ADAPTATION OF WATER DISTRIBUTION NETWORKS FOR URBAN RENEWAL

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

BY

MUSTAFA ERTAN ÇELİK

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

JULY 2015

Approval of the thesis:

ADAPTATION OF WATER DISTRIBUTION

NETWORKS FOR URBAN RENEWAL

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ABSTRACT

ADAPTATION OF WATER DISTRIBUTION NETWORKS FOR URBAN RENEWAL

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July 2015, 95 pages

Urban renewal managed by Turkish Municipalities and Housing Development Administration (TOKİ) causes increase in water consumption at particular nodes. This study aims to find permissible increase in discharge at a single node without affecting other nodes in Yayla neighborhood, which is part of N8.3 pressure zone. Initially, capacity of existing water distribution network should be investigated to determine whether consumption increase at particular nodes affects the system. Peak discharge drawn from N8.3 pressure zone in Ankara is 650 m^3/hr. This value can be increased up to 800 m^3/hr without adding any pump to the current system. Firstly, network analysis is carried out by using Linear Theory and results are compared with Watercad outputs. Then sensitivity analysis is conducted for the system. At the end of the study, maximum possible outflow at the single node without disturbing other nodes have been obtained as 96.52 m^3/hr for Yayla neighborhood. If this discharge is drawn from Yayla, minimum pressure head will be 40 m. To check the accuracy of the method, nodal demand was entered as 96.52 m^3/hr for a particular node in Watercad and network analysis was refreshed. After refreshing analysis, Watercad verified the method used in this study. Since minimum pressure head values are 40 m, the value guaranteed by the municipality, a satisfying result has been observed. A methodology is offered to the municipalities for adapting existing lots in the city for urban renewal.

Keywords: Urban Renewal, Water Distribution Network, Sensitivity Analysis, N8.3 Pressure Zone, Ankara

ÖZ

SU ŞEBEKELERİNİN
KENTSEL DÖNÜŞÜME UYARLANMASI

Çelik, Mustafa Ertan
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Nuri Merzi

Temmuz 2015, 95 sayfa

Türk belediyeler ve Toplu Konut İdaresi (TOKİ) tarafından yönetilen kentsel dönüşüm belirli düğüm noktalarında su sarfiyatında artışa neden olmaktadır. Bu çalışmada N8.3 basınç bölgesinde bulunan Yayla mahallesi çalışılmış olup, diğer düğüm noktalarını etkilemeden tek düğüm noktasından arttırılabilecek debiyi bulmak amaçlanmıştır. Öncelikli olarak belirli düğüm noktalarındaki artışın mevcut su şebekesini etkileyip etkilemediğinin araştırılması gerekmektedir. Ankara'da yer alan N8.3 basınç bölgesinde mevcut sistemden maksimum 650 m^3/saat debi çekilmektedir. N8.3 basınç bölgesinde mevcut şebekeye herhangi bir pompa eklemeden 800 m^3/saate kadar debi çekilebilir. Önce Lineer Teori kullanılarak şebekenin analizi yapılmış ve sonuçlar Watercad çıktıları ile karşılaştırılmıştır. Daha sonra hassasiyet analizi sisteme uygulanmıştır. Çalışmanın sonunda Yayla mahallesinde diğer düğüm noktalarını etkilemeden tek düğüm noktasından çekilebilecek maksimum debi 96.52 m^3/saat olarak elde edilmiştir. Şayet bu debi Yayla'dan çekilirse, minimum basınç yükü 40 m olacaktır. Yöntemin doğruluğunu kontrol etmek maksadıyla ilgili düğüm noktasının debisi 96.52 m^3/saat olarak Watercad'e girilmiş ve şebeke analizi yenilenmiştir. Yenilenen analiz sonrası Watercad bu çalışmada kullanılan yöntemi teyit etmiştir. Minimum basınç yüklerinin belediyenin temin ettiği 40 m lik basınç yükünü sağladığı gözlemlenmiştir. Mevcut sistemin kentsel dönüşüme uyarlanması için kullanılan yöntem belediyelere sunulmaktadır.

Anahtar Kelimeler: Kentsel Dönüşüm, Su Dağıtım Şebekesi, Hassasiyet Analizi, N8.3 Basınç Bölgesi, Ankara

This thesis is dedicated to my family…

ACKNOWLEGDMENTS

I want to send my special thanks to my supervisor and my family, who provided their endless supports during the thesis work.

Firstly, my supervisor, Assoc. Prof. Dr. Nuri Merzi, deserves the most special thanks as he is the one who offered this thesis topic to me. He suggested incisive solutions to the problems that I encountered during the thesis work. Also he always shared his wisdom and assistance. It has been a pleasure working with him.

I want to send my thanks to my mother Sultan Çelik, my father Erol Çelik and my sister Sıla Çelik. They always provided emotional support when I suffered from perturbation. I greatly appreciate their sincere supports.

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LIST OF ABBREVIATIONS

CT	Constant Tariff
DMA	District Metered Area
EPS	Extended Period Simulation
GIS	Geographical Information System
HGL	Hydraulic Grade Line
INS	Insulated System
JC	Junction
LG	Large Pump
MT	Multi Tariff
NHA	Node Head Analysis
SA	Sensitivity Analysis
SCADA	Supervisory Control and Data Acquisition
SM	Small Pump
T	Tank
WDN	Water Distribution Network

LIST OF SYMBOLS

C_{HW}	Hazen Williams Coefficient
C'_x	Modified Conductance of Pipe x
F_i	Node-Flow Continuity Equation
g	Gravitational Accelaration (m/s^2)
H	Total Head (m)
H_{jmin}	Minimum Total Head (m)
h_f	Friction Loss (m)
h_m	Minor Loss (m)
K	Pipe Resistance Coefficient
L	Pipe Length (m)
P	Pressure (kN/m^2)
Q	Discharge (m^3/hr)
q_i	Nodal Demand (m^3/hr)
R	Pipe Resistance
w_i	Weight of Junction
V	Velocity of Flow (m/s)
Z	Elevation Head (m)
γ	Specific Weight of Water (kN/m^3)
η	Pump Efficiency

CHAPTER 1

INTRODUCTION

1.1. General

Everybody understands the importance of water in our lives; clean water has already been a matter of human concern for thousands of years. It is a known fact that all major early civilisations considered an organised water supply system as an essential requisite of any sizeable urban settlement. Amongst the oldest, archaeological evidence on the island of Crete in Greece proves the existence of water transport systems as early as 3500 years ago, while the example of pipes in Anatolia points to water supply systems approximately 3000 years old (Mays, 2000).

Although about 71% of the Earth's surface is surrounded by water, 1% of the world's fresh water is drinkable. This limitation increases importance of water distribution systems. They should be designed and operated accurately while minimizing costs. Generally dams are main suppliers of clean water. However, some countries like Ghana have lack of infrastructure so rainwater harvesting systems used for collecting and storing rainwater from rooftops come into play (Web 1). In addition to sources, water distribution systems consist of hydraulic accessories like pumps, valves, and pipes.

Water distribution systems are complex systems because a lot of data like elevation, pipe diameter, pipe roughness, nodal demands have been required to solve the system. Moreover, there are some constraints like flow velocity and nodal pressure. Before 1970s, manual calculations had been made to solve for pressure and flow in the system. However, designs made before 1970s were more conservative and expensive. After 1970s, designers started to use computer programs to solve water distribution systems. With the help of Geographical Information System (GIS), digital terrain models showing topographical elevations, street and pipe locations have been prepared. Combination of computer programs and GIS usage enable designer to model system more accurately.

Monitoring Water Distribution Network (WDN) is as important as design. "Supervisory Control and Data Acquisiton (SCADA) systems are used to remotely control the operation of pump stations, valves, and other system infrastructure. They are also useful to collect data that includes pressures, flows, reservoir levels, valve positions, pump status and speed, chlorine levels, and other information that is useful to monitor the system. This information is collected at frequent intervals and stored for extended periods of time. SCADA is a good source of operational information" (AWWA, 2005).

Advances in computer usage does not only provide solutions for design and operation but also economical analysis. Optimization techniques like Genetic Algorithms have been used widely for water distribution networks over the last decade. Many alternatives were tried during the solution of the problem thus one of the best is selected. These techniques reduce the cost significantly.

1.2. History of Urban Renewal

Urban renewal firstly started in England in 19th century. The reason behind the project was the increase in population due to industrializing cities. Population increase resulted in health problems due to lack of infrastructure, transportation problems and housing need. As a reaction to this, government made a law named as housing legislation in 1851 in England. Industrialization brought similar problems to Paris. Baron Haussmann, as French prefect of the Seine, carried out under Napoleon III, as the Emperor of the Second French Empire, urban renewal program between 1853 and 1870 (Web 2). Most important difference between English and French model was spatial separation of the class. In other words, urban renewal was made according to the financial income of residents in England. On the other hand, residents from different financial income could live together in Paris. Then, urban renewal projects started to spread to the world. First and Second World Wars became an important actor for urban renewal. Some cities like Hiroshima, Nagasaki were completely destroyed during Second World War. It can be said that these were created out of nothing. After these World Wars, economic balance of countries changed. Singapore and USA cities could be given as notable urban renewal examples, which were affected by World Wars.

Urban renewal was first brought to Turkey's agenda in 1980s. Increasing in the number of shanties was the reason for discussing this subject. Dikmen Valley Urban Renewal Project was the first prepared project, which was aimed to replace shanties by high rise buildings at the end of 1980s (Web 3).

1.3. The Aim of the Study

Aim of this study is to determine maximum possible outflow at a single node without disturbing other nodes in a water distribution system. Capital cost of water supply system is very large therefore it is necessary to design and operate these systems with optimum cost. At first, existing system capacity should be investigated whether it can respond changes due to demand increase. Then, if it does not respond change in parameters, renewal of pipes, pumps or storage tank can be considered. This study can be grouped under two main headings; urban renewal, consumption increase at a single node. Urban renewal, which is managed by Turkish Municipalities and Housing Development Administration (TOKİ), is a current issue in Turkey. Shanties and abandoned regions have been replaced by high rise buildings basically according to the article 73th of Municipalities Law No.5393 (Web 4). This brings increase in population in its wake for some regions. Although designer of infrastructure projects make calculations according to the future demand generally after 30 years, he/she could not estimate urban renewal before 30 years. It is necessary to investigate capacity of the existing system. If the nodal demand is increased at a specific point, it is necessary to determine whether other points can draw discharge.

This thesis contains five chapters. Chapter 1, which is already covered, is an introductory part of the study. Then in Chapter 2, literature review will be presented. Especially, components and capacity of water distribution networks, aging of pipes and leakage terms will be explained in Chapter 2. The methodology proposed by Bhave (1991) is given at Chapter 3 to understand theoretical background of the study. Theory is supported by a numerical example to give an idea about application of the method for a small water distribution network. Conducted case study in N8.3 pressure zone, Ankara will be introduced in Chapter 4. This chapter is the fundamental part of the study in which maximum possible outflow at selected nodes without affecting other nodes are provided for a real WDN. Chapter 5, which is the last chapter, presents summary and conclusions.

CHAPTER 2

THEORETICAL CONSIDERATIONS

2.1. Introduction

A WDN consists of reservoirs, pipes, pumps and valves. Main objective of the system is to provide consumers with water at required pressures and quality. In order to deliver the required amounts of water to consumers these components should be properly designed and optimised. There are some important points at the planning stage of a WDN**.** Firstly, topographical properties of the region, current and estimated future water requirement of the region should be determined correctly. Secondly, different scenarios like using different types of pumps, changing location of reservoir should be studied to understand behaviour of the network. If these tasks are performed properly, networks would be managed better and more satisfactory customer service would be offered.

2.2. Components of Water Distribution Systems

2.2.1. Distribution Reservoirs

Distribution reservoirs are man-made structures used for meeting fluctuating demands imposed on a system. In case of emergency like failure of pumps, fire-fighting water can be supplied from storage of them for a length of time. Moreover, if a distribution reservoir does not exist, pressurized water will not reach to the remote area because increase in water demand will cause pressure drop. There are three types of distribution and service reservoirs namely surface reservoirs, standpipes and elevated tanks.

2.2.2. Pipes

Pipes are important elements of WDNs. Storage tanks, nodes and pumps are connected to each other by pipes. Three main types of pipes, which are main transmission line pipe, distribution network pipes, service connection pipes, are used in WDNs. Pipes used in WDNs can be categorised into three main groups:

- rigid: cast iron (CI), asbestos cement (AC), concrete

- semi-rigid: ductile iron (DI), steel

- flexible: polyvinyl chloride (PVC), polyethylene (PE), glass reinforced

plastic (GRP)

Pipe material directly affects roughness coefficient and aging of pipe. In this study, all pipes are made of ductile iron and Hazen-Williams coefficient C_{HW} is taken as 130. Moreover, depending on discharge passing through pipe, pipe diameter ranges between a few millimetres and a few meters in WDN.

2.2.3. Valves

A valve is a hydraulic accessory that is used for flow and pressure regulation in WDNs. There are many types of valves in a WDN, such as butterfly valves, float valves, check valves, pressure reducing valves, air valves, isolation valves.

2.2.3.1. Butterfly Valves

Butterfly valves, which are widely used in pumping stations, have the disc permanently located in the pipe, rotating around a horizontal or vertical axis. When the valve is fully open, the disc will be positioned in line with the flow.

2.2.3.2. Float Valves

To prevent reservoir overflow, float valves, which are automatically controlled by the surface water level in the reservoir, are used. There exists many sensors at different elevations in reservoir. Starting from the preset level, progressive throttling of the valve will occur as the water level rises, until the top level is reached. In this position, the valve will become fully closed. If water level is below the critical level, the valve will become fully opened.

2.2.3.3. Check Valves

Check valves are installed in pumping stations to prevent back-flow. In other words, these valves allow flow in one direction only.

2.2.3.4. Pressure Reducing Valves

Pressure reducing valves are used for regulating pressure between upstream and downstream of the valve. If pressure at upstream of valve is higher than preset value, the valve will start closing until the downstream pressure is equal to the preset pressure. In case of low pressure at upstream of valve, the valve operates as fully opened. Moreover, if downstream pressure is higher than upstream pressure, the valve is shut off. It can be said that these are kind of check valves.

2.2.3.5. Air Valves

Air valves are common devices in releasing air from pipelines. Air can accumulate during the filling of the pipeline or operation. Air accumulation affects conveying of water negatively. To overcome this problem, air valves are installed at local high points.

2.2.3.6. Isolation Valves

Isolation valves are special types of valves that completely prevent the path of flow of a fluid by isolating a portion of the system from fluid flow. Under normal operating conditions, isolation valves are fully open. They are closed under special circumstances, such as safety reasons or system repair. District Metered Areas (DMAs) are formed by isolation valves.

"While studying whole network in a water distribution system, isolation valves between different pressure zones are fully open and the system works interconnectingly totally. However, while studying with DMAs, all isolation valves must be closed, so water can not be transferred between different pressure zones, so these zones are not affected from each other. Isolation valves prevent interaction" (Koç, 2014).

2.2.4. Fire Hydrants

A fire hydrant is an active fire protection measure, and a source of water provided in most urban, suburban and rural areas with municipal water service to enable firefighters to tap into the municipal water supply to assist in extinguishing a fire.

If water flows in pipe less than 0.50 m/s, sedimentation due to minerals in water will be observed in pipes. This problem is named as “aging of pipes”. To overcome this problem, routine operation named as “flushing” should be done through fire hydrants. It should be done each 6 months and lasts for 5 to 10 minutes. Up to 50 lt/s water can be drawn during flushing. At initial stages of flushing it can be observed that coloured water flows because of accumulated particles in pipe. This is normal and temporary. After few minutes, colour of water starts to become normal. If flushing operation is not conducted periodically, frictional losses will increase because pipe material type will change.

