$Minimize\ Z = \sum_{j=1}^{n_t} (U^T) \tag{3.16}$$

Subject to constraints:

$$C_{ir,0} = C_{ir,final} \tag{3.17}$$

$$\underline{C} \leq C = A\,U^T + E\,[C^0]^T \leq \overline{C} \tag{3.18}$$

$$U^T \geq 0$$

where, $C_{ir,0}$ is the initial concentration at the response node, ir, $C_{ir,final}$ is the final concentration at the response node, ir, U^T is the column vector of the individual booster injections u^i_j, A is the response coefficient matrix shown in 3.10, C is the column vector

of concentration values at consumer demand nodes for all times tr, E is the impact coefficient matrix shown in 3.15, $(C^0)^T$ is the column vector of initial concentration values of consumer demand nodes, $\underline{C}$ and $\overline{C}$ are the column vectors of constant limit concentration values as bound constraints.

3.2.2 Calculation of Response and Impact Coefficients

The problem size of the optimal scheduling of the booster disinfection stations depends on the network size and the number of boosters as well as scheduling and monitoring time intervals. The main overburden in the problem is the determination of the response coefficients, α and the initial concentration impact coefficients, ε. One water quality simulation is needed to obtain responses of each consumer nodes within the water distribution network for each booster disinfection station injection at a certain time.

3.2.2.1 Calculation of Response Coefficients, α

Response coefficients, $\alpha_{ir,tr}^{i,j}$ are required for all input mass dosages u_i^j for all booster locations. Providing linearity and periodicity assumptions, which are to be illustrated in the next part, are satisfied, the response coefficients $\alpha_{ir,tr}^{i,j}$ can be computed numerically. Stepwise procedure is;

1. Select the number of injection intervals $j \times \Delta t$ in a dosage cycle of the booster disinfection station.

2. Start with a potential booster location, $i = 1$.

3. Select the booster disinfector type to be used (mass booster or a flow paced booster)

4. Start the injection with dosage time period $j = 1$ as shown in Figure 3.2a.

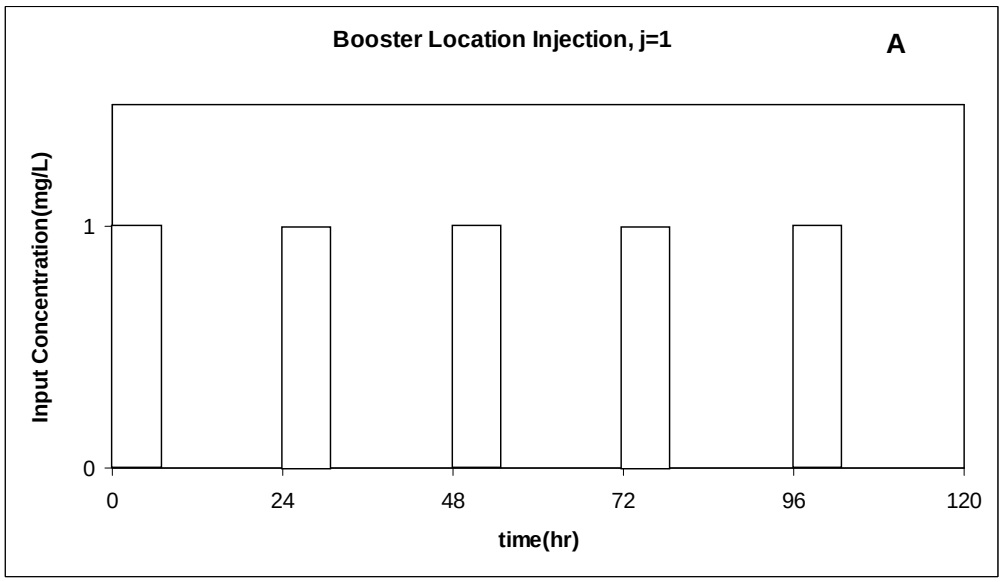
5. Select a proper dosage injection rate u_i^j, and set all other booster disinfection injections rates to zero.

6. Run a long-term water quality simulation until the average concentrations becomes constant as can be seen in Figure 3.2b.

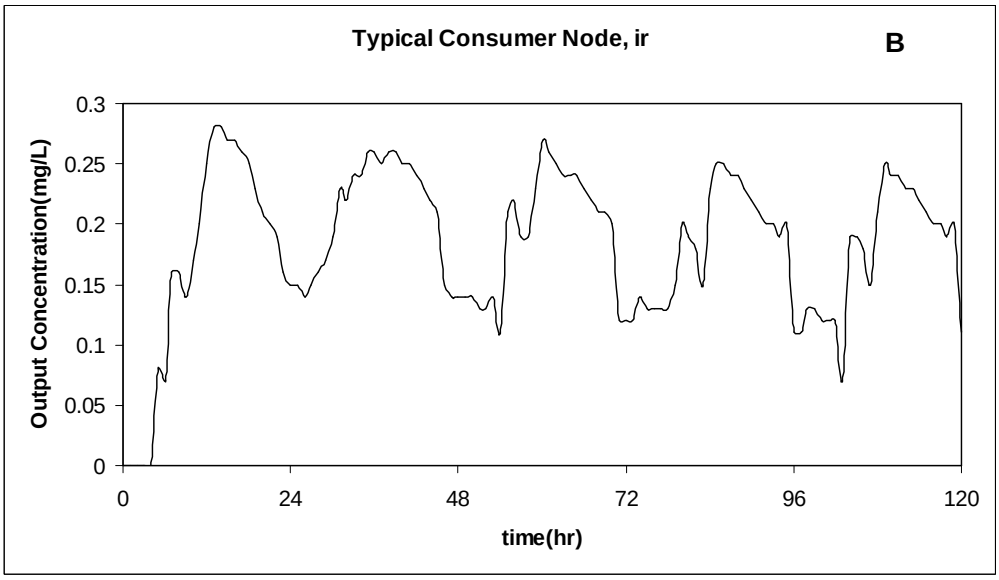
7. Store $\alpha_{ir,tr}^{i,j} = C_{ir,tr}/u_i^j$ for monitoring consumer nodes and tanks $ir = 1, 2, ..., ir_N$ for each monitoring time $tr = 1, 2, ..., 24$. Where the $C_{ir,tr}$ are the simulated concentrations in step 6.

8. Repeat steps 4-7 for the increment j by one until $j = n_t$ for the booster location i (i.e. for a typical daily injection, $n_t = 24$)

9. Repeat steps 2-8 for the increment i by one for all possible booster disinfection station locations.



(a)



(b)

Figure 3.2: Example calculation of response coefficient $\alpha_{ir,tr}^{i,j}$

Once all the response coefficients are determined formulation-1 LP problem can be solved with known vectors of $\alpha_{ir,tr}^{i,j}$ for decision variables of u_i^j with concentration values at monitoring user nodes as constraints.

3.2.2.2 Calculation of Impact Coefficients, ε

Similar to the response coefficients, impact coefficients, ε can be computed numerically by imposing an initial concentration at time = 0 in the water quality analysis. The effect of the initial concentrations to all response nodes are determined after water quality simulation for all monitoring times. However, a problem occurs while determining of the impact coefficients for a water distribution network. Once a unit concentration value is imposed at time = 0, the concentration of disinfectant starts to decay with water quality simulation time. After a certain time there will be no initial concentration effect. Similar to the response coefficients, $\alpha_{ir,tr}^{i,j}$, the impact coefficients should be determined just after the periodicity of the system hydraulics has maintained. However, when a unit injection for the impact coefficient has done at time = 0, there will be no concentration value before the system reaches cyclic condition as seen in Figure 3.3. Thus, one could not obtain the impact coefficient values, ε with a direct water quality simulation run. Such a problem is solved by starting the water distribution system with cyclic condition at time = 0 and running the system for 24 h. The procedure is:

1. Set the storage tank initial elevation to the value at which the system reaches the cyclic hydraulic condition.

2. Start with the node on which the initial concentration is to be set as $rn = 1$.

3. Set the initial quality of the node which is set in step 1 (i.e. rn) to unity.

4. Run the water quality analysis for 24 h.

5. Record the $\varepsilon_{ir,tr}^{rn} = C_{ir,tr}$ for all monitoring consumer nodes and tanks, and for all times, $tr = 1, 2, ..., 24$.

6. Increment rn by one in step 1, repeat steps 2-5 for all $rn = 1, 2, ..., ir_N$.

Since all the impact coefficient values, $\varepsilon_{ir,tr}^{rn}$ are computed, formulation-2 LP problem can be solved with the known values of response coefficients $\alpha_{ir,tr}^{i,j}$ for both decision variables of injections, u_i^j and initial concentrations, $C_{ir,0}$.

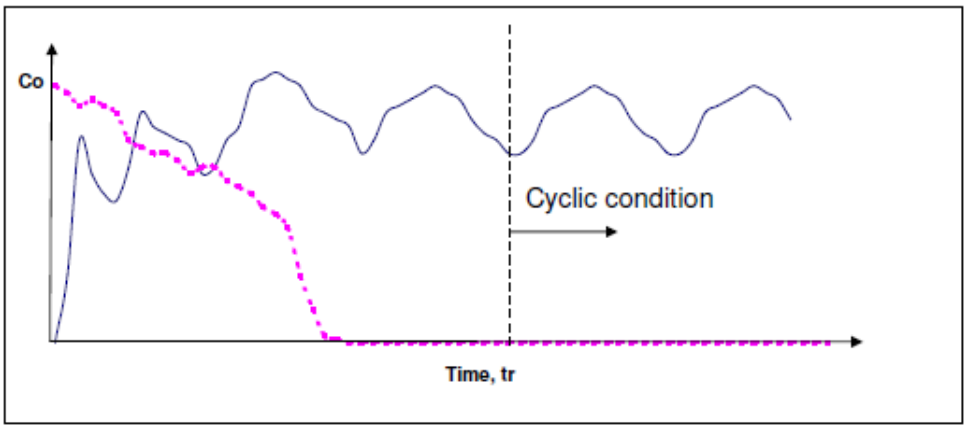


Figure 3.3: Initial Concentration Decay

3.3 Assumptions

The mathematical optimization formulations stated in Equations 3.1, 3.2, 3.4, and 3.5 require certain assumptions. In a water distribution system, the disinfectant residuals at the consumer monitoring nodes are affected significantly from the variations in water demand rates, from tank volumes and the different scheduling of the source or booster disinfection stations excessively. Thus, in order to reduce the complexity of the problem certain assumptions are necessary.

3.3.1 Booster Station Operation and Location

3.3.1.1 Booster Station Operation

The above mathematical formulations are independent from the booster operation type. The stated equations are general for a specified booster disinfector location. Depending on the need of the municipal water distribution network and desired control mechanism, different booster station operation alternatives could be applied as the municipal water distribution disinfection method. Each operation type has some advantages and disadvantages considering their functionality as well as practical application of the operation. As illustrated in Chapter 2.3, there are mainly three types of booster disinfection station classified according to the operation methodology. Mass boosters are the most practical way of application of the booster disinfection station since it adds a fix mass dosage into the flow with a specified schedule. The application and the control mechanism are much more easier than other methods. Flow paced booster type also a practical method of application which requires less control mechanism than set point booster

but more control than the mass booster. In flow paced booster the incoming flow to the booster location should be specified since this type of booster operates by adding flow proportional mass dosage to the water distribution network. As a last alternative, the set point booster operation, which requires much more feedback control than other types, operates according to the defined concentration set value. Set point booster adds concentration to the flow as long as the concentration inflow to the booster below this set point value.

3.3.1.2 Booster Locations

As a practical approach, the above mathematical optimization formulation assumes the known locations of booster disinfection stations. Once the booster disinfection station location(s) are known, the optimization problem becomes independent of the size of the network by considering the mass dosage injection minimization objective. Booster disinfection station locations are not searched. Booster injections for a given booster locations are solved. The potential booster locations are selected by trial water quality simulations by considering the most effective places within the water distribution network such as near the storage tanks, close to sources or at nodes along which the maintenance of the disinfectant residuals is difficult so at the far regions along the network.

3.3.2 Response at Monitoring Location and Linear Decay Kinetics

The main idea of the above optimization model is the linearity of the output concentrations at the consumer monitoring nodes with respect to the input mass dosages added at the booster disinfectant stations. This linearity assumption requires also the first order decay kinetics [5]. The response at the monitoring consumer node is defined as the chlorine residual, $C_{ir,tr}$ at the monitoring location resulting from the booster injection, u_i^j. Boccelli [5] illustrated the time-varying system hydraulics and chlorine dosages as a linear system, by applying linear superposition. Linear superposition principle means that there is a linear influence between the booster station injection and the corresponding response at the consumer monitoring location.

Thus the concentration at the monitoring location $C_{ir,tr}$ could be expressed as a linear function of the input mass dosage u_i^j at the booster location. The linear function is called response coefficient, $\alpha_{ir,tr}^{i,j}$ as stated in above formulations. Mathematically, it is defined as,

$$C_{ir,tr} = \alpha_{ir,tr}^{i,j} \times u_i^j \tag{3.19}$$

3.3.3 Periodicity and Monitoring Time Period

According to the previous works of Boccelli et al. [5] and Tryby et al. [6], periodic hydraulic dynamics and the chlorine injections are required for the solution of the booster disinfection optimization problem. Periodic hydraulic dynamics has reached after a long simulation run time when two successive daily concentration values are equal. The calculation of the response coefficients, $\alpha_{ir,tr}^{i,j}$ is achieved after the periodicity of the water distribution network is attained at every consumer monitoring node. The disinfectant residual concentrations at the monitoring nodes are sampled over a time horizon, T_c which is called impact cycle after the system periodicity is obtained, as demonstrated in Figure 3.4.

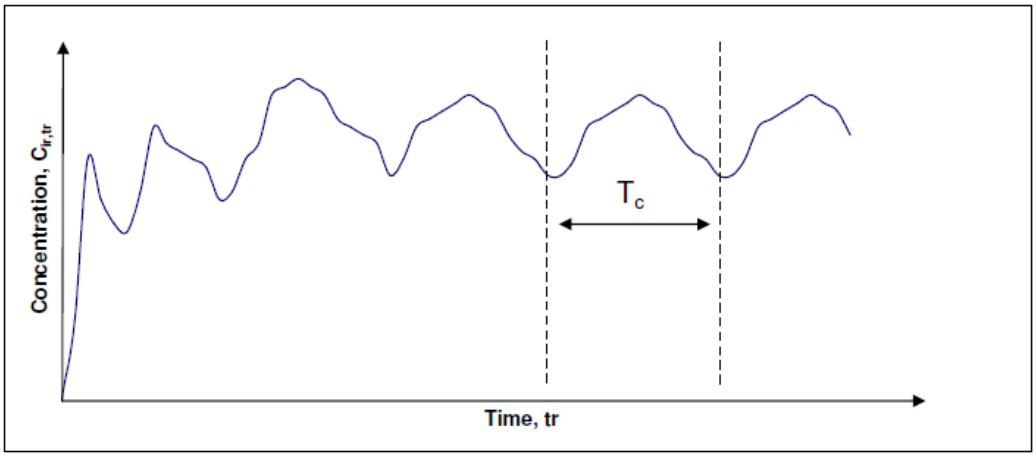


Figure 3.4: Set of Monitoring Times After Periodicity

The response coefficients $\alpha_{ir,tr}^{i,j}$, are considered in the problem when the difference between the response coefficients over two successive impact cycles are insignificant. This insignificance criteria used in this research is the time in which the difference between two successive response coefficients are less than 10^{-5}. Mathematically, response coefficients are used when,

$$|\alpha_{ir}^{imp(t)} - \alpha_{ir}^{imp(t-1)}| \leq 10^{-5} \tag{3.20}$$

where $\alpha_{ir}^{imp(t)}$ is the response coefficients at a certain consumer monitoring node for impact cycle t and $\alpha_{ir}^{imp(t-1)}$ is the response coefficient at the same node for the previous impact cycle $t-1$.

CHAPTER 4

PROGRAM DESIGN AND MODEL APPLICATION

4.1 Program Design

The formulations depending on finite-time consideration along Equations 3.11, 3.12, 3.16, and 3.18 are solvable by means of straightforward methods of the linear programming problems. As stated before the problem size with known locations and number of booster disinfection stations is independent from the network size. The number of decision variables in above formulations are directly the number of booster stations multiplied by the scheduling time intervals, so $n_b \times n_t$. However, the size of the constraint set in the above LP optimization formulations depends on the size of the network through the number of monitoring consumer nodes along which the disinfectant residual concentrations will be checked. The calculation of response coefficients, $\alpha_{ir,tr}^{i,j}$ of the booster injections in the first formulation and the impact coefficients, $\varepsilon_{ir,tr}^{rn}$ in the second formulation for all the consumer nodes for all injection time periods and monitoring time intervals, is the main computational burden of the the linear programming problem.

A code in C++ programming language is developed as an interface with the EPANET version 2.00.10 for the calculation of the response coefficients matrix, A and the impact coefficients matrix, E. The C++ code developed calls the EPANET by means of EPANET programmers toolkit [9], which is a dynamic link library(DLL), as a main program to achieve network hydraulics and the water quality simulations.

4.1.1 Program Development

The code developed with a user interface for the optimal booster disinfection scheduling in Figure 4.1, links the hydraulic and water quality simulation model of the EPANET and the linear programming solver of the MS EXCEL 2002. The response coefficients for the defined booster types, locations and the scheduling times are calculated for a desired municipal water distribution network by means of the program developed. In addition, the effect of the initial concentrations of all nodes in the network, to all consumer nodes are also calculated by means of the program as impact coefficients. The program executable file is given in Appendix-D.

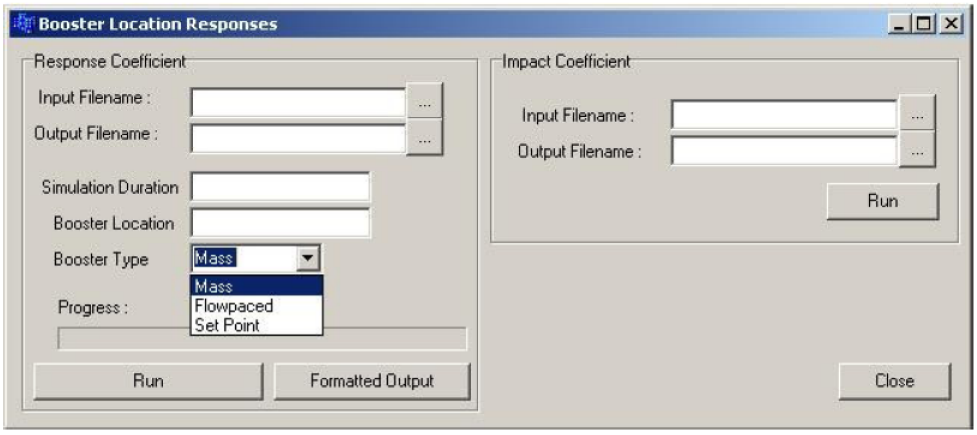


Figure 4.1: User Interface of the Program Developed

The algorithm for the developed program is as follows and as a flow chart in Figure 4.2:

1. The interfacing code basically reads two input files as entries: (a) EPANET input file and (b) booster disinfection station characteristics.

a. EPANET input file includes both physical and chemical network characteristics such as node elevations, pipe lengths and diameters, roughness coefficients, hydraulic and water quality time steps, tank elevations, pump characteristics, demand multipliers,chlorine decay constants. The application model EPANET input file is given in Appendix-C.

b. Booster disinfection characteristics are inputs which could be entered by means of the user interface of the code developed optionally. This file specifies the features of the booster disinfection station design. The entries are the desired location of the booster disinfection stations, booster station operation type, the mass dosage strength of the booster and the simulation duration.

2. Then the program reads the EPANET and booster characteristics as inputs and runs the simulation with a specified duration. Assuming each booster location acts independently, EPANET simulates the water distribution network hydraulics and the water quality to create the disinfectant residual concentrations for all consumer monitoring nodes for all monitoring times. The code reads the last 24 hours of the total simulation duration in order to satisfy the periodicity of the network hydraulics and the stationarity of the residual concentrations.

3. The residual concentrations are then generated as a matrix form of response coefficients $\alpha_{ir,tr}^{i,j}$ as an output of the program, for the linear programming solver of the MS EXCEL 2002.

4. Then necessary constraints for the chlorine limits and mathematical constraints are added to the LP problem in EXCEL. After that the optimal solutions for the total mass dosage applied for each injection period of the booster disinfector is calculated.

4.1.2 Program Verification

Solution of the optimal scheduling of booster disinfection station problem directly depends on the response and impact coefficients values of the water distribution network. Thus, the precise solution of the LP problem is highly effected by the accuracy of calculated response and impact coefficients. As illustrated in the above algorithm of the program developed, the code uses the water quality solver of the EPANET externally. The response and the impact coefficients obtained by the program should be checked with the manually obtained concentration values of the EPANET program. The verification of the coefficients is crucial for not only to check proper operation of the developed program but also to get accurate optimal solution for the scheduling LP problem.

Program verification is held out by using the same input file for the water distribution network for both EPANET and the code and running the system up to the same simulation time at which the coefficients become stationary. After that, the output concentration values obtained from EPANET itself and the code for the last 24 hours are compared. The EPANET program gives the water quality concentration values with two digits. However, the code developed does not have a certain limit for the concentration values. The code is able to calculate the response and impact coefficients up to 20 digits. A sample output for the EPANET and the code can be seen in Table 4.1.

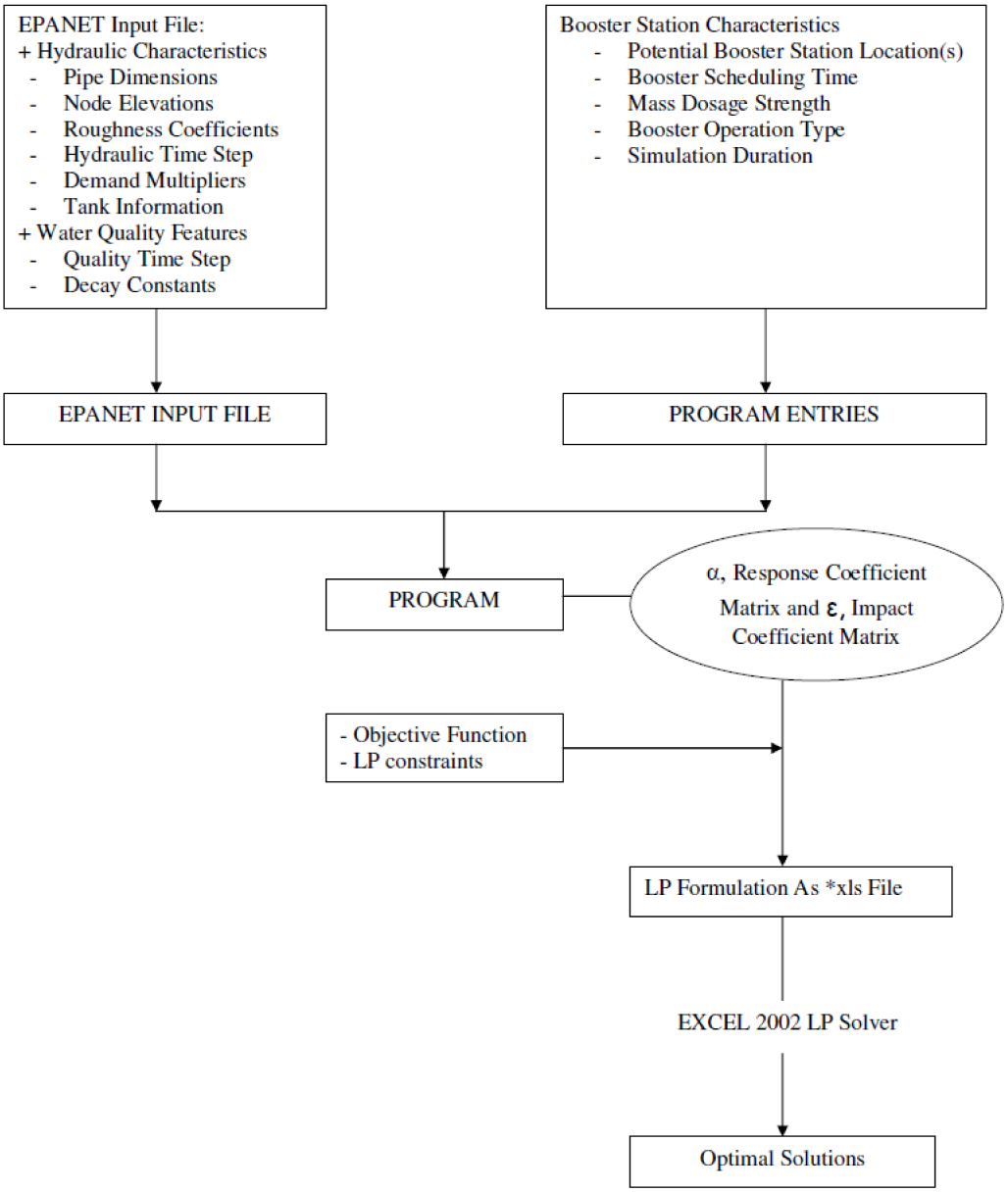


Figure 4.2: Flow Chart of the Program

Table 4.1: Output Precisions of Response Coefficients for a Sample Node

Time	EPANET	Program
0	0.00	0.00448312517255545
1	0.01	0.00966608058661222
2	0.04	0.03606951981782910
3	0.02	0.01969179324805740
4	0.02	0.01920760236680510
5	0.02	0.01853834465146060
6	0.02	0.01888795569539070
7	0.01	0.00684228446334600
8	0.01	0.00667423661798239
9	0.01	0.00651031592860818
10	0.01	0.00635032914578915
11	0.01	0.00619425112381577
12	0.01	0.00604698481038213
13	0.01	0.01269285846501590
14	0.01	0.01220957096666100
15	0.01	0.01239420101046560
16	0.01	0.01157770678400990
17	0.01	0.01179318502545360
18	0.01	0.01101657096296550
19	0.01	0.01074623316526410
20	0.01	0.01048230566084380
21	0.00	0.00483047263696790
22	0.00	0.00471176765859127
23	0.00	0.00459599634632468
24	0.00	0.00448306230828166

The response and the impact coefficients values can be calculated with the help of developed program. Less than an error of 0.005 is obtained in the resultant coefficients when compared to the ones calculated in EPANET. Figure 4.3 shows the coefficient values of developed program and the EPANET software for a sample water distribution network as an input at a representative consumer demand node. Program verification

for the model application of the current study is given in the Appendix-A for the various representative nodes of the application model network of this study.

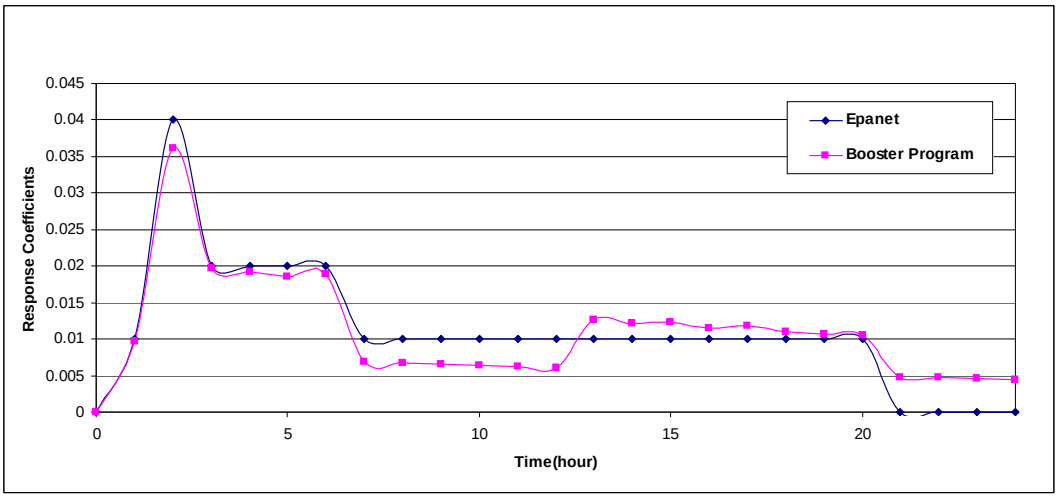


Figure 4.3: Verification of the Coefficients for a Sample Node

4.2 Model Application

A model application system has been designed in order to practice the performance and limitations of the optimal booster disinfection scheduling problem and to check applicability of the developed program for the calculation of response and impact coefficients in a water distribution network. The Brushy Plains water distribution network system (Example network in the EPANET version 2.0) with some modifications is used for the model application of this research. The network, shown in Figure 4.4, includes 34 consumer demand nodes, 1 storage tank, 47 pipes and a source with a pump station. Network represents a residential area of 5.18 km^2 through which the water is supplied from one source via pumps located at Node 1.

4.2.1 Network Hydraulic Model Description

Physical characteristics of the model network such as pipe lengths, diameters and the roughness coefficients are given in Table 4.2. The storage tank is located on Node 26 as completely mixed cylindrical tank with a diameter of 15.2 m. Minimum and the maximum water levels are 15.2 and 21.3 m, respectively measured from the bottom of storage tank. Pump located on Node 1 is modelled with a negative demand of $-4400 \times 10^{-5} m^3/s$ with certain pump demand multipliers shown in Table 4.3. The consumer demand node multipliers are also given in Table 4.3 for Nodes 1 to 36.

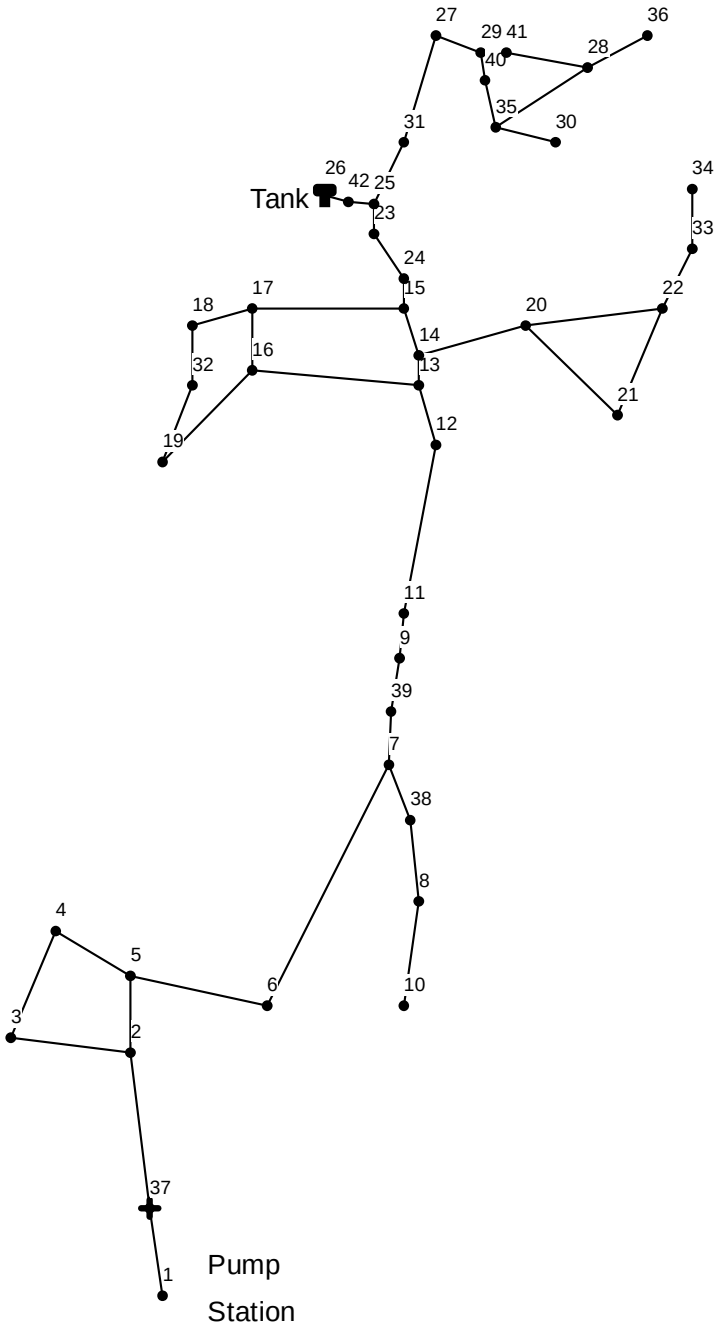


Figure 4.4: Schematic of the Model Application Network

Table 4.2: Network Pipe Data

Upstream Node	Downstream Node	Length(m)	Diameter(m)	Roughness Coefficients,C
1	37	1.0	0.3	100
37	2	730.0	0.3	100
2	5	240.0	0.3	100
2	3	400.0	0.2	100
3	4	370.0	0.2	100
4	5	300.0	0.3	100
5	6	370.0	0.3	100
6	7	820.0	0.3	100
7	38	1.0	0.3	140
7	39	1.0	0.3	100
8	10	300.0	0.2	140
9	11	210.0	0.3	100
11	12	580.0	0.3	100
12	13	180.0	0.3	100
13	14	120.0	0.3	100
14	15	90.0	0.3	100
13	16	460.0	0.2	100
15	17	460.0	0.2	100
16	17	180.0	0.2	100
17	18	210.0	0.3	100
18	32	110.0	0.3	100
16	19	430.0	0.2	100
14	20	340.0	0.3	100
20	21	400.0	0.2	100
21	22	400.0	0.2	100
20	22	400.0	0.2	100
24	23	180.0	0.3	100
15	24	80.0	0.3	100
23	25	90.0	0.3	100
25	42	30.0	0.3	100
25	31	180.0	0.3	100
31	27	120.0	0.2	100
27	29	120.0	0.2	100
29	40	1.0	0.2	100
29	41	1.0	0.2	100
22	33	300.0	0.2	100
33	34	120.0	0.2	100
32	19	150.0	0.2	100
35	30	300.0	0.2	100
28	35	210.0	0.2	100
28	36	90.0	0.2	100
38	8	370.0	0.3	140
39	9	120.0	0.3	100
40	35	150.0	0.2	100
41	28	730.0	0.2	100
42	26	1.0	0.3	100

Table 4.3: Demand and Pump Multipliers

Hour	Demand Multipliers	Pump Multipliers
1	1.19	0.96
2	0.97	0.96
3	0.9	0.96
4	0.9	0.96
5	0.82	0.96
6	1.12	0.96
7	1.21	0.00
8	0.6	0.00
9	0.6	0.00
10	1.27	0.00
11	2.39	0.00
12	0.9	0.00
13	0.85	0.80
14	0.61	1.00
15	1.36	1.00
16	0.54	1.00
17	0.24	1.00
18	0.71	0.15
19	0.3	0.00
20	0.6	0.00
21	1.19	0.00
22	1.49	0.00
23	1.12	0.00
24	1.16	0.00

4.2.1.1 Network Hydraulic Behavior

Network hydraulic dynamics of the application network is determined by the periodic water demands on a 24 h cycle illustrated above. The resulting hydraulic behavior of the network is given in Figure 4.5. The negative values of the flow to the tank represents the drainage of the storage tank i.e. inflow to the network system. During periods 0-6 h and 12-18 h the hydraulics controlled by mainly source via pumps and the tanks are filling during these periods. In periods 6-12 h and 18-24 h, the pumps are off and water drains from the storage tanks as a inflow to the water distribution network. Flow reversals occur in some pipe links through the network.

System network hydraulics repeats itself in a daily 24 h manner. Thus, the modelled network hydraulics are periodic on a 24 h cycles and are assumed to be repeated infinitely.

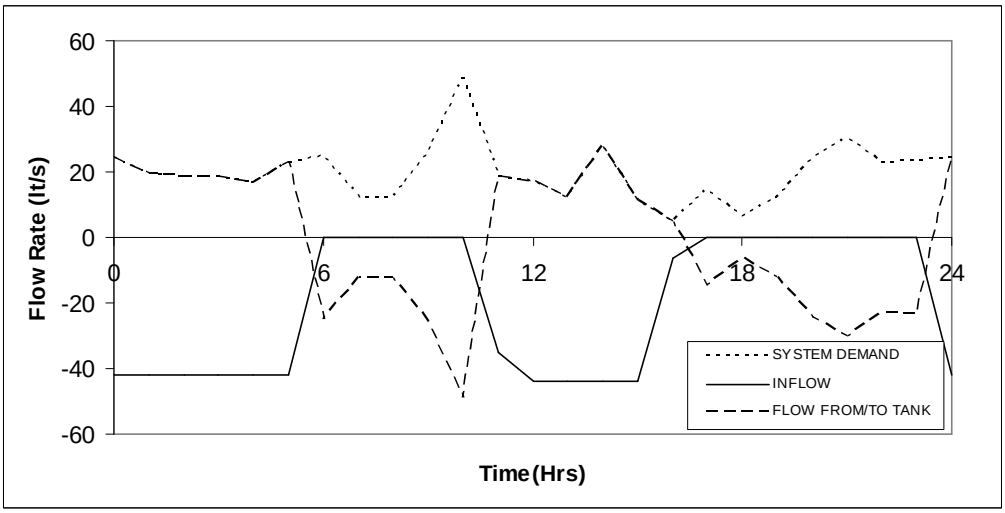


Figure 4.5: Network Hydraulic Behavior

4.2.2 Water Quality and Booster Location Model Description

The location and the operation of the booster disinfection stations are selected by considering the network hydraulics, applicability and engineering judgement. Potential booster disinfector locations are selected close to the storage tank and at the nodes along which the maintenance of the minimum required residuals is difficult. Booster locations 37-42 are selected by means of trial water quality simulation results as potential injection nodes which are shown in Figure 4.4. The Nodes through the 37-42 are added to the network links as dummy nodes according to their purposes. No positive demand is assigned to these nodes. These nodes are linked to the system nodes with 1.0 m of pipe to represent booster disinfection station at that node.