2.2.5. Pumps

To distribute water in a network, extra head is needed to lift water from lower level to higher level. Moreover, while conveying water through pipes, there exists minor and friction losses. Pumps are devices that supplies this extra head. A typical pump installation is given in Figure 2.1. Writing Bernoulli equation for points 1 and 2,

$$Z_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2*g} + h_p = Z_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2*g} + \sum h_f + \sum h_m \tag{2.1}$$

where,

Z : Elevation head

P : Pressure

γ : Specific weight of water

V : Velocity of flow

g : Gravitational accelaration

h_p : Pump head

h_f : Friction losses

h_m : Minor losses

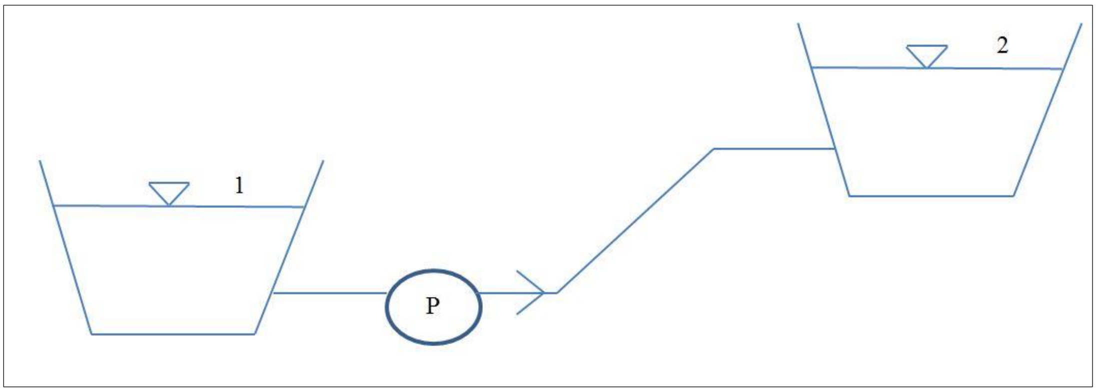

Figure 2.1 Typical Pump Installation

Initial and maintenance cost of pumps bring notable expenses to the WDNs. Therefore, it is very important to select proper type of pumps, number of pump units and arrangement of pumps for the design of pumping stations. Serial arrangement of pipes enable designer to elevate water to higher elevations. On the other hand, in parallel arrangement wider range of flow is possible. Since WDNs are designed according to the 30 years, water demand after 30 years should be considered by designer. Type of pumps, number of pump units and arrangement of pumps should be selected such that network can respond to the demand of residents after 30 years.

Electrical energy is converted to mechanical energy by electrical motor in pumps. With the help of driveshaft, mechanical energy is transferred to the pumps (Şendil, 2013). In general, pumps are classified as centrifugal pumps (roto-dynamic pumps) and positive displacement pumps. All pumps used in the case study are centrifugal pumps.

2.3. Pump Station Operations

2.3.1. Hydraulic Head Parameters in Pumping Systems

Static suction lift, static suction head, static discharge head, total static head and total dynamic head are five different head parameters in pumping systems. These terms are important to correlate pumps and source or discharge tanks.

Static suction lift exists when the source of supply is below the center line of the pump. In other words, it is the elevation difference between centerline of pump and water level in source tank. Static suction head exists when the source of supply is above the centerline of the pump. In other words, it is the elevation difference between centerline of pump and water level in source tank.

Elevation difference between centerline of pump and water level in discharge tank is static discharge head. Summation of static suction lift and static discharge head gives total static head. In other words, total static head is the elevation difference between water level in source tank and discharge tank. These terms are illustrated in Figure 2.2.

When friction and minor losses are added to total static head, total dynamic head or total head will be obtained. Total head equation is given below.

$$H_P = \Delta Z + h_l \qquad (2.2)$$

where,

H_p = Pump head

ΔZ = Total static head

h_l = Summation of friction and minor losses

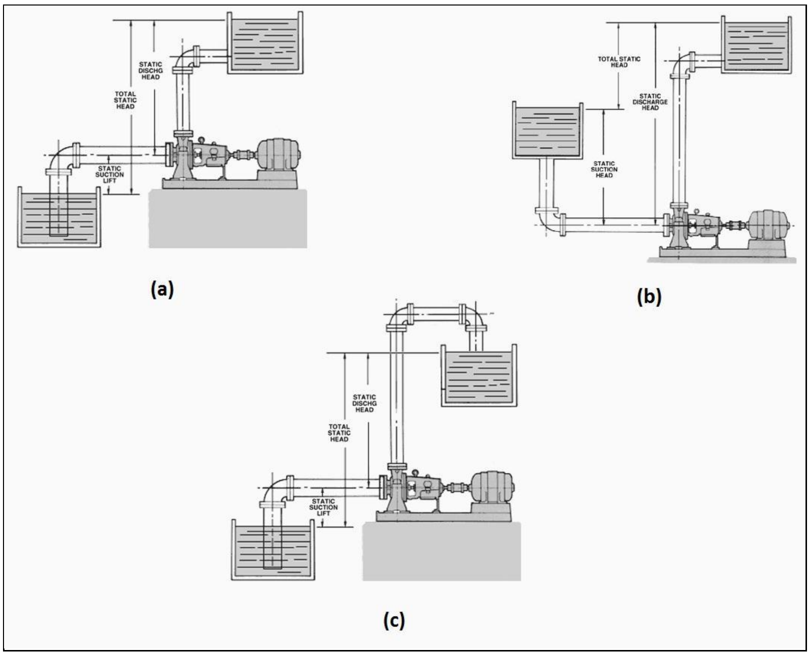

Figure 2.2 Head Terms in Different Pumping Systems (Karassik et al., 2008)

2.3.2. System Head-Discharge Curve

As long as water level does not change in two reservoirs, total static head remains constant. However, discharge passing through pump varies with time so head loss value changes. Total head loss equation is given below.

$$h_l = K * Q^n + h_m \quad (2.3)$$

where,

h_l = Total head loss

K = Pipe resistance coefficient

Q = Discharge

n = Exponent

h_m = Minor loss

Pump should provide pump head such that it can overcome both total static head and total head loss. If total static head and total head loss are added, the curve named as system head-discharge curve can be drawn. Typical System Head-Discharge Curve is given in Figure 2.3.

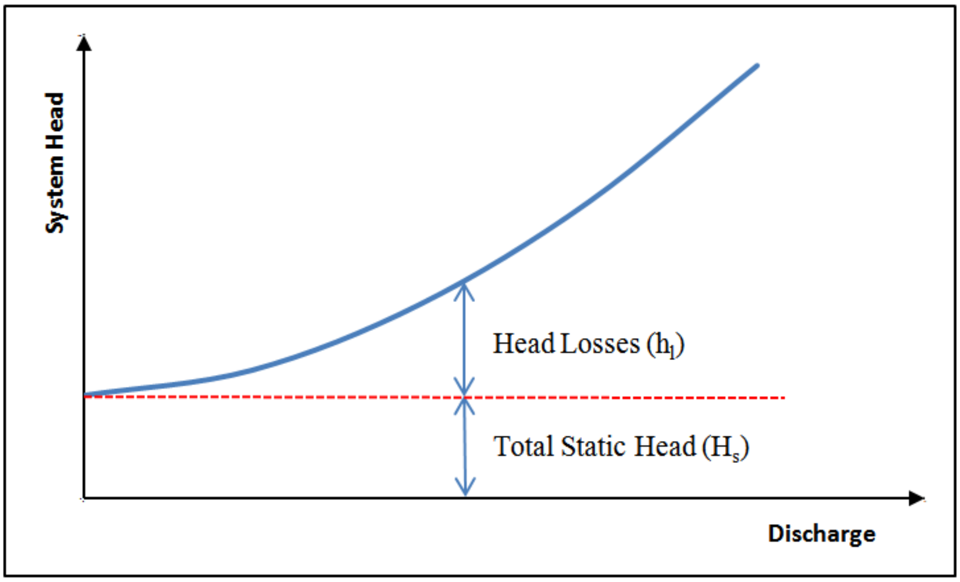

Figure 2.3 Typical System Head-Discharge Curve (Bhave, 1991)

2.3.3. Pump Head-Discharge Curve

There exists inverse proportion between discharge and pump head. If pump head is high, low discharge will pass through pipe and vice versa. Typical Pump Head-Discharge Curve is given in Figure 2.4.

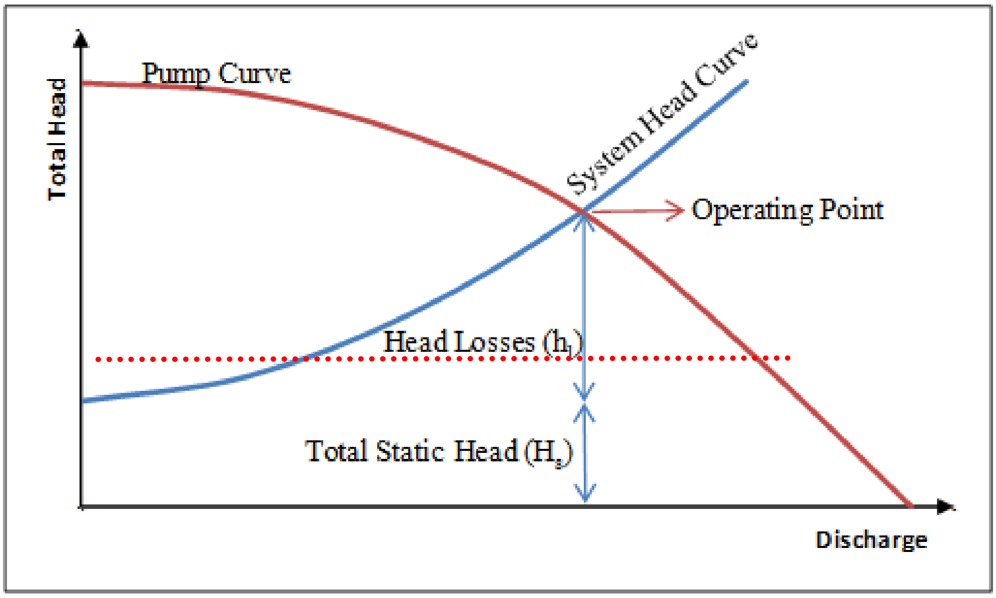

Figure 2.4 Typical Pump Head-Discharge Curve (Bhave, 1991)

As it can be seen from Figure 2.4 pump head-discharge curve intersects system head-discharge curve. Intersection of these curves is named as "operating point". In other words, this point gives information about discharge value while pump works. Moreover, pump head and total head loss can be seen by looking this point.

2.3.4. Effects of Valve Operations on System Head Curve

While drawing system head-discharge curve, it was mentioned that it is the summation of total static head, which is constant, and total head loss. Total head loss includes minor losses. Valve opening directly affects minor loss. Therefore, total head loss is affected by valve opening. If valve starts to be throttled total head loss will increase and system head curve will shift to the left. To clarify situation better, Figure 2.5 is given below.

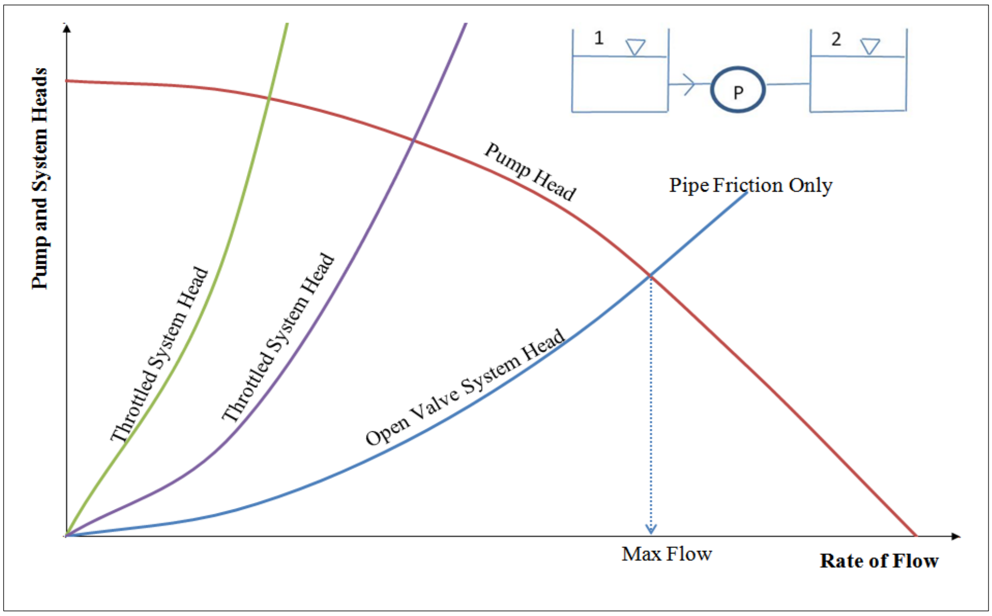

Figure 2.5 Effects of Valve Operations on System Head Curve (Karassik et al., 2008)

As can be seen from Figure 2.5 location of operating point shifts left if valve is throttled.

2.3.5. Pump Characteristic Curves

Pump head curve, pump power curve and pump efficency curve given in Figure 2.6 reflect characteristic of pump and these curves are obtained from manufacturers.

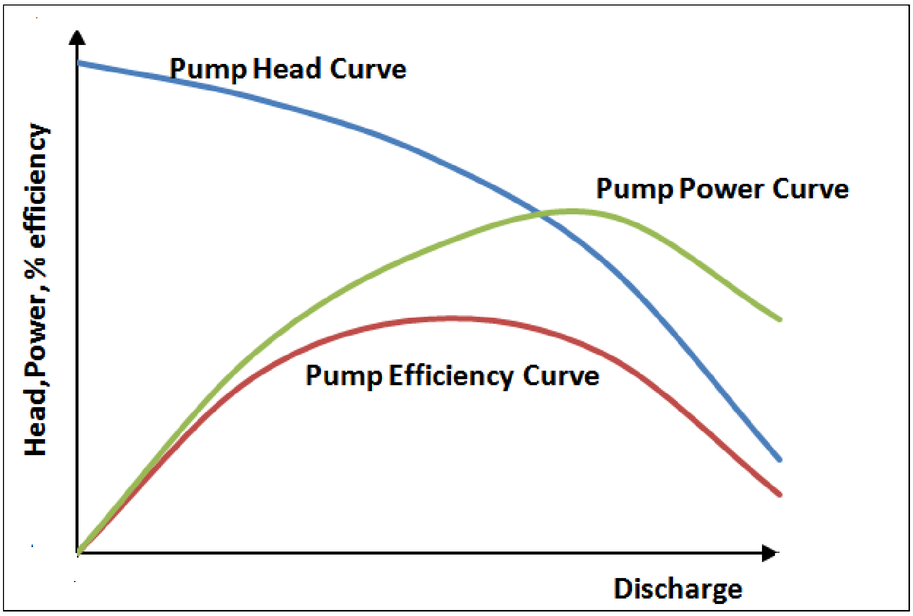

Figure 2.6 Pump Characteristic Curves

The power delivered by a pump is given by

$$P = \frac{\gamma * H_p * Q_p}{\eta} \qquad (2.4)$$

where,

P = Pump power (Watt),

$\boldsymbol{\gamma}$ = Specific weight of fluid (kN/m^3),

H_p = Pump head (m),

Q_p = Pump flow rate (m^3/s),

$\boldsymbol{\eta}$ = Pump efficiency

2.3.6. Pump Combinations

2.3.6.1. Pumps in Series

If high head is required in WDN, pumps can be connected in series. Reason for high head requirement in pumping station is that topographical elevation difference between pumping station and storage tank can be high and/or head loss through pipes can be high. Pumps in series arrangement can be remedy for these situations. If pumps are connected in series, same amount of water flows through each pump. For the same discharge value, heads will be additive while drawing combined pump head curve (Figure 2.7). Combined head (H), flow (Q), pump efficiency (***η***) and power (P) values of serial connected pumps are mathematically calculated by the following relations.

$$H = H_1 + H_2 + H_n \tag{2.5}$$

$$Q = Q_1 = Q_2 = Q_n \tag{2.6}$$

$$\eta = \left[\frac{H_1 + H_2 + H_n}{\frac{H_1}{\eta_1} + \frac{H_2}{\eta_2} + \frac{H_n}{\eta_n}}\right] \tag{2.7}$$

$$P = \frac{\gamma * Q * (H_1 + H_2 + H_n)}{\eta} \tag{2.8}$$

where 1, 2, ..., n indicate different pumps

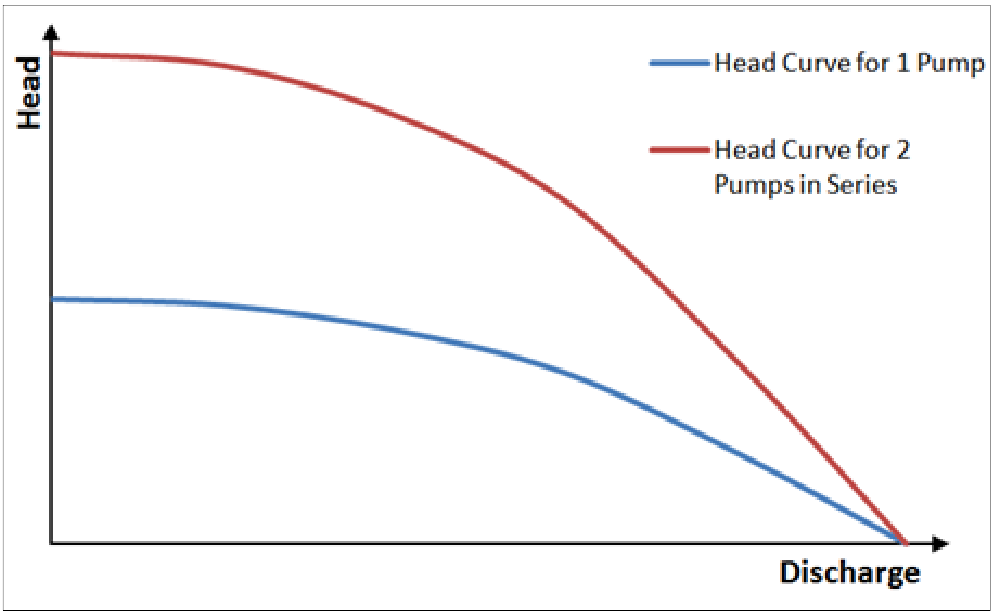

Figure 2.7 Head Curve of Pumps in Series

2.3.6.2. Pumps in Parallel

If a large variation in flow demand is required in WDN, pumps can be connected in parallel configuration. Moreover, demand can vary by time (Q_{night}, $Q_{average}$ and Q_{peak}) much, parallel arrangement of pumps enable designer to overcome this problem. In parallel connection the head provided by each pump is equal and discharges for the same head are additive (Figure 2.8). Combined head (H), flow (Q), pump efficiency (***η***) and power (P) values of parallel connected pumps are mathematically calculated by the following relations.

$$\mathrm{H} = \mathrm{H}_1 = \mathrm{H}_2 = \mathrm{H}_n \tag{2.9}$$

$$\mathrm{Q} = \mathrm{Q}_1 + \mathrm{Q}_2 + \mathrm{Q}_n \tag{2.10}$$

$$\eta = \left[\frac{\mathrm{Q}_1 + \mathrm{Q}_2 + \mathrm{Q}_n}{\frac{\mathrm{Q}_1}{\eta_1} + \frac{\mathrm{Q}_2}{\eta_2} + \frac{\mathrm{Q}_n}{\eta_n}}\right] \tag{2.11}$$

$$P = \frac{\gamma * \mathrm{H} * (\mathrm{Q}_1 + \mathrm{Q}_2 + \mathrm{Q}_n)}{\eta} \tag{2.12}$$

where 1, 2, ..., n indicate different pumps

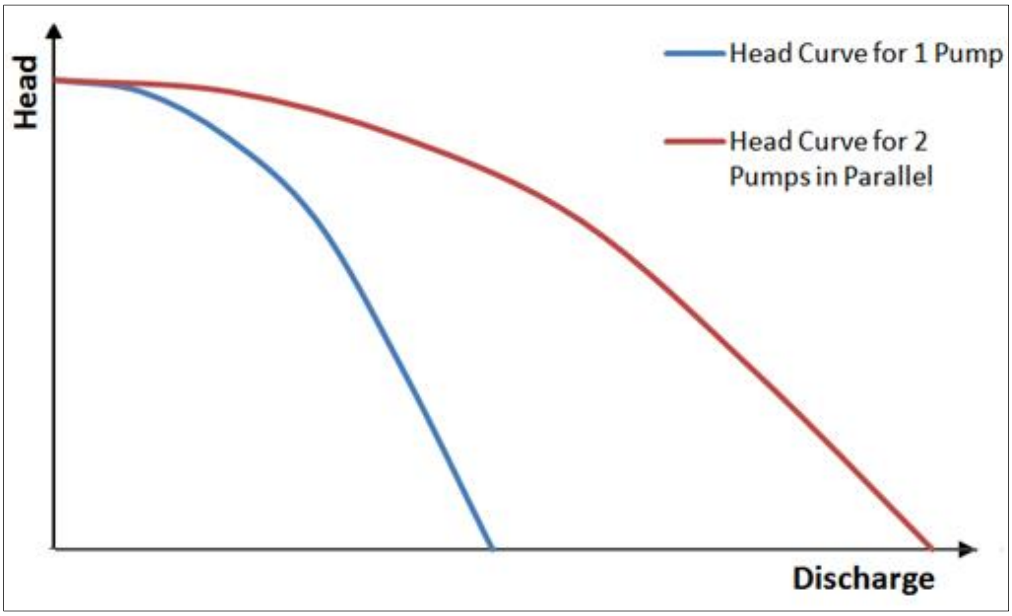

Figure 2.8 Head Curve of Pumps in Parallel

2.4. Aging of Pipes

WDNs are generally designed for a service life of 30 years. During project life time, if water flow velocity in pipe is less than 0.50 m/s, sedimentation due to minerals in water will be observed in pipes. This problem is named as "aging of pipes" and it can be seen in Figure 2.9. Pipe diameter can change due to this problem. Estimated pipe diameter can be different from real value because it can be time dependent.

Figure 2.9 Aging of Pipe (Web 5)

As mentioned earlier mostly ductile iron, steel, LDPE, HDPE and PVC pipes are used in distribution networks. To overcome aging of pipe, ductile iron pipe, which is the most suitable material, should be selected. In N8.3 pressure zone, where case study is conducted, network consists of this type of pipes.

2.5. Leakage Problem

While constructing models of WDN, leakage can be as important as nodal demand depending on leakage amount. There are two possible leakage locations. First one is connection between distribution network pipe and service connection pipe, which is indicated by blue circle in Figure 2.10. Another one is connection between service connection pipe and house, which is indicated by yellow circle in Figure 2.10.

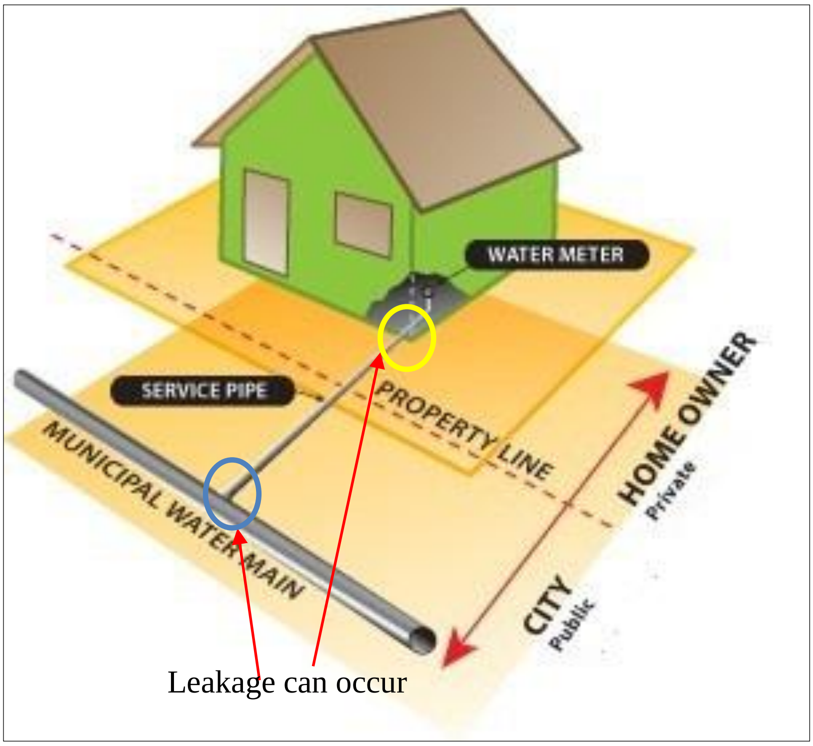

Figure 2.10 Schematic View of Connection of Pipes at which Leakage Can Be Observed (Web 6)

CHAPTER 3

METHODOLOGY

Vakilifard et al. (2013) stated that trial-and-error and post-optimality (sensitivity) analysis are used to determine how the optimal solution is affected by changes. As the name suggests, first method needs to change input data each time and refresh analysis. This method takes a long time if model consists of many variables. On the other hand, second method establishes upper and lower bounds for input data. Within boundary, input data can vary without causing violent changes to the current optimal solution. It helps him/her understand which input data affects solution most.

The problem in this study is expressed as the determination of the maximum nodal demand for an assumed minimum allowable pressure head without perturbating flow conditions (nodal demands and pressure heads) at other regions of the network. In this study Bhave's method (Bhave, 1991) is used based on sensitivity analysis (SA). This method is selected because it can give faster results than trial-and-error especially for large networks. Before giving the method, Linear Theory is explained to carry out network analysis. Then, theoretical background and an illustrative example of the methodology will be provided.

3.1. Solution of Nonlinear Equations in Water Distribution Networks

In order to find hydraulic grade line (HGL) values at WDN, it is necessary to solve nonlinear equations. However, there is no method that can directly solve nonlinear equations. Iterative methods like Hardy Cross, Newton-Raphson, Linear Theory have been commonly used in practice. Linear Theory will be used in this study. Although Hardy Cross method is simple, it converges very slowly and thus requires large number of iterations for large networks. Moreover, for some cases the method starts diverging and does not converge at all. On the other hand, Newton Raphson method converges faster than Hardy Cross method. Since Newton Raphson method is based on derivatives, it must find the derivative at estimated value. One of weaknesses is that a zero derivative may be encountered. Another is that initial guess may be too far from local root.

3.2. Linear Theory

Linear Theory is based on linearization of equations involved in pipe network analysis. The method starts with assumed values that can be pipe flow or pipe resistance. Then, assumed values are corrected at each trial. Iterative procedure is continued until satisfactory accuracy is reached. Linear Theory can be used in two forms, namely pipe discharge equations and nodal head equations.

3.2.1. Pipe Discharge Equations

Number of equations for pipe discharges should be equal to number of pipes. At first, node flow continuity equations are written for nodes with unknown HGL. Then, to equalize number of equations to number of pipes, basic loop and pseudo loop equations are added to node flow continuity equations. Node flow continuity equations are already linear but basic loop equations and pseudo loop equations, if any, are nonlinear. The nonlinear loop-head loss equations are written as

$$\sum_{x \in c} (R_{ox} \mid {}_tQ_x|^{n-1}) Q_x = 0, \qquad c = 1, 2, 3, \ldots, c \tag{3.1}$$

where,

R_{ox} = known resistance constant of pipe x

${}_tQ_x$ = assumed discharge in pipe x for the t^{th} iteration

Q_x = the unknown parameter

n = exponent

Equation (3.1) expressed in the linearized form becomes

$$\sum_{x \in c} {}_tR'_x \, Q_x = 0, \qquad c = 1 \ldots C \tag{3.2}$$

where,

${}_{t}R'_{x}$ = modified resistance constant of pipe x for the t^{th} iteration

$$ {}_{t}R'_{x} = R_{ox} \left| {}_{t}Q_{x} \right|^{n-1}, \tag{3.3} $$

Muir (1967), Wood and Charles (1972) have suggested that the pipe discharge, Q_x should be taken as unity for the first iteration. Thus for the first iteration, we have

$$ {}_{1}R'_{x} = R_{ox}, \qquad x = 1, 2, 3, \dots, x \tag{3.4} $$

in which ${}_{1}R'_{x}$ = modified resistance constant of pipe x for the first iteration. According to the procedure suggested by Wood and Charles (1972), the Q_x values obtained from the first iteration are taken as the assumed values for the second iteration for evaluating ${}_{2}R'_{x}$. Thus,

$$ {}_{2}Q_{x} = Q_{x(1)}, \qquad x = 1, 2, 3, \dots, x \tag{3.5} $$

in which ${}_{2}Q_{x}$ = assumed discharge in pipe x for the second iteration; $Q_{x(1)}$ = obtained discharge in pipe x for the first iteration. If this procedure of taking the obtained values of the previous iteration as the assumed values for the next iteration is continued further, it is observed that the Q_x values start oscillating. To prevent oscillations, taking the average of the assumed and obtained values in the previous iteration gives rapid convergence after second iteration. Thus,

$$ {}_{t}Q_{x} = \frac{{}_{(t-1)}Q_{x} + Q_{x(t-1)}}{2}, \quad x = 1, 2, 3, \dots, x, \qquad t = 3, 4, 5, \dots, t \tag{3.6} $$

3.2.2. Nodal Head Equations

Nodal head equations are written according to the nodes. Since number of nodes is equal to number of nodal head equations, loop equations are not necessary in the formulation of nodal head equations. While formulating node-flow equations, discharges through pipes can be written with the help of frictional loss formula, which is given below (Wood and Charles, 1972).

$$ h_f = R * Q^n \tag{3.7} $$

or

$$Q = \left(\frac{h_f}{R}\right)^{1/n} \quad (3.8)$$

where,

h_f = frictional loss through pipe

R = pipe resistance constant

Q = discharge in pipe

n = exponent

Node-flow continuity relationship at nodes can be written as

$$\sum_{\substack{i \\ connected\ to\ j \\ through\ x}} \left(\frac{H_i - H_j}{R_{ox}}\right)^{1/n} + q_{oj} = 0 \quad (3.9)$$

in which R_{ox} = known resistance constant of pipe x; H_i, H_j = known or assumed nodal heads; q_{oj} = nodal demand.

$$\sum_{\substack{i \\ connected\ to\ j \\ through\ x}} {}_tC'_x({}_tH_i - {}_tH_j) + q_{oj} = 0 \quad (3.10)$$

in which ${}_tC'_x$ = modified conductance of pipe x for the t^{th} iteration ${}_tH_i$, ${}_tH_j$ = known or assumed nodal heads, for the t^{th} iteration at nodes i, j respectively; q_{oj} = nodal demand

$${}_tC'_x = \left|\frac{{}_tQ_x}{{}_th_x}\right|, \qquad x = 1, 2, 3, \ldots, x \quad (3.11)$$

in which ${}_tQ_x$, ${}_th_x$ = discharge and head loss in pipe x for the t^{th} iteration, respectively. To begin the iterative procedure, it is necessary to initialize the discharge and thus head loss in a pipe. Collins and Johnson (1975) stated that if the values, ${}_tC'_x$ are taken equal to $C'_{x(t-1)}$ overcorrection occurs. To prevent this problem, they suggest following equation after first iteration.

$$_{t}C'_{x} = \frac{_{(t-1)}C'_{x} + \quad C'_{x(t-1)}}{2}, \qquad x = 1, 2, 3, \ldots, x, \qquad t = 2, 3, 4, \ldots, t \tag{3.12}$$

in which $_{(t-1)}C'_{x}$ = assumed modified conductance of pipe x, $C'_{x(t-1)}$ = obtained modified conductance of pipe x for the $(t\text{-}1)^{th}$ iteration. Application of this method with sensitivity analysis is given at Section 3.3.2.