Here Node 37 is modelling the conventional source injection of the network. Comparison with the booster nodes and the conventional source injection has been achieved by means of this control node. Booster Node 38 is located to maintain residual along the network branch including Nodes 8 and 10. Similarly Node 39 booster location serves the upper region of the network on the mainline. Booster locations at Nodes 40 and 41 are located in order to maintain minimum residuals along the far distance of the water distribution network. The booster near the storage tank is the Node 42 booster.

Monitoring constraints for the consumer demand nodes stated in Equation 3.2 are taken as $\underline{C} = 0.20\,mg/l$ and $\overline{C} = 4.0\,mg/l$ over a 24 h monitoring time period using 1 h monitoring time step ($tr = 1, 2, ..., 24$). Booster station injection pattern time step is selected as 1 h ($j = 1, 2, ..., 24$) with a total of 24 h period to coincide with the hydraulic cycle time of 24 h. Total simulation time is set to 960 h to satisfy stationarity

of the response coefficients and the last 24 h results are used for the coefficients. Tank concentration becomes stationary after about 280 h water quality simulation as shown in Figure 4.6. Thus, 960 h of water quality simulation is adequate for the calculation of response coefficients to be on the safe side.

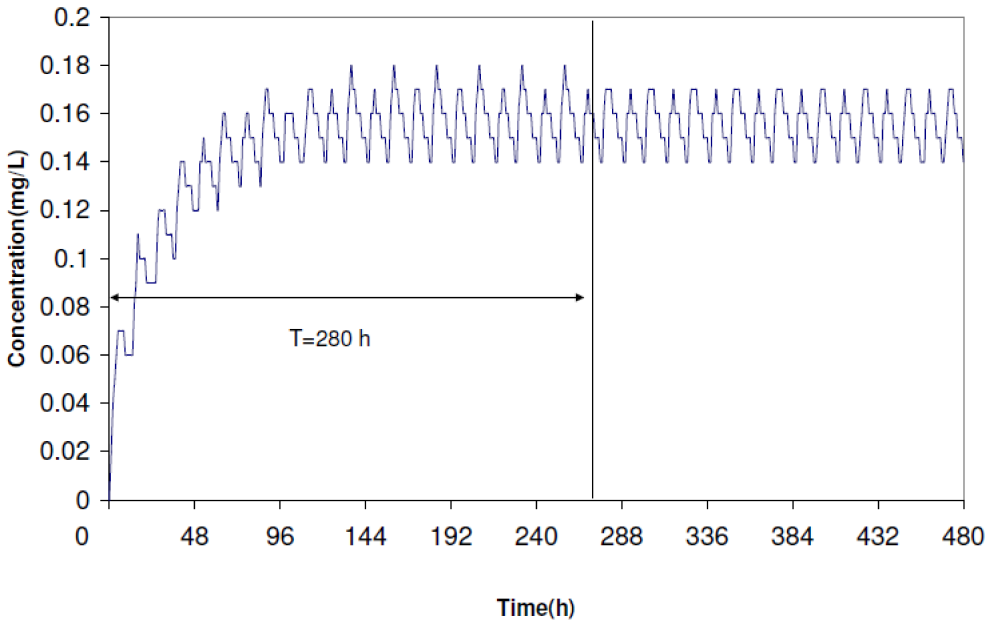


Figure 4.6: Tank Concentration Stationarity

The global bulk and wall decay coefficients used in this study are $k_b = 0.53\,day^{-1}$ and $k_w = 5.1\,mm/day$, respectively. Booster disinfector operation type is selected as mass booster representation by considering the ease of operation. Flow paced type booster operation is also applied to the network to see the resulting behavior.

Ten dynamic simulation cases shown in Table 4.4 are tested to see the resulting behavior of the network to the location and number of booster disinfection stations. The first five cases are solved for the first formulation of this study, thus does not include the effect of initial quality. In the consequent five cases the initial quality effect is introduced and second formulation is solved. Case I-A, represents the conventional source injection, the disinfectant is injected only from the water treatment plant of the water distribution network. In Case II-A, the selected booster nodes are added to the system and water quality analysis is achieved for more than one disinfectant source for the network to observe influence of the additional booster disinfection stations on maintenance of the minimum residual requirements. In Case III-A, the results of Case II-A is considered and booster locations with low injection rates are discarded. An additional booster disinfector is added at the storage tank in Case IV-A as Node 42. In

Case V-A, booster locations with low injection rates are discarded by considering the results of Case IV-A. Similarly, the cases I-B, II-B, III-B, IV-B and V-B investigate the same booster locations by including the initial quality effect.

Table 4.4: Simulation Cases

	Case	Booster Location(s)	Source Type	Simulation Type	Initial Quality
Formulation-1	I-A	37 (i.e.source)	MB	Dynamic	not included
	II-A	37,38,39,40,41	MB	Dynamic	not included
	III-A	37,39	MB	Dynamic	not included
	IV-A	37,38,39,40,41,42	MB	Dynamic	not included
	V-A	37,39,42	MB	Dynamic	not included
Formulation-2	I-B	37 (i.e.source)	MB	Dynamic	included
	II-B	37,38,39,40,41	MB	Dynamic	included
	III-B	37,39	MB	Dynamic	included
	IV-B	37,38,39,40,41,42	MB	Dynamic	included
	V-B	37,39,42	MB	Dynamic	included

CHAPTER 5

RESULTS AND ANALYSIS

The model application of this research for the cases stated in Table 4.4 results in different booster disinfection injection mass amounts with different behaviors. The amount of the disinfectant to be supplied to maintain minimum required residuals through the consumer demand nodes are obtained for each case. Tank concentrations and uniformity of the disinfectant mass along the nodes are also investigated. The network input file with the specified characteristics in previous chapter including both system hydraulics and the water quality booster model is simulated with the developed program. The response of the network is obtained mathematically as a response matrix. The mathematical LP formulation with the desired constraints are solved with the LP solver for each simulation case separately to get optimal results for the disinfectant mass to be injected while maintaining the chlorine limits at all consumer nodes within the water distribution network. Note that even for such a small application network, there are $34 \times 24 \times Number\,of\,Booster(s)$ constraints for the linear programming optimization problem.

5.1 Results

5.1.1 Formulation-1 Cases

Cases I-A, II-A, III-A, IV-A and V-A are solved for the first formulation of this study. One to five booster locations are investigated additional to the source location.

5.1.1.1 Conventional Injection (Case I-A)

The Case-I-A, which models the source only injection type for the water distribution network model, results with large mass injection rate as 21.24 kg/day as shown in

Table 5.1. The large injection amount are observed during the hydraulics periods of 0-6 h and 12-18 h as expected since the system hydraulics are controlled by mainly the source during these periods. Along these periods the source, i.e. the water treatment plant as a conventional method, is injecting the chlorine mass to the system to maintain the $\underline{C} = 0.2\,mg/l$ and $\overline{C} = 4.0\,mg/l$ disinfectant constraints. During the periods 6-12 h and 18-24 h the feeder pumps of the water distribution network are off, thus there is no source injection along these periods.

Table 5.1: Case I-A, Conventional Injection, Source Only

Node-37,Source Booster	
Period(h)	Mass Dosage, u (mg/min)
1	516.34
2	1375.47
3	516.34
4	517.95
5	517.86
6	623.24
7	0.00
8	0.00
9	0.00
10	0.00
11	0.00
12	3653.80
13	2629.94
14	537.85
15	538.23
16	726.59
17	2599.59
18	0.00
19	0.00
20	0.00
21	0.00
22	0.00
23	0.00
24	0.00
Σu (kg/day)	21.24

5.1.1.2 Booster Disinfection Stations (Cases II-A, III-A, IV-A, V-A)

The Case II-A, in which the booster nodes of 38, 39, 40, and 41 are introduced to the system additional to the conventional source injection at node 37, includes addition of the booster disinfection stations to the system. As shown in Table 5.2, large injection rates occur at boosters 37 (i.e. source) and 39 whereas relatively smaller values of disinfectant is injected from other booster locations. Since the source injection and

the booster location at node 39 are located on the mainline of the water distribution network, the main disinfectant feeding process is achieved by means of these boosters mainly. The other booster locations, i.e. nodes 38, 40 and 41 operates to serve necessary amount of disinfectant residual concentration to the network branches on which they are located. The Case II-A reduces the total disinfectant mass applied to the network to a value of 20.53 kg/day.

Table 5.2: Case-II-A, Additional Booster Stations at Nodes 38 to 41

Node-37,38,39,40 and 41 Booster Locations					
Period(h)	Mass Dosage, u (mg/min)				
	37	38	39	40	41
1	516.34	0.00	0.00	0.00	0.00
2	517.87	0.00	0.00	0.00	0.00
3	517.80	0.00	0.00	0.00	0.00
4	517.81	0.00	0.00	0.00	0.00
5	517.87	0.00	0.00	0.00	0.00
6	644.48	0.00	0.00	0.02	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	1219.21	0.00	0.00
12	1485.23	0.00	1080.61	0.00	0.00
13	1652.23	0.00	0.00	0.00	0.00
14	537.85	0.00	0.00	0.00	0.00
15	538.23	0.00	572.49	0.00	0.00
16	758.38	0.00	0.00	0.05	0.00
17	2625.47	0.00	0.00	0.04	0.01
18	0.00	0.00	0.00	0.21	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	556.13	0.00	0.00
Σu (kg/day)	15.59	0.00	4.94	0.00	0.00

The Case III-A takes the results of the Case II-A into account and discards the booster locations with lower injection rates. The booster locations at nodes 38, 40 and 41 show relatively low mass injection rates when compared to the source location at node 37 and the booster station at 39. Thus, even if the optimization formulation introduced in this research assumes known locations of the booster disinfection stations, proper booster locations could be decided by means of examining the case results. The Case II-A results reveals that the booster stations located at nodes 38, 40 and 41 have less

applicability and could be omitted. The Case III-A analyzes only the booster stations at nodes 37 and 39. As shown in Table 5.3 nearly the same injection amount is obtained in Case III-A when the booster locations with low injection rates used in Case II-A are discarded. A injected mass of 20.59 kg/day is obtained in Case III-A which is slightly a higher value than the one results in Case II-A. However, by considering the initial implementation cost of the booster locations, the number of the stations reduces two from five.

Table 5.3: Case III-A, Booster Stations at Nodes 37 and 39

Node-37 and 39 Booster Locations		
Period(h)	Mass Dosage, u (mg/min)	
	37	39
1	516.34	0.00
2	611.82	0.00
3	529.16	0.00
4	534.48	0.00
5	516.34	0.00
6	646.49	0.00
7	0.00	0.00
8	0.00	0.00
9	0.00	0.00
10	0.00	0.00
11	0.00	2103.92
12	753.43	895.25
13	2194.57	0.00
14	575.83	0.00
15	538.20	0.00
16	759.16	0.00
17	2624.02	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00
21	0.00	0.00
22	0.00	0.00
23	0.00	0.00
24	0.00	503.66
Σu (kg/day)	15.55	5.04

Case IV-A introduces a booster location at the output location of the storage tank of the water distribution system as node 42. As illustrated in Table 5.4 the most of the injection rates exist at source (node 37), node 39 booster and the tank booster at node 42. The other booster locations of nodes 38, 40 and 41 show lower injection rates as stated in previous cases. The injection pattern at the source follows the pump operation schedule as the injection is occurring at 0-6 h and the 12-18 h time intervals. However,

the booster node 42 added just after the storage tank operates with accordance to the tank drainage cycle, which is 6-12 h and 18-24 h time intervals. Most of the injection achieved by the booster node 42 is between these time periods since the storage tank starts to feed the network when the pumps are off. This time substitution of the source and the storage tank in the system significantly reduces the chlorine mass used for the disinfection. System is controlled by mainly the source injection between 0-6 h and 12-18 h interval and the storage tank booster at node 42 starts to dominate the system between 6-12 h and 18-24 h periods. Total disinfectant mass applied to the network is found to be 14.14 kg/day. There is nearly 35 % reduction in the chlorine mass applied to the network when compared to the conventional source injection.

Table 5.4: Case IV-A, Booster Stations at Nodes 37 to 42

Node-37,38,39,40,41 and 42 Booster Locations						
Period(h)	Mass Dosage, u (mg/min)					
	37	38	39	40	41	42
1	516.59	1.68	0.00	0.27	0.36	0.00
2	517.85	3.20	67.07	0.11	0.30	0.00
3	517.80	0.00	85.01	0.00	0.00	0.00
4	556.28	1.31	51.66	0.48	0.00	0.00
5	517.97	1.30	74.41	0.00	0.38	0.00
6	656.93	0.00	0.00	0.56	0.37	0.00
7	0.00	4.79	0.00	0.18	0.06	282.06
8	0.00	0.33	0.00	0.00	0.00	134.04
9	0.00	1.64	0.00	0.00	0.00	148.49
10	0.00	0.00	17.17	0.13	0.00	308.45
11	0.00	0.24	112.18	0.00	0.27	622.51
12	522.53	0.22	0.00	0.00	0.00	0.00
13	809.84	0.74	0.00	0.00	0.05	0.00
14	607.78	0.00	0.00	0.00	0.02	0.00
15	730.04	0.48	40.32	0.15	0.19	0.00
16	678.13	0.00	0.00	0.11	0.00	0.00
17	14.77	0.00	0.00	0.04	0.08	0.00
18	0.00	0.00	0.00	0.35	0.00	77.13
19	0.00	0.00	0.00	0.00	0.15	70.82
20	0.00	0.00	0.00	0.00	0.00	100.34
21	0.00	0.00	0.00	0.00	0.23	205.67
22	0.00	0.00	32.58	0.06	0.00	278.84
23	0.00	1.45	0.00	0.00	0.47	260.00
24	0.00	0.00	0.00	0.12	0.29	181.46
Σu (kg/day)	9.57	0.03	0.69	0.00	0.00	3.84

Similar to the Case III-A, Case V-A takes the results of the Case IV-A into account and discards the booster locations with lower injection rates. The booster locations at nodes 38, 40 and 41 show relatively low mass injection rates when compared to the

source location at node 37 and booster stations at node 39 and node 42. Case V-A results an injected mass of 14.84 kg/day which is slightly larger than the one obtained in case IV-A. Disinfectant injection amounts for Case V-A are given in Table 5.5.

Table 5.5: Case V-A, Booster Stations at Nodes 37, 39 and 42

Node-37,39 and 42 Booster Locations			
Period(h)	Mass Dosage, u (mg/min)		
	37	39	42
1	696.07	0.00	0.00
2	583.04	0.00	0.00
3	549.55	0.00	0.00
4	579.74	0.00	0.00
5	595.43	0.00	0.00
6	661.52	0.00	0.00
7	0.00	2.25	245.13
8	0.00	0.00	117.64
9	0.00	2.12	132.54
10	0.00	6.64	367.97
11	0.00	145.79	624.42
12	521.59	0.00	0.00
13	728.88	0.00	0.00
14	607.30	0.00	0.00
15	576.99	0.00	0.00
16	755.38	31.73	0.00
17	368.68	0.00	0.00
18	0.00	0.00	113.71
19	0.00	0.00	38.66
20	0.00	0.00	93.80
21	0.00	0.00	231.44
22	0.00	21.48	334.57
23	0.00	0.00	313.62
24	0.00	1.31	258.46
Σu (kg/day)	10.40	0.30	4.14

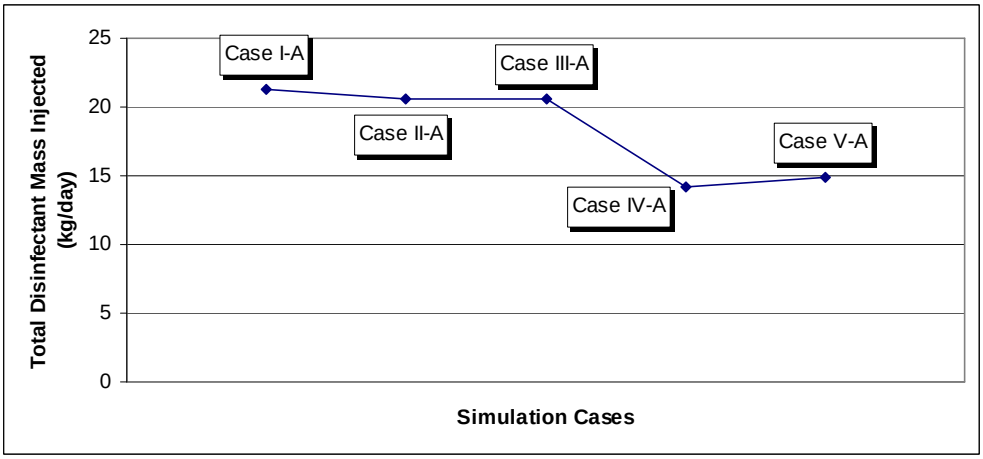


Figure 5.1: Disinfectant Mass Applied for Cases I-A, II-A, III-A, IV-A, V-A

The total disinfectant mass applied to the water distribution network for each simulation case of first formulation is given in Figure 5.1. Concentration values of all consumer demand nodes obtained from Formulation-1 for all cases are given in Appendix-B.

5.1.2 Formulation-2 Cases

The effect of the initial quality, which may exist at the consumer monitoring nodes at the beginning of the simulation, is added in Cases I-B, II-B, III-B, IV-B and V-B for the same boosters locations of Cases I-A, II-A, III-A, IV-A, V-A and the source. In Cases I-B to V-B, the initial concentrations of the consumer demand nodes are solved as decision variables of the LP problem. In a real existing water distribution network system, the values of the initial concentrations at consumer nodes are to be known from the field measurements. However, in this study, the initial concentrations $C_{rn,0}$, of the consumer nodes are solved as unknowns stated in Equation 3.5 in the mathematical expression. Solution is achieved by means of impact coefficients of the network, $\varepsilon_{ir,tr}^{rn}$ formed by the developed computer program for LP formulation. Since the size of the problem is considerable, the LP solver used for the problem had some difficulties in solving the additional equality constraint in Equation 3.4. As a solution for this issue, the equality constraint of the problem is converted into less than or equal to constraint [8]. Then the LP problem is solved with modified constraint of $C_{ir,0} \leq C_{ir,final}$.

5.1.2.1 Conventional Injection (Case I-B)

Similar to the Case I-A, source only injection results in higher amount of disinfectant as shown in Table 5.6. As expected, the total disinfectant injected to the system reduces when compared to the cases in which there is no initial concentration. Since the water distribution network water quality simulation starts with an initial quality at consumer nodes, the amount of the disinfectant injected decreases. The total disinfectant used reduces nearly 50 % from a value of 21.24 kg/day in Case I-A to a value of 11.30 kg/day in Case I-B in which initial quality of the distribution network introduced as decision variables.

Table 5.6: Case I-B, Conventional Injection, Source Only

Node-37,Source Booster	
Period(h)	Mass Dosage, u (mg/min)
1	516.34
2	517.87
3	517.80
4	517.81
5	551.12
6	616.19
7	0.00
8	0.00
9	0.00
10	0.00
11	0.00
12	2219.85
13	537.85
14	538.41
15	692.83
16	623.16
17	0.00
18	0.00
19	0.00
20	0.00
21	0.00
22	0.00
23	0.00
24	0.00
Σu (kg/day)	11.30

5.1.2.2 Booster Disinfection Stations (Cases II-B, III-B, IV-B, V-B)

In Case II-B, the booster nodes of 38, 39, 40 and 41 are added to the source injection at node 37. Second formulation is considered and initial quality of the consumer demand nodes are also solved as decision variables subjected to the constraint of $C_{ir,0} \leq C_{ir,final}$. As illustrated in Table 5.7, booster at nodes 37 (i.e. source) and 39 shows higher injection rates when compared to the other booster stations. The total amount of disinfectant used in Case II-B is 10.54 kg/day which is significantly less than the injected disinfectant value of 20.53 kg/day in Case II-A by considering the initial quality effect. Addition of the booster stations in Case II-B to the conventional source injection of Case I-B also reduces the total disinfectant need from 11.30 kg/day to 10.54 kg/day.

Table 5.7: Case II-B, Additional Booster Stations at Nodes 38 to 41

Node-37,38,39,40 and 41 Booster Locations					
Period(h)	Mass Dosage, u (mg/min)				
	37	38	39	40	41
1	516.34	0.00	0.00	0.00	0.00
2	517.87	1.34	0.00	0.00	0.00
3	517.80	0.00	0.00	0.00	0.00
4	543.43	0.85	0.00	0.00	0.00
5	517.74	1.00	0.00	0.00	0.00
6	656.93	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	5.24	0.00	0.00
11	0.00	0.00	3.06	0.00	0.00
12	875.00	1.05	30.27	0.00	0.00
13	543.94	0.00	0.00	0.00	0.00
14	588.71	0.00	0.00	0.00	0.00
15	550.61	0.00	0.00	0.00	0.00
16	730.92	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	720.16	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00
Σu (kg/day)	9.45	0.01	1.09	0.00	0.00

The Case III-B similar to the Case III-A, eliminates the booster locations with lower injection rates in Case II-B. The booster nodes of 38, 40 and 41 in Case II-B are discarded since injection rates of the booster locations are not proper when considering applicability. Nearly the same amount of disinfectant is needed as shown in Table 5.8 by using only two booster stations at nodes 37 and 39 instead of introducing five booster stations as analyzed in Case II-B. A total mass of 10.64 kg/day is obtained in Case III-B which is very close to the value of 10.54 kg /day in Case II-B.

Table 5.8: Case III-B, Booster Stations at Nodes 37 and 39

Node-37 and 39 Booster Locations		
Period(h)	Mass Dosage, u (mg/min)	
	37	39
1	599.81	0.00
2	517.55	0.00
3	575.69	0.00
4	606.04	0.00
5	518.52	0.00
6	656.93	0.00
7	0.00	0.00
8	0.00	0.00
9	0.00	0.00
10	0.00	18.85
11	0.00	0.00
12	755.25	0.00
13	545.20	0.00
14	593.44	0.00
15	555.17	0.00
16	727.63	0.00
17	0.00	0.00
18	0.00	0.00
19	0.00	0.00
20	0.00	0.00
21	0.00	0.00
22	0.00	0.00
23	0.00	720.13
24	0.00	0.00
Σu (kg/day)	9.58	1.06

Case IV-B introduces a booster station at node 42 which is located at the output of the storage tank of the water distribution network application model. As shown in the Table 5.9, most of the injection occurs at source and the tank booster. Since the tank booster operates according to the network system fill and drain cycle, operation of source and tank injections substitute each other. In the first 0-6 h interval the pump is operating and source injection dominates. Then in the next 6-12 h interval the pump is off and tank starts to fill the system with operating booster station at node 42. The total disinfectant mass applied to the network is found as 9.43 kg/day. Introducing the initial quality also reduces the total disinfectant used when compared with the value of Case IV-A of the first formulation which is 14.14 kg/day.

Table 5.9: Case IV-B, Booster Stations at Nodes 38 to 42

Node-37,38,39,40,41 and 42 Booster Locations						
Period(h)	Mass Dosage, u (mg/min)					
	37	38	39	40	41	42
1	519.45	2.44	0.00	0.00	0.00	0.00
2	519.73	2.08	0.00	0.00	0.00	0.00
3	520.01	0.00	0.00	0.00	0.00	0.00
4	561.62	1.40	0.00	0.00	0.00	0.00
5	520.54	1.36	0.00	0.00	0.00	0.00
6	656.93	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.22	0.00	0.00	0.00	2.70
10	0.00	0.46	3.49	0.00	0.00	30.29
11	0.00	1.59	0.00	0.00	0.00	35.81
12	445.06	1.50	0.00	0.00	0.00	0.00
13	548.45	0.00	0.00	0.00	0.00	0.00
14	615.78	0.00	0.00	0.00	0.00	0.00
15	576.68	0.00	0.00	0.00	0.00	0.00
16	709.72	0.00	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	25.88
19	0.00	0.00	0.00	0.00	0.00	12.51
20	0.00	0.00	0.00	0.00	0.00	27.27
21	0.00	0.00	0.00	0.00	0.00	59.28
22	0.00	0.00	0.00	0.00	0.00	80.82
23	0.00	0.00	0.00	0.00	0.00	67.20
24	0.00	0.00	0.00	0.00	0.00	0.00
Σu (kg/day)	8.92	0.02	0.01	0.00	0.00	0.49

The Case V-B similar to the Case V-A, eliminates the booster locations with lower injection rates in Case IV-B. The booster nodes of 38, 40 and 41 in Case IV-B are discarded. Case V-B results an injected mass of 9.72 kg/day. Injection amounts are given in Table 5.10.

Table 5.10: Case V-B, Booster Stations at Nodes 37, 39 and 42

Node-37,39 and 42 Booster Locations			
Period(h)	Mass Dosage, u (mg/min)		
	37	39	42
1	631.11	0.00	0.00
2	519.73	0.00	0.00
3	601.24	0.00	0.00
4	631.75	0.00	0.00
5	520.54	0.00	0.00
6	656.93	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00
9	0.00	10.78	0.00
10	0.00	5.56	18.17
11	0.00	0.00	14.84
12	445.06	0.00	0.00
13	548.45	0.00	0.00
14	611.87	0.00	0.00
15	572.91	0.00	0.00
16	713.37	0.00	0.00
17	0.00	0.00	0.00
18	0.00	0.00	20.75
19	0.00	0.00	10.38
20	0.00	0.00	23.13
21	0.00	0.00	51.24
22	0.00	0.00	70.95
23	0.00	0.00	59.83
24	0.00	11.30	0.00
Σu (kg/day)	9.29	0.04	0.39

The total disinfectant mass applied to the water distribution network for each simulation case of second formulation with initial quality effect is given in Figure 5.2. Concentration values of all consumer demand nodes obtained from Formulation-2 for all cases are given in Appendix-C.

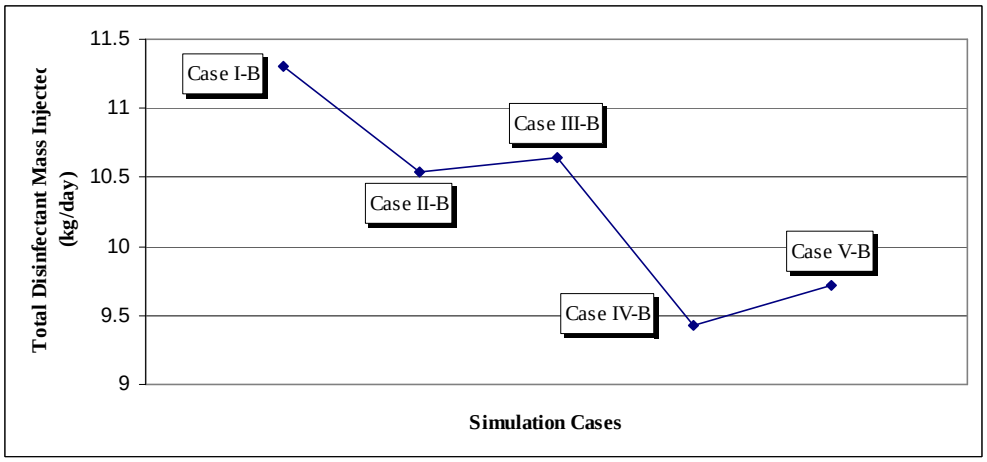
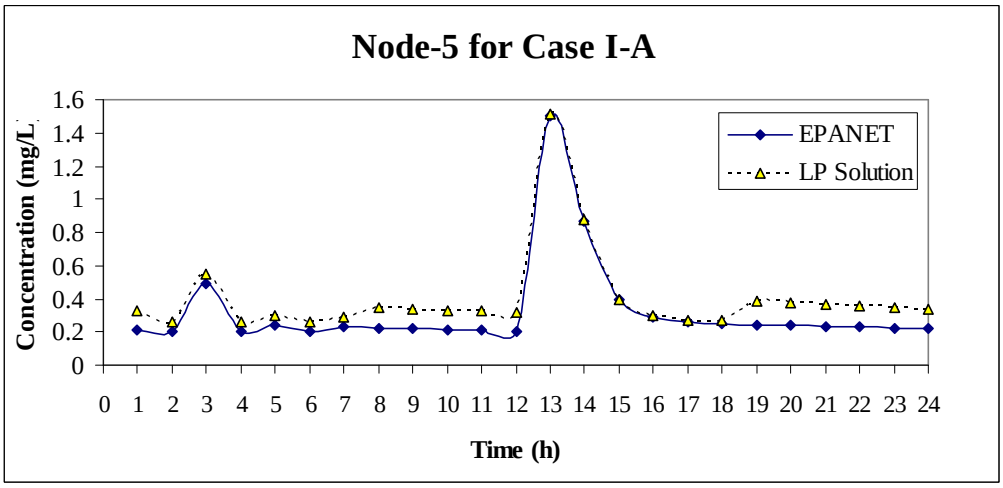


Figure 5.2: Disinfectant Mass Applied for Cases I-B, II-B, III-B, IV-B, V-A

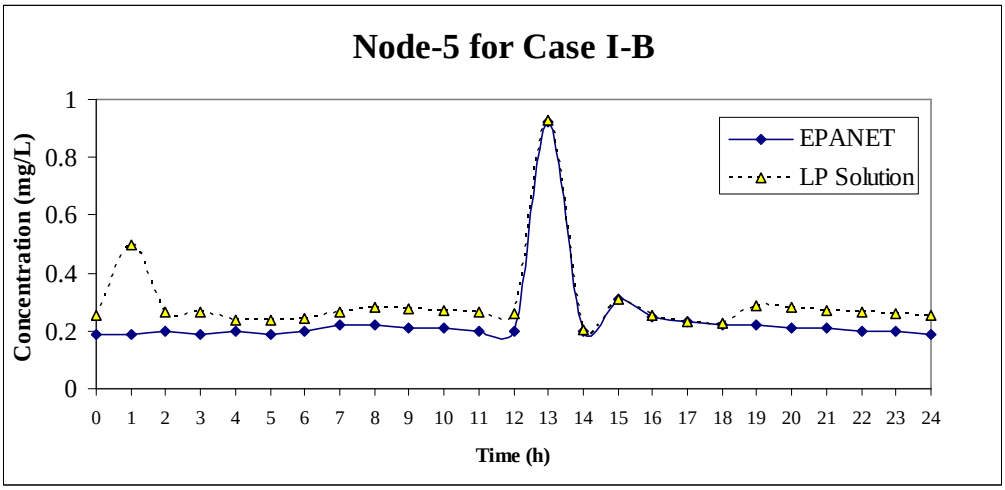
5.2 Analysis

5.2.1 Validation of Linear Superposition

The formulation for the optimal scheduling of the booster disinfection stations is based on the assumption of linear superposition of the response of individual injections of the stations at the consumer demand nodes. Thus the solutions of the LP problem should be checked for the validity of the linear superposition principle. The individual responses of the booster nodes 37 to 42 are obtained by means of the developed computer program and the LP problem stated is solved once the response matrix, A is generated. The optimal injection rates for each time interval of each booster location is determined as soon as the LP problem was solved. Then obtained optimal injection values for each time interval for each booster is introduced to the EPANET software separately. After assigning the optimal results to the booster locations, the water quality simulation was run to get the concentration values along the consumer demand nodes. The concentration values of the consumer demand nodes found previously as constraints in the LP problem are compared with the ones obtained directly from the EPANET software as shown in Figure 5.3a and Figure 5.3b for a representative Node-5. Linear superposition principle applies for both formulation-1 and formulation-2. It can be observed that there is a small difference between the concentration values obtained from LP solution and the EPANET software. The difference in between is resulting from the round-off errors in the LP solution and the linear programming solver methodology. The mass dosage applied in the calculation of the response coefficients for the LP problem should be large enough to reduce round-off error in the calculations. A value of 500 mg/min is used as a source strength value at booster locations while calculating the response coefficients. Source strength is the same parameter as individual injections u_j^i. The concentration values obtained from EPANET software are less than the ones obtained from LP solution. Minimum concentration limit of 0.2 mg/L is not satisfied at some demand nodes of the network while EPANET results are concerned. Higher minimum concentration limit value could be introduced into the LP solution as bound constraints to satisfy lower limit of the disinfectant in EPANET simulation. The validation of linear superposition principle for some other representative nodes of model network is given in Appendix-D for both formulations. A node close to the source, at the mainline of the network and at a far point are selected for validation.



(a) Node-5, Case I-A



(b) Node-5, Case I-B

Figure 5.3: Validation of Linear Superposition Principle

5.2.2 Tank Concentrations

Storage tanks used in the municipal water distribution networks are associated with large amount of water volumes. Thus, the disinfectant concentration within storage tanks are significant by considering the tank drain cycles along which the tanks are feeding the network system. The tanks concentrations corresponding the simulation cases stated above for the model application are also analyzed in the study. As shown in the Figure 5.4 Cases I-A, II-A, III-A show relatively higher tank concentrations when compared to the Cases IV-A and V-A in which a Node-42 booster is located at the exit of the tank. The booster at Node-42 serves as a disinfectant source and reduces the necessity for the tank concentration. Thus, the tank concentration for Cases IV-A

and V-A are smaller than the other simulation cases. The profiles of Cases I-A, II-A, III-A require the tank to satisfy necessary amount of disinfectant residual along consumer demand nodes. The storage tanks in the water distribution network systems are important contributors while the disinfection is considered.

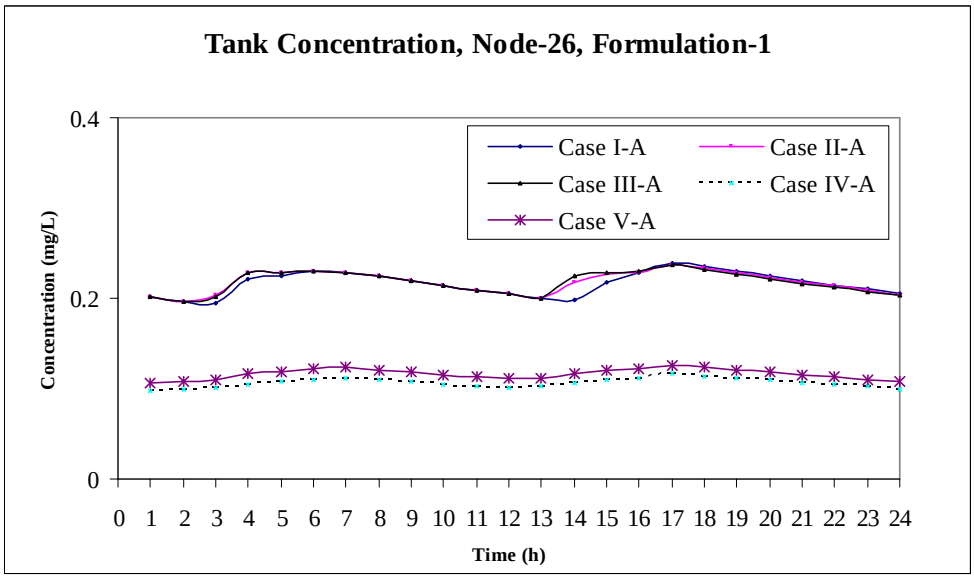
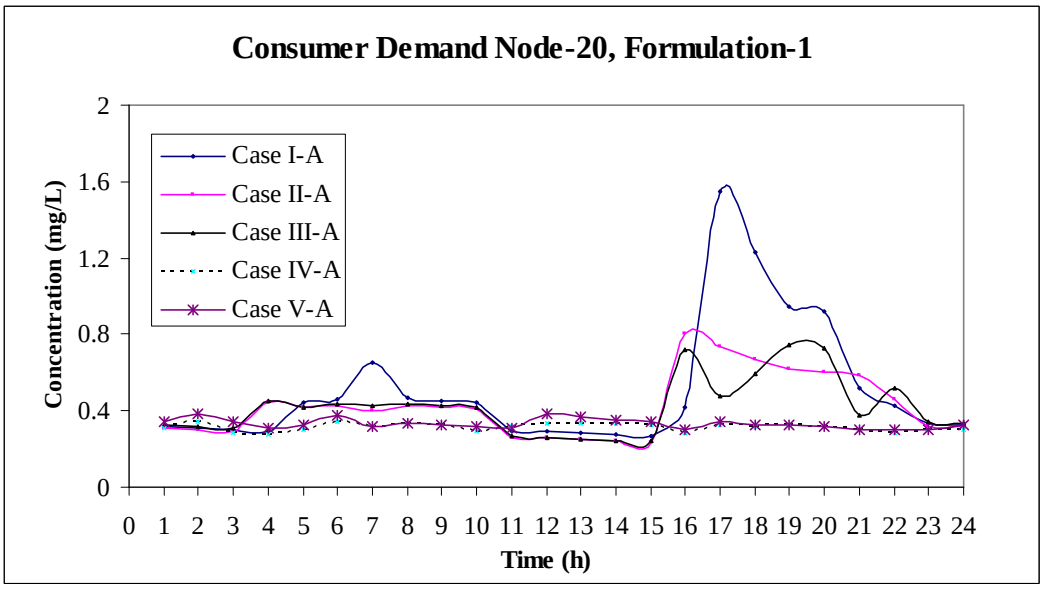


Figure 5.4: Tank Concentration Profile

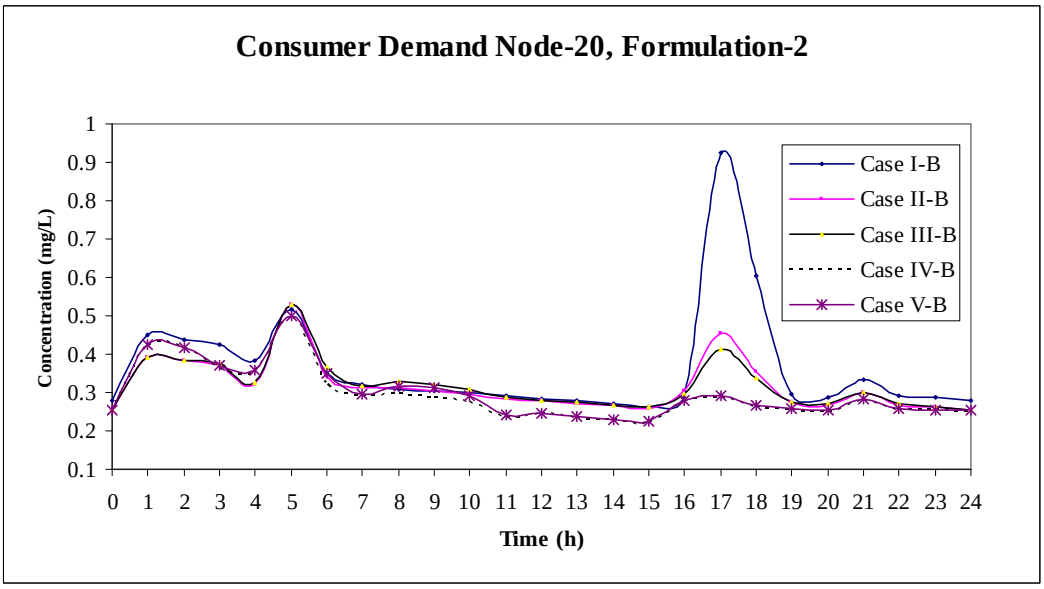
5.2.3 Uniform Residual Concentration

One of the objectives of this study is the provision of the uniform disinfectant concentration along consumer demand nodes within the water distribution network. The required residual concentrations are obtained along the monitoring nodes by forcing the $\underline{C} = 0.2\,mg/L$ and $\overline{C} = 4.0\,mg/L$ constraints in the problem. Additional to the minimum and maximum chlorine limits, the consumers should also be exposed a more uniform disinfectant distribution as the number of booster disinfector increases. In order the achieve this goal, concentration values of a representative consumer demand node in the model network is investigated with respect to the increasing number of booster disinfection stations as shown in Figure 5.5a and Figure 5.5b for both formulations. A far consumer demand node, Node-20 in which maintenance of the residual concentrations is difficult, is considered in the analysis. As can be seen in below figures, as the number of booster stations are increasing with the Cases I to V, the fluctuations in the nodal concentrations are decreasing. Thus, more uniform distribution of the residual chlorine mass is obtained by introducing the new booster locations. Additionally, the concentration fluctuations for the same Node-20 are decreased significantly in formulation-2

when compared to formulation-1 for each cases. Since less amount of disinfectant is injected in second formulation, it results in more uniform chlorine distribution along the water distribution network. The uniform residual maintenance and concentration of all demand nodes corresponding to each simulation cases and formulations are given in Appendix-B and Appendix-C.



(a) Node-20 Concentration Profile for Formulation-1



(b) Node-20 Concentration Profile for Formulation-2

Figure 5.5: Uniform Concentration Profile

5.2.4 Comparison of Formulation-1 and Formulation-2

The main concern which differs Formulation-1 from Formulation-2 of this research is the inclusion of the initial quality of the consumer demand nodes. Formulation-1 does not consider the initial qualities and assumes water distribution network is simulated from time = 0 in which there is no actual nodal concentrations. Whereas, in formulation-2, the initial concentrations are stated as unknowns of the LP formulation in this study. The additional constraint added in Equation 3.4 introduces the equality of the initial and final concentrations at a demand node. The water quality simulation achieved by means of adding initial concentrations as decision variables in the problem, forces the cyclic condition of the system. In other words, stationarity of the concentrations is tried to be achieved faster by equating the initial concentrations of all consumer demand nodes and storage tank to the final values of the disinfectant concentrations at the end of a typical daily cycle. However, model application results reveal that putting initial qualities into problem has no significant effect on decreasing the simulation time required for stationarity. As shown in Figure 5.6, the time needed for the system to reach stationarity does not differ noticeably between two formulations. The concentration values at the nodes starts with initial concentration values obtained from the LP problem as decision variables. Then it follows a pattern which is more uniform than the no initial concentrations case of first formulation. Actually, the initial concentrations are known in a real case from the field studies and measurements. Thus, the initial concentration values for the consumer demand nodes could be introduced into the problem as input at the beginning of the analysis as known input values.

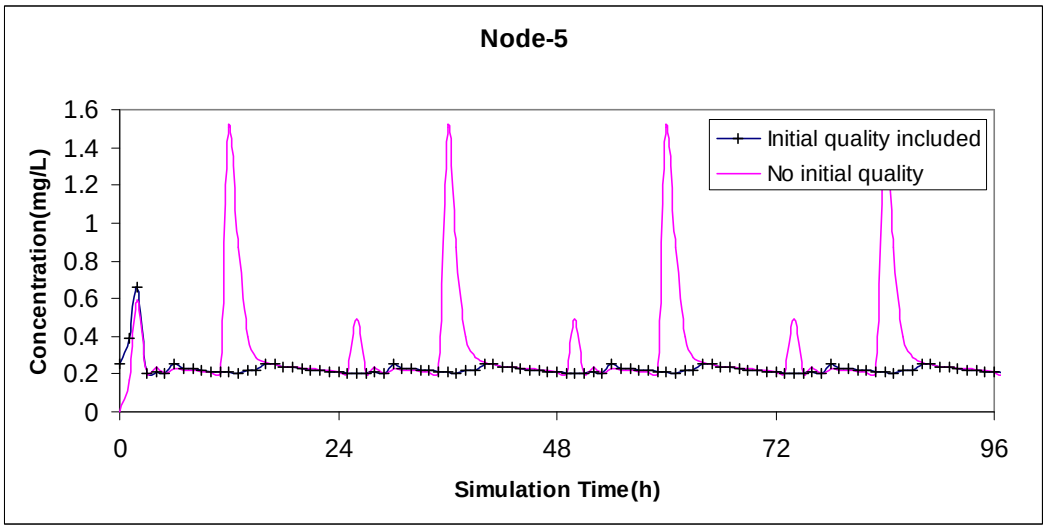


Figure 5.6: Effect of Initial Quality on Total Simulation Time

Additionally, formulation-2 provides more uniform distribution of disinfectant and reduces chlorine concentration fluctuations along demand nodes. Figure 5.5a and Figure 5.5b illustrate the nodal concentration of Node-20 for each cases of both formulations, the formulation-2 results in less concentration peak values than formulation-1. Besides this, solution of the optimal disinfectant injection LP problem gives less amount of chlorine in second formulation since Formulation-2 introduces the initial qualities as decision variables. Addition of initial concentrations reduces the amount of disinfectant need for the water distribution network.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The main goal of this research was the investigation of the efficiency of booster disinfection stations on minimizing the total disinfectant (i.e.chlorine) mass applied to the water distribution networks while maintaining adequate amount of residual concentrations at all consumer demand nodes as well as providing more uniform chlorine concentrations throughout the network. The model formulation and the network model application reinforced that implementation of booster disinfection stations, as an alternative to the conventional source injection, is an effective method for the stated objectives of this study. The conclusions drawn from the objectives incorporated in the design of this research, optimization methodology, and the assumptions could be assembled in three main titles:

(i) Minimization of total disinfectant mass injection;

Disinfection in municipal water distribution networks is mostly achieved by means of chlorine addition at the source point which are the water treatment plants. This method of conventional injection is practical and easy by considering the operational point of view. However, the amount of disinfectant mass applied to the network should be increased in some cases in order to maintain required amount of chlorine along the far point of the water distribution network. This increase in the amount of injected chlorine mass in the water treatment plants results in higher chlorine concentrations along the nodes which are close to the source point. Higher amount of disinfectant may lead to formation of disinfectant-by-products which are potential carcinogens. Thus, introducing additional injection locations as booster disinfection stations is an effective method of decreasing injected chlorine mass to the network system. As the number of

booster disinfection stations increases the amount of disinfectant applied to the network is decreasing which may also decrease the possibility of disinfectant-by-product formation. The model application of this study reveals that, implementation of the booster stations provides nearly 40% reduction in the total mass of the disinfectant used in the water distribution network. Additionally, the cost of disinfection of the municipal water distribution network is directly related to the cost of disinfectant mass applied. The total cost of the disinfectant is also reduced by means of implementing booster disinfection stations since the amount of injected mass was significantly lowered.

(ii)Maintaining required residual concentration and uniform concentration distribution;

The other objective of this research is the maintenance of the chlorine concentrations within certain limits in order to increase quality of the drinking water. The mathematical LP formulation constraints enforces the chlorine concentrations along the consumer demand nodes to be in limits of the SDWAA. Provision of the disinfectant concentrations between specified limits at the users tap, prevents taste and odor problems associated with drinking water. Besides this, booster disinfection application with a proper scheduling also enhances more uniform chlorine concentration distribution at the consumer demand nodes. The variation of the disinfectant concentration between the maximum and minimum limits decreases significantly. Thus, the consumers are exposed to a chlorine concentration within limits as well as with a more uniform distribution by means of booster disinfection.

(iii)Optimization methodology and the assumptions,

The mathematical formulation of the optimization problem of this study is mainly based on the linear theory and the first order decay kinetics of the disinfectant transport in water distribution networks. Linear superposition principle is applied to the individual responses of the booster disinfection injections.The response of each booster injection to the consumer demand nodes are obtained by means of developed computer program and the response matrix is generated. Once the response matrix is formed the linear optimization problem was solved for the optimal results for booster injections at each booster location. The water quality simulation was achieved up to a time in which the two successive response coefficients at a node is equal to satisfy stationarity of the system hydraulics and the chlorine concentrations.

There are two mathematical formulations that are used for the linear optimization problem in this research. In the first one, the optimal booster disinfection scheduling

problem is solved for minimizing the total chlorine mass objective with disinfectant concentration limit constraints. Additional to the first formulation the effect of initial concentrations of the consumer demand nodes are included in the second formulation as unknowns. Besides this, a constraint that forces the initial and final concentration at a node is also introduced. Simulation time required to satisfy stationarity of the concentrations at consumer nodes was thought to be shorter than first formulation. However, there was no significant change obtained by considering the simulation time. Whereas, more uniform disinfectant concentration distributions are obtained. Even the initial concentrations of the nodes are known from the field measurement in a real case, introducing the initial concentrations as unknowns represents the real case by reducing the total mass to be injected since there always be a chlorine concentration along an existing water distribution network. In both formulations, a new time discretization scheme of 24 h with 1 h injection interval is used for the booster disinfection stations.

Another assumption that makes the solution simpler is the known location of the booster disinfection stations. Formulation assumes that the booster station locations are known. The locations of the booster are chosen according to the engineering judgement and at the critical nodes of the water distribution network to provide required residual concentrations. There are two main difficulties to find the booster disinfection locations. Firstly, once the booster locations are included as unknowns in the problem, the size of the problem directly depends on the size of the network and a criteria for a proper booster location should be introduced mathematically. The second challenge of unknown booster locations is the solution performance of the optimization formulation and the algorithm developed for the computer program. Even if the assumption of known booster disinfection stations is used in the research, examination of results of the model application eliminates the unnecessarily selected booster locations. In other words, proper locations for the booster stations could be selected once the LP problem is solved for the optimal mass dosage values.

The different booster station operation strategies was also included in the developed computer program. Developed computer program allows the user to change booster operation type. Operation type of the booster station depends on the purpose and necessity for more control. Mass type of booster operation is more flexible and easy to operate since a constant mass dosage injection is held out. Flow-paced or set-point type of booster operations need more control of incoming flow and requires feedback data or real-time flow measurement at the stations.

As a final remark, application of booster disinfection stations as an alternative to the conventional source injection, is an effective method for water distribution network chlorination. Booster stations provide significant savings in chlorine mass applied while enhancing more uniform redistribution of the disinfectant mass at consumer demand nodes. The trade off between cost of implementing booster stations, i.e. number of stations and mass applied and the maintenance of the required residual concentrations within specified limits for high potable water quality and health standards was the main concern of this study.

6.2 Future Work

In this research optimization model for the booster station scheduling assumes known locations of the stations. A possible improvement could be added to the problem that would introduce also the booster locations as unknowns. This modification to the current problem brings difficulties in the optimization model as well as in the solution of the problem. Difficulties introduced to the problem highly depend on the network size and the optimization methodology. The computer code developed in this study achieves water quality simulations as a sub-program which calls EPANET software externally. Then, the obtained response matrix was taken and the optimization formulation was solved by means of another solver. Development of a more comprehensive computer program that combines the optimal scheduling and location problem with the optimization solver, would increase the performance of the problem solution. Additionally, computer program could also be modified to allow different types of booster operations in more detail and different optimization techniques for the problem. More flexibility then would be provided.

Since, a general input file of EPANET software is used in the developed program, any municipal water distribution network system could be solved for optimal booster disinfection provided the network system to be analyzed was modelled in EPANET. Thus, a case study for a certain district municipal water distribution system is considered to observe real behavior of the developed computer program and the model formulation. Affect of increasing size of the network with more complex system dynamics would be investigated with the help of a real case study.

REFERENCES

[1] R. J. Bull, "Health effects of drinking water disinfectants and disinfectant by-products," *Environmental Science & Technology* **16**(10), pp. 554A–559A, 1982. 1

[2] A. K. Deb and A. K.Sarkar, "Optimization in design of hydraulic network," *Journal of the Sanitary Engineering Division* **97**(2), pp. 141–159, 1971. 2

[3] U.Zessler and U. Shamir, "Optimal operation of water distribution systems," *Journal of Water Resources Planning and Management* **115**(6), pp. 735–752, 1989. 2

[4] C. R. Mark R. Wiesner and J. L.Cohon, "Optimal water treatment plant design," *Journal of Environmental Engineering* **113**(3), pp. 567–584, 1987. 2

[5] D. L. Boccelli, M. E. Tryby, J. G. Uber, L. A. Rossman, M. L. Zierolf, and M. M. Polycarpou, "Optimal scheduling of booster disinfection in water distribution systems," *Journal of Water Resources Planning and Management* **124**(2), pp. 99–111, 1998. 3, 12, 17, 28, 29

[6] M. E. Tryby, D. L. Boccelli, J. G. Uber, and L. A. Rossman, "Facility location model for booster disinfection of water supply networks," *Journal of Water Resources Planning and Management* **128**(5), pp. 322–333, 2002. 3, 29

[7] M. Propato and J. G. Uber, "Linear least-squares formulation for operation of booster disinfection systems," *Journal of Water Resources Planning and Management* **130**(1), pp. 53–62, 2004. 3

[8] K. Lansey, F. Pasha, S. Pool, W. Elshorbagy, and J. Uber, "Locating satellite booster disinfectant stations," *Journal of Water Resources Planning and Management* **133**(4), pp. 372–376, 2007. 3, 17, 48

[9] R. L.A., *EPANET 2 User's Manual*, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati,OH, 2000. 5, 8, 12, 30

[10] M. C. R.M. Clark and L.M.Mays, *Applying water quality models - Computer modelling of free-surface and pressurized flow*, Kluwer Dordrecht, Netherlands, 1993. 6

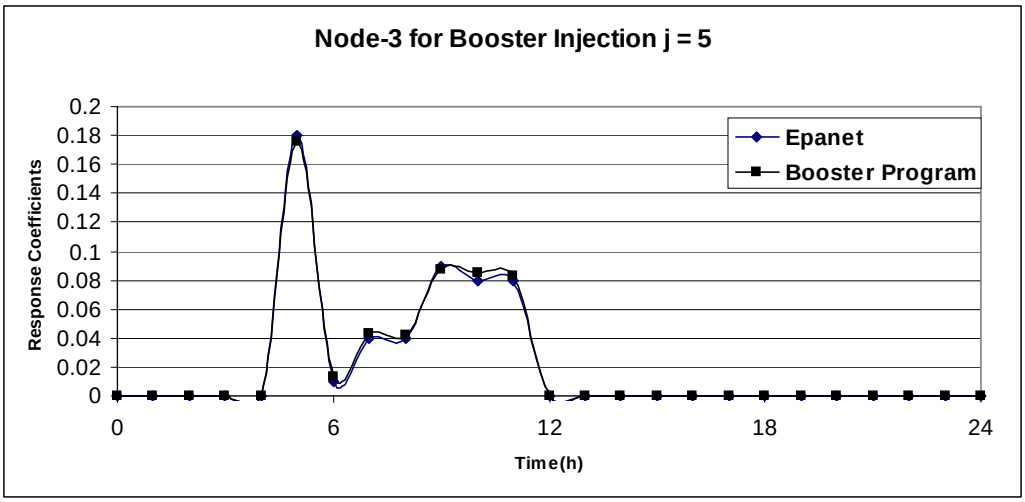
[11] W. G.C., *Handbook of chlorination and alternative disinfectants.*, John Wiley and Sons, New York,NY, 1999. 7

[12] L. A. Rossman, R. M. Clark, and W. M. Grayman, "Modeling chlorine residuals in drinking-water distribution systems," *Journal of Environmental Engineering* **120**(4), pp. 803–820, 1994. 7

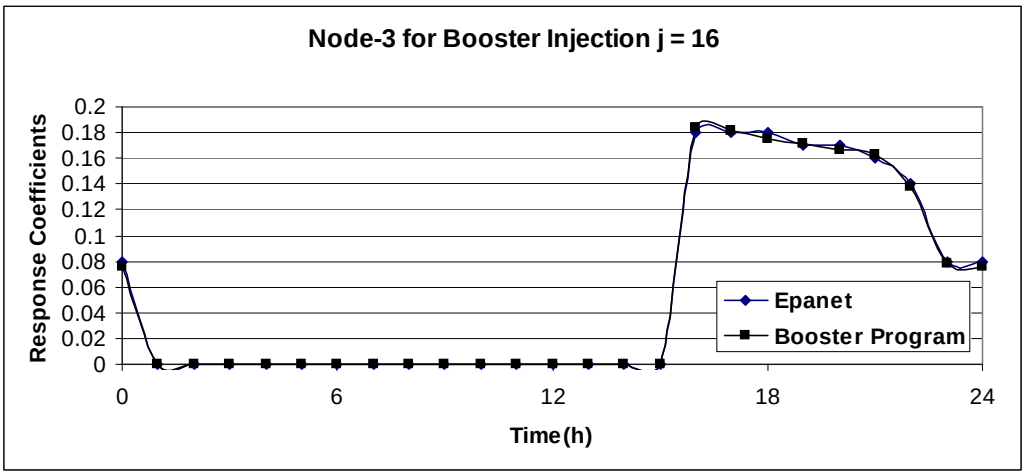
[13] M. D. a. M. L. Chow, V.T., *Applied Hydrology*, McGraw-Hill Book Co.Inc.,NewYork,NY, 1988. 13

APPENDIX A

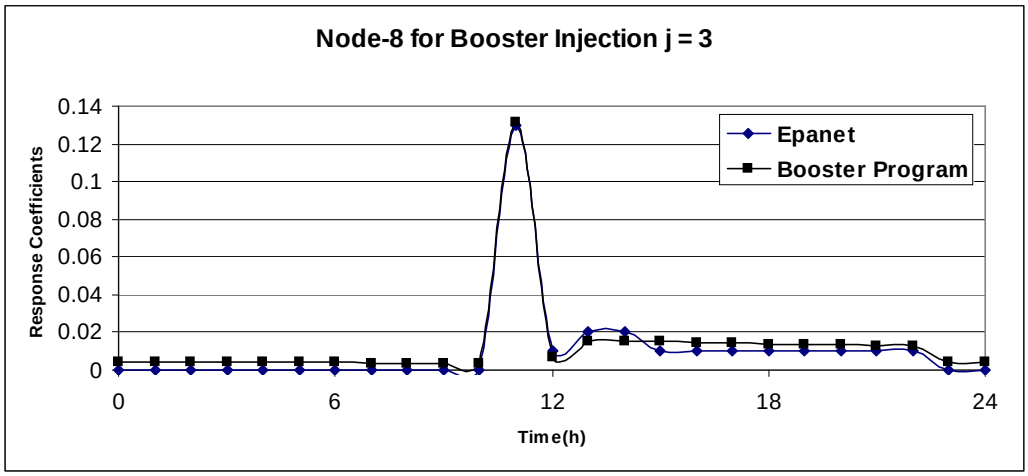
PROGRAM VERIFICATION



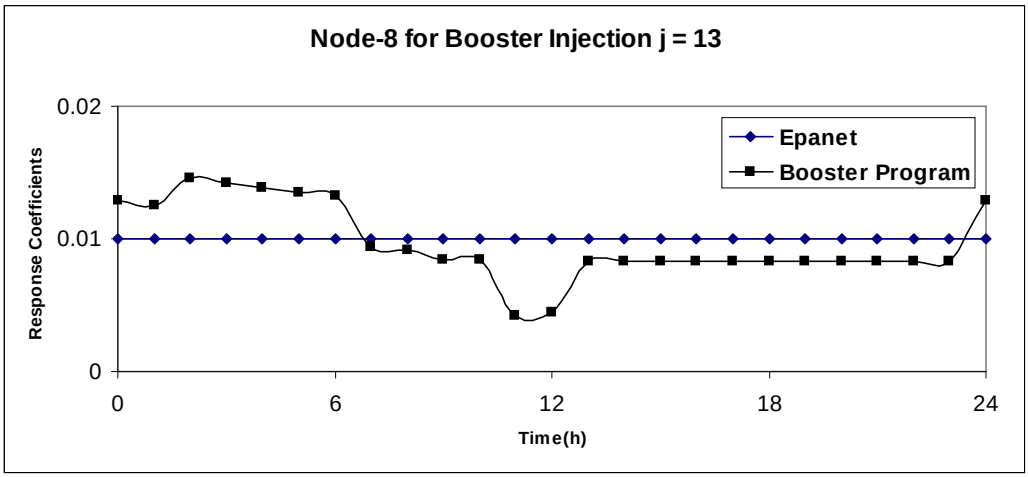
A.1. Response Coefficients for Node-3 Corresponding to Booster Injection, j = 5



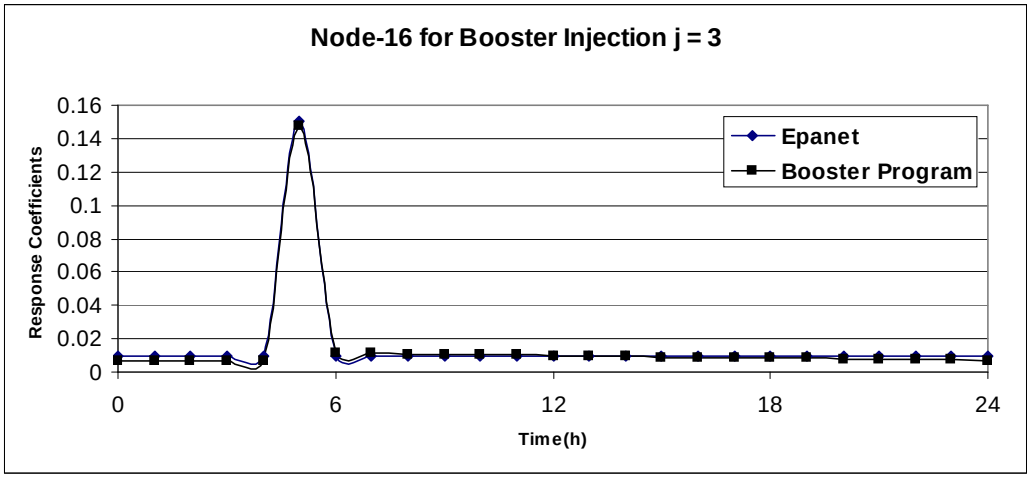
A.2. Response Coefficients for Node-3 Corresponding to Booster Injection, j = 16



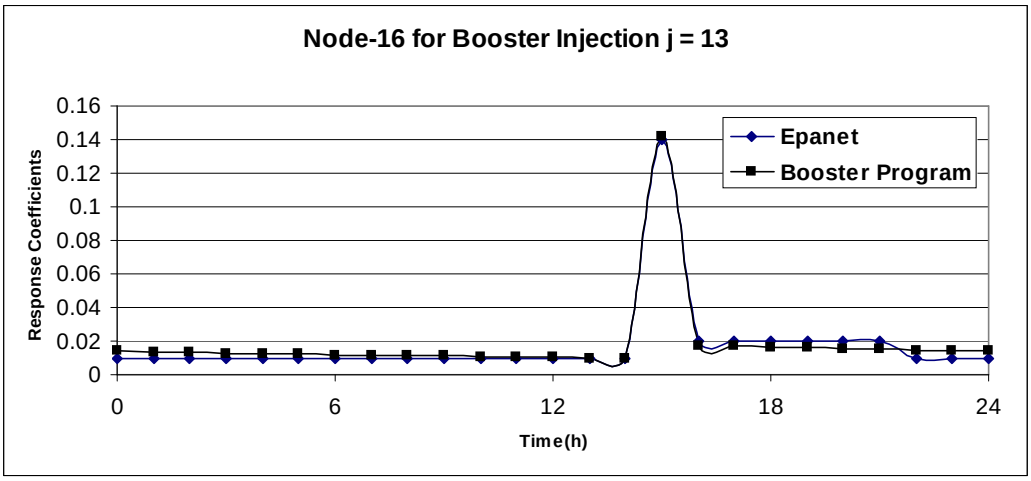
A.3. Response Coefficients for Node-8 Corresponding to Booster Injection, j = 3



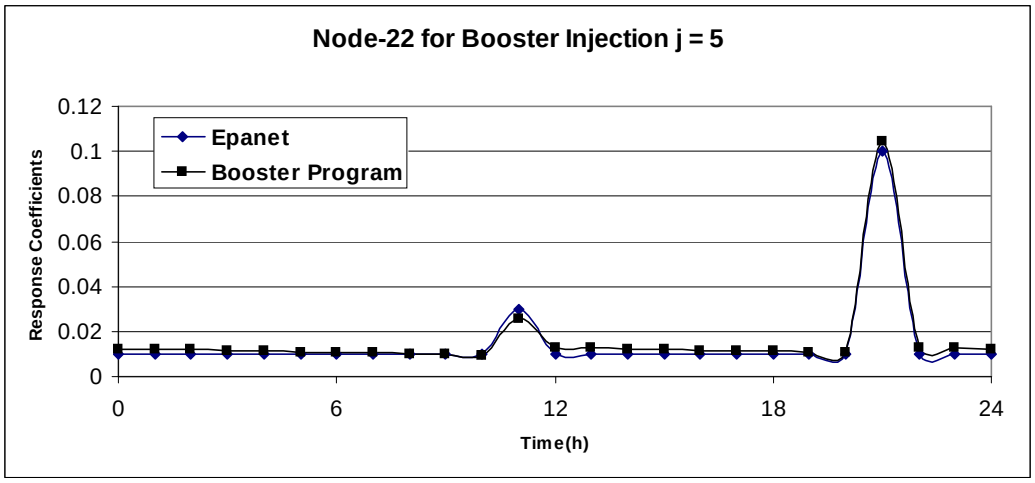
A.4. Response Coefficients for Node-8 Corresponding to Booster Injection, j = 13



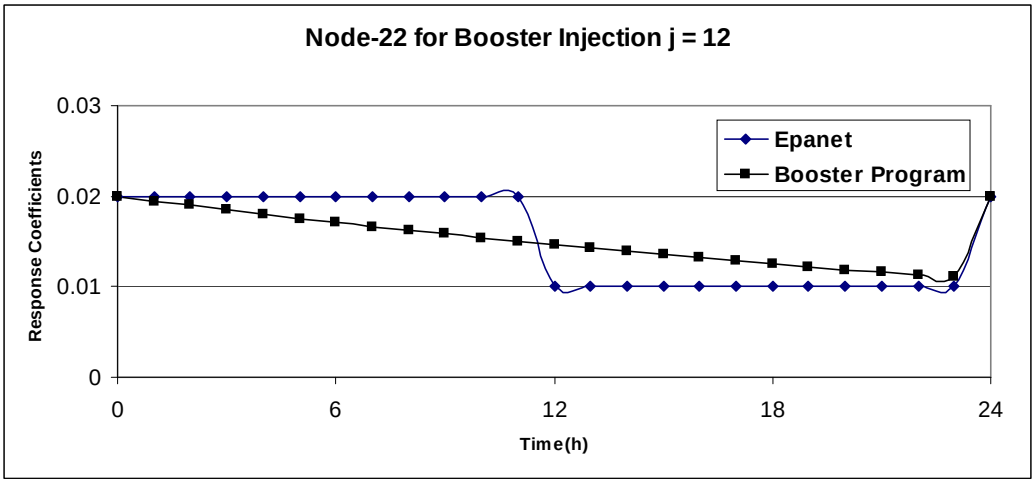
A.5. Response Coefficients for Node-16 Corresponding to Booster Injection, j = 3



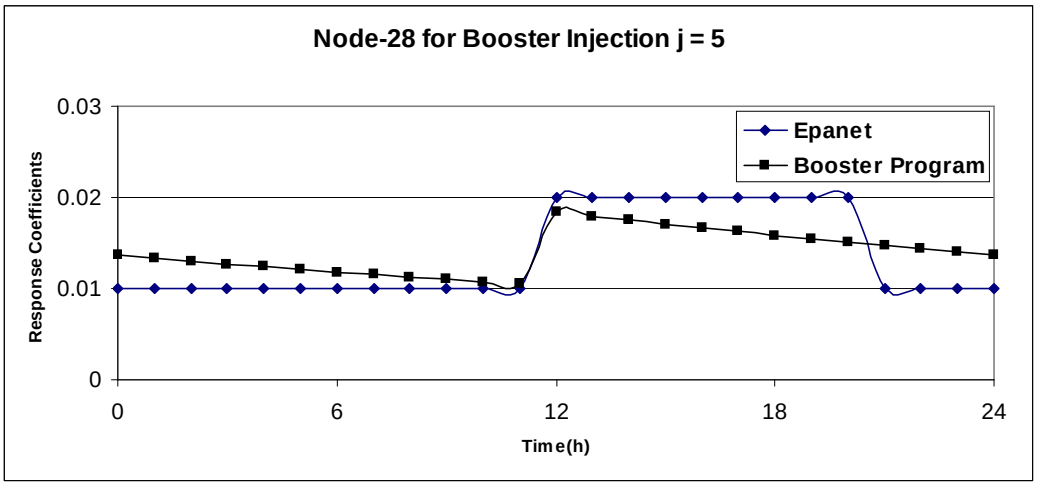
A.6. Response Coefficients for Node-16 Corresponding to Booster Injection, j = 13



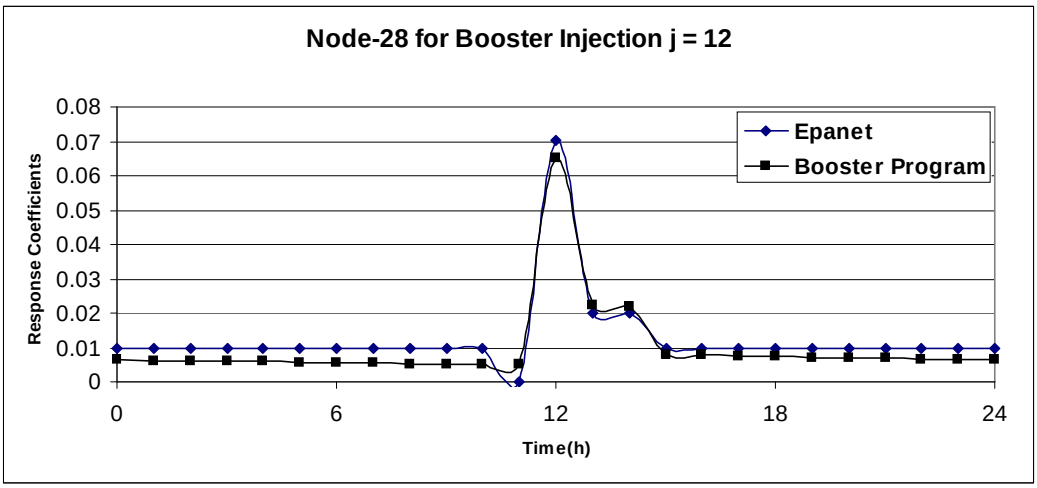
A.7. Response Coefficients for Node-22 Corresponding to Booster Injection, j = 5



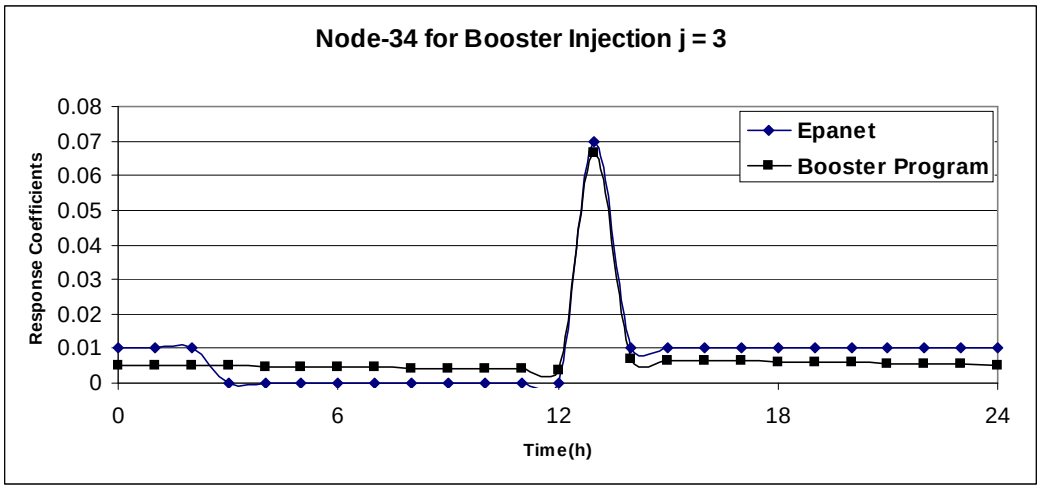
A.8. Response Coefficients for Node-22 Corresponding to Booster Injection, j = 12



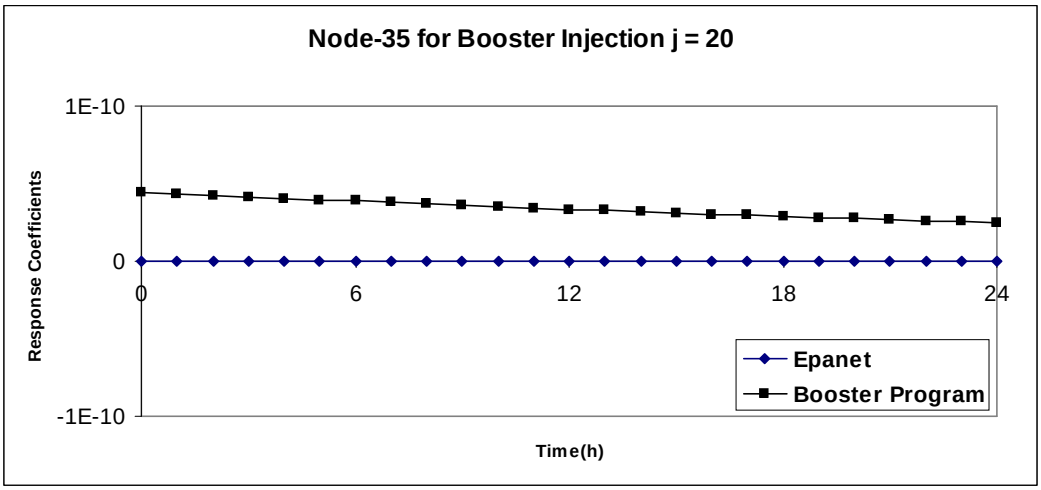
A.9. Response Coefficients for Node-28 Corresponding to Booster Injection, j = 5