3.2.2.1. Darcy-Weisbach Friction Loss Equation

Equation (3.7) is the general form of frictional loss formula. In WDNs, head loss through pipes is calculated by two equations, namely Darcy-Weisbach and Hazen-Williams. Darcy-Weisbach equation is given in Equation (3.13).

$$h_f = \frac{f * L}{2 * g * D * A^2} * Q^2 \tag{3.13}$$

or

$$h_f = RQ^2 \tag{3.14}$$

where,

h_f = frictional loss through pipe (m)

f = Darcy –Weisbach friction factor

L = pipe length (m)

g = gravitational acceleration (m/s^2)

D = pipe diameter (m)

A = cross-sectional area of a pipe (m^2)

Q = discharge in pipe (m^3/s)

R = pipe resistance constant

As can be seen from Equation (3.14), n equals to 2 in Darcy-Weisbach equation. Moreover, f can be found by Moody Diagram or equations, which are Colebrook-White, Swamee-Jain. Equations can be used according to the flow regime. In WDNs, flow regime depending on velocity of flow and pipe diameter varies from pipe to pipe. If Reynolds Number (Re) is less than 2000, Colebrook-White and Swamee-Jain can not be used. In that case, only Moody Diagram can be used to find f. Re can be calculated by following equation.

$$\mathrm{Re} = \frac{\mathrm{V} * \mathrm{D}}{\gamma} \tag{3.15}$$

where,

Re = Reynolds Number

V = velocity of flow (m/s)

D = pipe diameter (m)

γ = kinematic viscocity of water (= 10^{-6} m^2/s at 20 ^oC)

3.2.2.2. Hazen-Williams Friction Loss Equation

Since linear theory is an iterative method, Darcy-Weisbach equation is impractical because Moody Diagram should be used at each iteration. Instead of this equation, Hazen-Williams equation is used due to its simplicity. However, Darcy-Weisbach equation is more accurate because its friction coefficient f depends on both flow regime and type of pipe material. On the other hand, Hazen-Williams coefficient C_{HW} depends only on type of pipe material and age of pipe. Hazen-Williams equation is given in Equation (3.16).

$$\mathrm{h_f} = \frac{10.68 * L}{{C_{HW}}^{1.852} * D^{4.87}} * Q^{1.852} \tag{3.16}$$

or

$$\mathrm{h_f} = \mathrm{RQ}^{1.852} \tag{3.17}$$

where,

h_f = frictional loss through pipe (m)

C_{HW} = Hazen-Williams coefficient

L = pipe length (m)

D = pipe diameter (m)

Q = discharge in pipe (m^3/s)

R = pipe resistance constant

As can be seen from Equation (3.17), n equals to 1.852 in Hazen-Williams equation. Linear theory can be applied in two forms, which are pipe discharge equations and nodal head equations. In this study, equations involved in pipe network analysis have been linearized by nodal head equations. Moreover, frictional loss through pipes have been calculated by Hazen-Williams equation, which means that exponent n has been taken as 1.852.

3.3. Sensitivity Analysis of Water Distribution Networks

3.3.1. Theory

While applying sensitivity analysis, single parameter denoted as y_k is chosen. y_k is a variable that user can change its value. If its value increase/decrease, network allows some range that other nodes will not be affected. In other words, same nodal demands before and after analysis can be drawn by other nodes. Head equations denoted as F_j should be written to construct mathematical model of the system. Taking derivative of F_j with respect to y_k ,

$$\frac{\partial \mathrm{F_j}}{\partial y_k} = 0, \qquad j = 1, 2, 3, \dots, j \tag{3.18}$$

j: index for nodes

F_j can contain other variables (v_f) dependent on y_k so Equation (3.18) can be extended to

$$\frac{\partial \mathrm{F_j}}{\partial y_k} + \sum \frac{\partial F_j}{\partial v_f}\left\{\frac{\partial v_f}{\partial y_k}\right\} = 0, \quad j = 1, 2, 3, \dots, j \tag{3.19}$$

$$\left[\frac{\partial F_j}{\partial v_f}\right]\left\{\frac{\partial v_f}{\partial y_k}\right\} = -\frac{\partial \mathrm{F_j}}{\partial y_k} \tag{3.20}$$

v_f : free variable

In Equation (3.20) [] represents a matrix and {} a column vector. Note that v_f and y_k can be nodal head, nodal demand or pipe resistance. Bhave (1991) stated that "results taken from sensitivity analysis are not exact because they are derivatives at a point. However, it is a fast way for comparing possible changes". In this study, Chapter 15.2: Sensitivity Analysis in Analysis of Flow in Water Distribution Networks (Bhave, 1991) is used as a main guide.

3.3.2. Example Related to Sensitivity Analysis

To clarify theory, numerical example is given in Figure 3.1. In this example node 1 is a source node with HGL=100.00 m and node 2, 3, 4, 5, 6 are fed from node 1. The question is that using sensitivity analysis, determine the maximum possible outflow at node 3 without affecting the outflows at all other nodes. Given values are presented in Table 3.1.

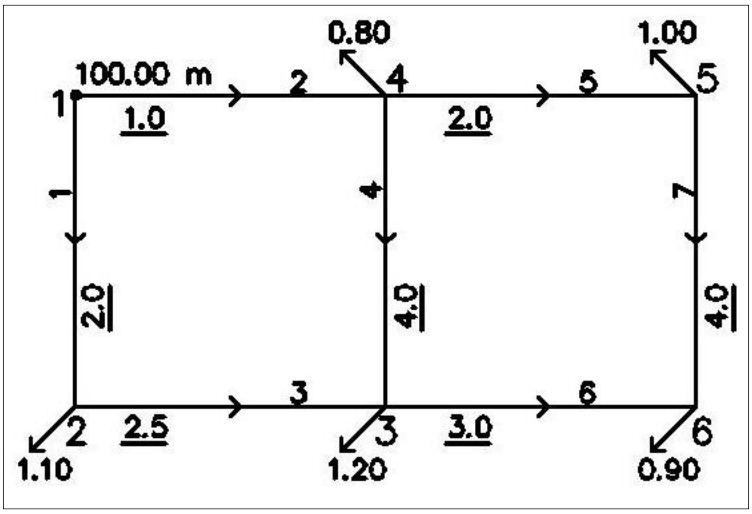

Figure 3.1 Sensitivity Analysis Problem (Bhave, 1991)

The head loss in pipes is given by $h_f = RQ^{1.852}$

R : pipe resistance constant (shown underlined in Figure 3.1)

Q : pipe discharge in m^3/min

q : nodal demand in m^3/min

Table 3.1 Given Values

Node	$q_i(m^3/min)$	H_i^{min} (m)
1	-5.00	100.00
2	1.10	90.00
3	1.20	87.00
4	0.80	89.40
5	1.00	88.80
6	0.90	88.00

The Node Head Analysis (NHA) solution of the network is given in the Table 3.3. The linearized H equations written for the node-flow continuity relationship at nodes 2, ..., 6 are, respectively,

$${}_tC'_1\,(100 - H_2) - {}_tC'_3\,(H_2 - H_3) - 1.10 = 0 \tag{3.21}$$

$${}_tC'_3\,(H_2 - H_3) + {}_tC'_4\,(H_4 - H_3) - {}_tC'_6\,(H_3 - H_6) - 1.20 = 0 \tag{3.22}$$

$${}_tC'_2\,(100 - H_4) - {}_tC'_5(H_4 - H_5) - {}_tC'_4\,(H_4 - H_3) - 0.80 = 0 \tag{3.23}$$

$${}_tC'_5\,(H_4 - H_5) - {}_tC'_7\,(H_5 - H_6) - 1.00 = 0 \tag{3.24}$$

$${}_tC'_6\,(H_3 - H_6) + {}_tC'_7\,(H_5 - H_6) - 0.90 = 0 \tag{3.25}$$

Equations (3.21), ..., (3.25) can be rearranged and expressed as, respectively,

$$H_2\,({}_tC'_1 + {}_tC'_3) - H_3\,({}_tC'_3) = 100\,({}_tC'_1) - 1.10 \tag{3.26}$$

$$H_2\,({}_tC'_3) - H_3\,({}_tC'_3 + {}_tC'_4 + {}_tC'_6) + H_4\,({}_tC'_4) + H_6\,({}_tC'_6) = 1.20 \tag{3.27}$$

$$H_3\,({}_tC'_4) - H_4\,({}_tC'_2 + {}_tC'_4 + {}_tC'_5) + H_5\,({}_tC'_5) = 0.80 - 100\,({}_tC'_2) \tag{3.28}$$

$$H_4\,({}_tC'_5) - H_5\,({}_tC'_5 + {}_tC'_7) + H_6\,({}_tC'_7) = 1.00 \tag{3.29}$$

$$H_3\,({}_tC'_6) + H_5\,({}_tC'_7) - H_6\,({}_tC'_6 + {}_tC'_7) = 0.90 \tag{3.30}$$

Equations (3.26), ..., (3.30) expressed in the matrix form give Equation (3.31)

$$\begin{bmatrix} C'_1 + C'_3 & -C'_3 & 0 & 0 & 0 \\ C'_3 & -(C'_3 + C'_4 + C'_6) & C'_4 & 0 & C'_6 \\ 0 & C'_4 & -(C'_2 + C'_4 + C'_5) & C'_5 & 0 \\ 0 & 0 & C'_5 & -(C'_5 + C'_7) & C'_7 \\ 0 & C'_6 & 0 & C'_7 & -(C'_6 + C'_7) \end{bmatrix}_t * \begin{bmatrix} H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{bmatrix} = \begin{bmatrix} 100\,(C'_1) - 1.10 \\ 1.20 \\ 0.80 - 100\,(C'_2) \\ 1.00 \\ 0.90 \end{bmatrix}_t \tag{3.31}$$

Discharges in pipes are assumed to be 0.1 m^3/min for the first iteration. The corresponding ${}_1h_x$ and ${}_1C'_x$ values are obtained from Equations (3.7) and (3.11) respectively. Therefore, for the first iteration Equation (3.31) becomes

$$\begin{bmatrix} 6.401 & -2.845 & 0 & 0 & 0 \\ 2.845 & -6.994 & 1.778 & 0 & 2.371 \\ 0 & 1.778 & -12.446 & 3.556 & 0 \\ 0 & 0 & 3.556 & -5.334 & 1.778 \\ 0 & 2.371 & 0 & 1.778 & -4.149 \end{bmatrix} * \begin{bmatrix} H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{bmatrix} = \begin{bmatrix} 354.507 \\ 1.200 \\ -710.414 \\ 1.000 \\ 0.900 \end{bmatrix} \tag{3.32}$$

Solving Equation (3.32), HGL values will be $H_{2(1)}$ = 99.44 m, $H_{3(1)}$ = 99.13 m, $H_{4(1)}$ = 99.58 m, $H_{5(1)}$ = 99.17 m, $H_{6(1)}$ = 98.93 m. The corresponding values of $h_{x(1)}$, $Q_{x(1)}$ [using Equation (3.7)] and $C'_{x(1)}$, [using Equation (3.11)] are obtained.

Table 3.2 First and Second Iteration Values of the Example

		Iteration 1						Iteration 2			
Pipe	R_o	${}_1Q_X$ (m^3/min)	${}_1h_x$ (m)	${}_1C'_x$	$h_{x(1)}$ (m)	$Q_{x(1)}$ (m^3/min)	$C'_{(x)(1)}$	${}_2C'_x$	$h_{x(2)}$ (m)	$Q_{x(2)}$ (m^3/min)	$C'_{(x)(2)}$
1	2	0.1	0.028	3.556	0.558	0.502	0.900	2.228	0.892	0.647	0.725
2	1	0.1	0.014	7.112	0.424	0.629	1.484	4.298	0.701	0.825	1.178
3	2.5	0.1	0.035	2.845	0.310	0.324	1.045	1.945	0.456	0.399	0.875
4	4	0.1	0.056	1.778	0.444	0.305	0.688	1.233	0.648	0.374	0.578
5	2	0.1	0.028	3.556	0.402	0.420	1.046	2.301	0.615	0.529	0.860
6	3	0.1	0.042	2.371	0.199	0.231	1.161	1.766	0.275	0.275	1.001
7	4	0.1	0.056	1.778	0.241	0.219	0.910	1.344	0.308	0.251	0.813

The average of, ${}_1C'_x$ and $C'_{(x)(1)}$ is taken as ${}_2C'_x$ for the second iteration. Therefore, Equation (3.32) now becomes

$$\begin{bmatrix} 4.173 & -1.945 & 0 & 0 & 0 \\ 1.945 & -4.944 & 1.233 & 0 & 1.766 \\ 0 & 1.233 & -7.832 & 2.301 & 0 \\ 0 & 0 & 2.301 & -3.645 & 1.344 \\ 0 & 1.766 & 0 & 1.344 & -3.110 \end{bmatrix} * \begin{bmatrix} H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \end{bmatrix} = \begin{bmatrix} 221.696 \\ 1.200 \\ -428.987 \\ 1.000 \\ 0.900 \end{bmatrix} \tag{3.33}$$

Solving Equation (3.33), HGL values will be $H_{2(2)}$ = 99.11 m, $H_{3(2)}$ = 98.65 m, $H_{4(2)}$ = 99.30 m, $H_{5(2)}$ = 98.68 m, $H_{6(2)}$ = 98.38 m. The first two iterations are shown in Table 3.2. The iterative procedure is continued and when ε_{max} ,which is written according to the assumed values of modified conductance of pipe ${}_tC'_x$ and obtained values of modified conductance of pipe $C'_{x(t)}$, is less than 0.0001, iteration is stopped. To clarify ε concept better, ε values belong to first iteration is given through Equations (3.34), ..., (3.40).

$\varepsilon = |{}_1C'_1 - C'_{1(1)}| = |3.556 - 0.900| = 2.656$ (3.34)

$\varepsilon = |{}_1C'_2 - C'_{2(1)}| = |7.112 - 1.484| = 5.629$ (3.35)

$\varepsilon = |{}_1C'_3 - C'_{3(1)}| = |2.845 - 1.045| = 1.800$ (3.36)

$\varepsilon = |{}_1C'_4 - C'_{4(1)}| = |1.778 - 0.688| = 1.091$ (3.37)

$\varepsilon = |{}_1C'_5 - C'_{5(1)}| = |3.556 - 1.046| = 2.510$ (3.38)

$\varepsilon = |{}_1C'_6 - C'_{6(1)}| = |2.371 - 1.161| = 1.209$ (3.39)

$\varepsilon = |{}_1C'_7 - C'_{7(1)}| = |1.778 - 0.910| = 0.868$ (3.40)

ε_{max} for the first iteration is 5.629. Finally, HGL values will be $H_{2(31)}$ = 92.31 m, $H_{3(31)}$ = 89.96 m, $H_{4(31)}$ = 92.68 m, $H_{5(31)}$ = 89.34 m, $H_{6(31)}$ = 88.86 m. To check accuracy of method, example given in Figure 3.1 is also solved by Watercad. Results are compared in Table 3.3.