A.10. Response Coefficients for Node-28 Corresponding to Booster Injection, j = 12



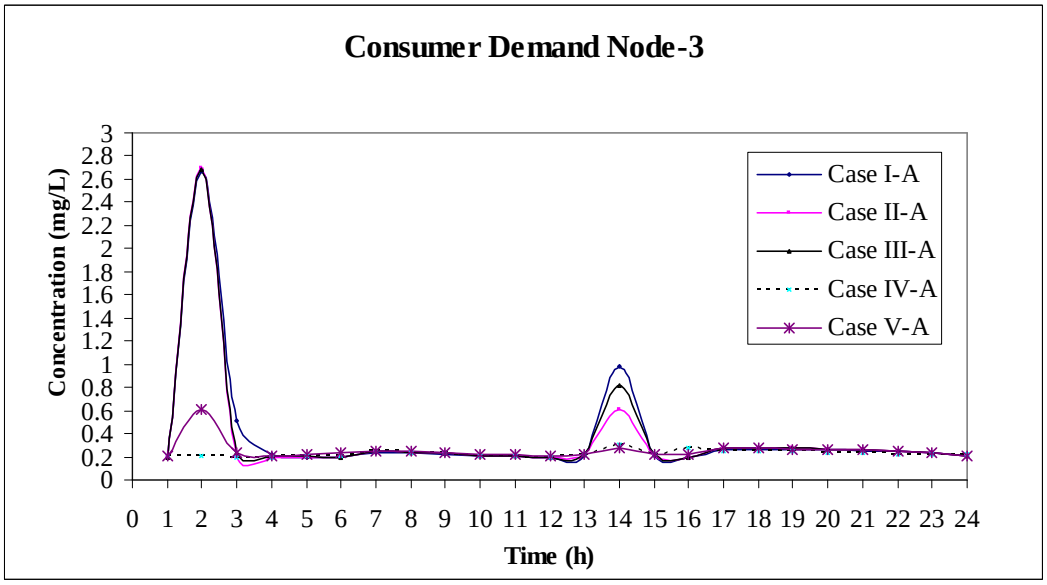
A.11. Response Coefficients for Node-34 Corresponding to Booster Injection, j = 3



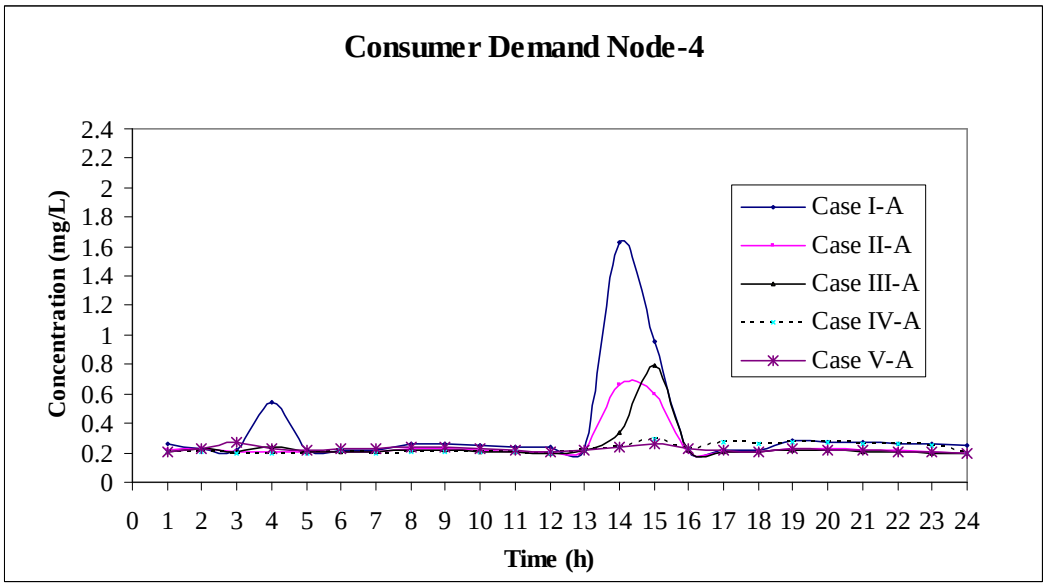
A.12. Response Coefficients for Node-35 Corresponding to Booster Injection, j = 20

APPENDIX B

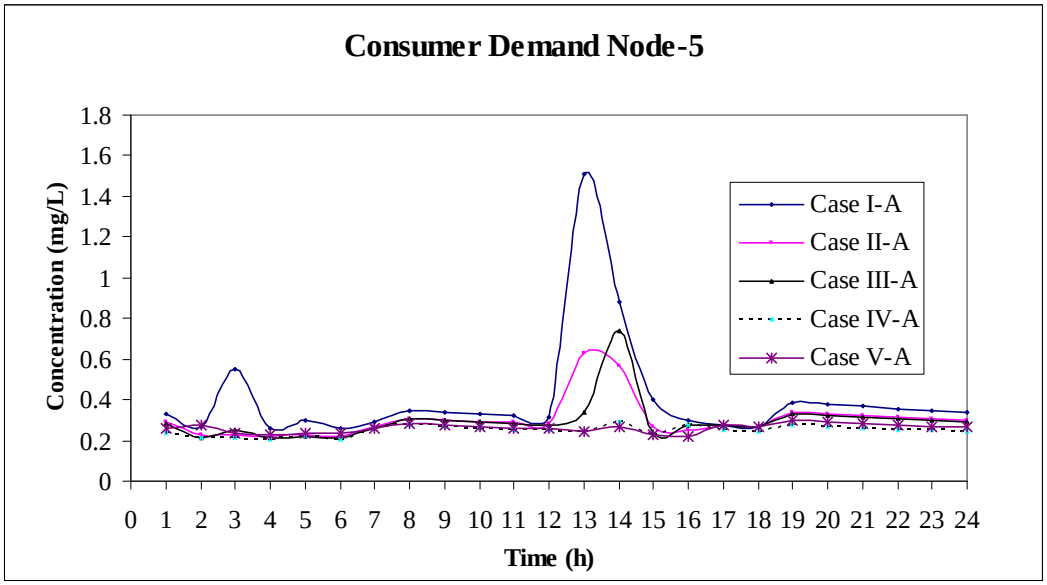
CHLORINE CONCENTRATIONS (FORMULATION-1)



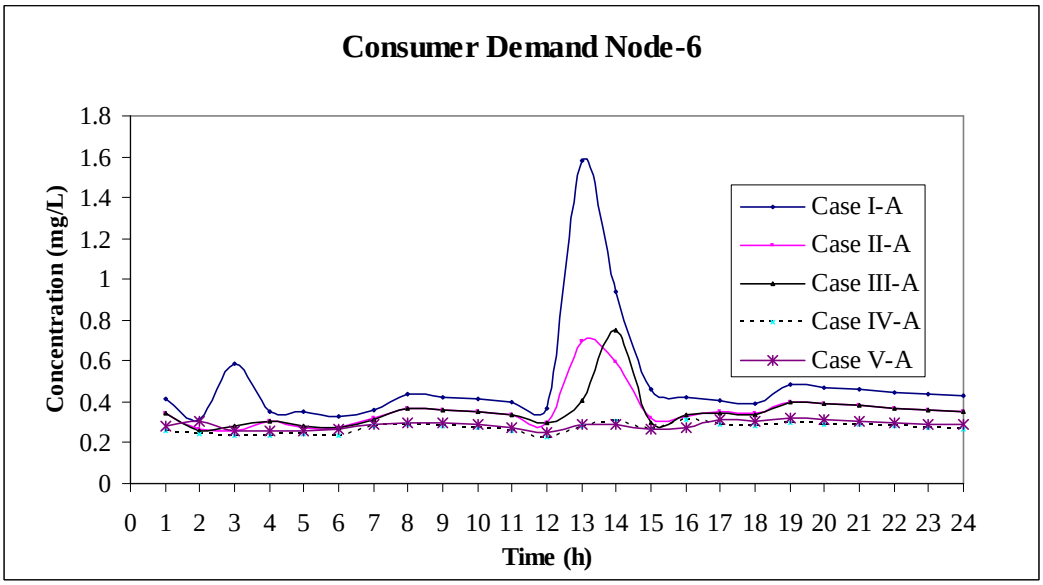
B.1. Chlorine Concentration at Node-3



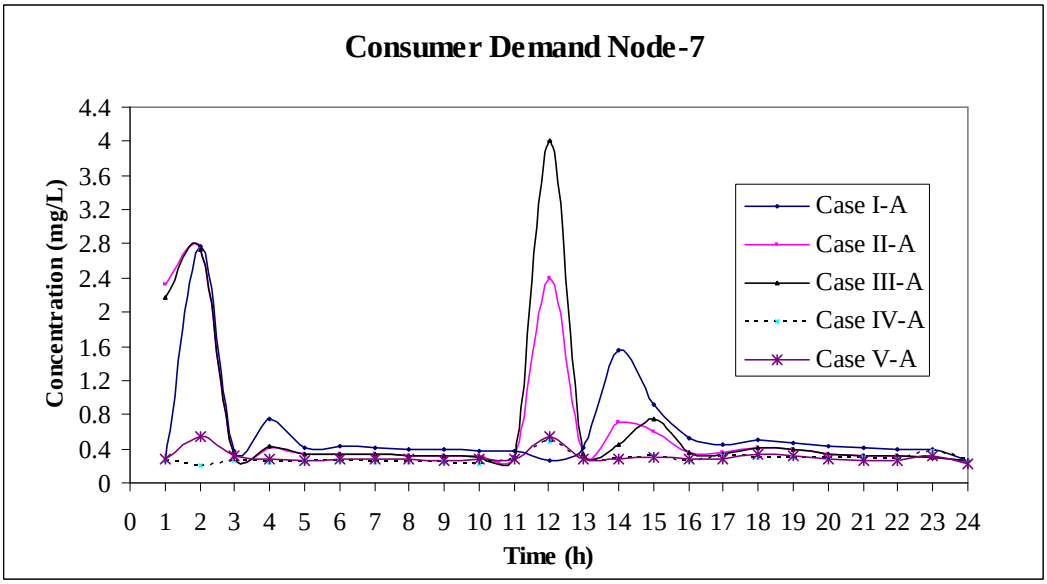
B.2. Chlorine Concentration at Node-4



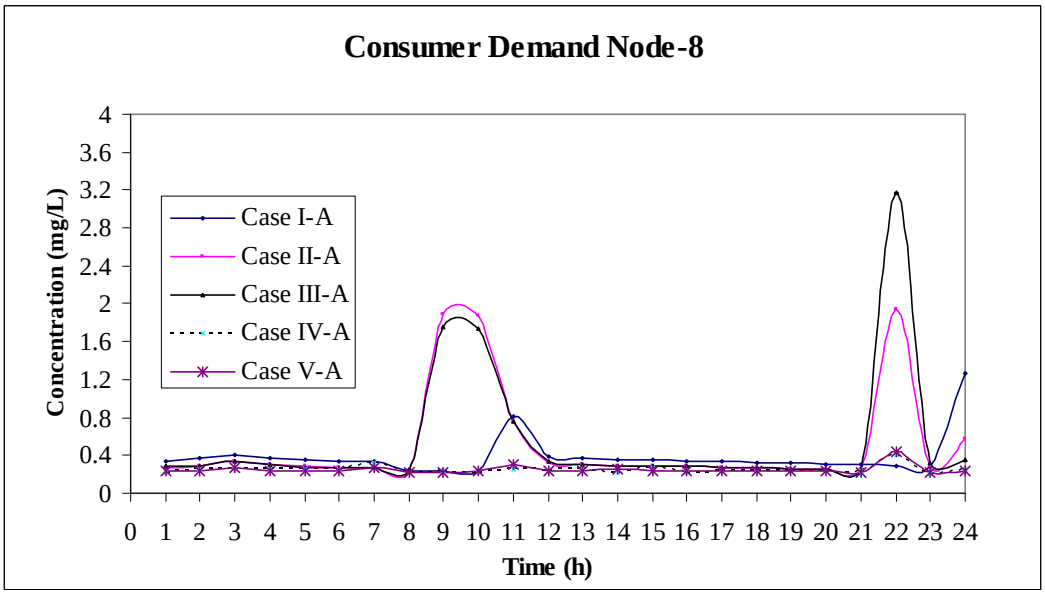
B.3. Chlorine Concentration at Node-5



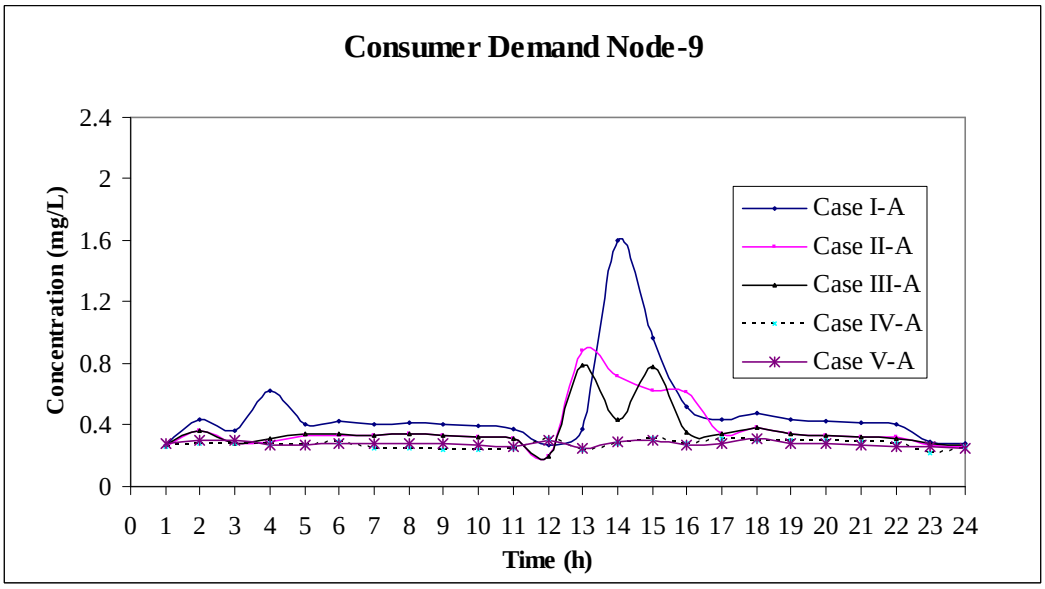
B.4. Chlorine Concentration at Node-6



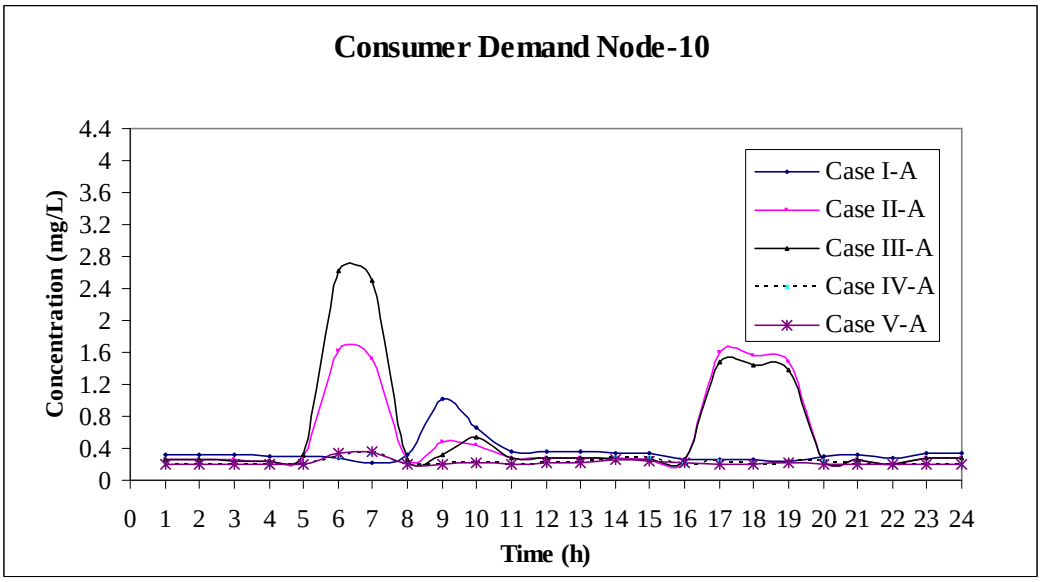
B.5. Chlorine Concentration at Node-7



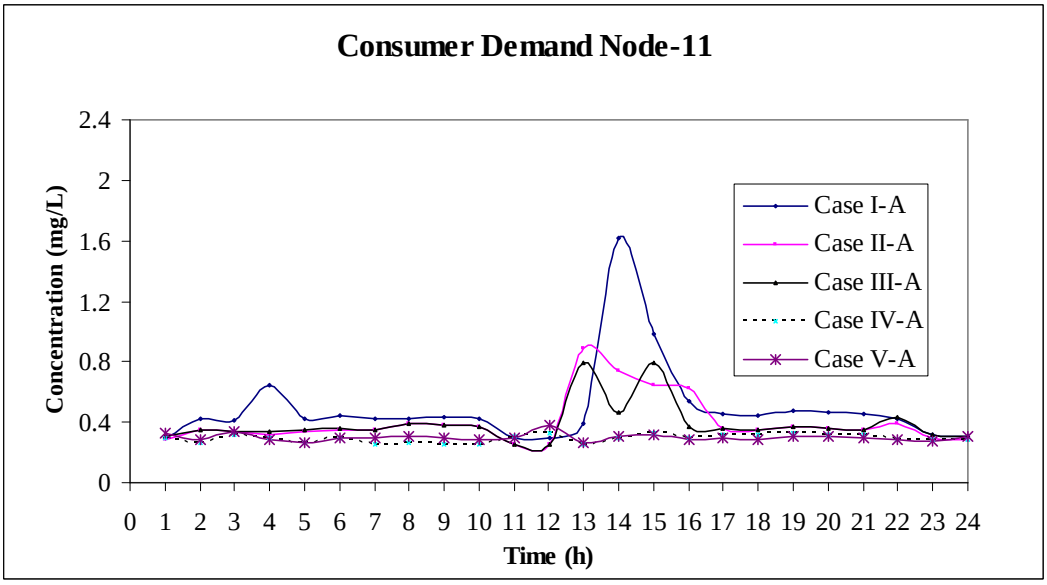
B.6. Chlorine Concentration at Node-8



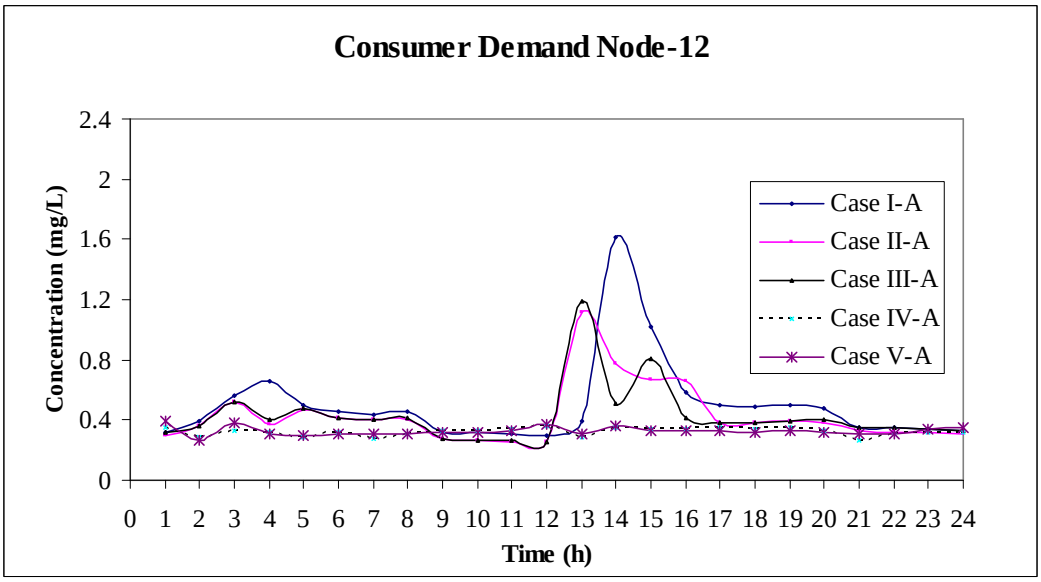
B.7. Chlorine Concentration at Node-9



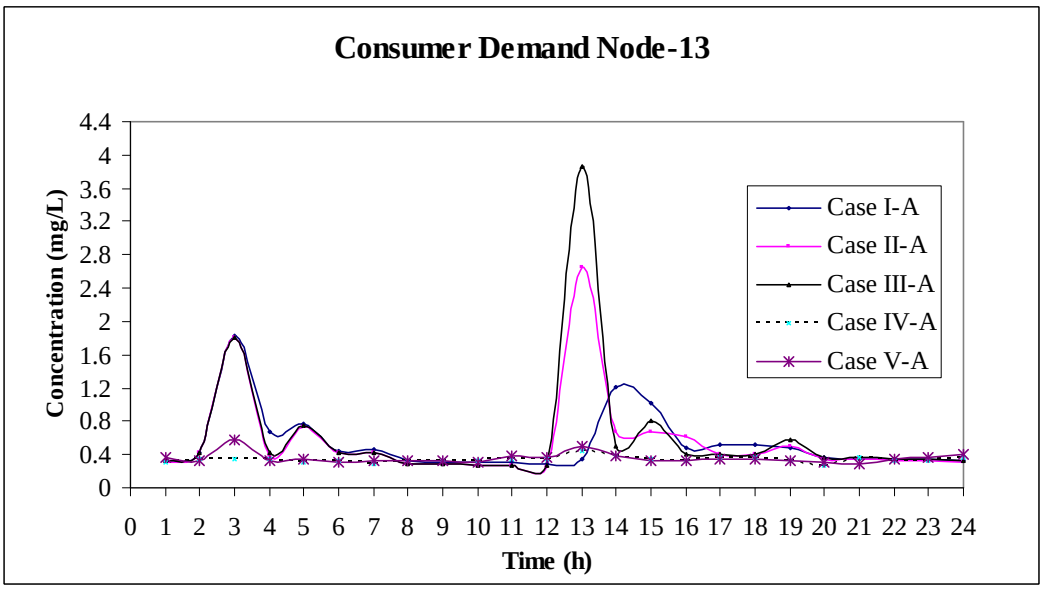
B.8. Chlorine Concentration at Node-10



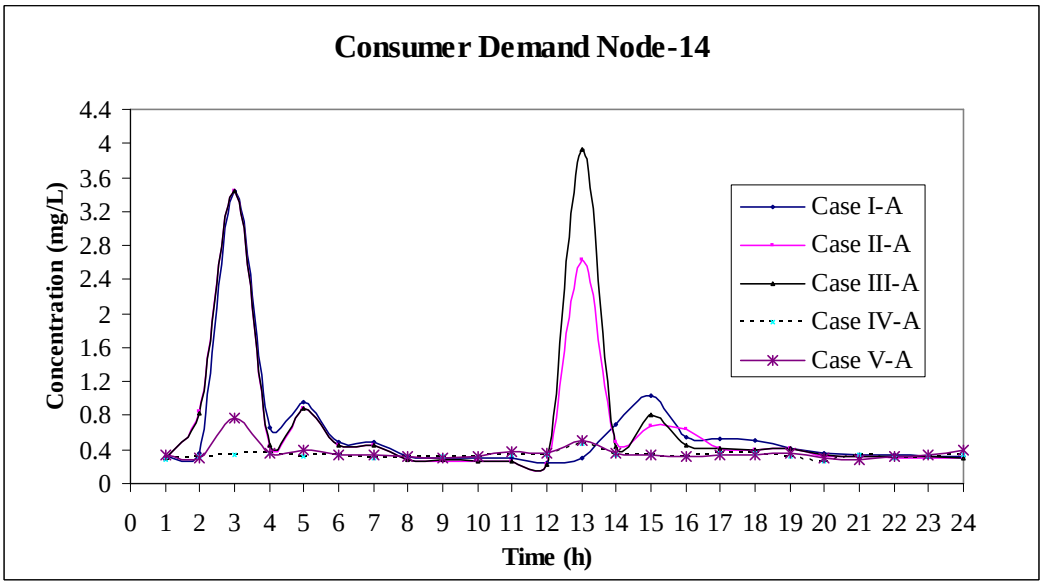
B.9. Chlorine Concentration at Node-11



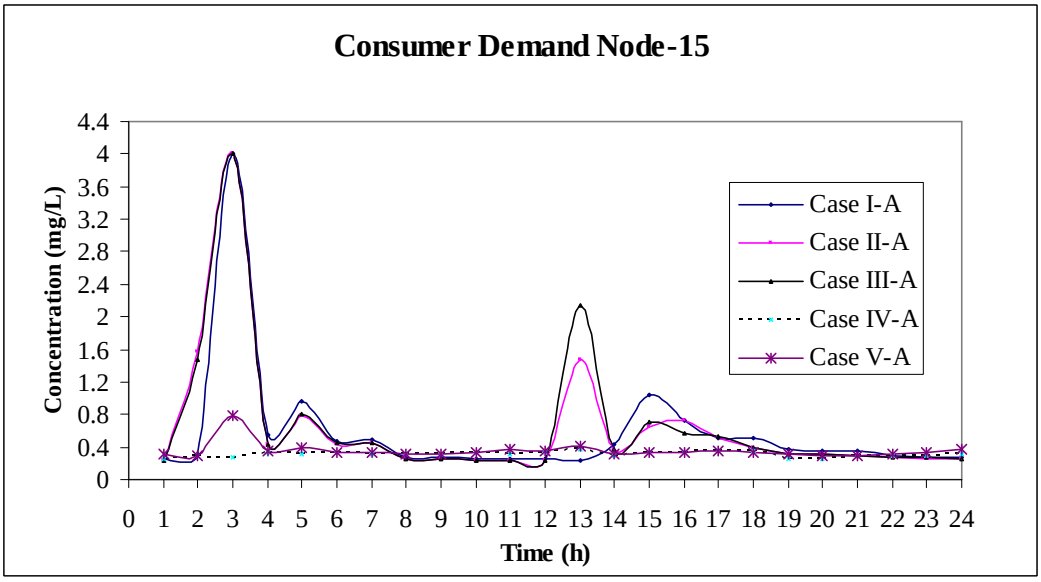
B.10. Chlorine Concentration at Node-12



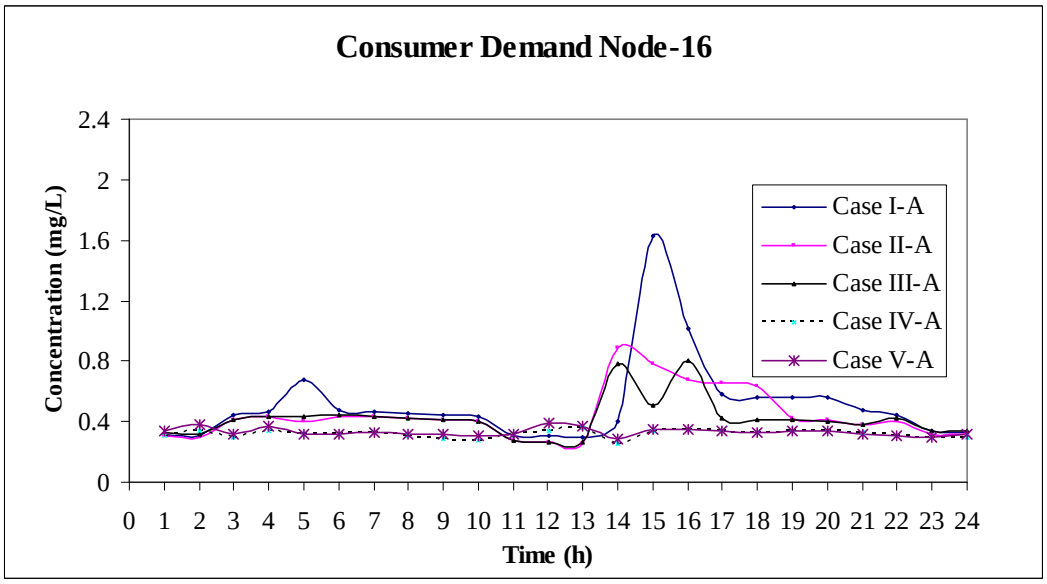
B.11. Chlorine Concentration at Node-13



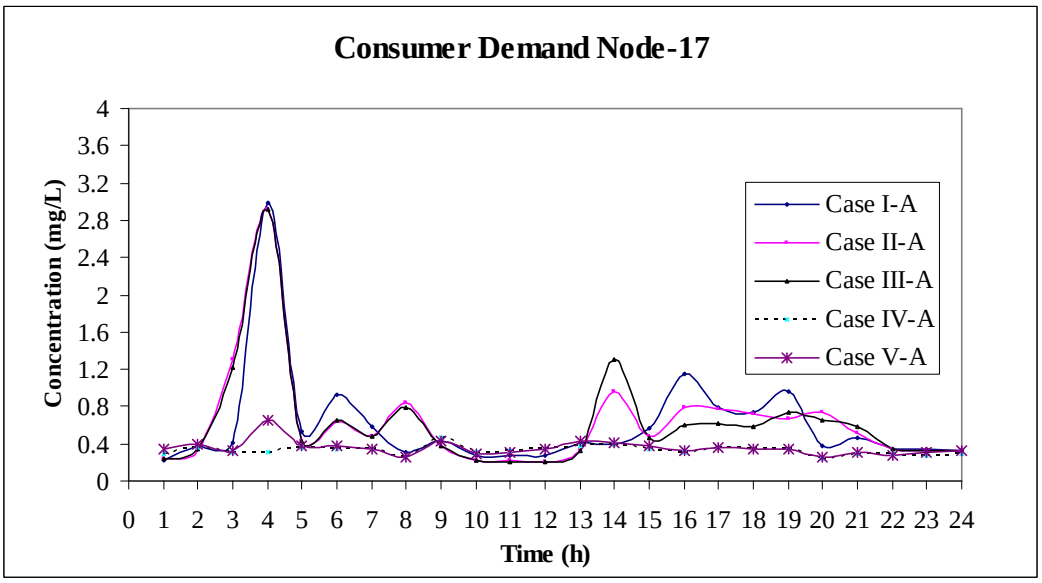
B.12. Chlorine Concentration at Node-14



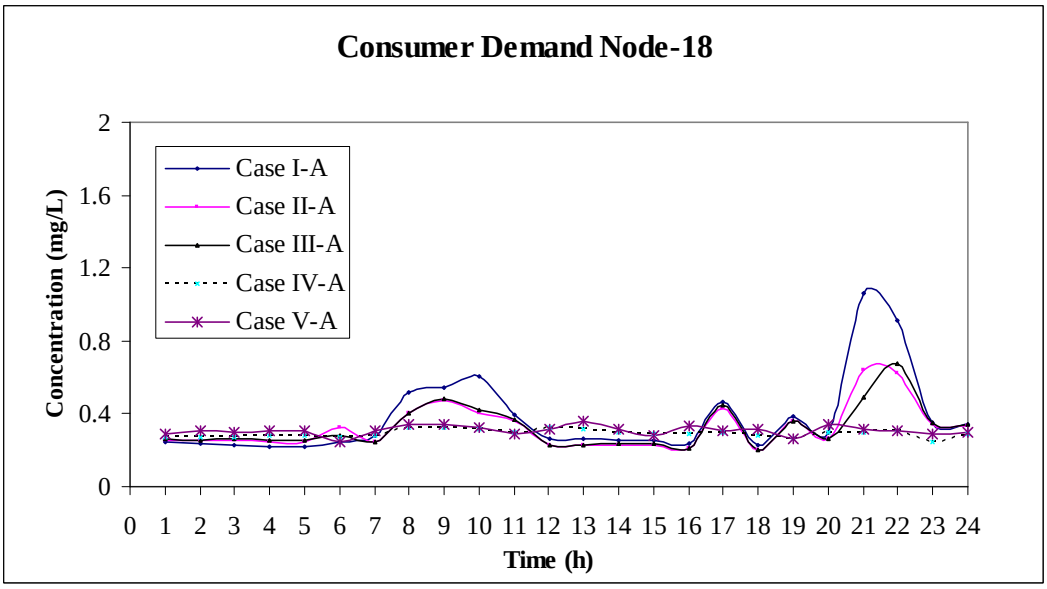
B.13. Chlorine Concentration at Node-15



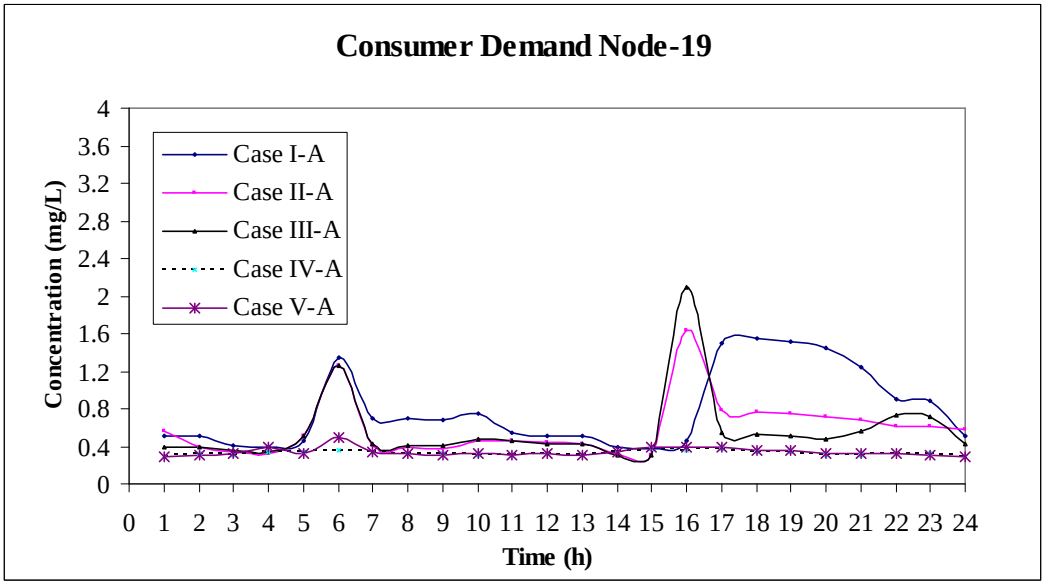
B.14. Chlorine Concentration at Node-16



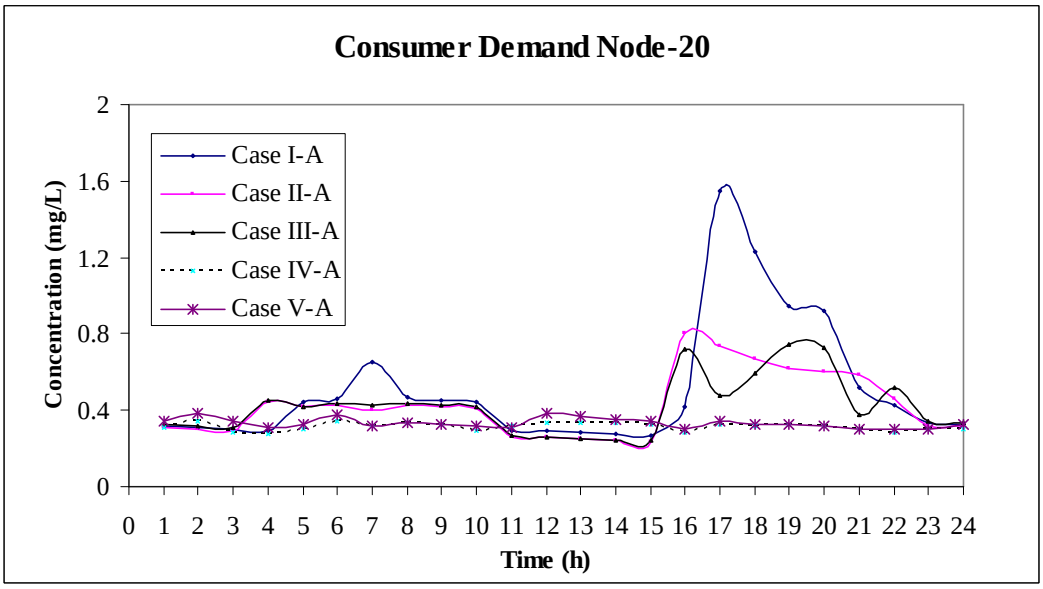
B.15. Chlorine Concentration at Node-17



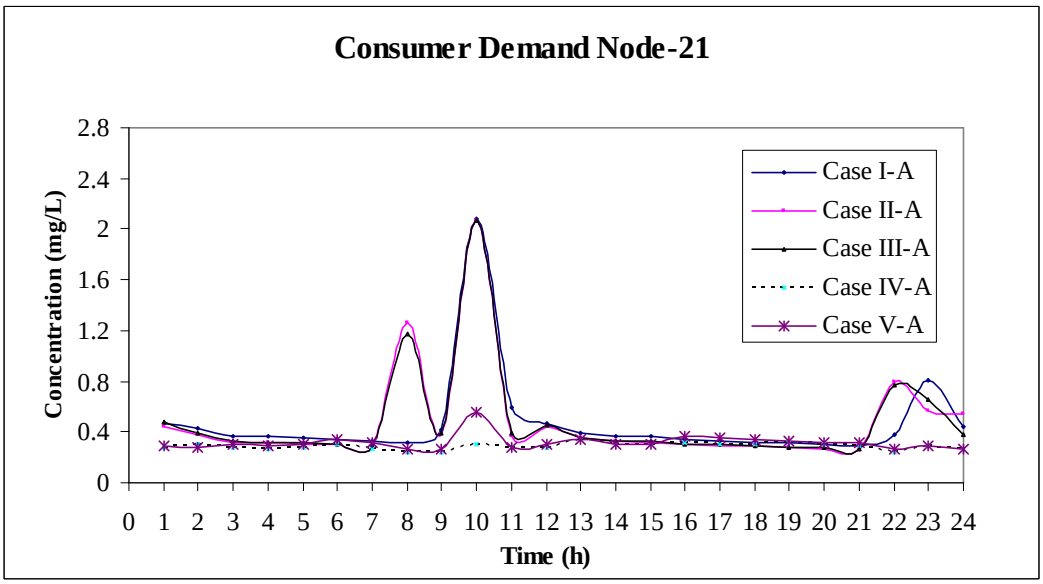
B.16. Chlorine Concentration at Node-18



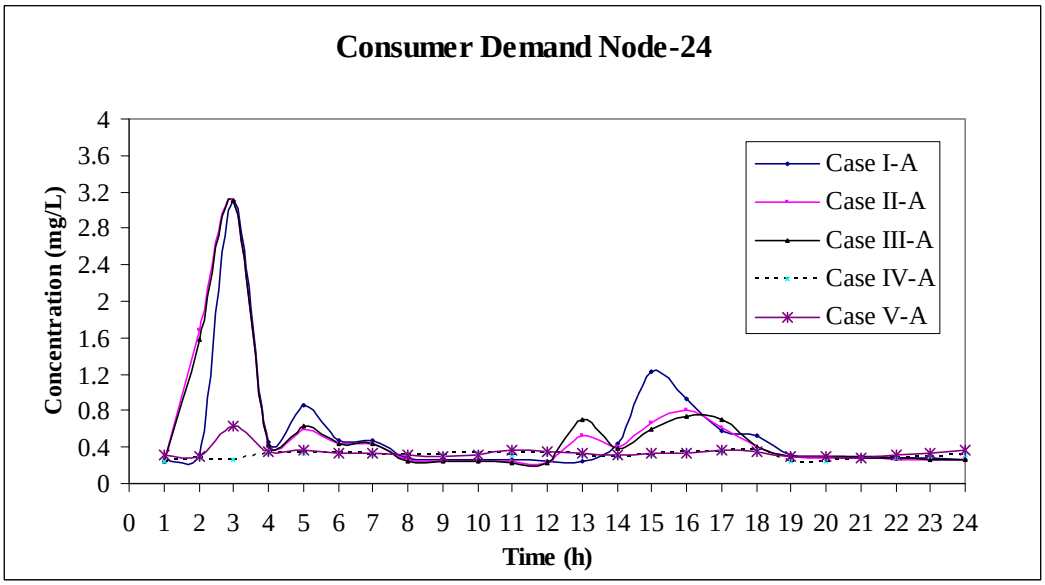
B.17. Chlorine Concentration at Node-19



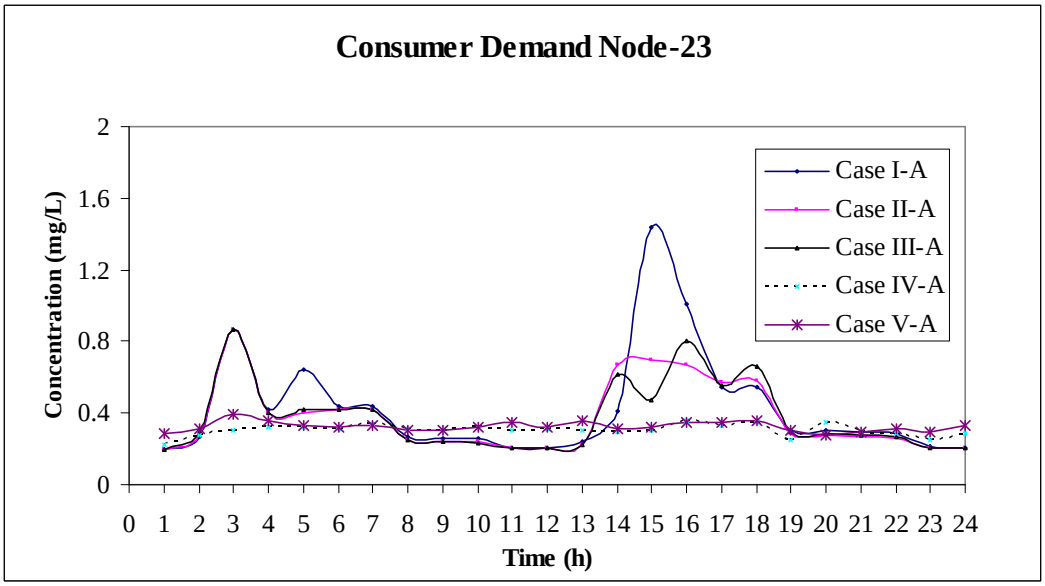
B.18. Chlorine Concentration at Node-20



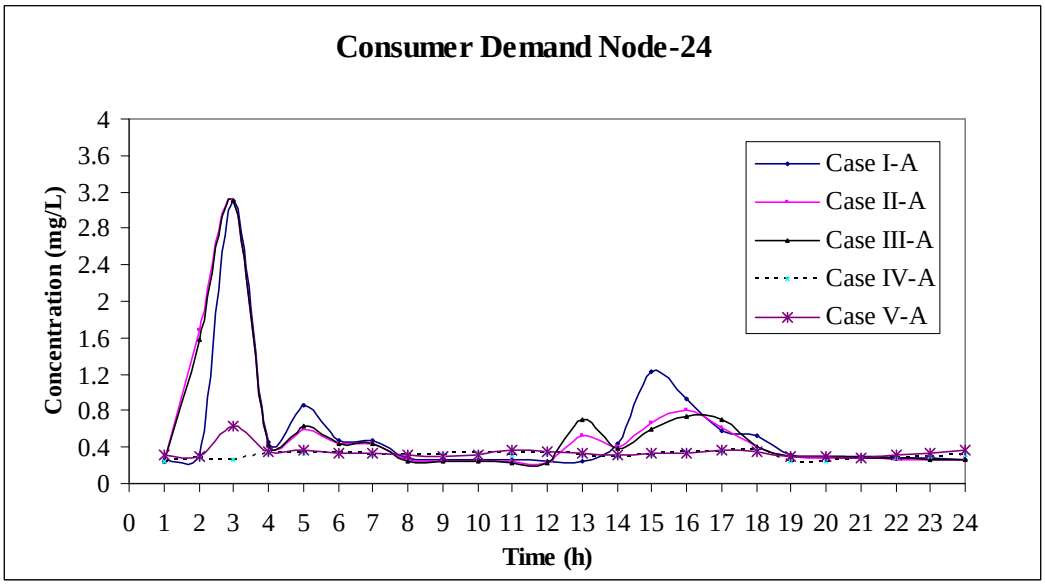
B.19. Chlorine Concentration at Node-21



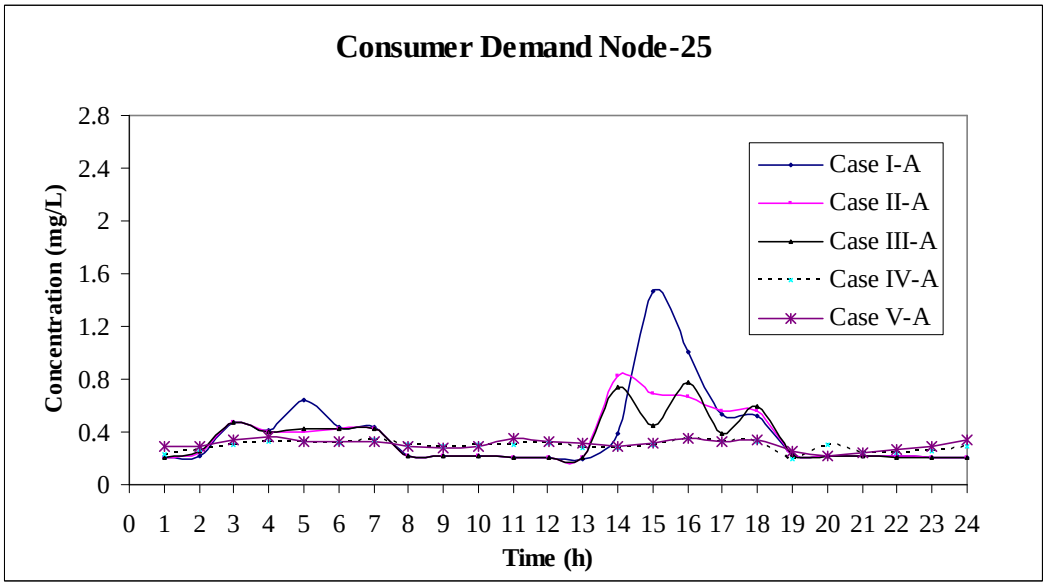
B.20. Chlorine Concentration at Node-22



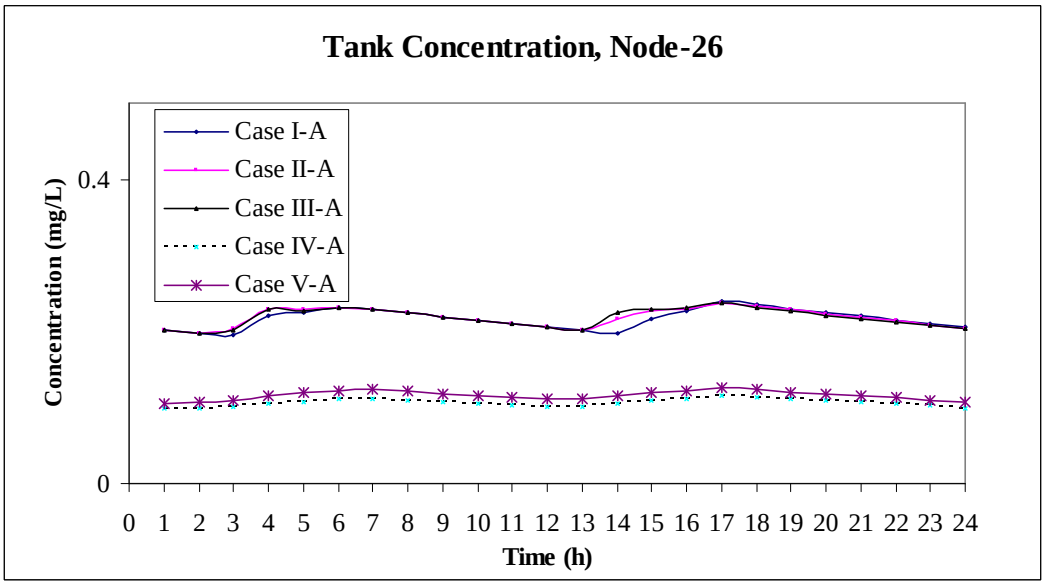
B.21. Chlorine Concentration at Node-23



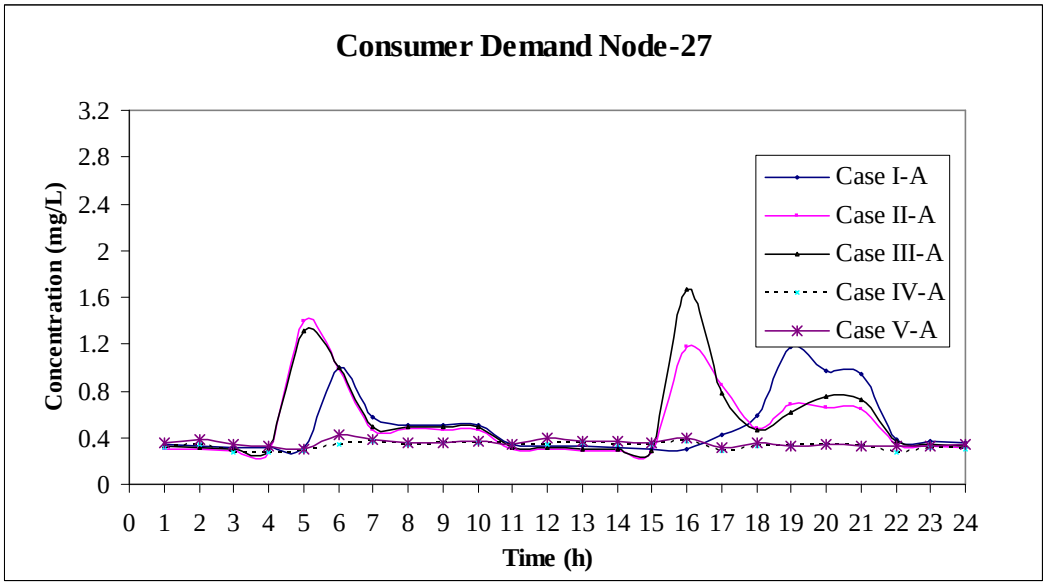
B.22. Chlorine Concentration at Node-24



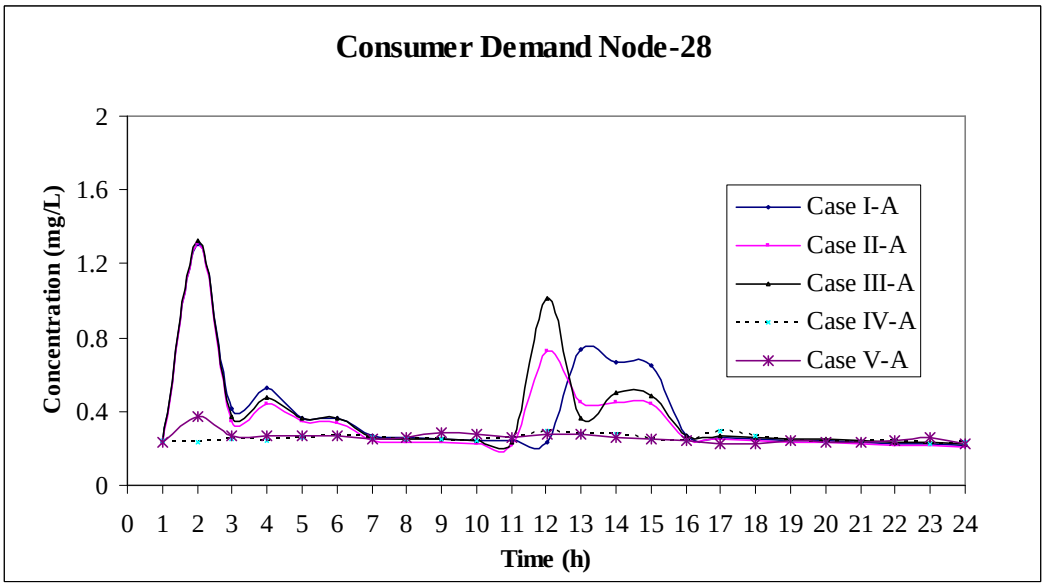
B.23. Chlorine Concentration at Node-25



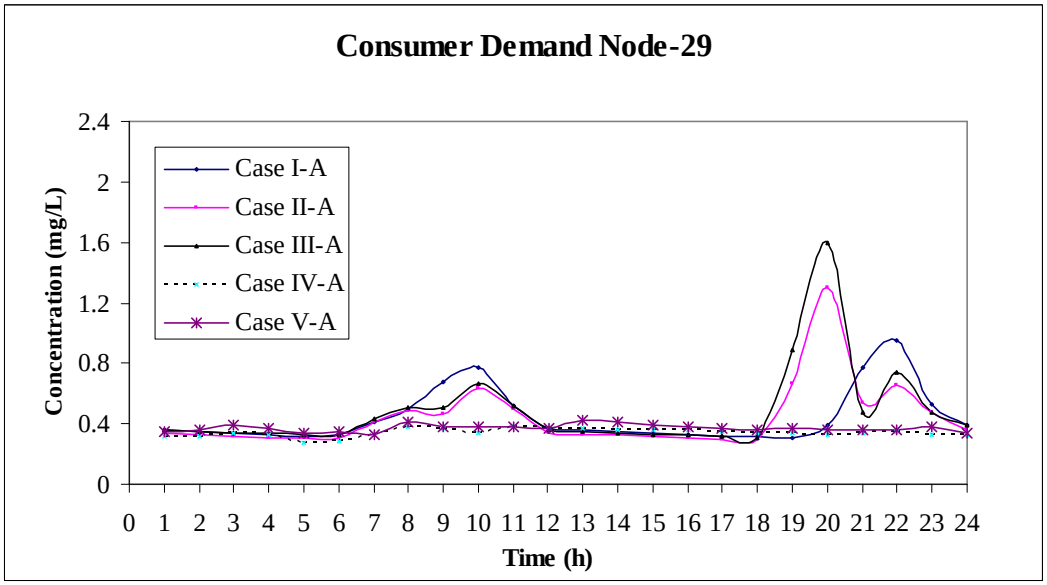
B.24. Chlorine Concentration at Storage Tank, Node-26



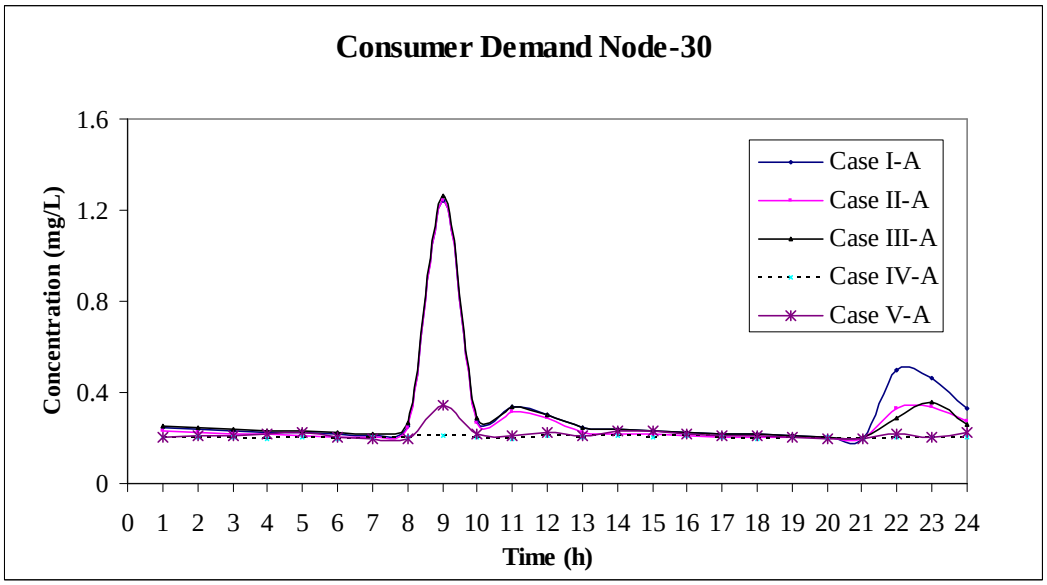
B.25. Chlorine Concentration at Node-27



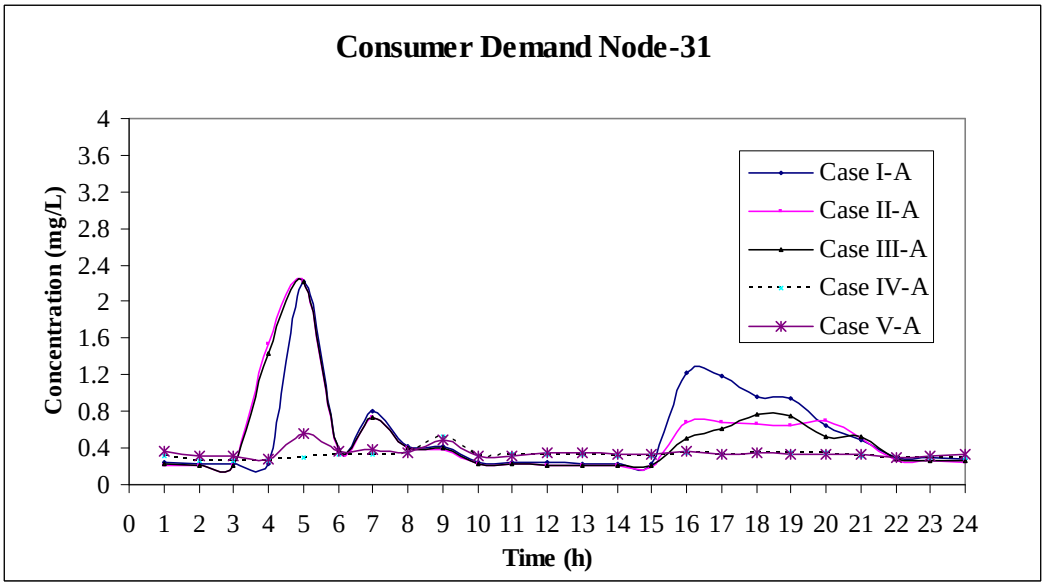
B.26. Chlorine Concentration at Node-28



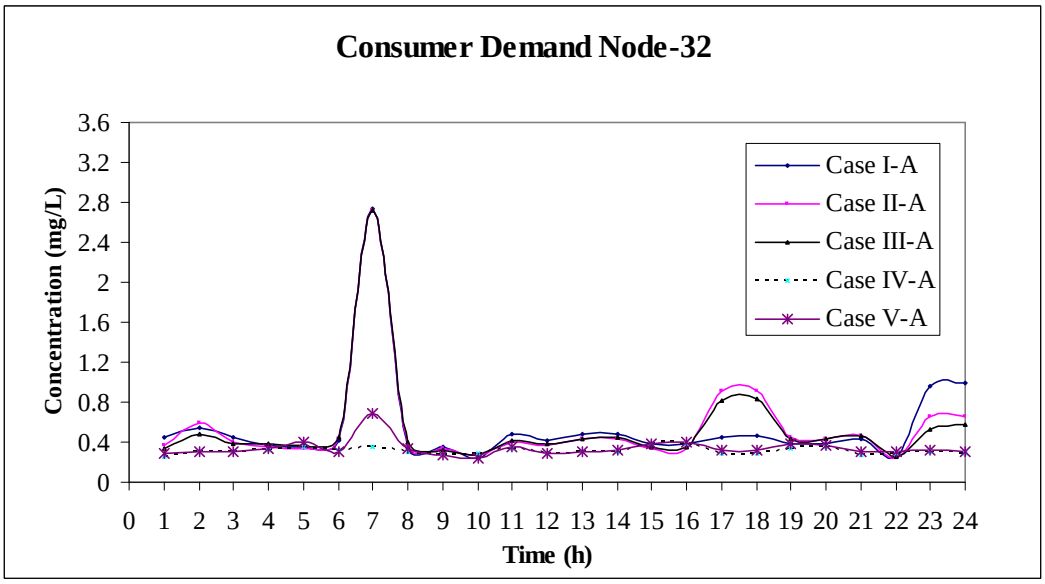
B.27. Chlorine Concentration at Node-29



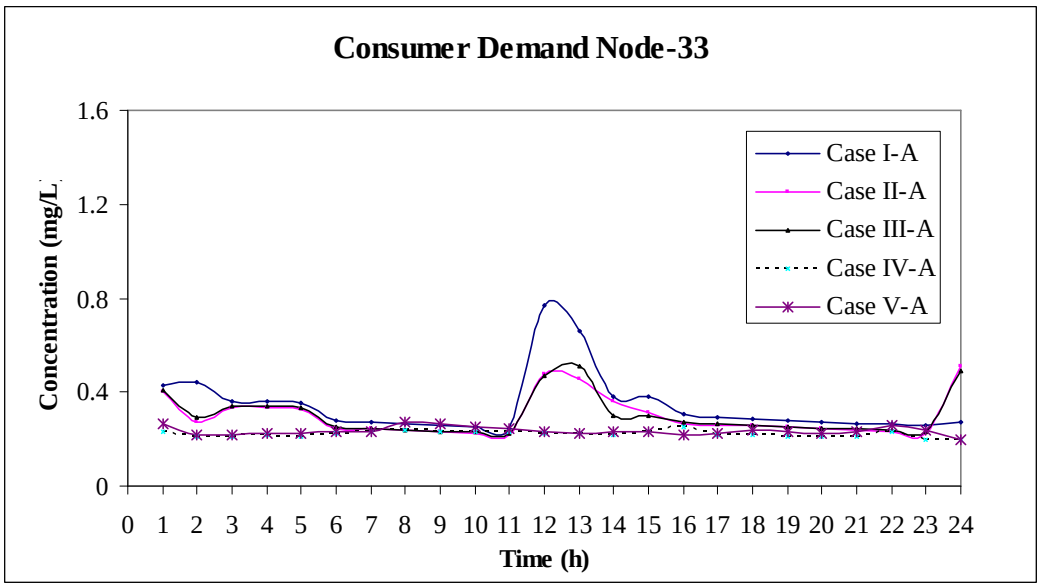
B.28. Chlorine Concentration at Node-30



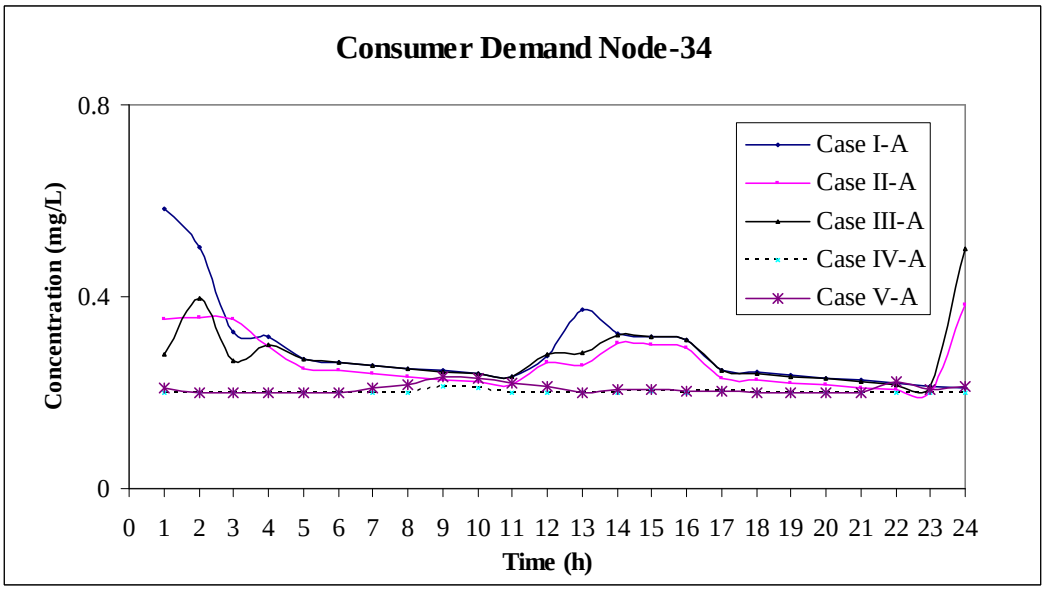
B.29 Chlorine Concentration at Node-31



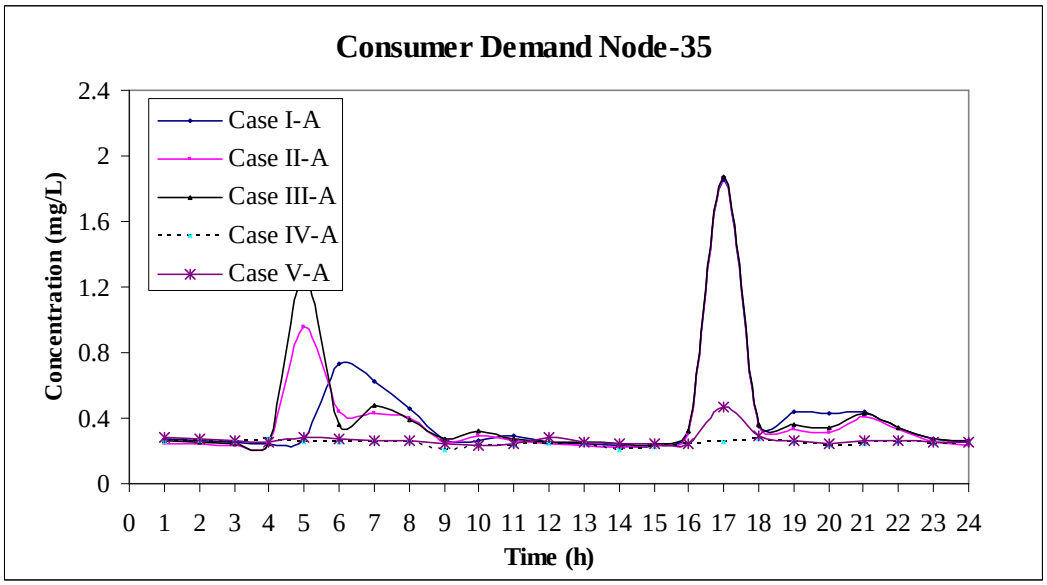
B.30. Chlorine Concentration at Node-32



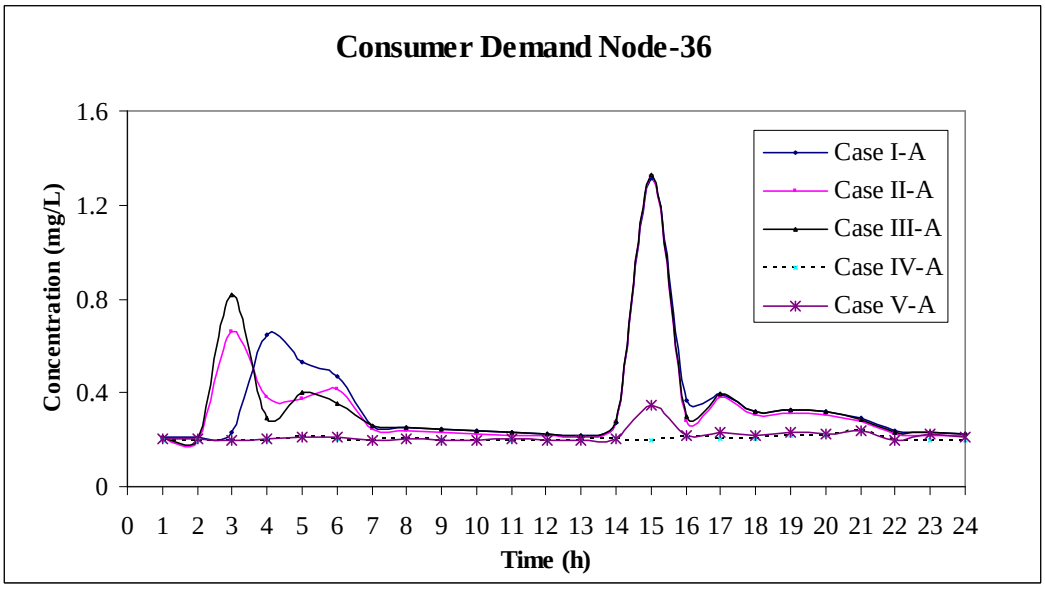
B.31. Chlorine Concentration at Node-33



B.32. Chlorine Concentration at Node-34



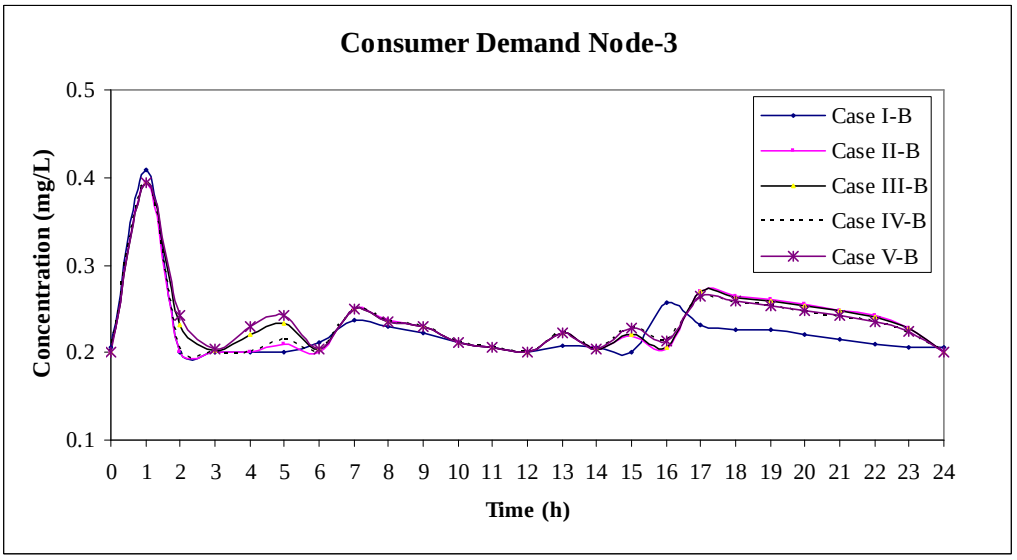
B.33. Chlorine Concentration at Node-35



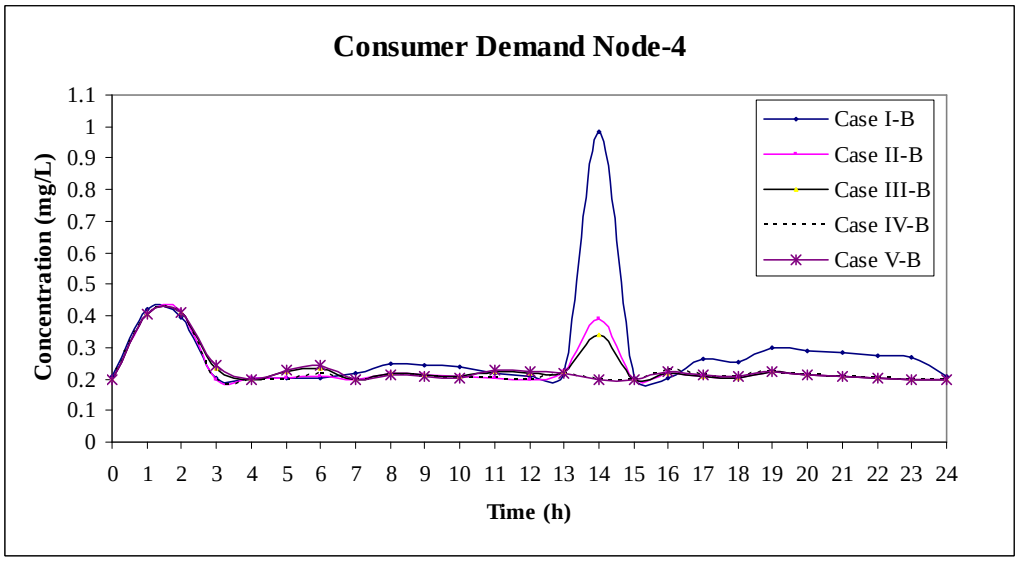
B.34. Chlorine Concentration at Node-36

APPENDIX C

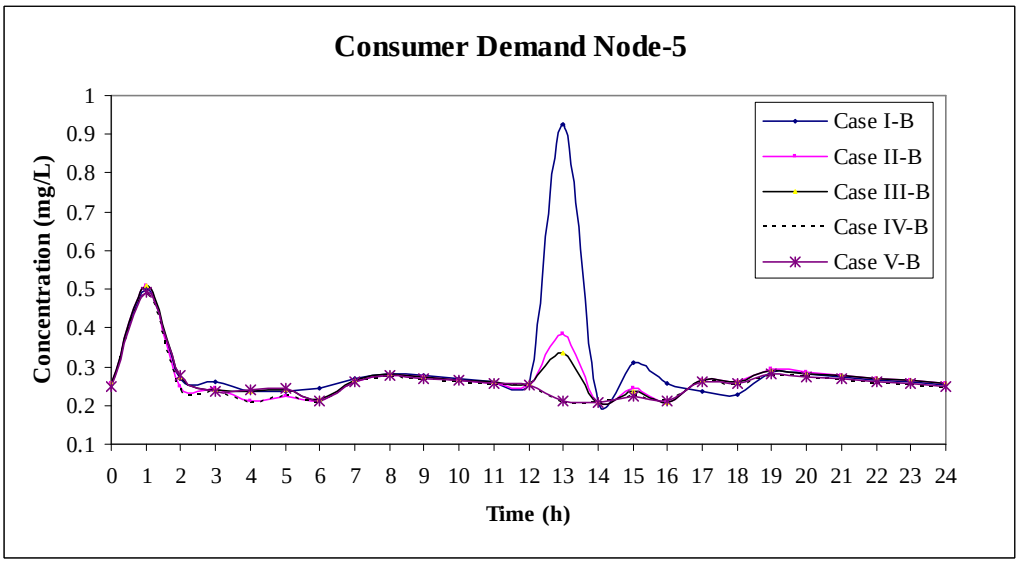
CHLORINE CONCENTRATIONS (FORMULATION-2)