Table 3.3 Comparison of HGL Values

	COMPARISON of HGL VALUES	
Label	Linear Theory Result (m)	Watercad Result (m)
H_2	92.314	92.310
H_3	89.956	89.952
H_4	92.677	92.676
H_5	89.339	89.335
H_6	88.858	88.854

After completing Node Head Analysis (NHA), sensitivity analysis proposed by Bhave can be made now. When the nodal demand at node 3 increases, HGL values of all nodes decrease. This decrease in HGL for each node can continue until some point where minimum permissible HGL value is reached.

q_3 : selected variable (y_k)

q_1, H_2, H_3, H_4, H_5 and H_6 : free variables (v_f)

The node-flow continuity equations at nodes are given below respectively

$$F_1 = -\left(\frac{100 - H_2}{2.0}\right)^{0.54} - \left(\frac{100 - H_4}{1.0}\right)^{0.54} + q_1 = 0 \quad (3.41)$$

$$F_2 = \left(\frac{100 - H_2}{2.0}\right)^{0.54} - \left(\frac{H_2 - H_3}{2.5}\right)^{0.54} - 1.10 = 0 \tag{3.42}$$

$$F_3 = \left(\frac{H_2 - H_3}{2.5}\right)^{0.54} + \left(\frac{H_4 - H_3}{4.0}\right)^{0.54} - \left(\frac{H_3 - H_6}{6.0}\right)^{0.54} - q_3 = 0 \tag{3.43}$$

$$F_4 = \left(\frac{100 - H_4}{1.0}\right)^{0.54} - \left(\frac{H_4 - H_3}{4.0}\right)^{0.54} - \left(\frac{H_4 - H_5}{2.0}\right)^{0.54} - 0.80 = 0 \tag{3.44}$$

$$F_5 = \left(\frac{H_4 - H_5}{2.0}\right)^{0.54} - \left(\frac{H_5 - H_6}{4.0}\right)^{0.54} - 1.00 = 0 \tag{3.45}$$

$$F_6 = \left(\frac{H_3 - H_6}{3.0}\right)^{0.54} + \left(\frac{H_5 - H_6}{4.0}\right)^{0.54} - 0.90 = 0 \tag{3.46}$$

Taking derivative of F_j with respect to y_k in the matrix form

$$\begin{bmatrix} \frac{\partial F_1}{\partial q_1} & \frac{\partial F_1}{\partial H_2} & 0 & \frac{\partial F_1}{\partial H_4} & 0 & 0 \\ 0 & \frac{\partial F_2}{\partial H_2} & \frac{\partial F_2}{\partial H_3} & 0 & 0 & 0 \\ 0 & \frac{\partial F_3}{\partial H_2} & \frac{\partial F_3}{\partial H_3} & \frac{\partial F_3}{\partial H_4} & 0 & \frac{\partial F_3}{\partial H_6} \\ 0 & 0 & \frac{\partial F_4}{\partial H_3} & \frac{\partial F_4}{\partial H_4} & \frac{\partial F_4}{\partial H_5} & 0 \\ 0 & 0 & 0 & \frac{\partial F_5}{\partial H_4} & \frac{\partial F_5}{\partial H_5} & \frac{\partial F_5}{\partial H_6} \\ 0 & \frac{\partial F_6}{\partial H_3} & 0 & 0 & \frac{\partial F_6}{\partial H_5} & \frac{\partial F_6}{\partial H_6} \end{bmatrix} * \begin{bmatrix} \frac{\partial q_1}{\partial q_3} \\ \frac{\partial H_2}{\partial q_3} \\ \frac{\partial H_3}{\partial q_3} \\ \frac{\partial H_4}{\partial q_3} \\ \frac{\partial H_5}{\partial q_3} \\ \frac{\partial H_6}{\partial q_3} \end{bmatrix} = - \begin{bmatrix} \frac{\partial F_1}{\partial q_3} \\ \frac{\partial F_2}{\partial q_3} \\ \frac{\partial F_3}{\partial q_3} \\ \frac{\partial F_4}{\partial q_3} \\ \frac{\partial F_5}{\partial q_3} \\ \frac{\partial F_6}{\partial q_3} \end{bmatrix} \tag{3.47}$$

Substituting the values of the partial derivatives,

$$\begin{bmatrix} 1 & 0.1454 & 0 & 0.2161 & 0 & 0 \\ 0 & -0.3672 & 0.2219 & 0 & 0 & 0 \\ 0 & 0.2219 & -0.5796 & 0.1612 & 0 & 0.1966 \\ 0 & 0 & 0.1612 & -0.5906 & 0.2133 & 0 \\ 0 & 0 & 0 & 0.2133 & -0.5709 & 0.3576 \\ 0 & 0 & 0.2858 & 0 & 0.3576 & -0.6434 \end{bmatrix} * \begin{bmatrix} \frac{\partial q_1}{\partial q_3} \\ \frac{\partial H_2}{\partial q_3} \\ \frac{\partial H_3}{\partial q_3} \\ \frac{\partial H_4}{\partial q_3} \\ \frac{\partial H_5}{\partial q_3} \\ \frac{\partial H_6}{\partial q_3} \end{bmatrix} = - \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{3.48}$$

Table 3.4 Summary Table

Node	q_i (m^3/min)	H_i^{min} (m)	q_i (m^3/min)	H (obtained from linearization) (m)	Available Excess Head (m)	Free Variable V_f	$\partial V_f/\partial q_3$	Permissible Increase in q_3 (m^3/min)	H for Increased q_3 (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	-	100.00	-5.00	100.00	-	q_1	1.00	-	100.00
2	1.10	90.00	1.10	92.31	2.31	H_2	-3.16	0.73	91.89
3	1.20	87.00	1.20	89.96	2.96	H_3	-5.23	0.57	89.26
4	0.80	89.40	0.80	92.68	3.28	H_4	-2.82	1.16	92.30
5	1.00	88.80	1.00	89.34	0.54	H_5	-3.85	0.14	88.80
6	0.90	88.00	0.90	88.86	0.86	H_6	-4.46	0.19	88.26

3.4. Discussion of Results

In Table 3.4, Columns (2), (3) and (4) have been given at the beginning of the example. HGL values at column (5) have been calculated by Linear Theory using nodal head equations. Column (6) can be obtained by subtracting column (3) from column (5). Column (7) indicates free variables. Column (8) shows that if q_3 is increased by 1 m^3/min, free variables (q_1, H_2, H_3, H_4, H_5 and H_6) are subject to these amount of changes in Table 3.4. For example, H_2 and H_3 would decrease by 3.16 m and 5.23 m. Column (8) is a kind of static analysis because change amount of q_3 is constant 1m^3/min. On the other hand, column (9) permissible increase in q_3 shows different amount of change of q_3 and it is obtained by dividing column (6) to column (8). For example, if q_3 is increased by 0.73 m^3/min, H_2 would become 90.00 m the minimum required value. Similarly, H_3 would become 87.00 m while increasing q_3 by 0.57 m^3/min. By looking column (9), minimum amount of change for q_3 is 0.14 m^3/min, which belongs to node 5. It can be said that node 5 is a control node because after this value H_5 would be less than 88.80 m. In other words, maximum possible outflow that can be drawn from node 3 without affecting other nodes is 1.20 + 0.14 = 1.34 m^3/min. If q_3 is increased by 0.14 m^3/min, total heads will be at column (10). Working range of the technique proposed by Bhave (1991) is presented in Appendix B.

CHAPTER 4

CASE STUDY

4.1. Study Area

Study area is N8.3 pressure zone of Ankara water distribution system. It is located at the main North pressure zone. N8.3 is situated mainly at Keçiören and partially at Yenimahalle districts; its population is estimated about 50,000. Northern Sancaktepe, Southern Sancaktepe, Şehit Kubilay, Upper Çiğdemtepe, Lower Çiğdemtepe and Yayla neighborhoods constitute N8.3 pressure zone. Google Earth of this zone can be observed in Figure 4.1. Schematic presentation of the DMAs; including transmission pipes and distribution pipes is given in Figure 4.2.

In fact, there exist two operating conditions for the network, namely DMA (district metered area) and whole network. N8.3 consists of six DMAs:

- N8.3-1 Northern Sancaktepe DMA
- N8.3-2 Southern Sancaktepe DMA
- N8.3-3 Şehit Kubilay DMA
- N8.3-4 Upper Çiğdemtepe DMA
- N8.3-5 Lower Çiğdemtepe DMA
- N8.3-6 Yayla DMA

DMA can be defined as "an area which has a defined and permanent boundary, usually containing 500-3000 properties, into which flows are continually monitored "(Farley, 2001). "DMAs are physically connected at each pressure zone in the field but isolation valves are closed to block flow between DMAs" (Şendil, 2013). DMAs are created by using isolation valves at the entrance; therefore, it can be said that DMA is an insulated system. According to Apaydın (2013), N8.3 pressure zone serves for 50,000 people; spatial distribution of the population is presented in Table 4.1.

Table 4.1 Populations of DMAs in N8.3 Pressure Zone (Apaydın, 2013)

DMA	Population
Yayla	10,228
Northern Sancaktepe	7,756
Southern Sancaktepe	5,248
Şehit Kubilay	11,161
Upper Çiğdemtepe	7,791
Lower Çiğdemtepe	7,816

At the entrance of each DMA, there exists a measurement chamber (Figure 4.1); pressures and discharges are measured by manometers and ultrasonic flowmeters mounted on inlet pipes passing through measurement chambers. Discharges measured through measurement chambers are used to obtain daily demand curve of each DMA.

Figure 4.1 N8.3 Network Satellite Preview (Google Earth) (Ar, 2011)

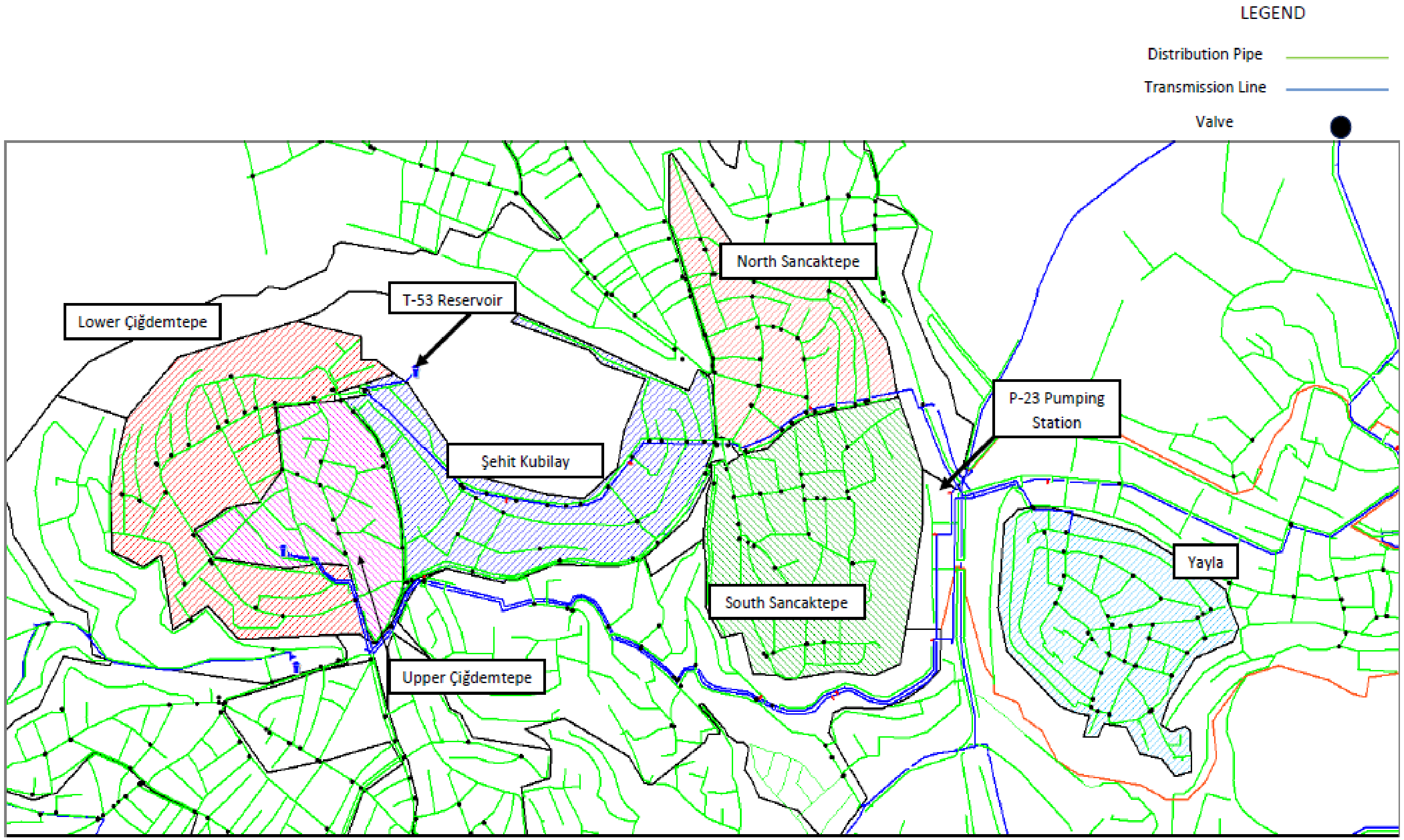

Figure 4.2 Sub-Zones of N8.3 (Ar, 2011)

Case study is conducted in Yayla DMA. Service contours are given as 1058 m and 1113 m. The source for N8.3 pressure zone is Ivedik Treatment Plant; potable water reaches N8.3 by pursuing the pump stations P1, P2, P12 and P23. The flowpath followed is indicated in Figure 4.3.

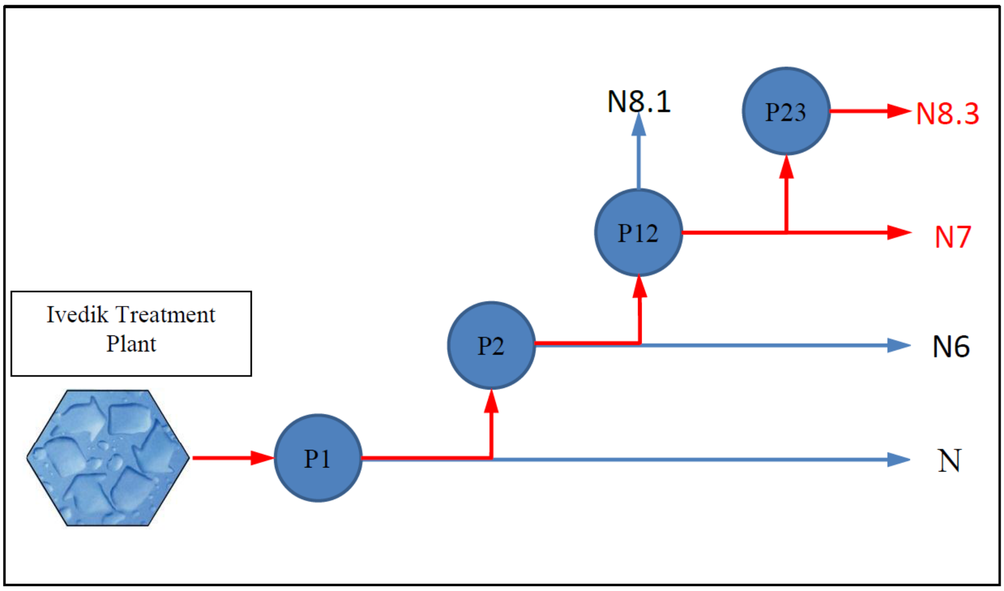

Figure 4.3 Flow Path of N8.3 Pressure Zone (Şendil, 2013)

Characteristics of storage tank T53 and pumps at P23 pump station are given in Table 4.2 and 4.3.

Table 4.2 Characteristics of Storage Tank T53 (Şendil, 2013)

Volume	5000 m^3
Cross- Section Area	800 m^2
Height	6.50 m
Base Elevation	1 149.83 m

Table 4.3 Characteristics of Pumps at P23 Pump Station (Şendil, 2013)

Pump Number	Pump 1 and 2	Pump 3
Manufacturer	SUMAS	SMS
Design Flow	188 m^3/hr	350 m^3/hr
Design Head	45 m	45 m
Pump Efficiency	74 %	80 %

In general, a WDN consists of pipes, nodes, pumps and a storage tank. In this study, a node actually represents zoning area surrounded by houses, schools, shopping malls, residences. N8.3 pressure zone is a developing region. In other words, some houses or buildings have already been replaced by high rise buildings or residences due to urban renewal. One of them is presented on the right side of the road in Çiğdemtepe neighborhood (Picture 4.1).