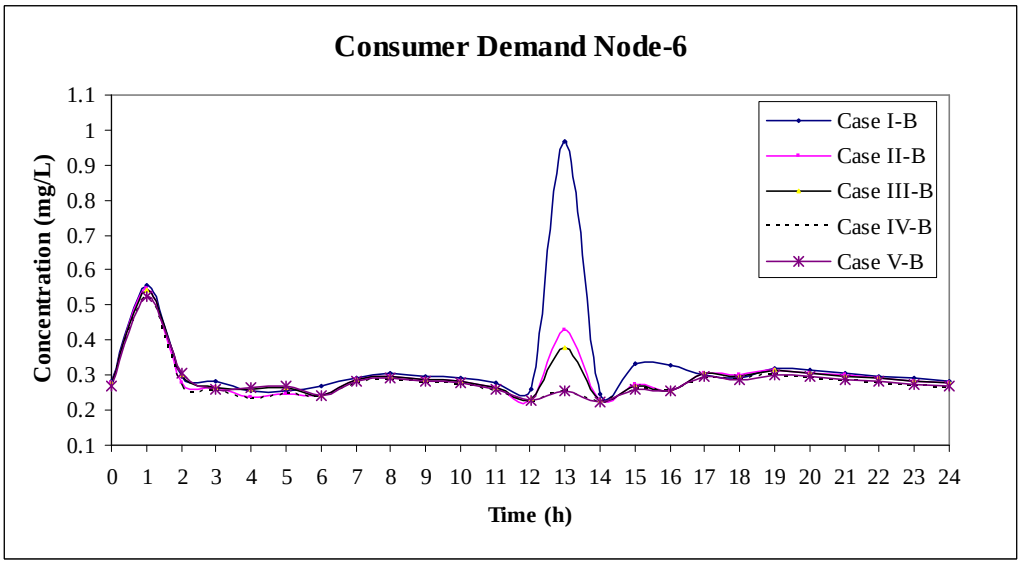
C.1. Chlorine Concentration at Node-3



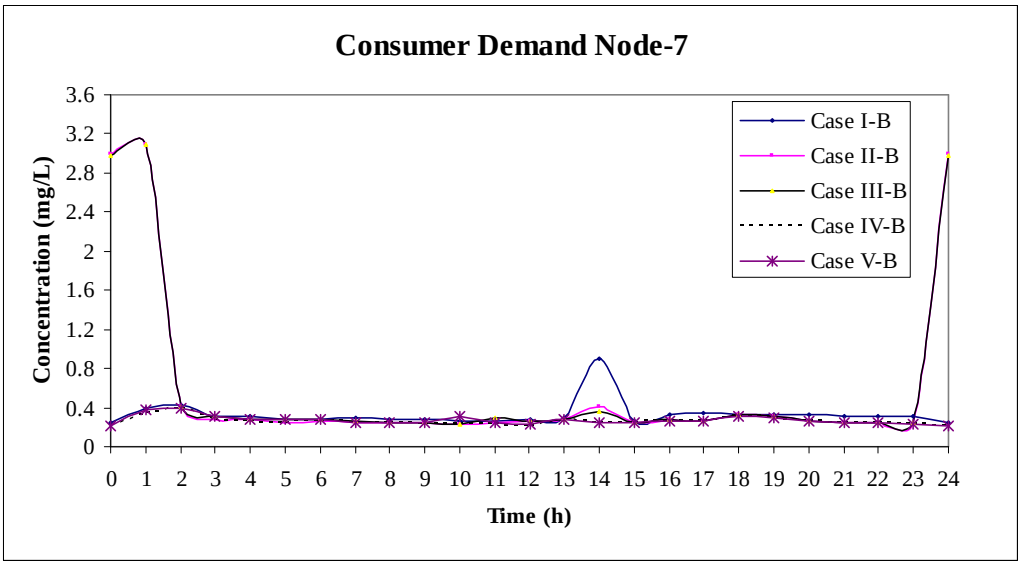
C.2. Chlorine Concentration at Node-4



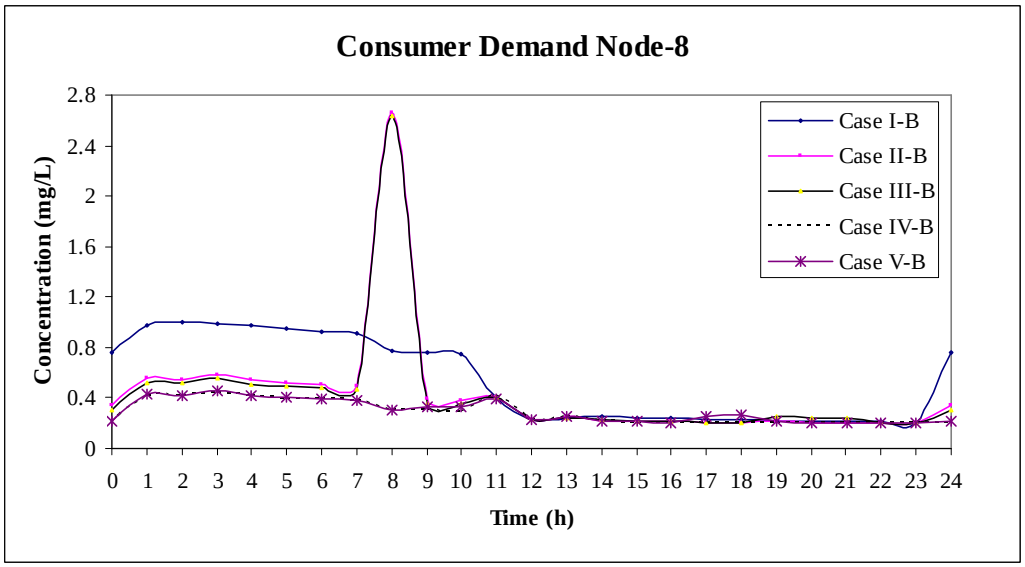
C.3. Chlorine Concentration at Node-5



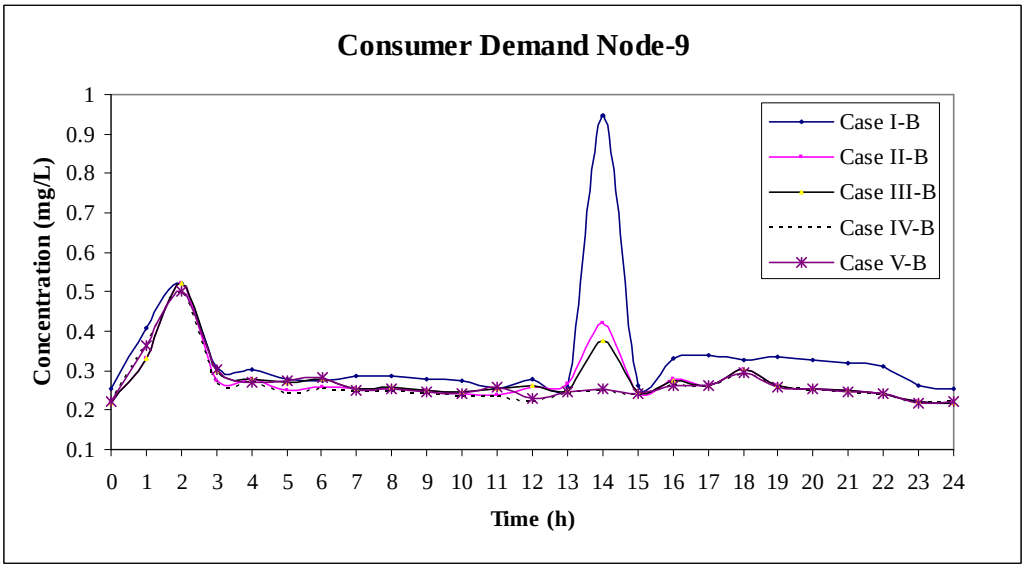
C.4. Chlorine Concentration at Node-6



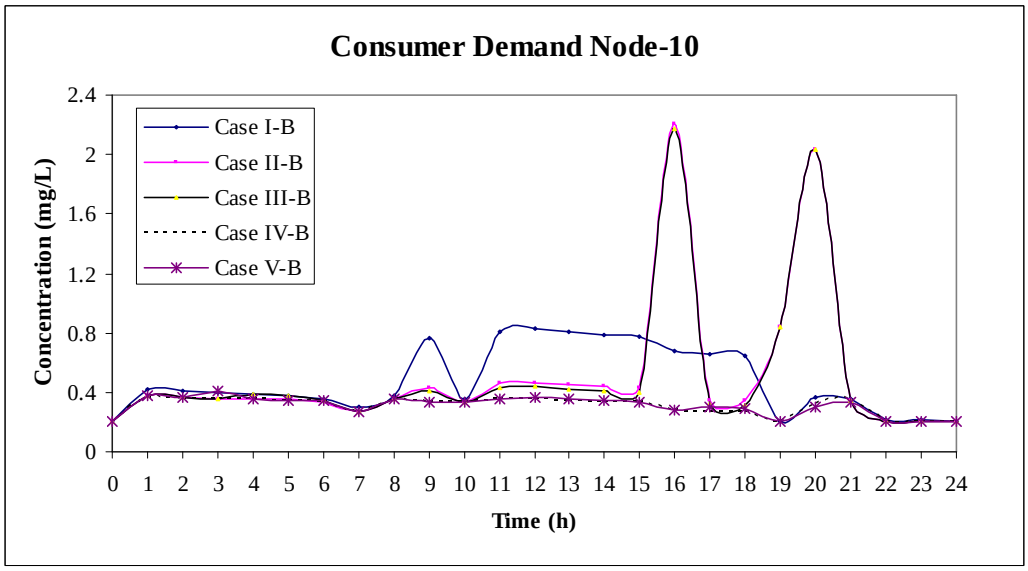
C.5. Chlorine Concentration at Node-7



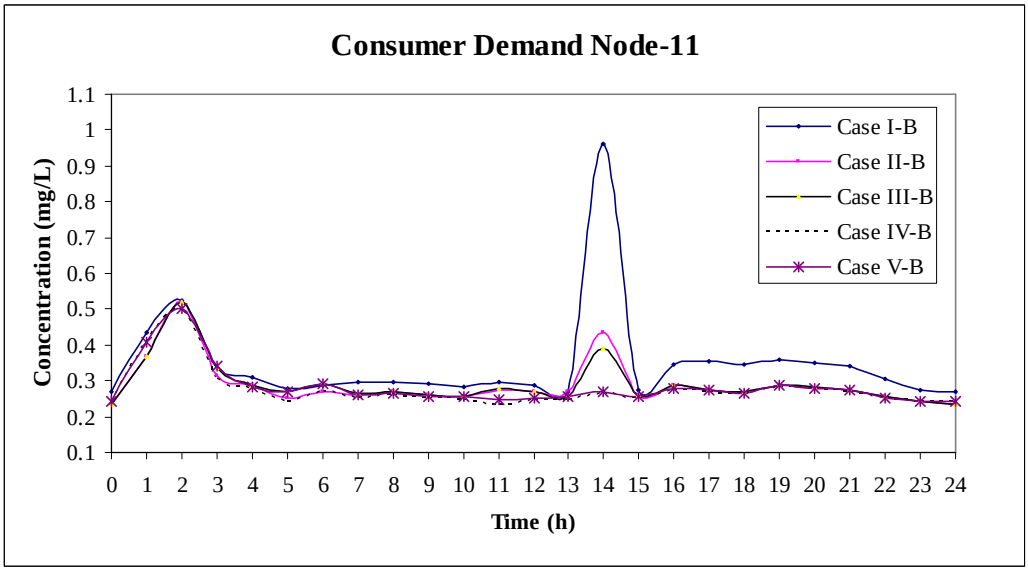
C.6. Chlorine Concentration at Node-8



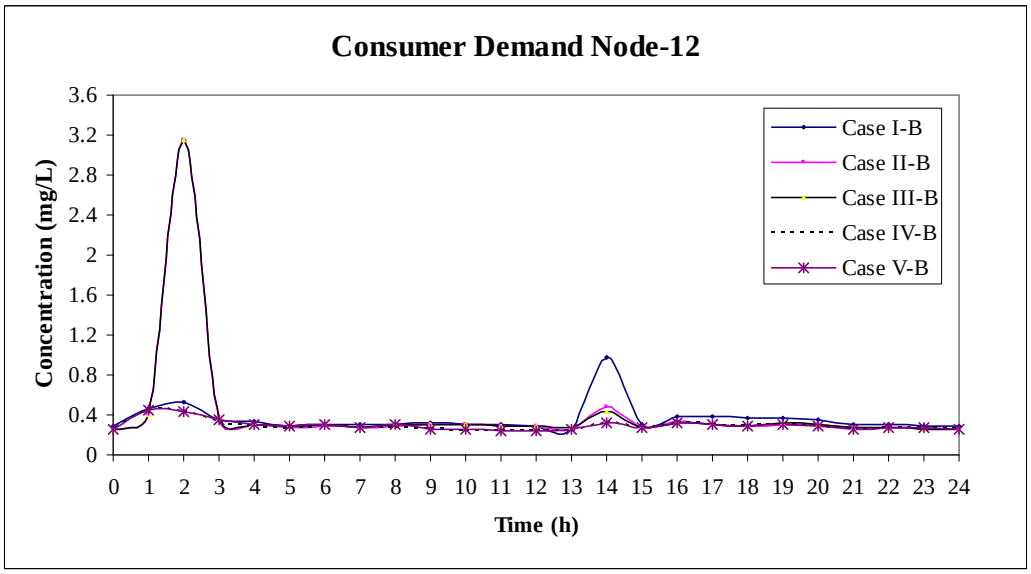
C.7. Chlorine Concentration at Node-9



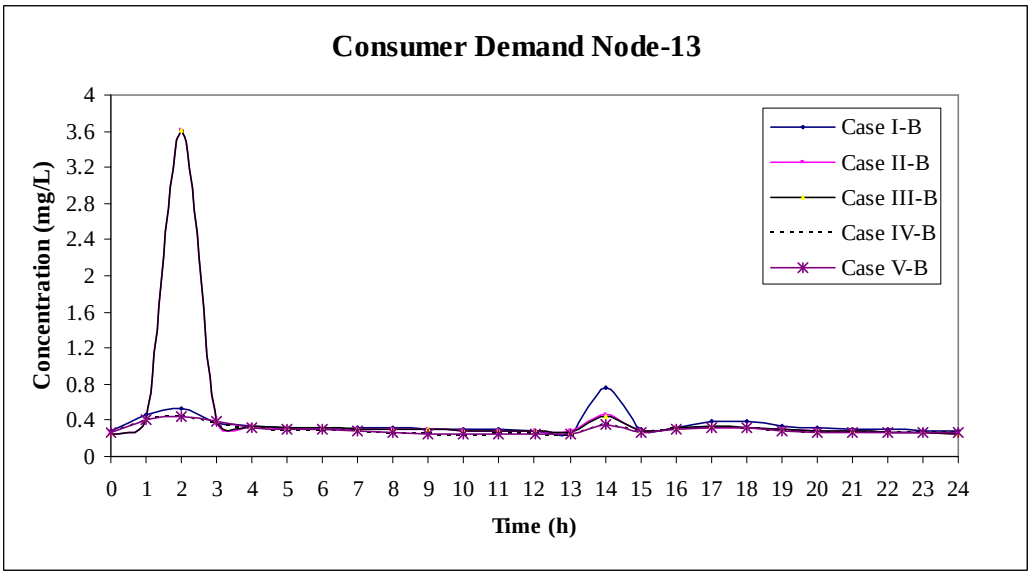
C.8. Chlorine Concentration at Node-10



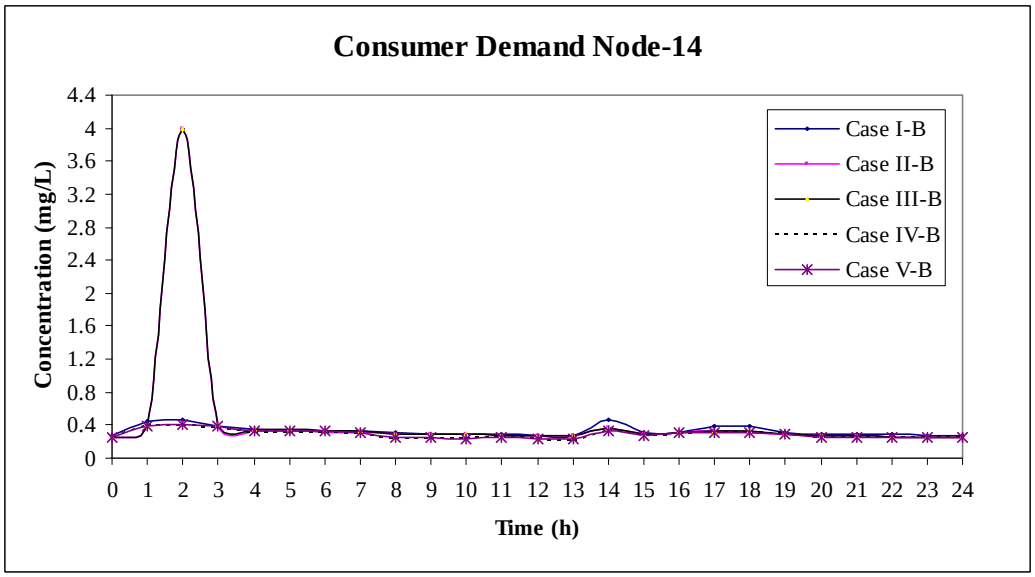
C.9. Chlorine Concentration at Node-11



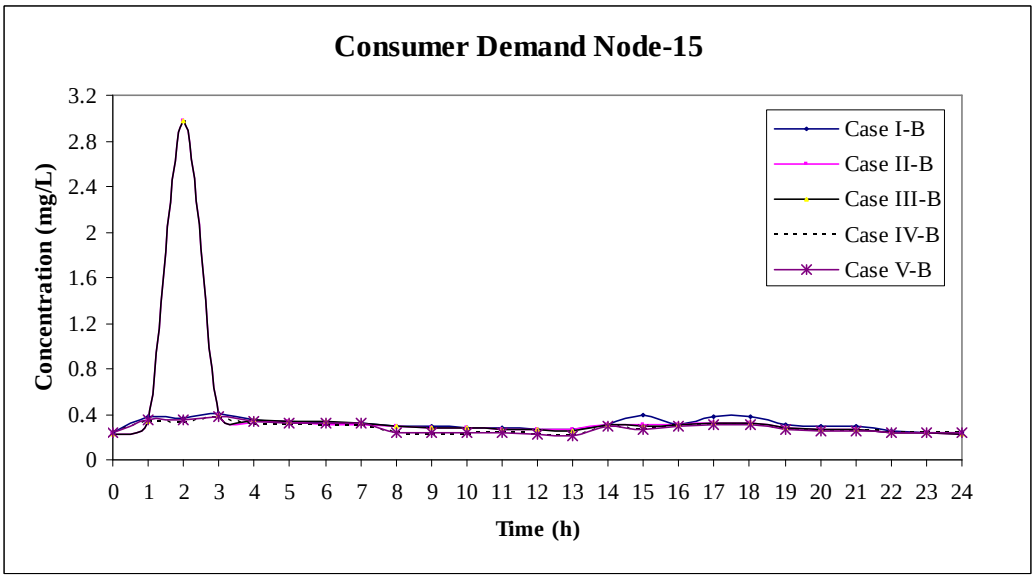
C.10. Chlorine Concentration at Node-12



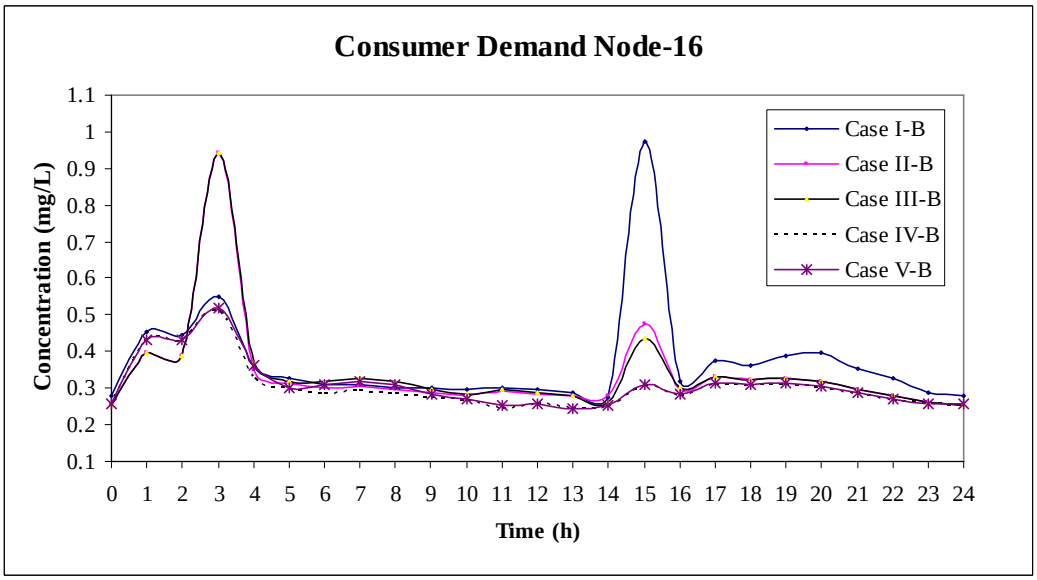
C.11. Chlorine Concentration at Node-13



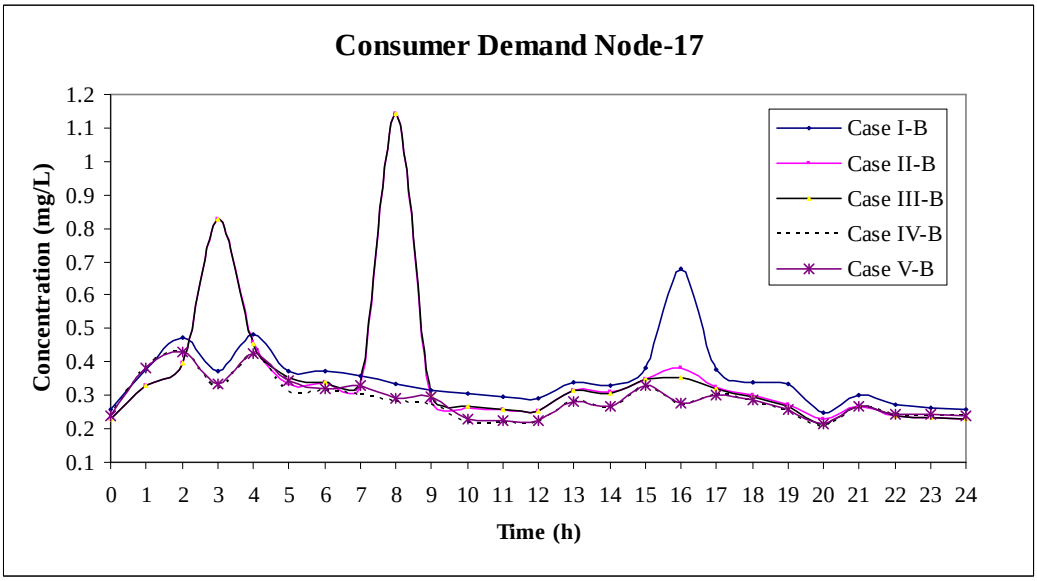
C.12. Chlorine Concentration at Node-14



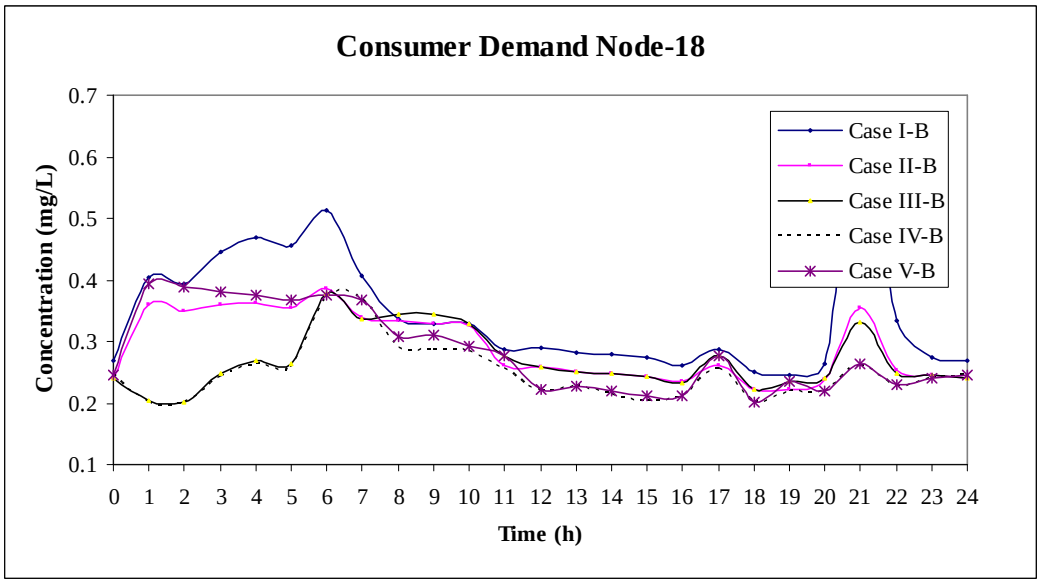
C.13. Chlorine Concentration at Node-15



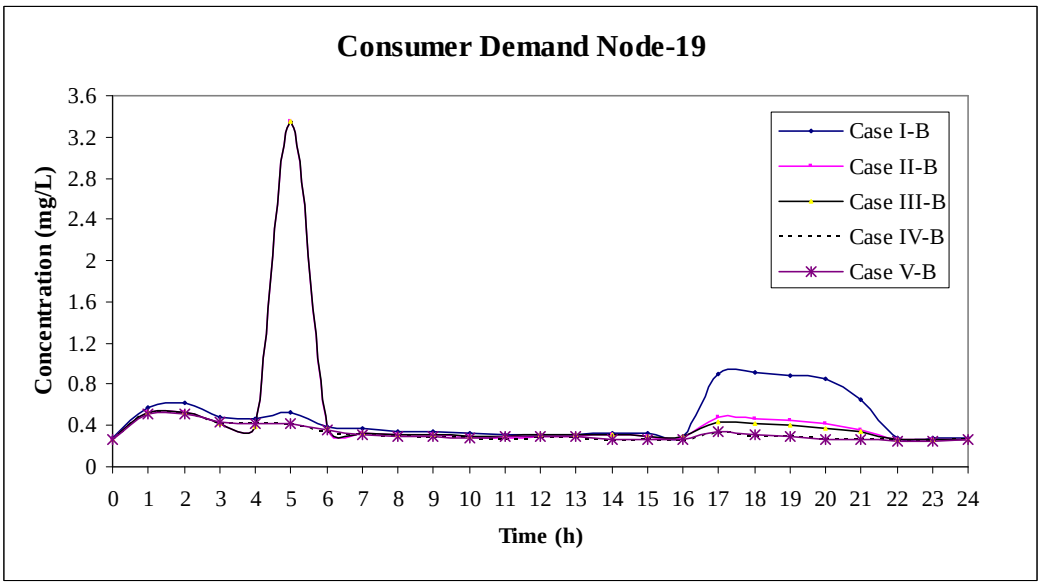
C.14. Chlorine Concentration at Node-16



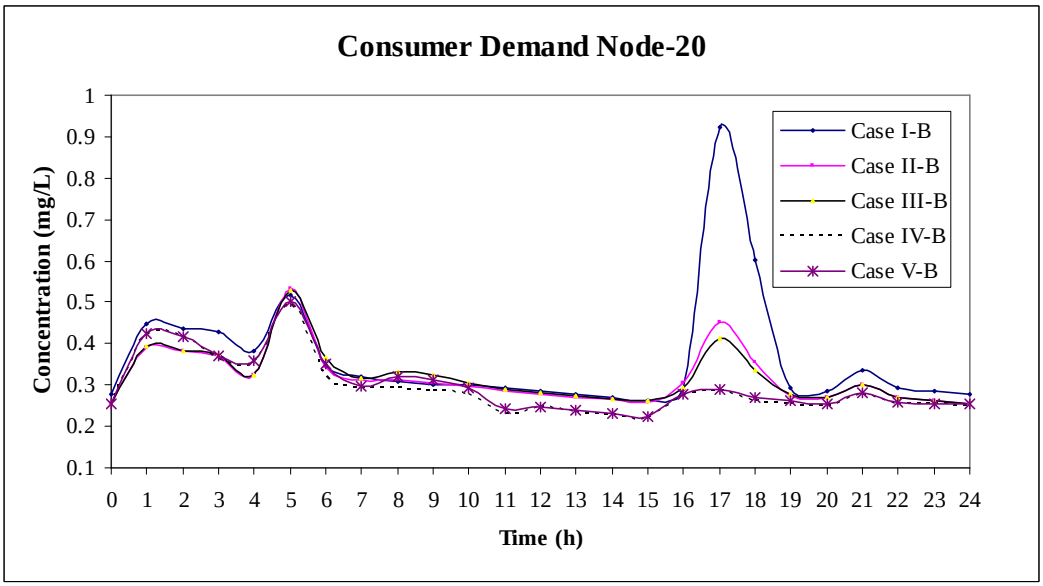
C.15. Chlorine Concentration at Node-17



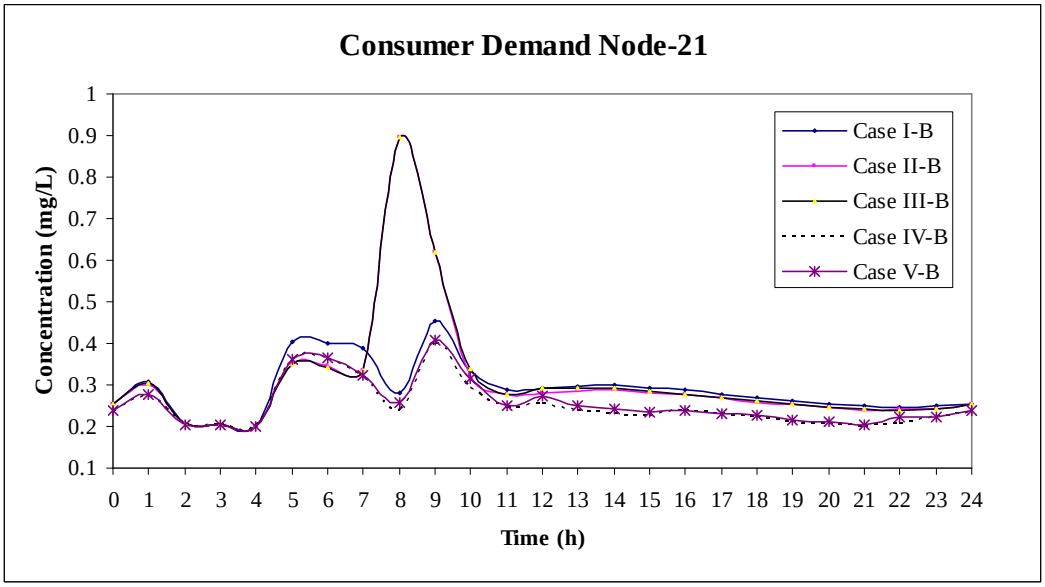
C.16. Chlorine Concentration at Node-18



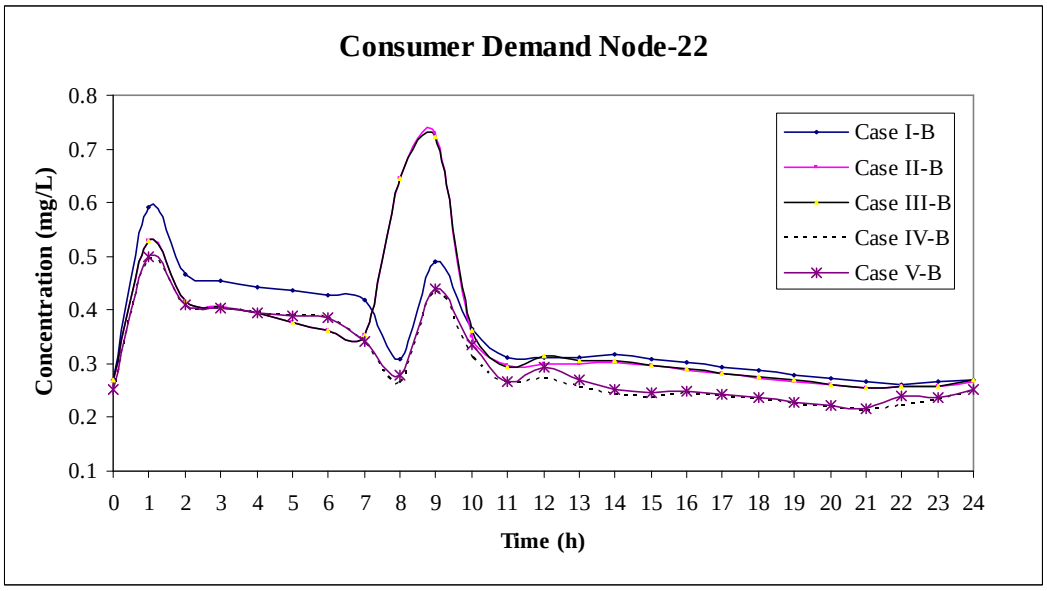
C.17. Chlorine Concentration at Node-19



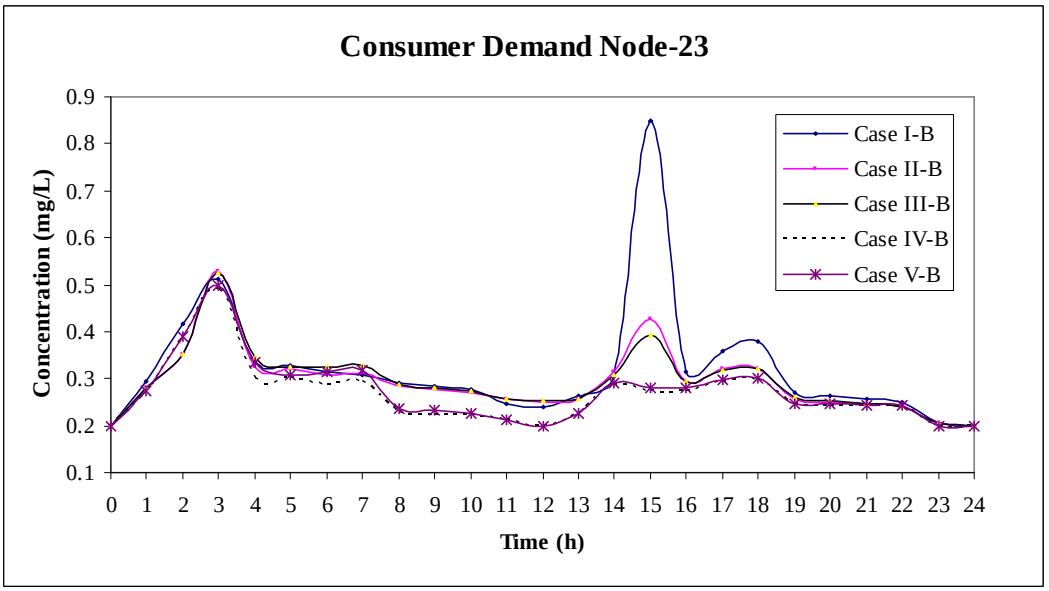
C.18. Chlorine Concentration at Node-20



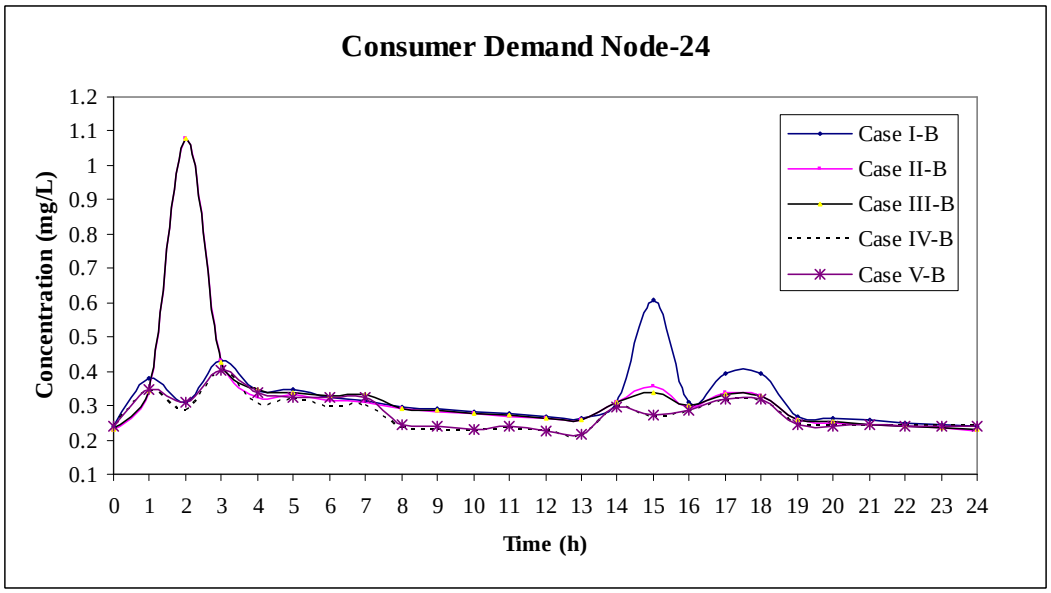
C.19. Chlorine Concentration at Node-21



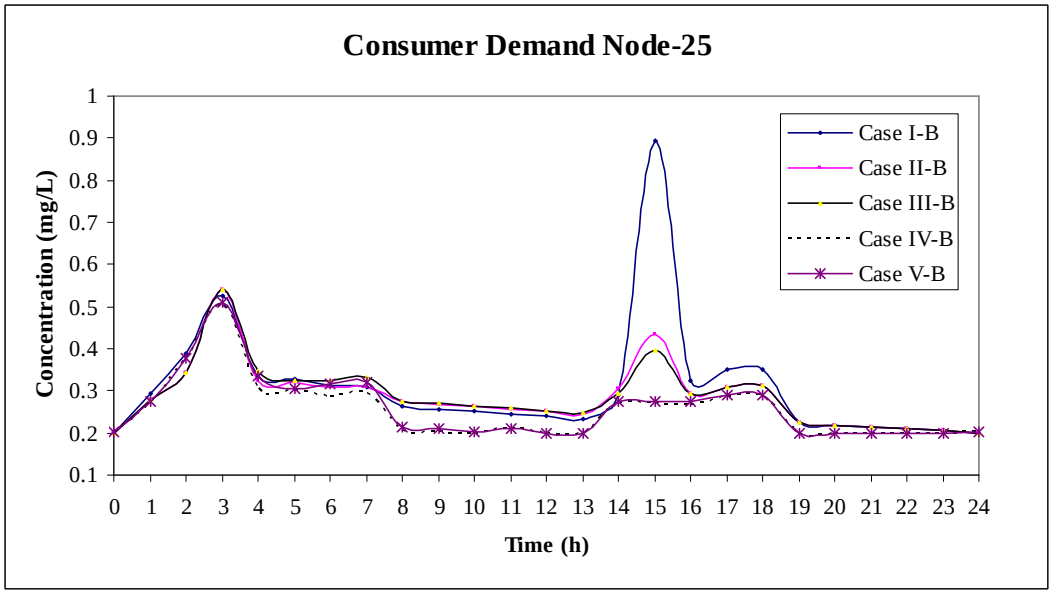