Picture 4.1 Çiğdemtepe Neighborhood (Web 7)

Within urban renewal, there will be demand increase due to residences. It can be asked that how much area in terms of hectare is affected due to change in discharge. Answer of this question is given at the end of Chapter 4. Using the Geographic Information System (GIS) software Mapinfo, Yayla neighborhood's area is obtained according to the construction plan. Output of program is given in Figure 4.4.

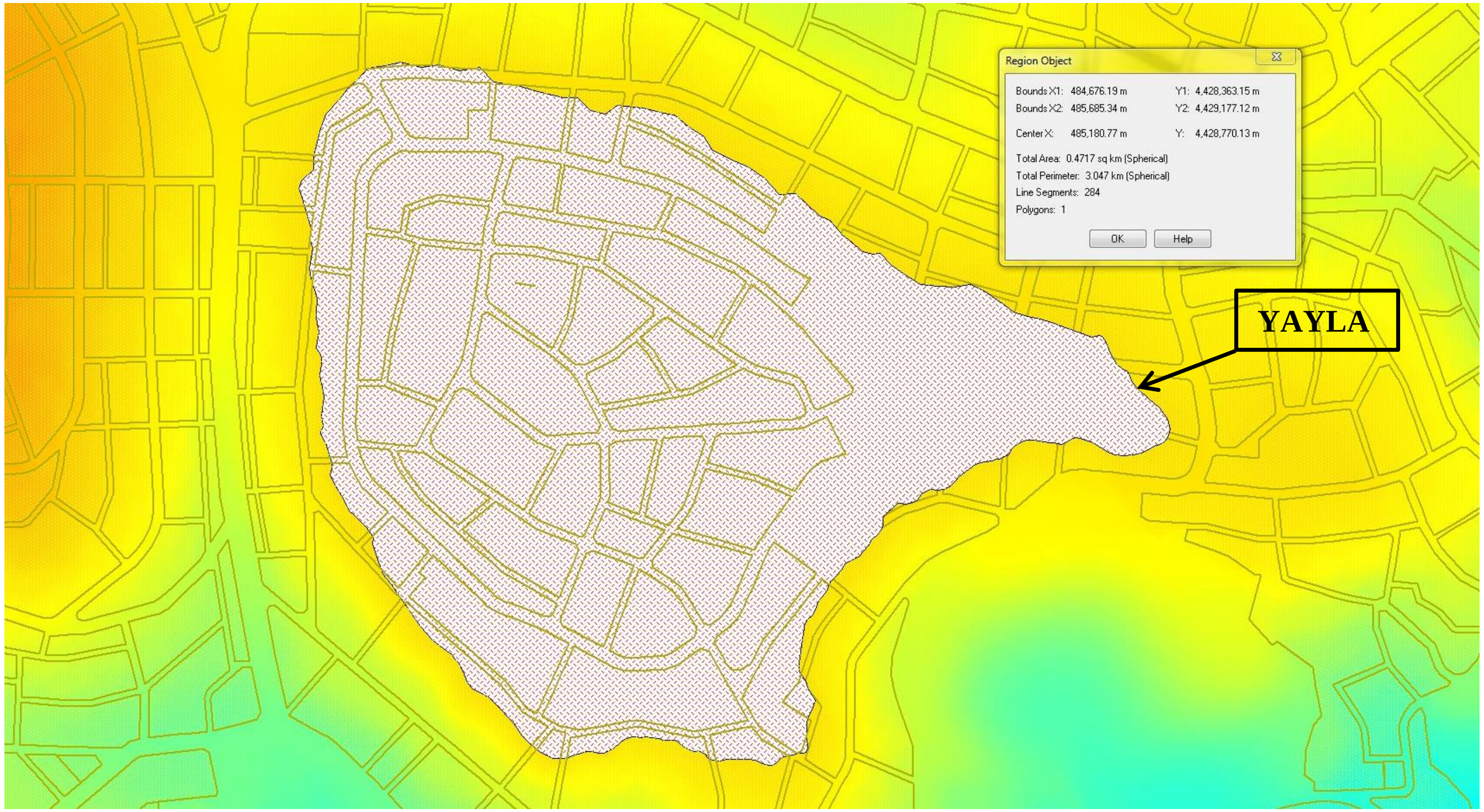

Figure 4.4 Yayla Neighborhood (DMA)

Yayla neighborhood is still being developed. Many facilities like apartment houses, schools, shopping malls have been built and some shanties have been pulled down according to the urban renewal based on the article 73th of Municipalities Law No.5393. This will cause population increase in the near future. Generally, increase in consumption of potable water may cause problems. For example, if new residence has 30 stories, residents at the upper stories may not use water due to low pressure head. Sensitivity analysis gives an idea about the critical region, which could have a pressure problem. The methodology employed is explained below:

1) In general, the study area (pressure zone) has been assumed to have a pressure head of 40 m for the existing situation (Figure 4.5).

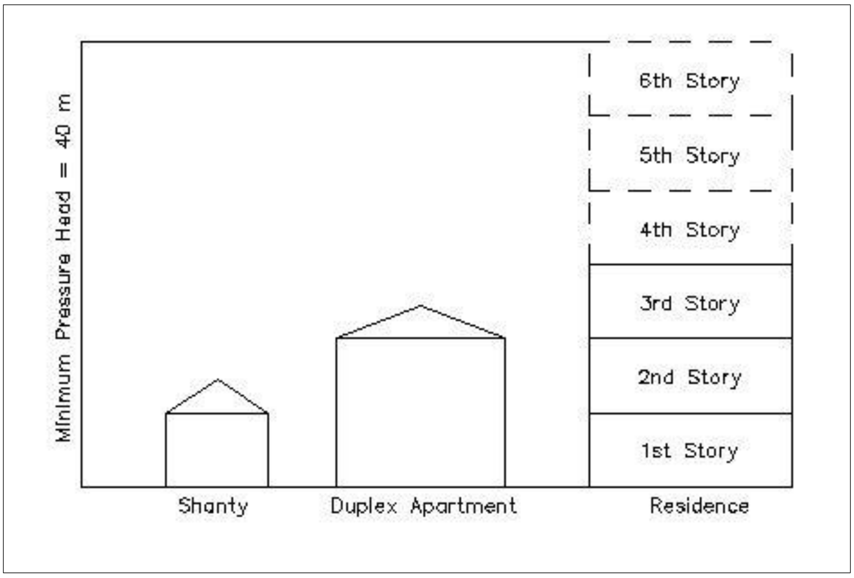

Figure 4.5 Existing Situation for the Built-Up Area in N8.3 Pressure Zone

2) The developer is assumed to select the node at which the nodal demand is to be maximized without disturbing existing nodal pressure heads in the neighborhood (DMA).

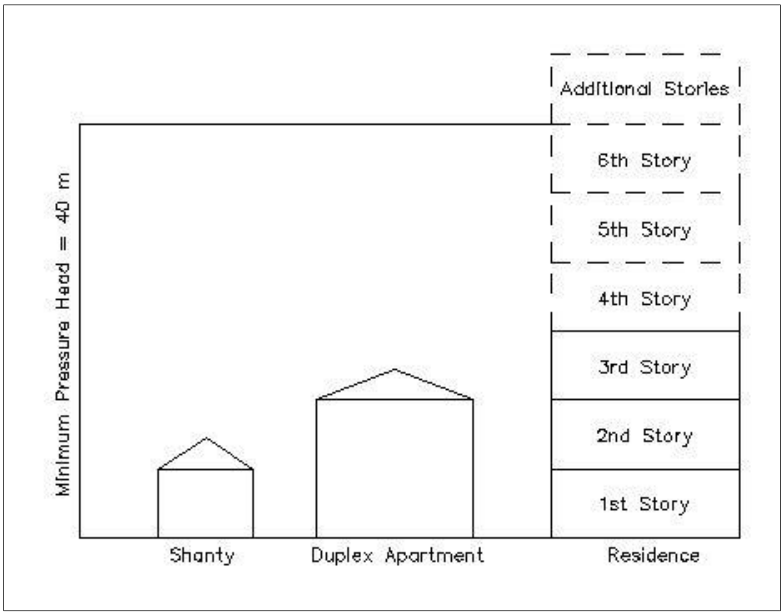

Figure 4.6 Hypothetical Situation That Reflects One Possible Future of Built-Up Area in N8.3 Pressure Zone

If at the end of the analysis, permissible increase in discharge at a particular node without disturbing other regions is higher than existing situation, the developer may want to extract this discharge by adding new stories to residence (Figure 4.6). However, for some cases low pressure head problem can be faced with and this is developer's responsibility. To overcome low pressure head problem at upper stories of the residence, hydrophore may be used to solve the problem.

3) After having realized the project at the selected node, another developer can use the same methodology for selecting next available node.
4) How about if one developer has decided to develop the area (red one in Figure 4.7) around a node with a "very high" demand so that other developers cannot find a possibility to realize similar projects? In order to avoid such situations:

- Firstly, NHA of neighborhood should be made. Secondly, municipality should assign minimum pressure head value and sensitivity analysis (SA) should be conducted. Finally, the municipality should assign allowable nodal demands according to the SA results.

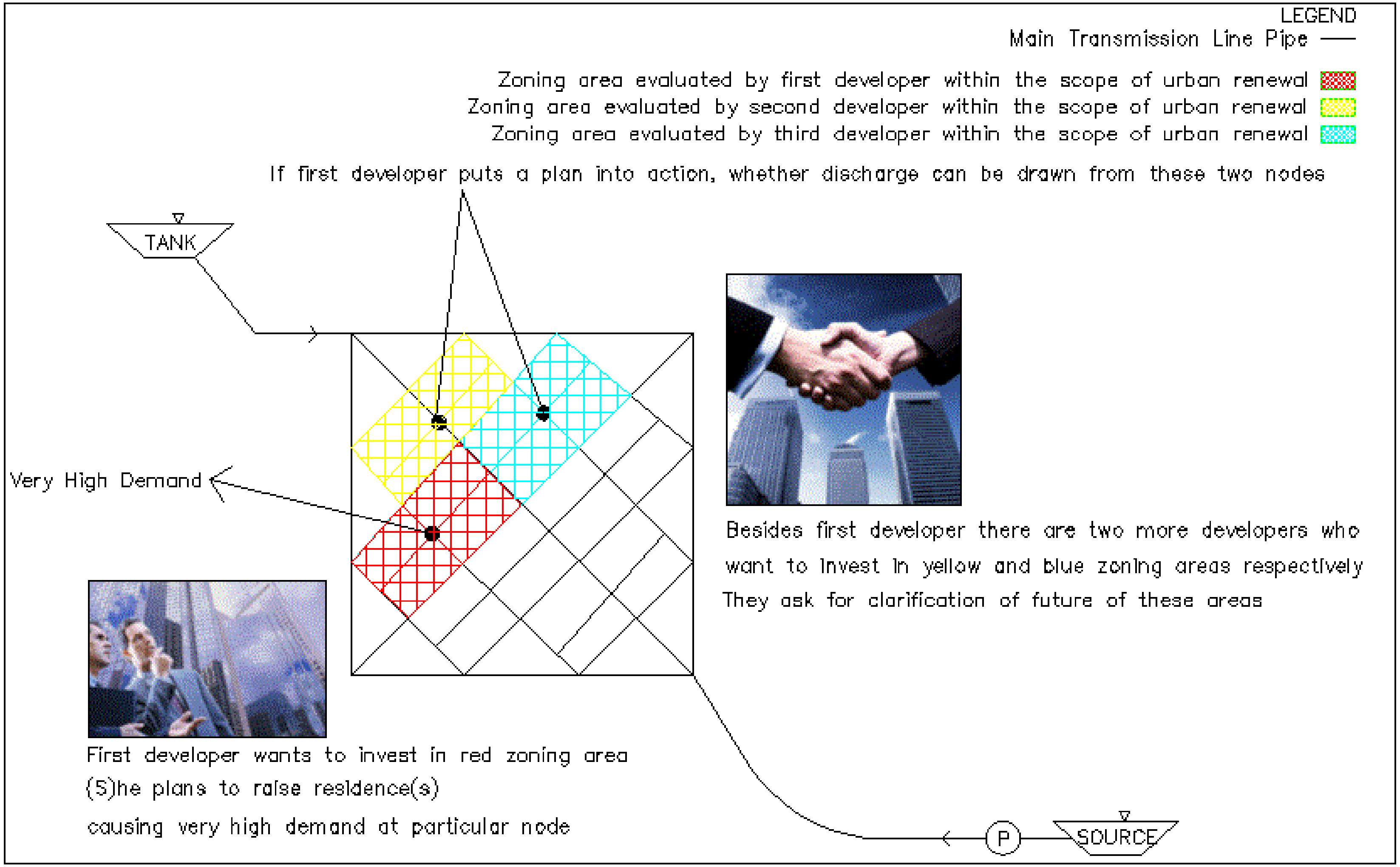

Figure 4.7 Schematic View of Problem

For operational reasons, the network has been run as DMAs. Insulated system has been studied under five different scenarios. These are:

- INS-1PMP (SM)
- INS-1PMP (LG)
- INS-2PMP (SM+SM)
- INS-2PMP (SM+LG)
- INS-3PMP (SM+SM+LG)

Terms used in scenarios are described below as,

- INS: Insulated system is running with isolated DMAs. Isolation valves are closed.
- #PMP: Number of active pump
- SM: Small capacity pump, which is SUMAS-429 at P23 pump station
- LG: Large capacity pump, which is SMS-493 at P23 pump station
- CT: Constant tariff energy price
- MT: Multi tariff energy price

Şendil (2013) gives Table 4.4 and Figure 4.8 to illustrate scenarios and terms more clearly.

Table 4.4 Scenario Codes and Their Definitions of N8.3 Pressure Zone (Şendil, 2013)

Scenario Code	Scenario No	Insulated System	Uninsulated System	# of Active Pump	Pump #1 SM-SUMAS-429	Pump #2 SM-SUMAS-429	Pump #3 LG-SMS-493	Constant Tariff	Multi Tariff
INS-1PMP(SM)-CT	1	X		1	X			X	
INS-1PMP(LG)-CT	2	X		1			X	X	
INS-2PMP(SM+SM)-CT	3	X		2	X	X		X	
INS-2PMP(SM+LG)-CT	4	X		2	X		X	X	
INS-3PMP(SM+SM+LG)-CT	5	X		3	X	X	X	X	
INS-1PMP(SM)-MT	6	X		1	X				X
INS-1PMP(LG)-MT	7	X		1			X		X
INS-2PMP(SM+SM)-MT	8	X		2	X	X			X
INS-2PMP(SM+LG)-MT	9	X		2	X		X		X
INS-3PMP(SM+SM+LG)-MT	10	X		3	X	X	X		X

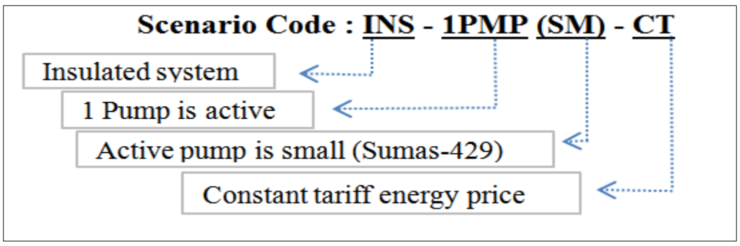

Figure 4.8 First Scenario Code of N8.3 Pressure Zone (Şendil, 2013)

As it can be seen above, pumps are tested in different combinations. Since Şendil's (2013) study is related to optimization, the criteria which he looks for in scenarios are the energy prices. In case of constant tariff, total energy cost of pumps in 24 hours is constant. On the other hand, multi tariff energy price is variable according to time interval. Energy prices and energy costs of insulated system with constant and multi tariff prices are given in Table 4.5, 4.6 and 4.7 respectively.