C.20. Chlorine Concentration at Node-22



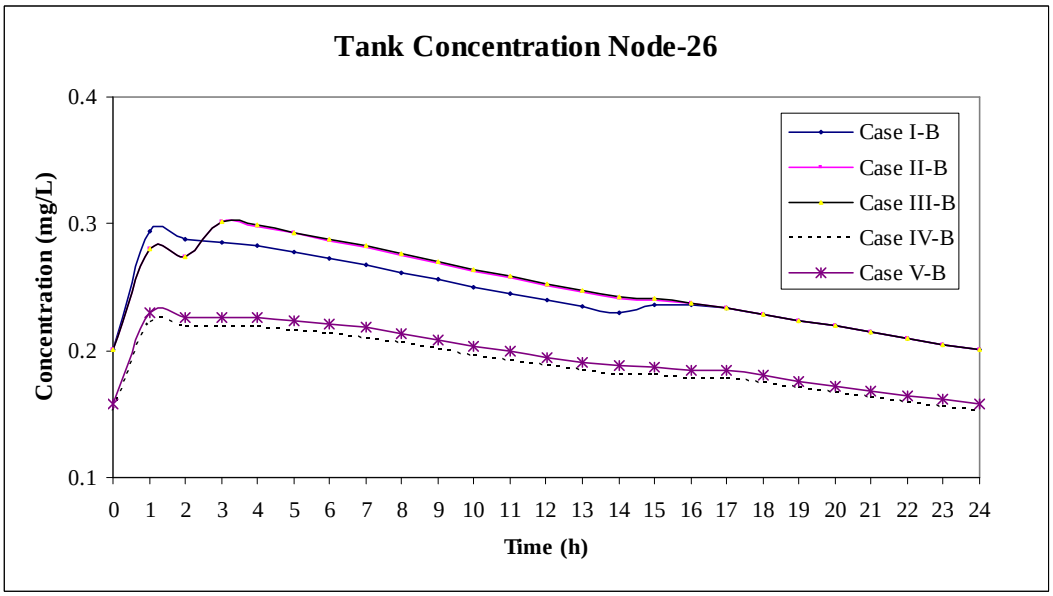
C.21. Chlorine Concentration at Node-23



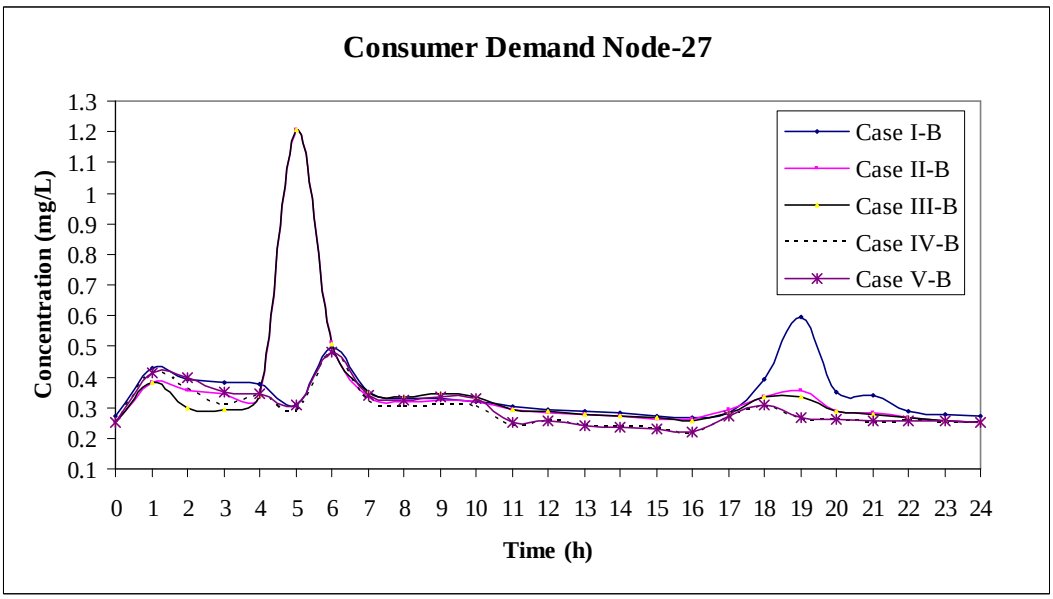
C.22. Chlorine Concentration at Node-24



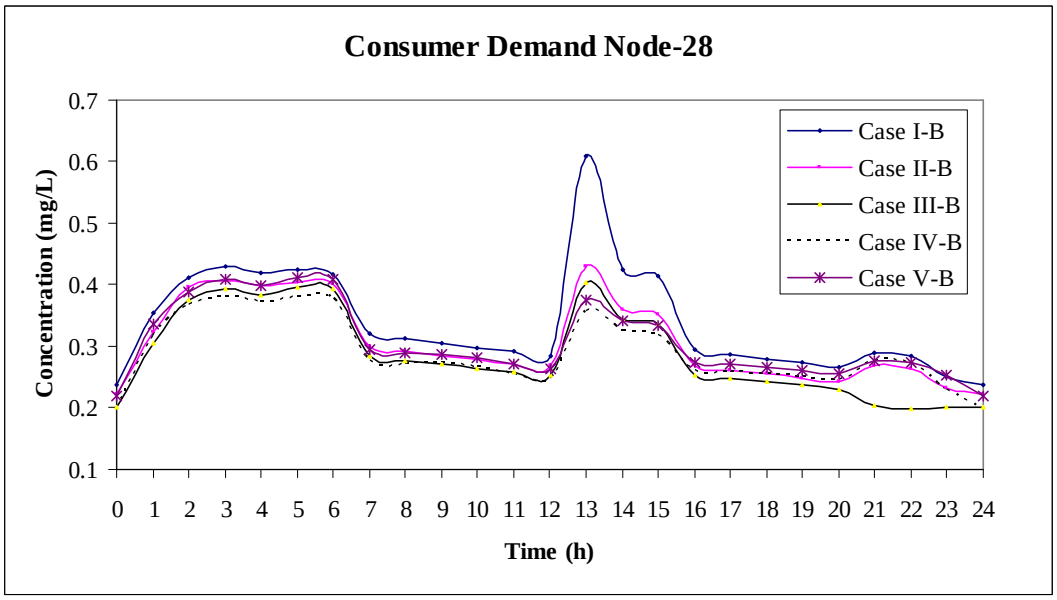
C.23. Chlorine Concentration at Node-25



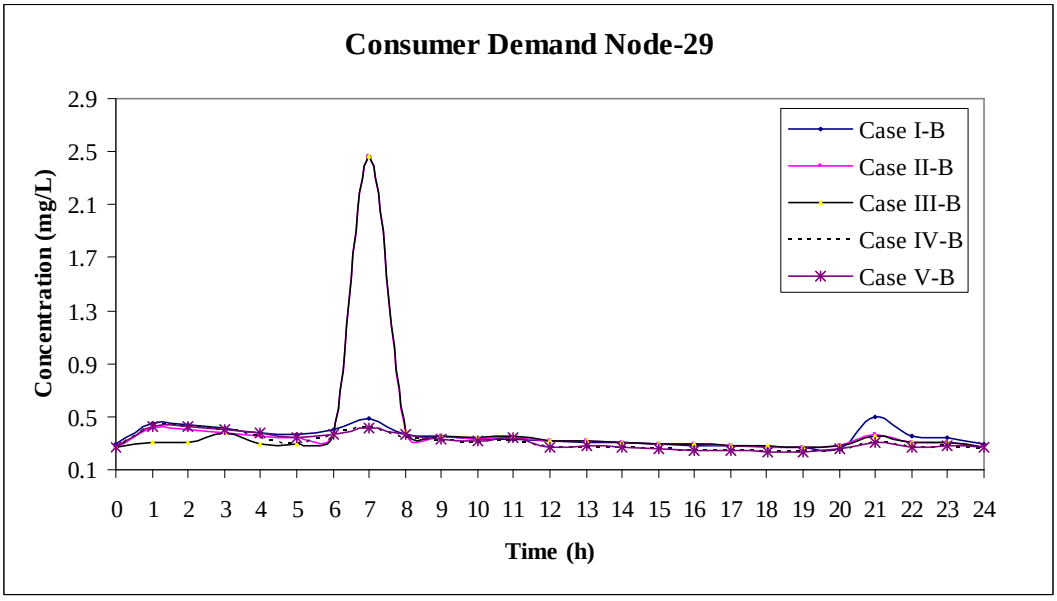
C.24. Chlorine Concentration at Storage Tank, Node-26



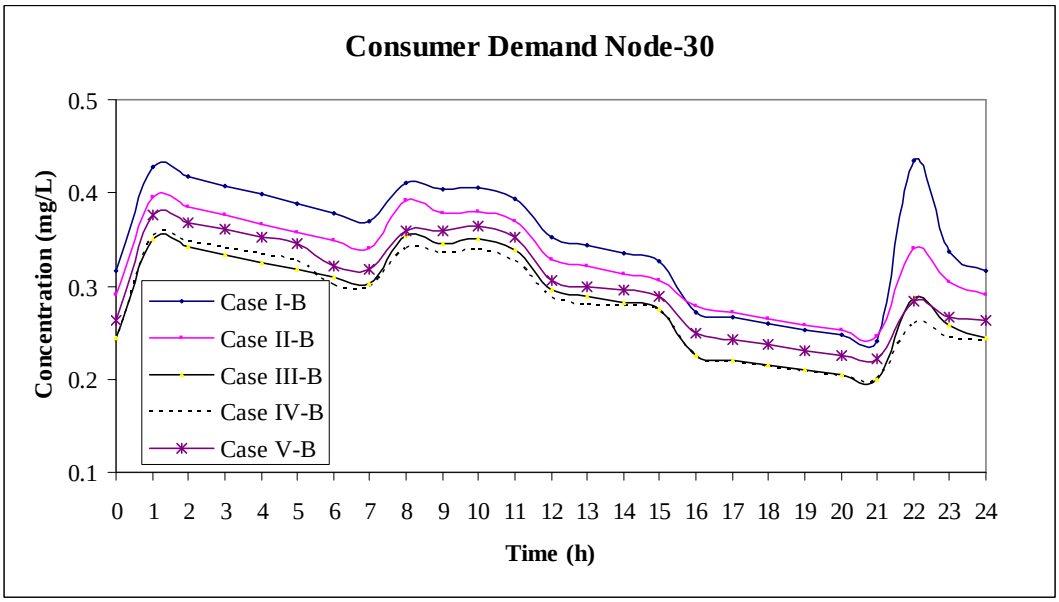
C.25. Chlorine Concentration at Node-27



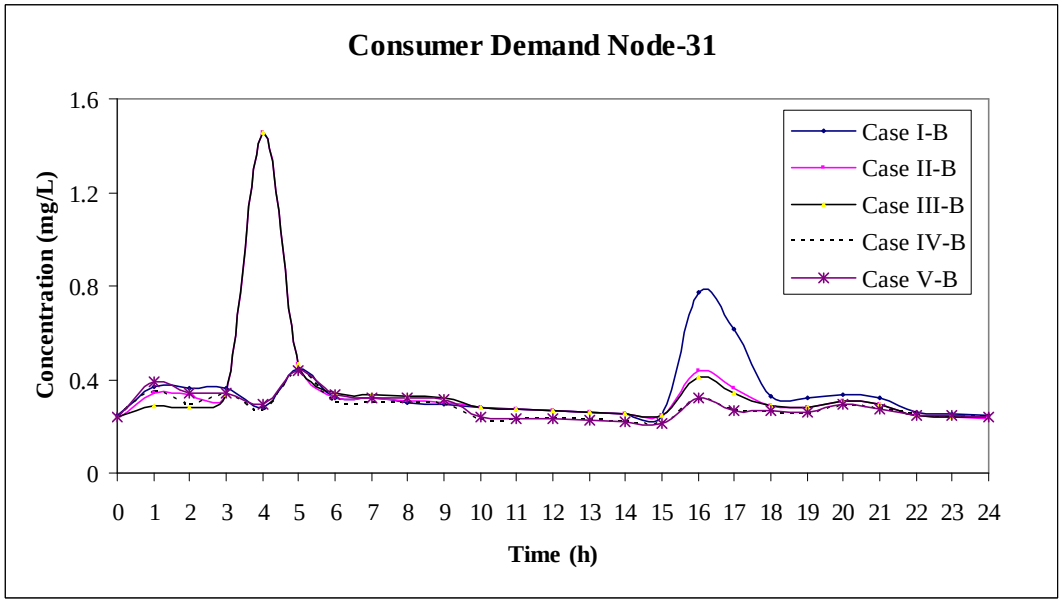
C.26. Chlorine Concentration at Node-28



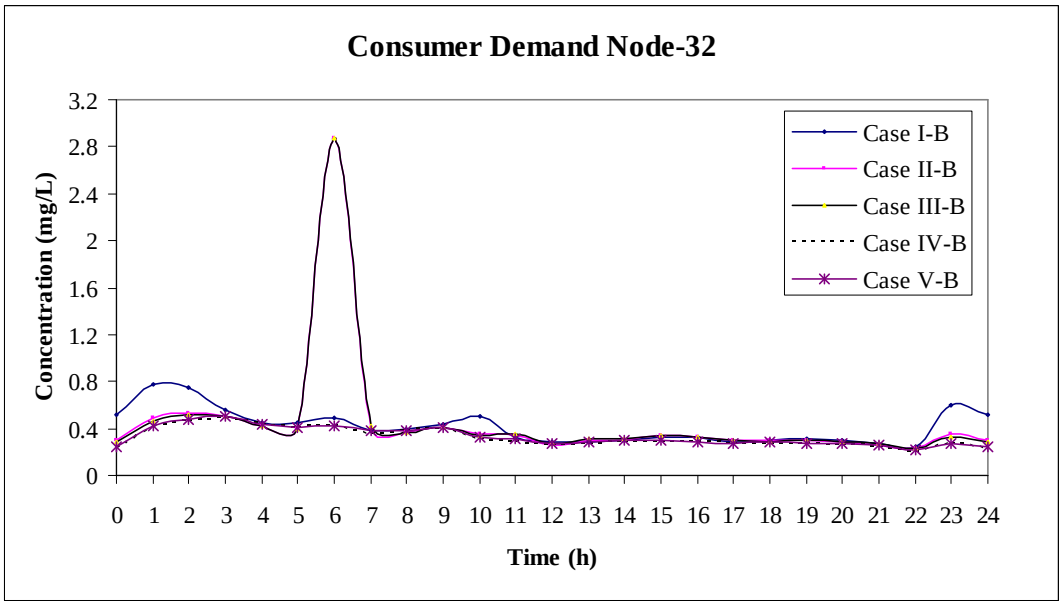
C.27. Chlorine Concentration at Node-29



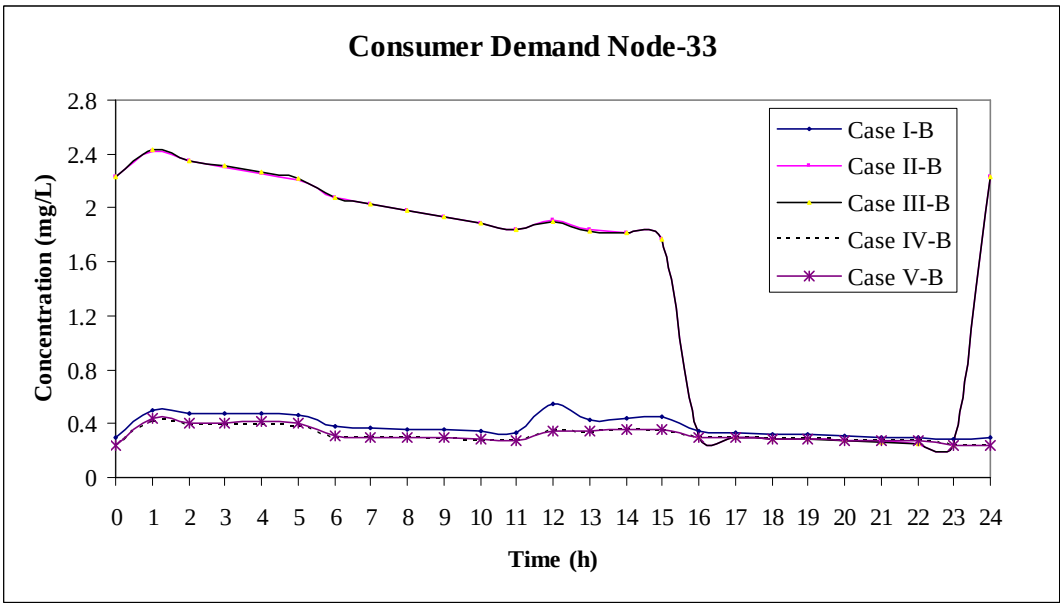
C.28. Chlorine Concentration at Node-30



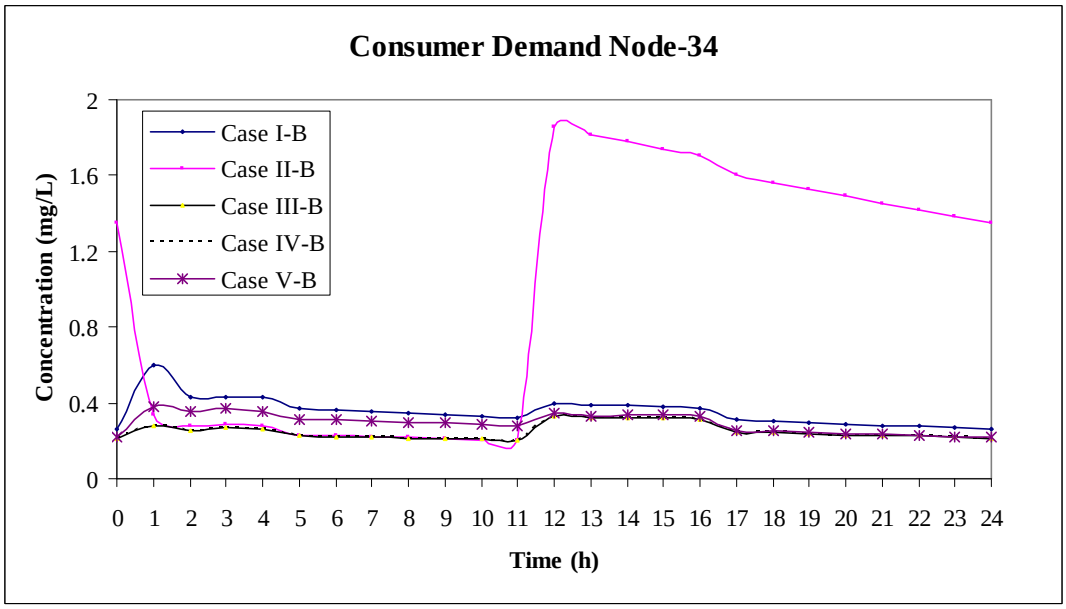
C.29 Chlorine Concentration at Node-31



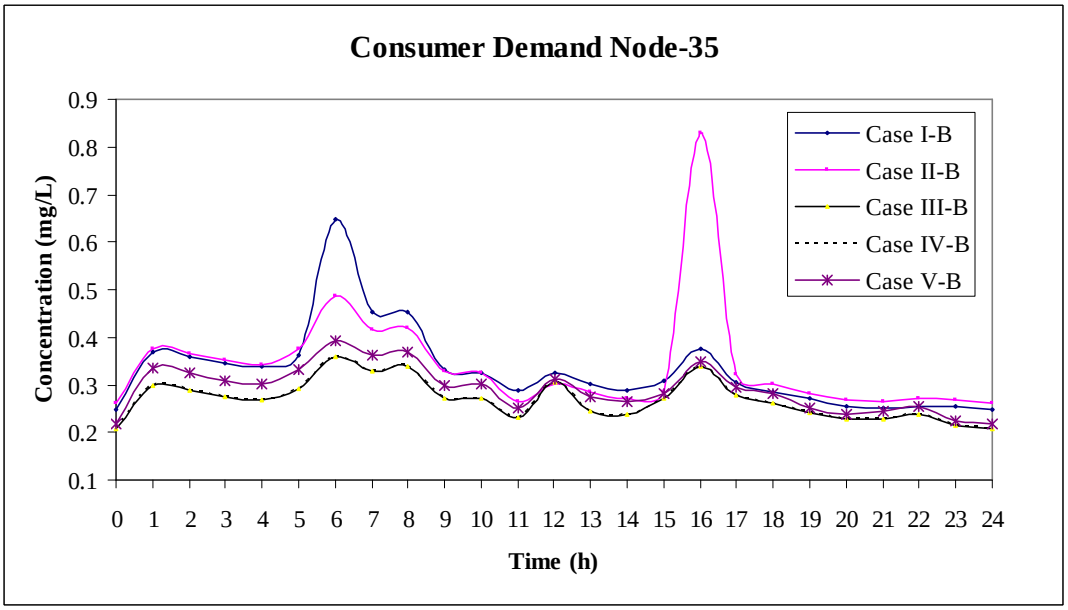
C.30. Chlorine Concentration at Node-32



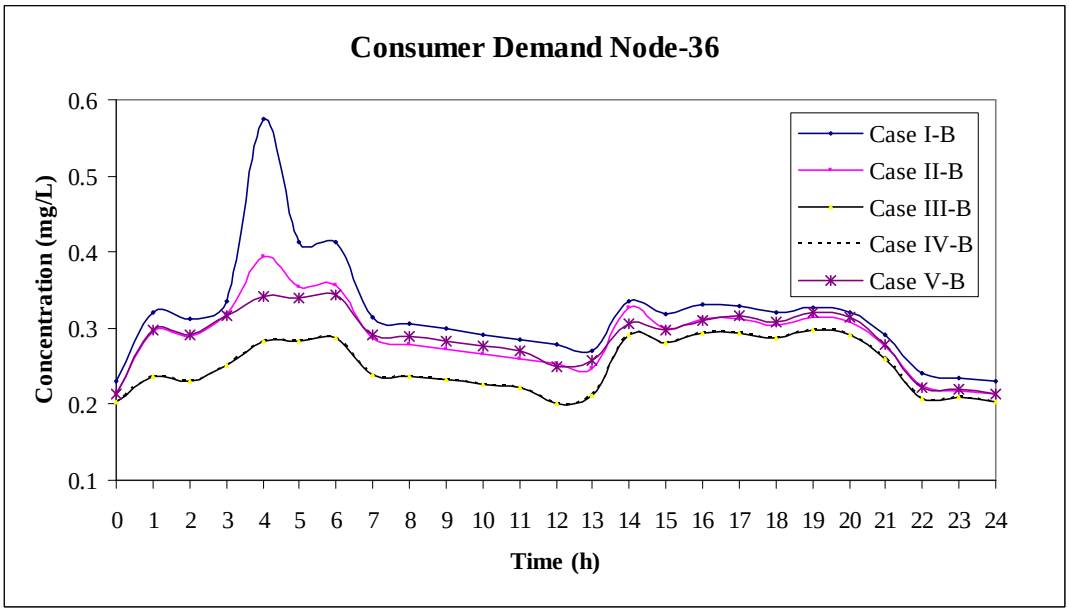
C.31. Chlorine Concentration at Node-33



C.32. Chlorine Concentration at Node-34



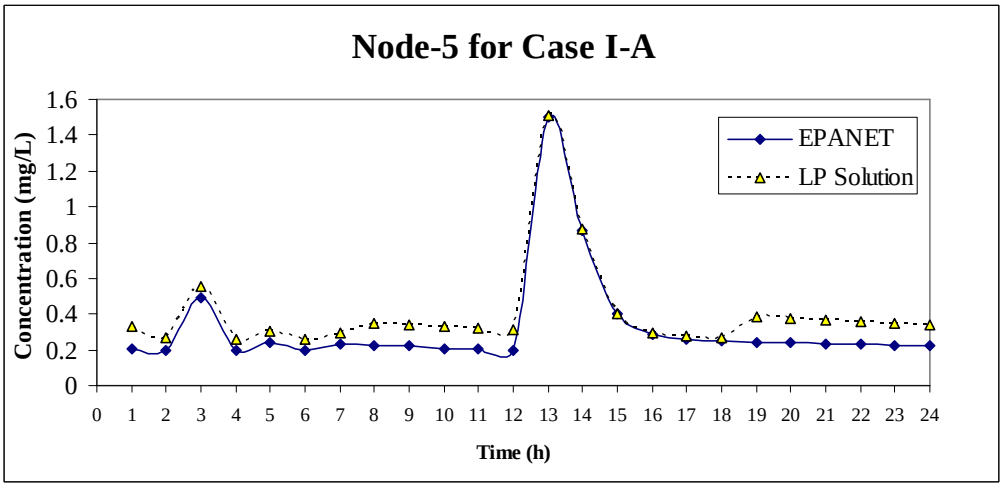
C.33. Chlorine Concentration at Node-35



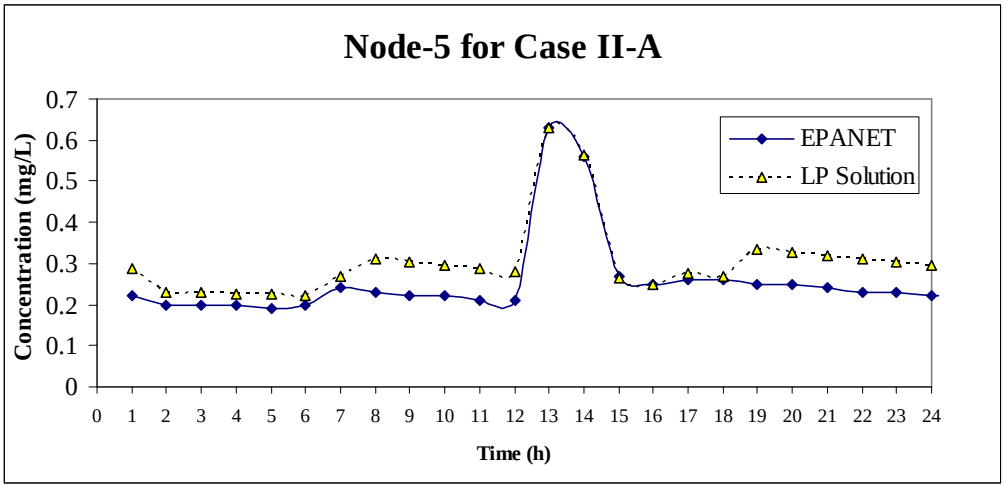
C.34. Chlorine Concentration at Node-36

APPENDIX D

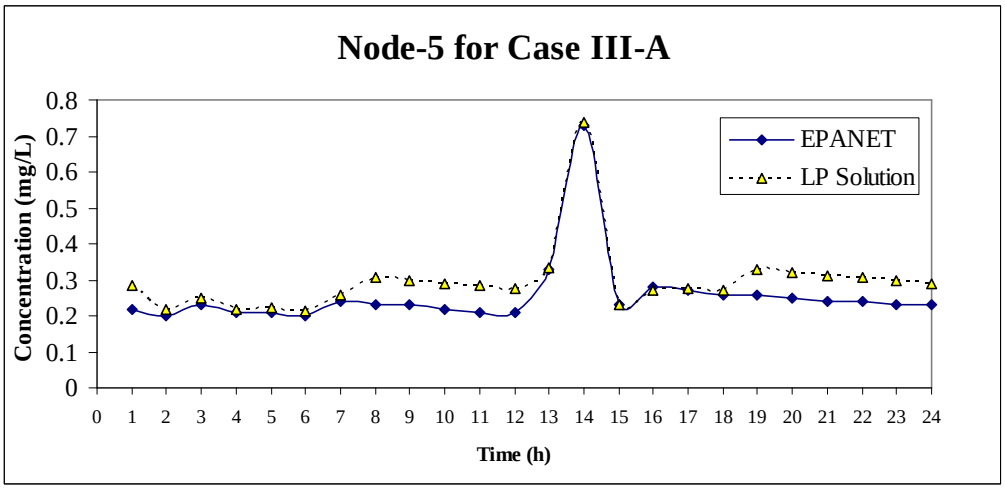
VALIDATION OF LINEAR SUPERPOSITION



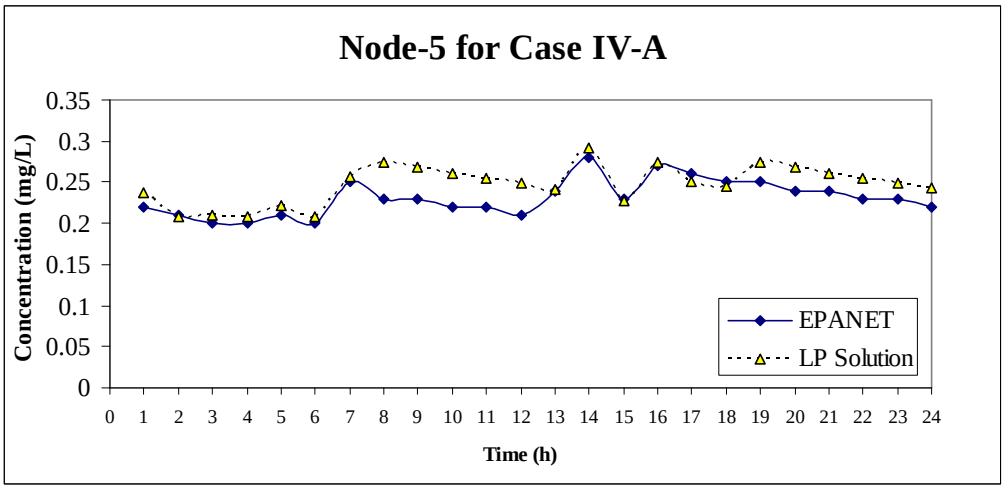
D.1. Validation of Linear Superposition at Node-5 for Case I-A



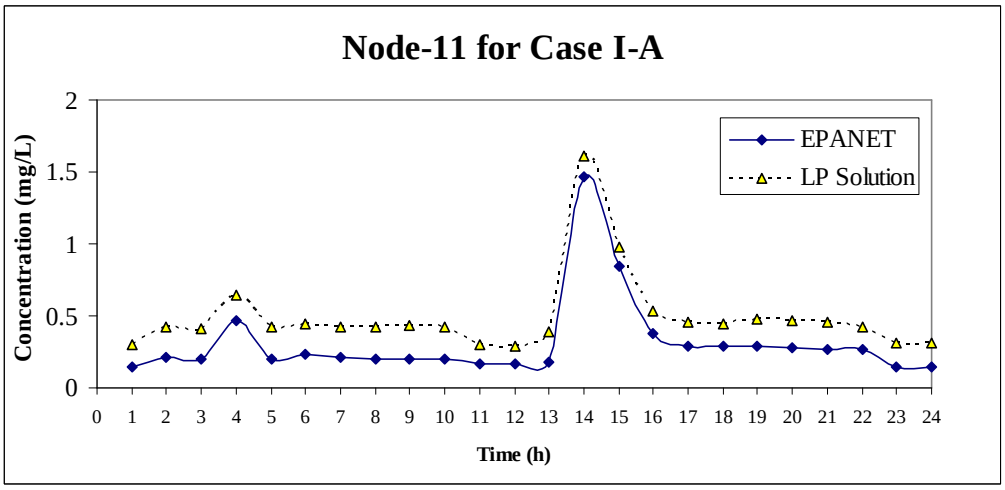
D.2. Validation of Linear Superposition at Node-5 for Case II-A



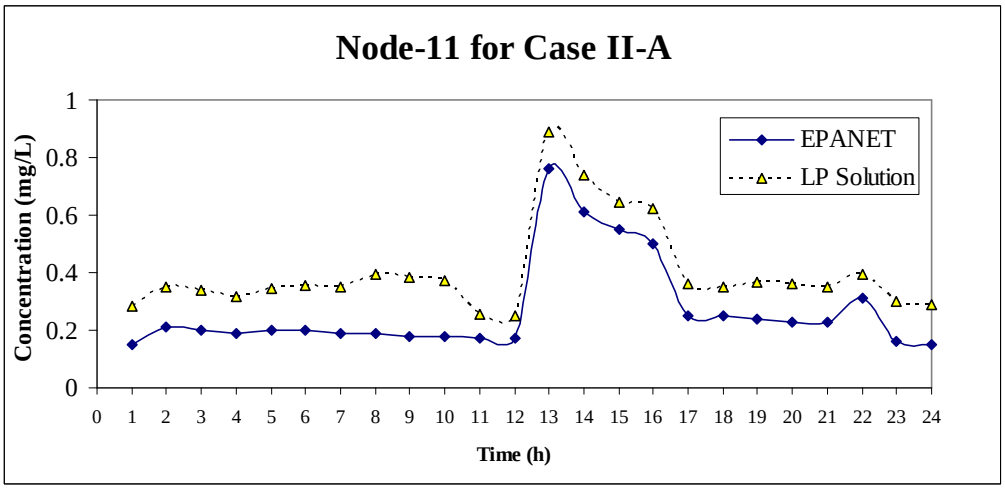
D.3. Validation of Linear Superposition at Node-5 for Case III-A



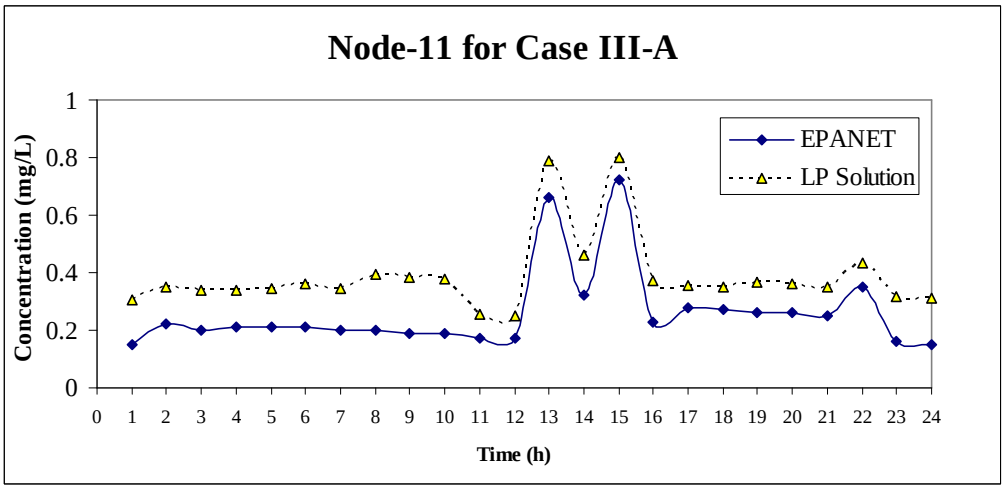
D.4. Validation of Linear Superposition at Node-5 for Case IV-A



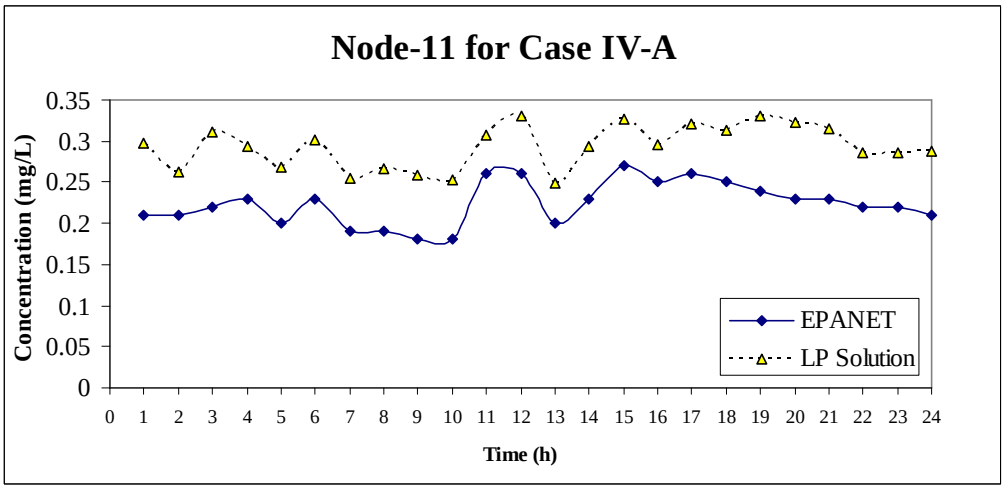
D.5. Validation of Linear Superposition at Node-11 for Case I-A



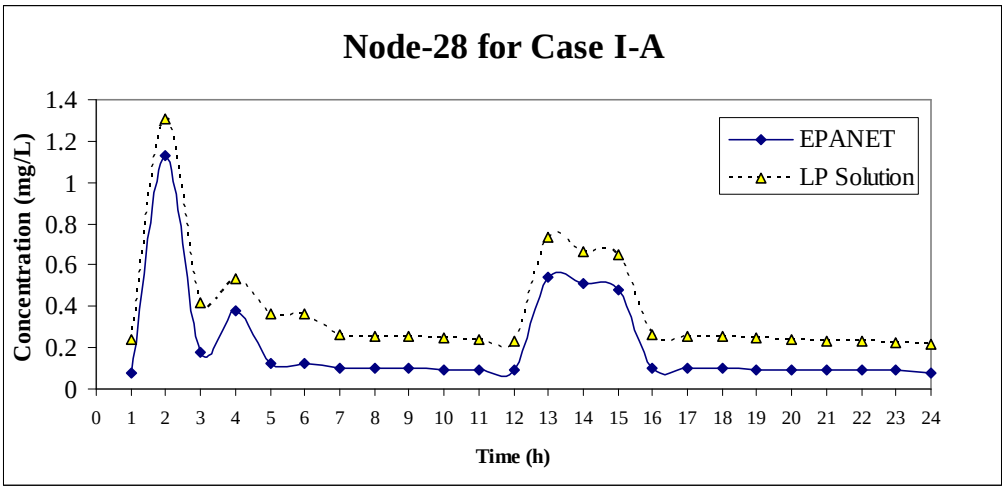
D.6. Validation of Linear Superposition at Node-11 for Case II-A



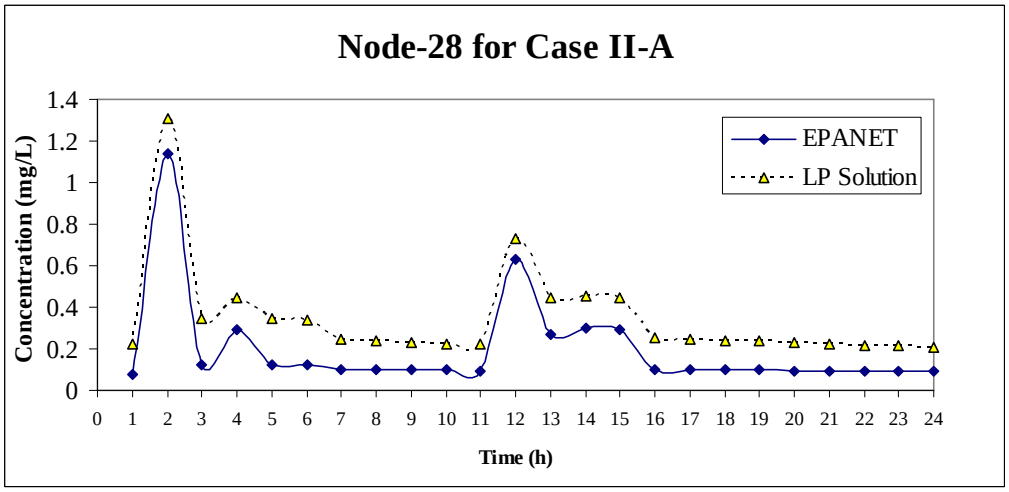
D.7. Validation of Linear Superposition at Node-11 for Case III-A



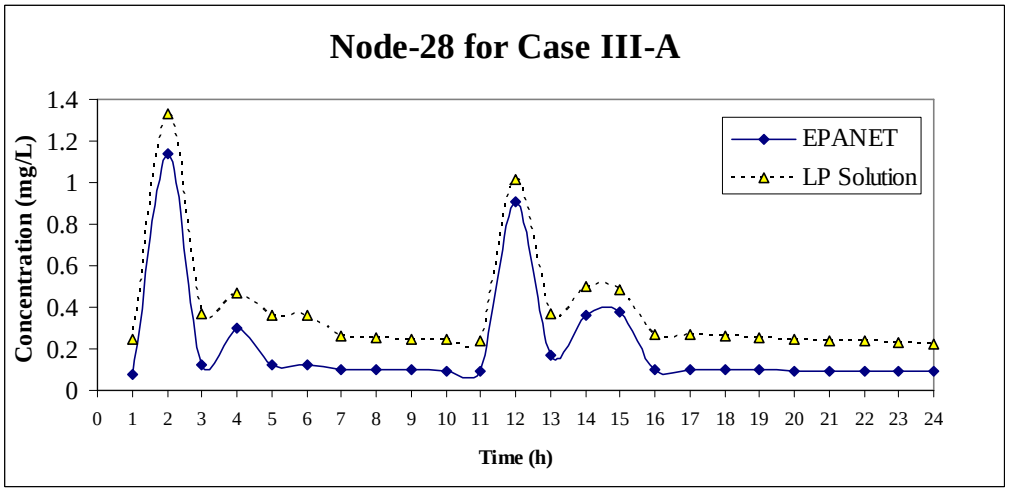
D.8. Validation of Linear Superposition at Node-11 for Case IV-A



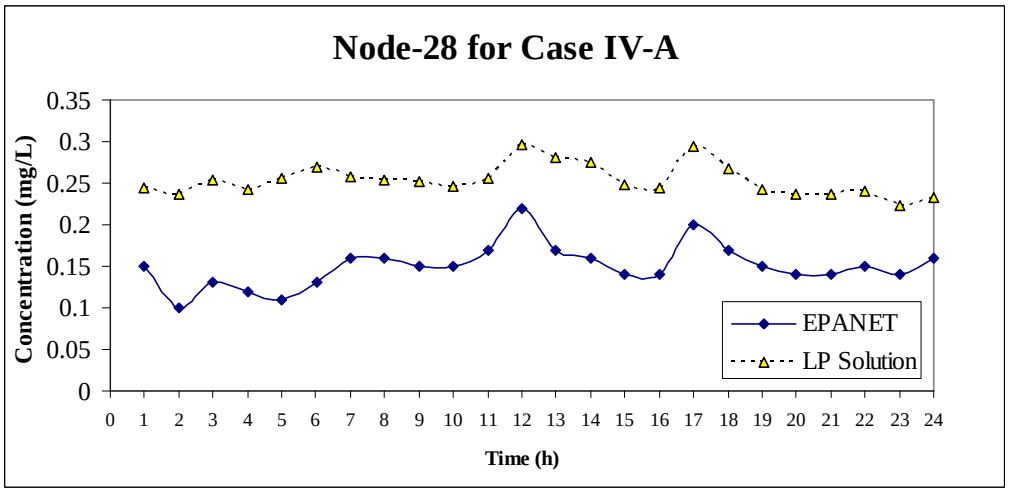
D.9. Validation of Linear Superposition at Node-28 for Case I-A



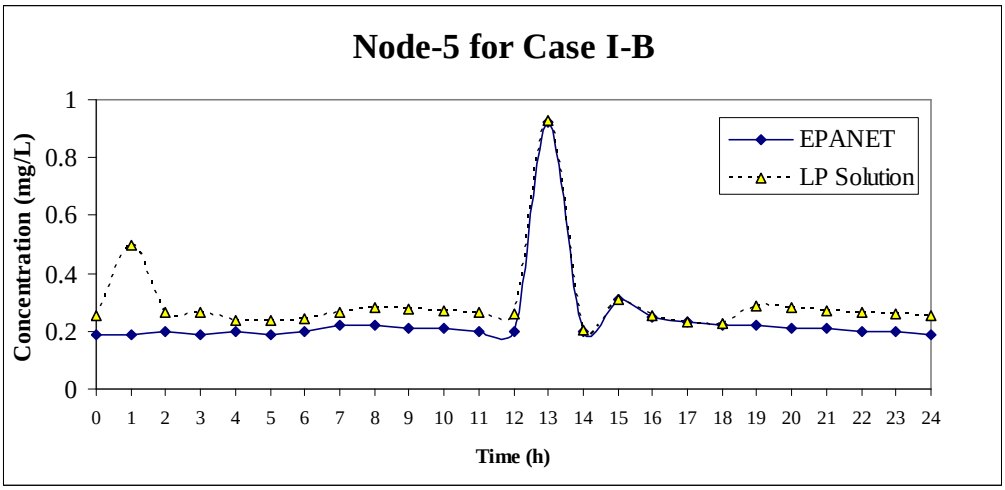
D.10. Validation of Linear Superposition at Node-28 for Case II-A



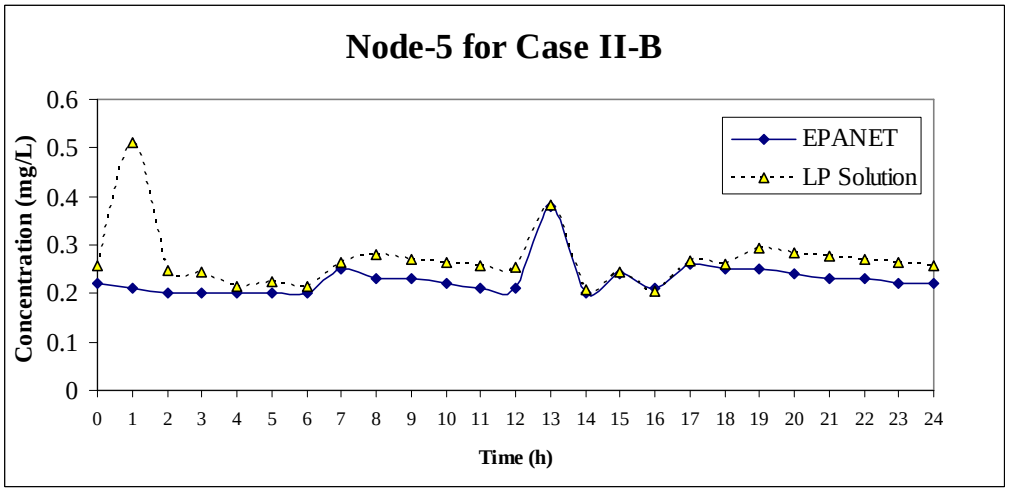
D.11. Validation of Linear Superposition at Node-28 for Case III-A



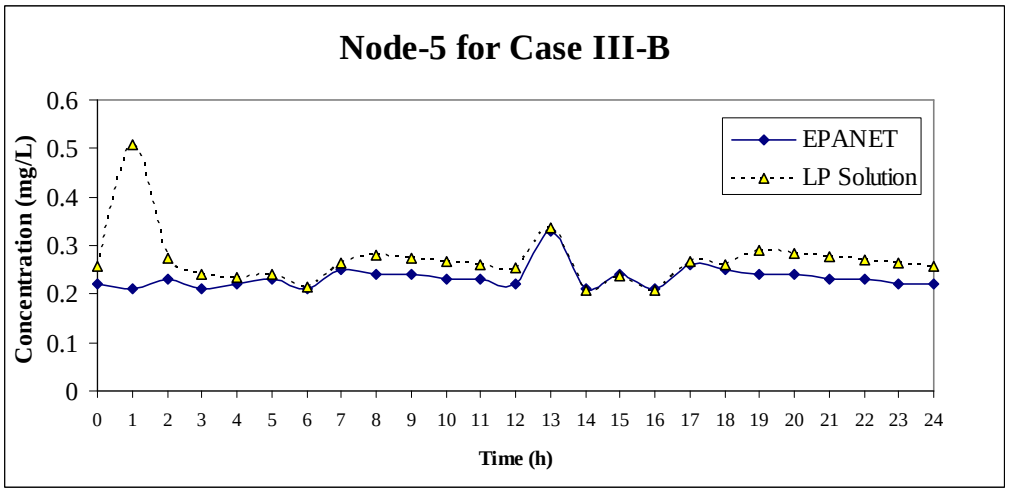
D.12. Validation of Linear Superposition at Node-28 for Case IV-A



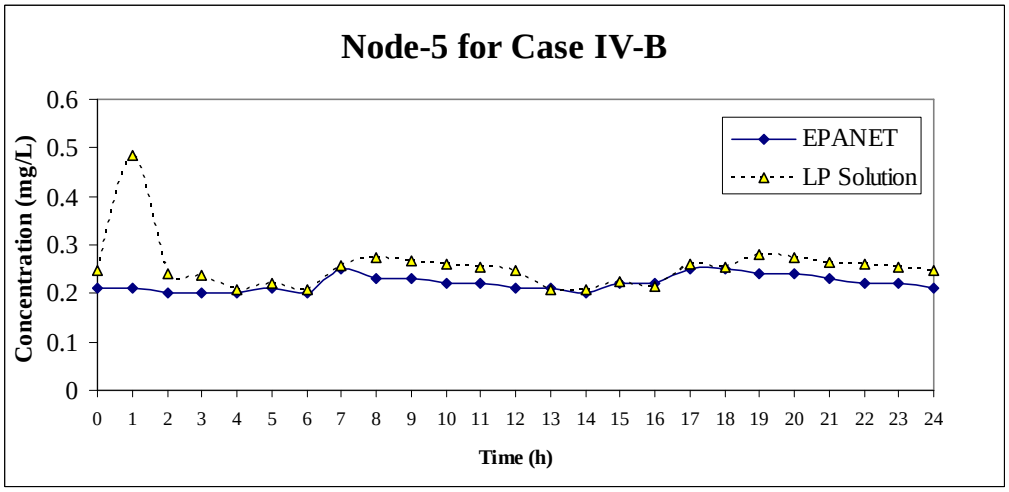
D.13. Validation of Linear Superposition at Node-5 for Case I-B



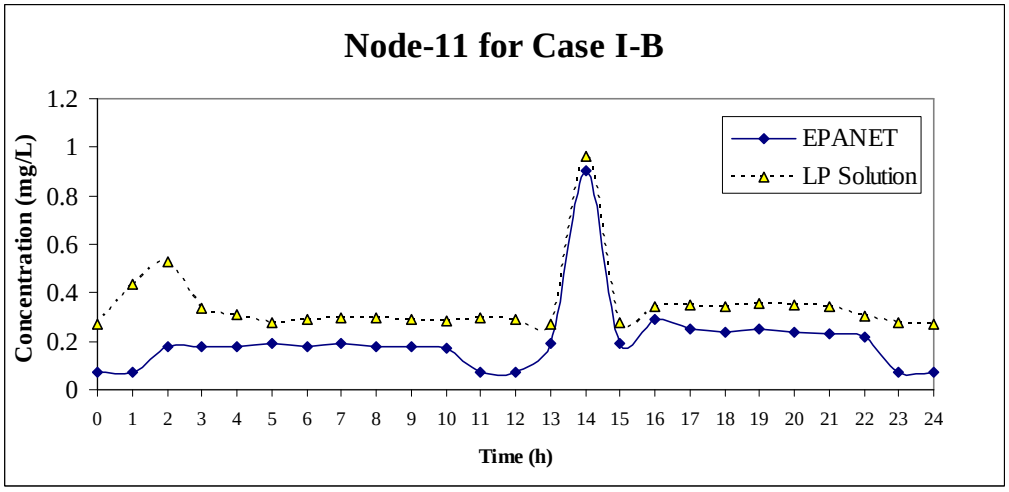
D.14. Validation of Linear Superposition at Node-5 for Case II-B



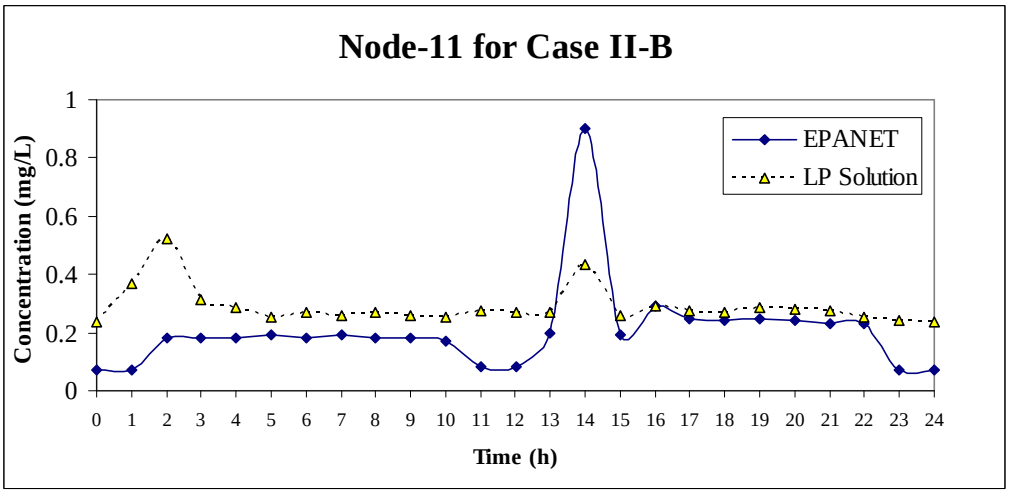
D.15. Validation of Linear Superposition at Node-5 for Case III-B



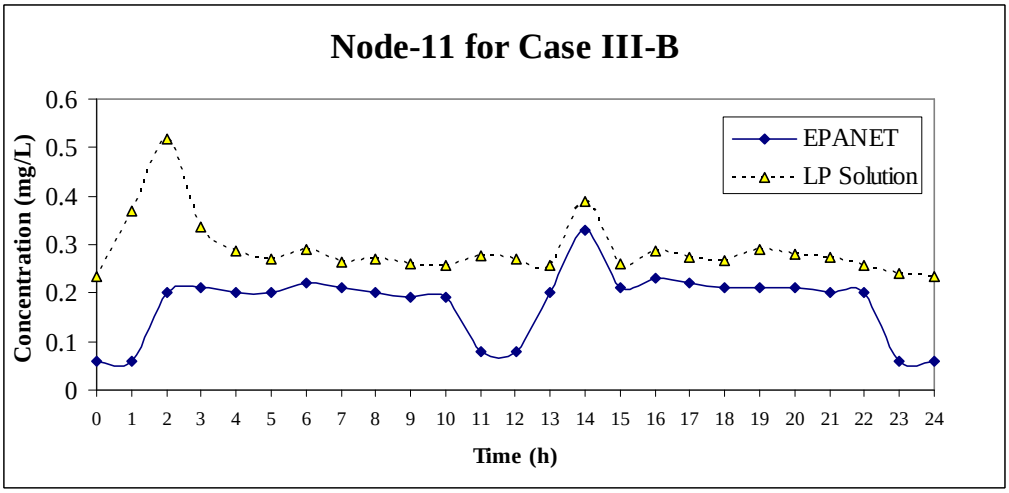
D.16. Validation of Linear Superposition at Node-5 for Case IV-B



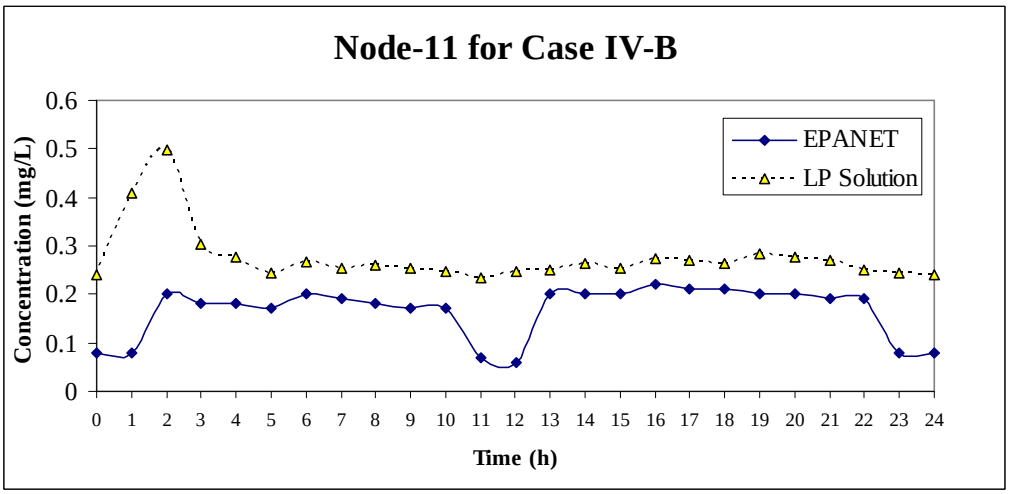
D.17. Validation of Linear Superposition at Node-11 for Case I-B



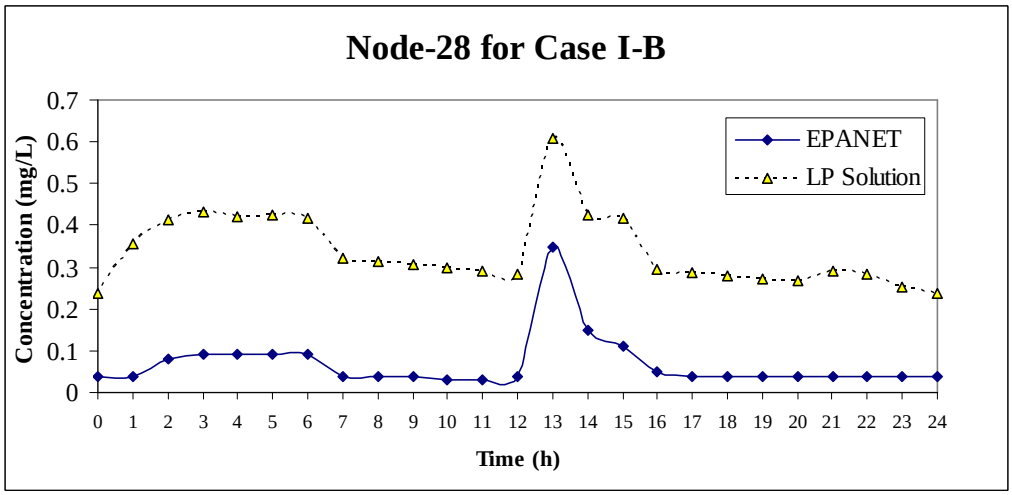
D.18. Validation of Linear Superposition at Node-11 for Case II-B



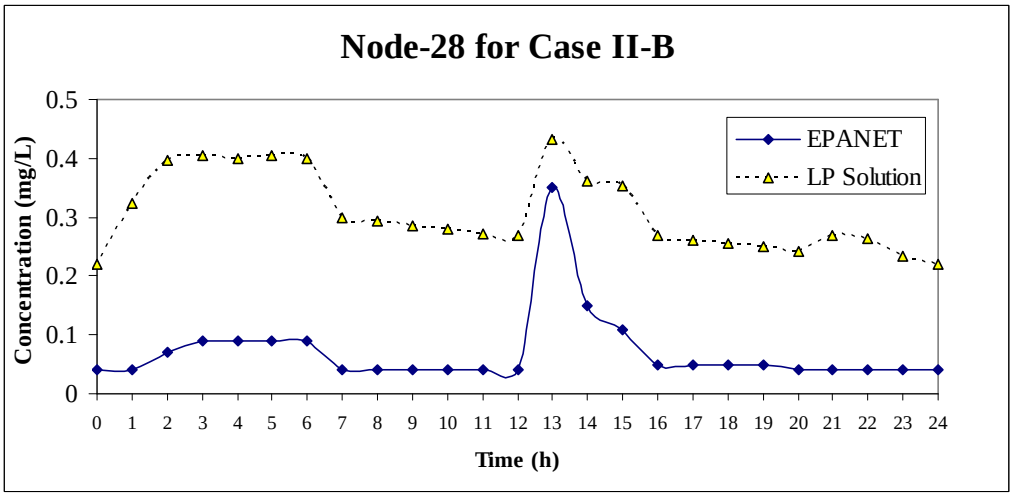
D.19. Validation of Linear Superposition at Node-11 for Case III-B



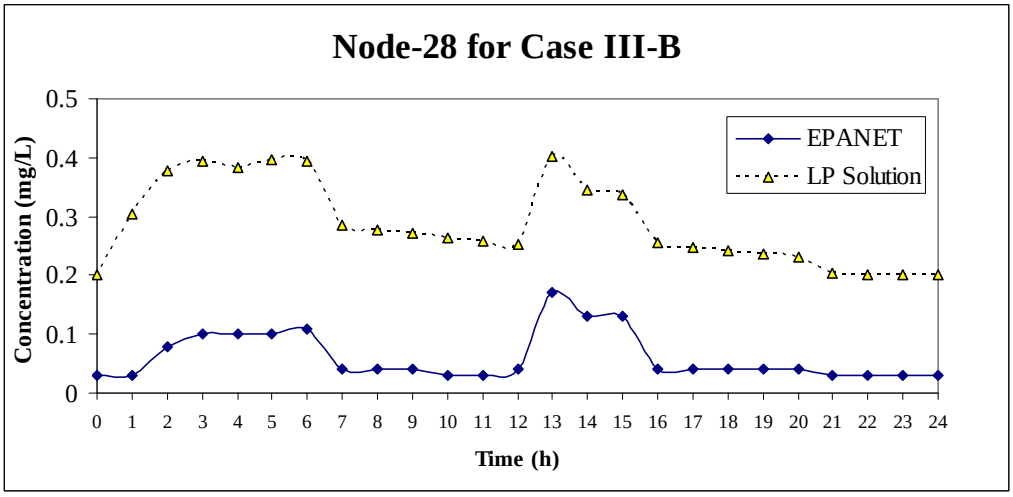
D.20. Validation of Linear Superposition at Node-11 for Case IV-B



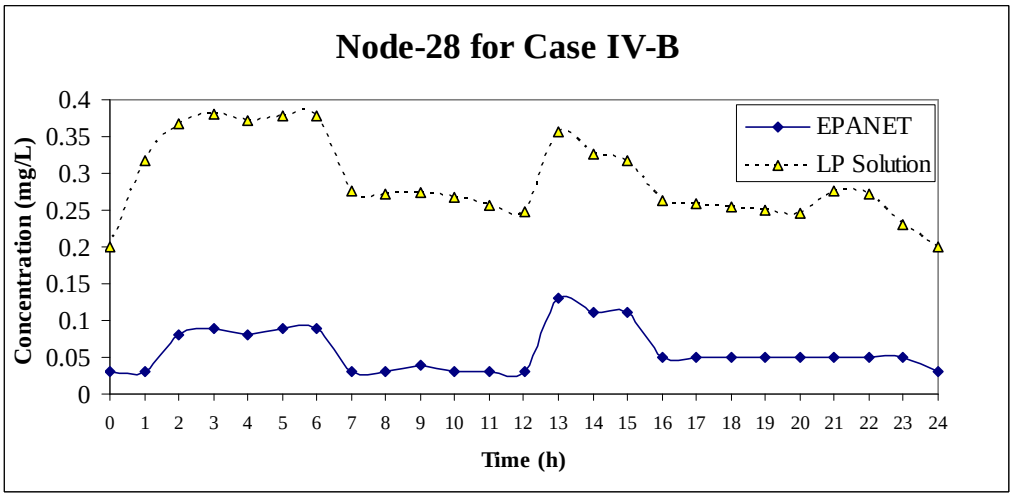
D.21. Validation of Linear Superposition at Node-28 for Case I-B



D.22. Validation of Linear Superposition at Node-28 for Case II-B



D.23. Validation of Linear Superposition at Node-28 for Case III-B



D.24. Validation of Linear Superposition at Node-28 for Case IV-B

APPENDIX E

MODEL EPANET INPUT FILE

[TITLE]
EPANET Example Network 2

[JUNCTIONS]

;ID	Elev	Demand	Pattern	
1	50	-694	3	;
2	100	8	2	;
3	60	14	2	;
4	60	8	2	;
5	100	8	2	;
6	125	5	2	;
7	160	4	2	;
8	110	9	2	;
9	180	14	2	;
10	130	5	2	;
11	185	34.8	2	;
12	210	16	2	;
13	210	2	2	;
14	200	2	2	;
15	190	2	2	;
16	150	20	2	;
17	180	20	2	;
18	100	20	2	;
19	150	5	2	;
20	170	19	2	;
21	150	16	2	;
22	200	10	2	;
23	230	8	2	;
24	190	11	2	;
25	230	6	2	;
27	130	8	2	;
28	110	0	2	;
29	110	7	2	;
30	130	3	2	;
31	190	17	2	;
32	110	17	2	;
33	180	1.5	2	;
34	190	1.5	2	;
35	110	0	2	;
36	110	1	2	;
37	0	0		;
38	0	0		;
39	0	0		;
40	0	0		;
41	0	0		;
42	0	0		;

[RESERVOIRS]

;ID	Head	Pattern

[TANKS]

;ID	Elevation	InitLevel	MinLevel	MaxLevel	Diameter	MinVol	VolCurve
26	235	56.7	50	70	50	0	

[PIPES]

;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status
2	2	5	800	12	100	0	Open
3	2	3	1300	8	100	0	Open
4	3	4	1200	8	100	0	Open
5	4	5	1000	12	100	0	Open
6	5	6	1200	12	100	0	Open
7	6	7	2700	12	100	0	Open
10	8	10	1000	8	140	0	Open
11	9	11	700	12	100	0	Open
12	11	12	1900	12	100	0	Open
13	12	13	600	12	100	0	Open
14	13	14	400	12	100	0	Open
15	14	15	300	12	100	0	Open
16	13	16	1500	8	100	0	Open
17	15	17	1500	8	100	0	Open
18	16	17	600	8	100	0	Open
19	17	18	700	12	100	0	Open
20	18	32	350	12	100	0	Open
21	16	19	1400	8	100	0	Open
22	14	20	1100	12	100	0	Open
23	20	21	1300	8	100	0	Open
24	21	22	1300	8	100	0	Open
25	20	22	1300	8	100	0	Open
26	24	23	600	12	100	0	Open
27	15	24	250	12	100	0	Open
28	23	25	300	12	100	0	Open
30	25	31	600	12	100	0	Open
31	31	27	400	8	100	0	Open
32	27	29	400	8	100	0	Open
35	22	33	1000	8	100	0	Open
36	33	34	400	8	100	0	Open
37	32	19	500	8	100	0	Open
39	35	30	1000	8	100	0	Open
40	28	35	700	8	100	0	Open
41	28	36	300	8	100	0	Open
1	1	37	1	12	100	0	Open

33	37	2	2399	12	100	0	Open
42	7	38	1	12	100	0	Open
43	38	8	1199	12	100	0	Open
44	7	39	1	12	100	0	Open
45	39	9	399	12	100	0	Open
46	29	40	1	8	100	0	Open
47	40	35	499	8	100	0	Open
48	29	41	1	8	100	0	Open
49	41	28	699	8	100	0	Open
50	26	42	1	12	100	0	Open
51	42	25	99	12	100	0	Open

[PUMPS]

;ID	Node1	Node2	Parametc

[VALVES]

;ID	Node1	Node2	Diameter	Type	Setting	MinorLoss

[TAGS]

[DEMANDS]

;Junction	Demand	Patter	Category

[STATUS]

;ID	Status/Setting

[PATTERNS]

;ID	Multipliers					
;demand						
2	1.19	0.97	0.9	0.9	0.82	1.12
2	1.21	0.6	0.6	1.27	2.39	0.9
2	0.85	0.61	1.36	0.54	0.24	0.71
2	0.3	0.6	1.19	1.49	1.12	1.16
;source						
3	0.96	0.96	0.96	0.96	0.96	0.96
3	0	0	0	0	0	0.8
3	1	1	1	1	0.15	0
3	0	0	0	0	0	0
;injection						
1	516.34	1375	516	518	518	623
1	0	0	0	0	0	3654
1	2629.84	538	538	727	2600	0
1	0	0	0	0	0	0

[CURVES]

;ID	X-Value	Y-Value

[CONTROLS]
[RULES]
[ENERGY]

Global Efficiency	75
Global Price Demand	0
Charge	0

[EMITTERS]

;Junction	Coefficient

[QUALITY]

;Node	InitQual
1	1
2	1
3	1
4	1
5	0
6	1
7	1
8	1
9	1
10	1
11	0
12	1
13	1
14	1
15	1
16	1
17	1
18	1
19	1
20	0
21	1
22	1
23	1
24	1
25	1
27	1
28	1
29	1
30	1
31	1
32	1
33	1
34	1
35	1
36	1
26	0

[SOURCES]

;Node	Type	Quality	Pattern
37	MASS	1	1

[REACTIONS]

;Type	Pipe/Tank	Coefficien

[REACTIONS]

Order Bulk	1
Order Tank	1
Order Wall	1
Global Bulk	-0.53
Global Wall	-0.0167
Limiting Pot.	0
Roughness Cor.	0

[MIXING]

;Tank	Model

[TIMES]

Duration	960
Hydraulic Timest	01:00
Quality Timestep	00:05
Pattern Timestep	01:00
Pattern Start	00:00
Report Timestep	01:00
Report Start	00:00
Start ClockTime	8:00 AM
Statistic	NONE

[REPORT]

Status	No
Summary	No
Page	0

[OPTIONS]

Units	GPM
Headloss	H-W
Specific Gravity	1
Viscosity	1
Trials	40
Accuracy	0.001
Unbalanced	Continue 10
Pattern	1
Demand Multiplie	1
Emitter Exponen	0.5
Quality	Fluoride mg/L
Diffusivity	1
Tolerance	0.01

[COORDINATES]

;Node	X-Coord	Y-Coord
1	21	4
2	19	20
3	11	21
4	14	28
5	19	25
6	28	23
7	36	39
8	38	30
9	36	42
10	37	23
11	37	49
12	39	60
13	38	64
14	38	66
15	37	69
16	27	65
17	27	69
18	23	68
19	21	59
20	45	68
21	51	62
22	54	69
23	35	74
24	37	71
25	35	76
27	39	87
28	49	85
29	42	86
30	47	80
31	37	80
32	23	64
33	56	73
34	56	77
35	43	81
36	53	87
37	20.21	9.7
38	37.37	35.3
39	36.01	40.1
40	42.26	84.2
41	43.64	85.9
42	33.91	75.9
26	33	76

```
[VERTICES]
;Link                X-Coord   Y-Coord

[LABELS]
;X-Coord          Y-Coord          Label & Anchor Node
 24.00           7.00            "Pump"
 24.00           4.00            "Station"
 26.76           77.42            "Tank"

[BACKDROP]
 DIMENSIONS           8.75    -0.2   58.3   91.2
 UNITS               None
 FILE
 OFFSET                      0        0

[END]
```

APPENDIX F

COMPUTER PROGRAM EXECUTABLE FILE