Table 4.5 Energy Prices (Şendil, 2013)

Time Interval	Energy Price (TL/kWh)	
	Constant Tariff	Multi Tariff
Day 06:00-17:00	0.2486	0.2336
Peak 17:00-22:00	0.2486	0.3556
Night 22:00-06:00	0.2486	0.1456

Table 4.6 Energy Costs of Insulated System with Constant Tariff Energy Prices (Şendil, 2013)

Scenario Code	Calculated Energy Cost (TL)
INS-3 PMP (SM+SM+LG)-CT	183.411
INS-2 PMP (SM+LG)-CT	172.364
INS-1 PMP (LG)-CT	171.610
INS-2 PMP (SM+SM)-CT	186.718
INS-1 PMP (SM)-CT	195.254

Table 4.7 Energy Costs of Insulated System with Multi Tariff Energy Prices (Şendil, 2013)

Scenario Code	Calculated Energy Cost (TL)
INS-3 PMP (SM+SM+LG)-MT	123.456
INS-2 PMP (SM+LG)-MT	124.667
INS-1 PMP (LG)-MT	126.353
INS-2 PMP (SM+SM)-MT	140.724
INS-1 PMP (SM)-MT	176.663

Since minimum energy cost is obtained at INS-3PMP (SM+SM+LG)-MT, which has energy cost of 123.456 TL/day, results of this have been used while studying Yayla neighborhood. While analyzing Yayla network, EPS (Extended Period Simulation) has been used because many parameters like nodal demands, HGL are time dependent.

4.2. Skeletonization of Yayla Neighborhood

4.2.1. General Concept

Skeletonization is a term used to describe process of eliminating smaller-diameter pipes or replacing them by equivalent pipes and considering only important pipes in preparation of the mathematical model of a network. Simplification of model enables user to formulate model in shorter time.

4.2.2. Watercad Skelebrator Skeletonizer

Yayla neighborhood taken from Şendil (2013) has too many nodes and pipes, so this situation makes calculations difficult. To shorten the calculation time, network has been skeletonized by using Skelebrator Skeletonizer in Watercad. This toolbox is able to perform five different techniques which are smart pipe removal, branch collapsing, series pipe merging, parallel pipe merging and inline isolating valve replacement. While using Skelebrator Skeletonizer, program lists possible actions. For example parallel pipe merging and inline isolating valve replacement show zero possible action. Smart pipe removal option has not been used while skeletonization. Branch Collapsing and Series Pipe Merging have been applied to the Yayla neighborhood and junction number is decreased from 147 to 40. While performing Series Pipe Merging length is used as a dominant criteria.

Brief descriptions of techniques used in this study are given below.

Branch Collapsing: Illustrated diagrams are given in Figure 4.9.

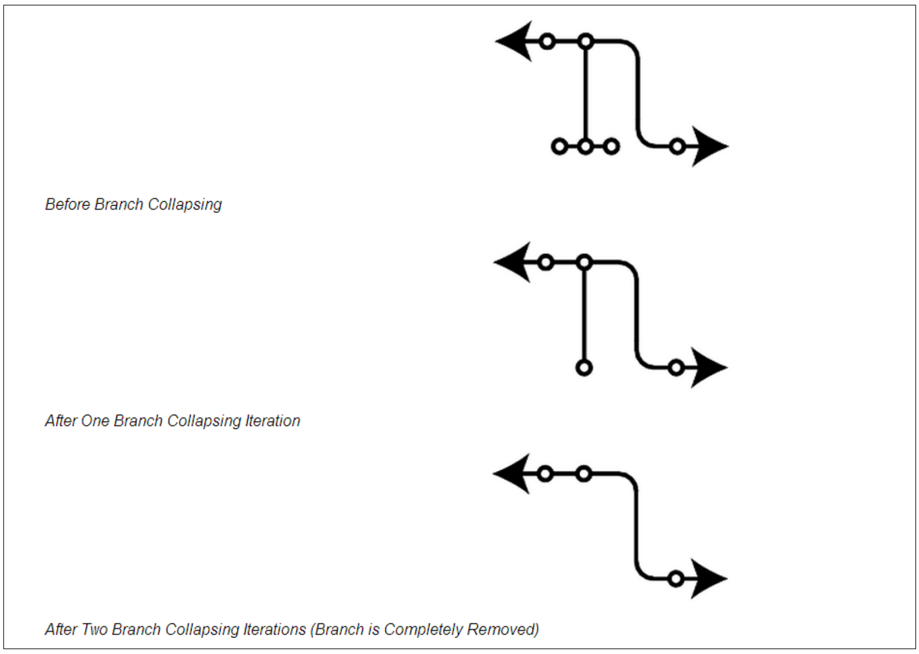

Figure 4.9 Branch Collapsing Process (Bentley WaterCAD V8i User's Guide, 2009)

Example from Yayla neighborhood is given in Figure 4.10 and 4.11 to clarify branch collapsing process better.

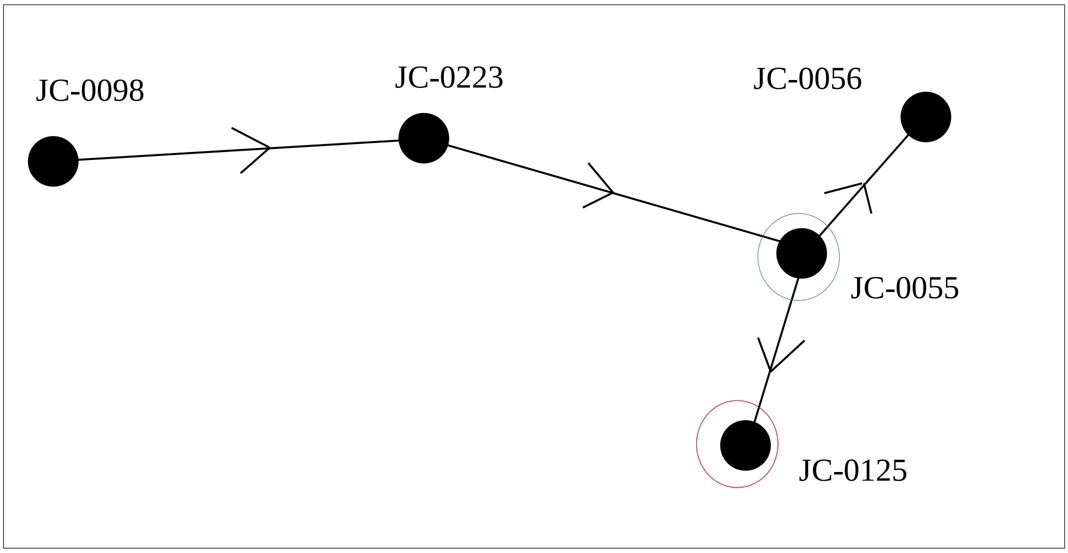

Figure 4.10 Before Branch Collapsing Process

JC-0125 indicated by red circle in Figure 4.10 will subject to branch collapsing. Nodal demands of JC-0125 red one and JC-0055 blue one are 0.039 and 0.129 m^3/hr respectively.

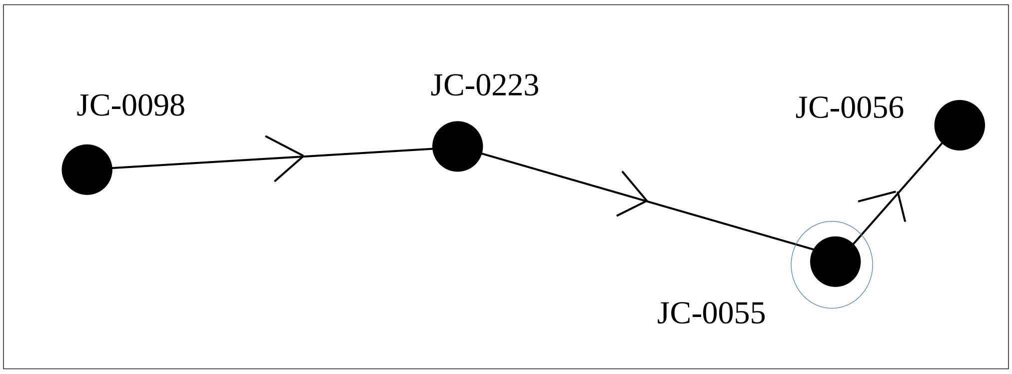

Figure 4.11 After Branch Collapsing Process

JC-0125 is deleted now, which can be seen from Figure 4.11 and its nodal demand is added to JC-0055 indicated by blue circle. Nodal demand of JC-0055 becomes 0.168 m^3/hr after branch collapsing.

Series Pipe Merging: Illustrated diagrams are given in Figure 4.12.

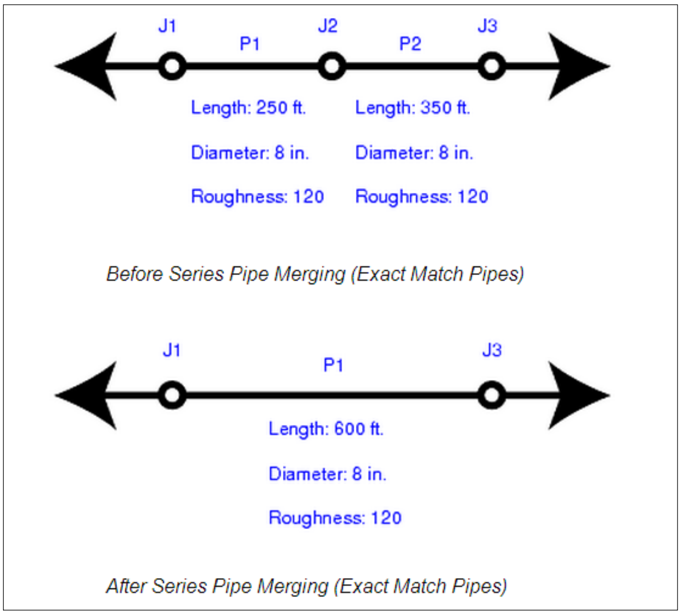

Figure 4.12 Series Pipe Merging Process
(Bentley WaterCAD V8i User's Guide, 2009)

Example from Yayla neighborhood is given in Figure 4.13 and 4.14 to clarify series pipe merging process better.

JC-0024 between JC-0154 and JC-0025 in Figure 4.13 will be subjected to series pipe merging. Nodal demand of JC-0024 will be shared between JC-0154 and JC-0025 according to pipe lengths.

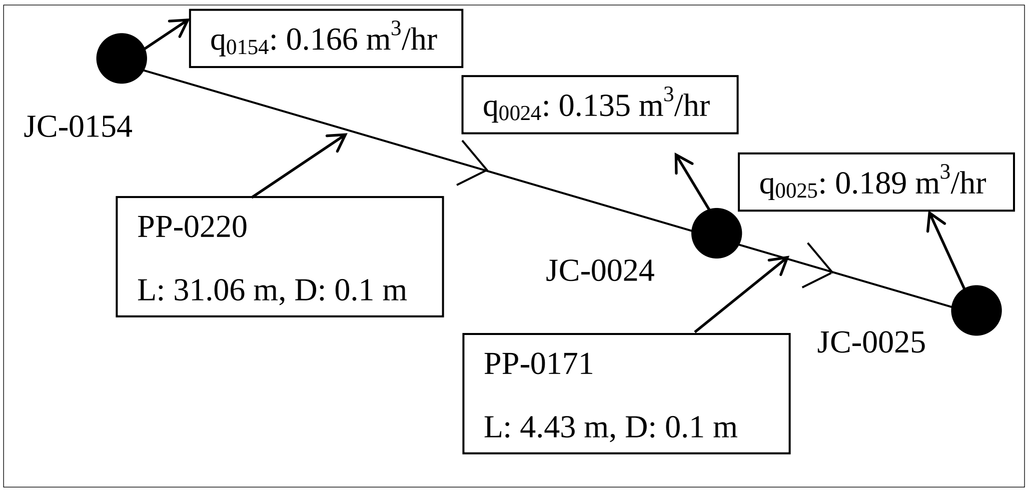

Figure 4.13 Before Series Pipe Merging Process

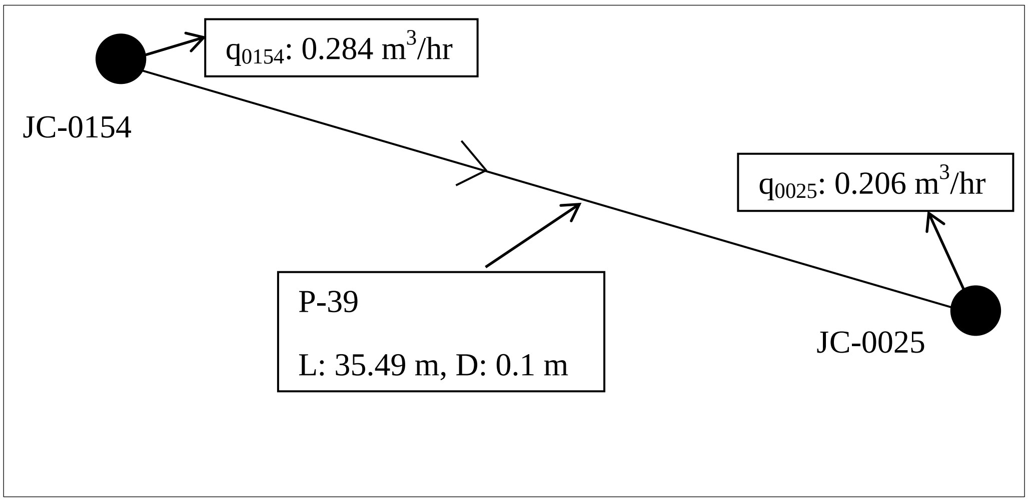

Figure 4.14 After Series Pipe Merging Process

JC-0024 is deleted now, which can be seen from Figure 4.14, and demand increase due to series pipe merging indicated by Δ can be calculated as

$$\Delta \text{ for JC} - 0154 = \left(\frac{31.06}{35.49}\right) * 0.135 = 0.118\,\frac{\text{m}^3}{\text{hr}} \qquad (4.1)$$

$$\Delta \text{ for JC} - 0025 = \left(\frac{4.43}{35.49}\right) * 0.135 = 0.017\,\frac{\text{m}^3}{\text{hr}} \qquad (4.2)$$

4.3. Capacity of N8.3 Pressure Zone

Before carrying out sensitivity analysis, existing pump combination graph is drawn to estimate the capacity of the system. If maximum possible outflow at particular node without affecting the outflows at other nodes is too high at the end of the study, a new pump should be added in parallel to the existing pump at the pump house in N8.3 pressure zone. N8.3 has 2 SUMAS-429 and 1 SMS-493 pumps. Pump characteristics are given in Figure 4.15 and 4.16.

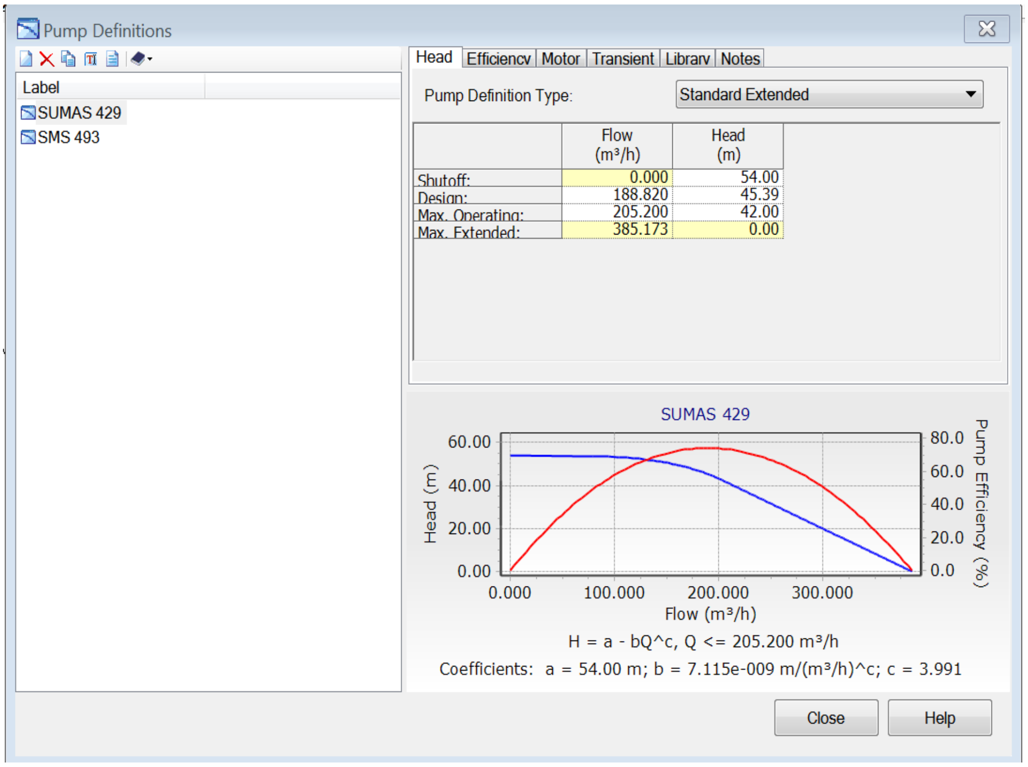

Figure 4.15 Pump Characteristics of SUMAS-429

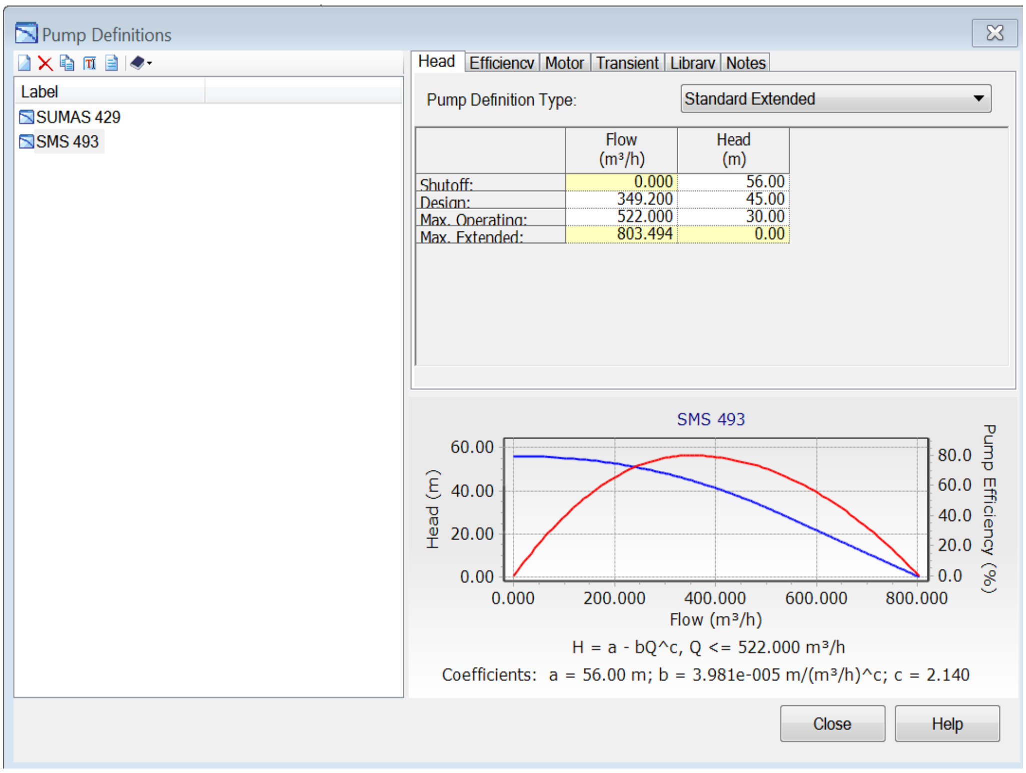

Figure 4.16 Pump Characteristics of SMS-493

Since pump combination is parallel, discharge values are additive for the same head. Combined pump curve is given in Figure 4.17.

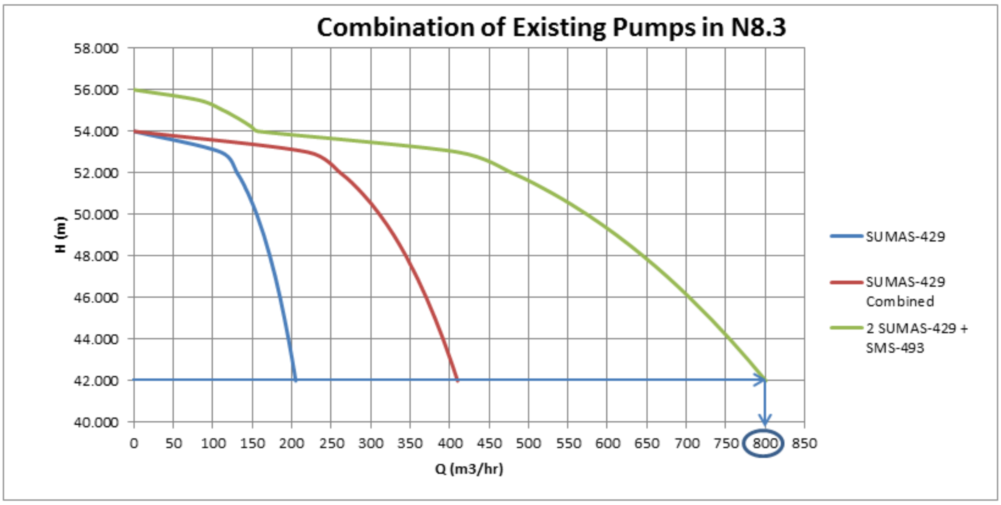

Figure 4.17 Combination of Existing Pumps in N8.3

From Figure 4.17, existing system allows the designer approximately 800 m^3/hr. Maximum discharge drawn from N8.3 is 650 m^3/hr. It means that extra 150 m^3/hr can be drawn from the system without adding new pump to the current system.

4.4. Urban Renewal Study of Yayla Neighborhood

4.4.1. General

Yayla daily demand curve given in Figure 4.18 has local maximum points, twelfth hour is selected while studying Yayla Neighborhood. The Watercad configuration of N8.3 can be seen in Figure 4.19. JC-0702 is selected as a source node because it is close to the outlet of pumps. Since pumps are working at 22:00-06:00 and 15:00-16:00, at 12:00 water comes from T53 to the junction JC-0702. Discharge value drawn from the network will be higher after carrying out sensitivity analysis. Therefore HGL value of JC-0702, which is 1153.16 m, will be less. If water in T53 is not sufficient, it is meaningless to perform sensitivity analysis. EPS results of T53 is given in Table 4.8 to understand situation better.

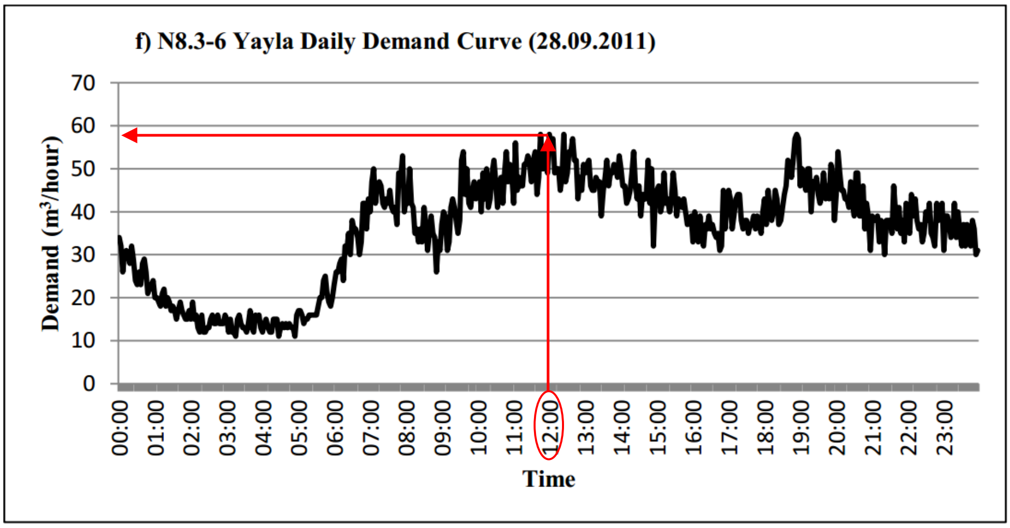

Figure 4.18 Yayla Daily Demand Curve (Şendil, 2013)

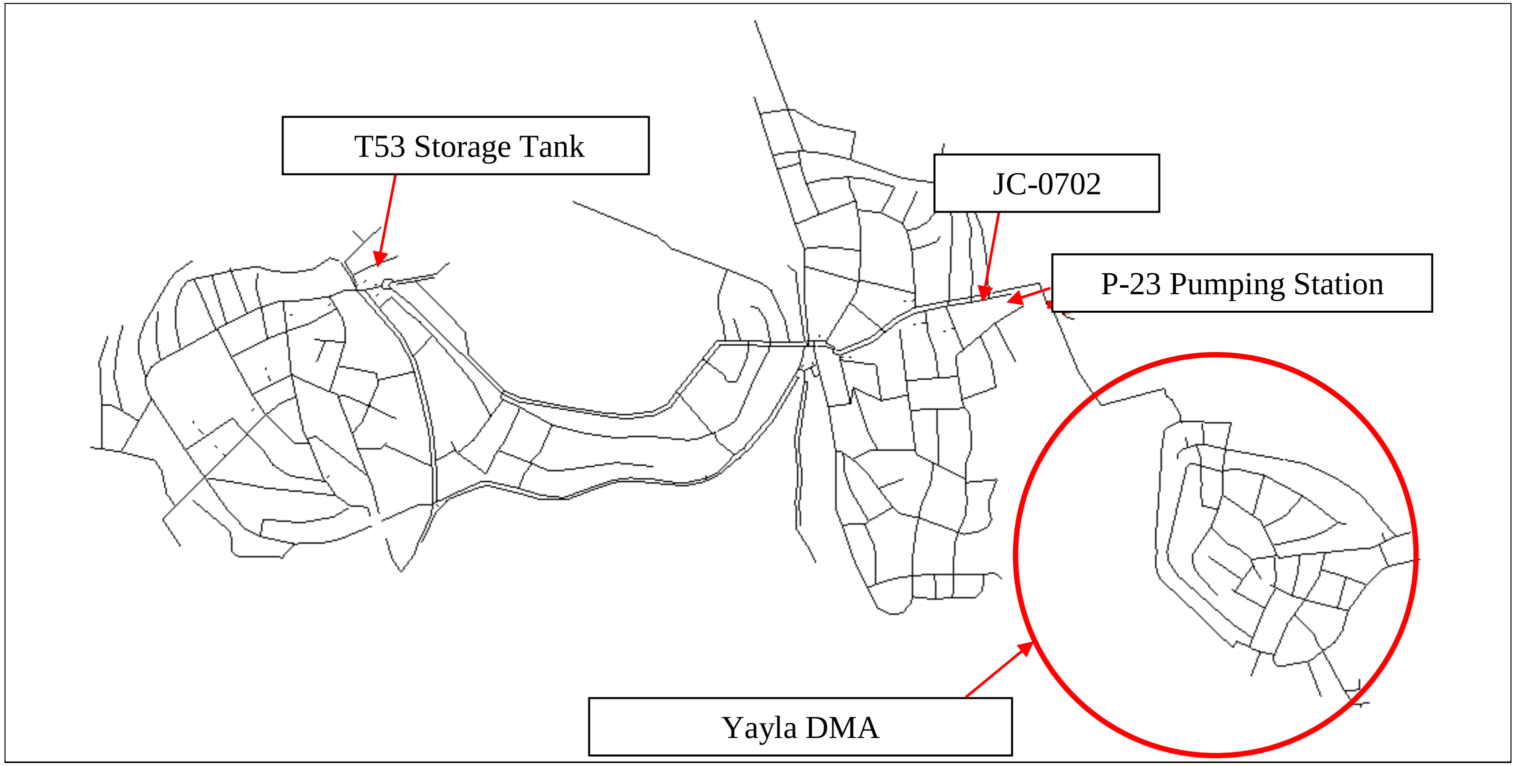

Figure 4.19 Watercad View of N8.3

Table 4.8 EPS Results of T53

EPS Results - T53 (Tank)

Time (hours)	Hydraulic Grade (m)	Level (Calculated) (m)	Pressure (m H2O)	Volume (Calculated) (m³)	Flow (In net) (m³/h)	Flow (Out net) (m³/h)
0.00	1.152.32	2.50	2.5	599.99	495.258	-495.258
1.00	1.152.94	3.12	3.1	1.095.23	375.053	-375.053
2.00	1.153.41	3.59	3.6	1.470.28	516.640	-516.640
3.00	1.154.05	4.23	4.2	1.986.95	261.745	-261.745
4.00	1.154.38	4.56	4.6	2.248.65	255.959	-255.959
5.00	1.154.70	4.88	4.9	2.504.63	71.920	-71.920
6.00	1.154.79	4.97	5.0	2.576.55	-138.939	138.939
7.00	1.154.62	4.80	4.8	2.437.60	-183.031	183.031
8.00	1.154.39	4.57	4.6	2.254.60	-173.275	173.275
9.00	1.154.17	4.35	4.3	2.081.31	-197.227	197.227
10.00	1.153.93	4.11	4.1	1.884.08	-220.822	220.822
11.00	1.153.65	3.83	3.8	1.663.28	-239.894	239.894
12.00	1.153.35	3.53	3.5	1.423.37	-234.634	234.634
13.00	1.153.06	3.24	3.2	1.188.76	-220.856	220.856
14.00	1.152.78	2.96	3.0	967.89	-208.452	208.452
15.00	1.152.52	2.70	2.7	759.42	138.013	-138.013
16.00	1.152.69	2.87	2.9	897.41	136.493	-136.493
17.00	1.152.86	3.04	3.0	1.033.91	-198.409	198.409
18.00	1.152.61	2.79	2.8	835.50	-215.834	215.834
19.00	1.152.34	2.52	2.5	619.70	-223.344	223.344
20.00	1.152.07	2.25	2.2	396.33	-202.005	202.005
21.00	1.151.81	1.99	2.0	194.35	-181.514	181.514
22.00	1.151.59	1.77	1.8	12.83	184.740	-184.740
23.00	1.151.82	2.00	2.0	197.56	473.081	-473.081
24.00	1.152.41	2.59	2.6	670.65	493.006	-493.006

As mentioned in Table 4.2, height of tank T53 is 6.50 m. At 12:00 water level is 3.53 m, which is higher than half height of tank. In this study, it is assumed that water in tank would be enough for the network at 12:00 after completing sensitivity analysis. EPS results of JC-0702 for the original network is given in Table 4.9.

Table 4.9 EPS Results of JC-0702

EPS Results - JC-0702 (Junction)

Time (hours)	Hydraulic Grade (m)	Pressure (m H2O)	Pressure Head (m)	Demand (m³/h)
0.00	1.154.83	94.1	94.28	0.000
1.00	1.154.44	93.7	93.89	0.000
2.00	1.155.88	95.1	95.33	0.000
3.00	1.154.84	94.1	94.28	0.000
4.00	1.155.14	94.4	94.59	0.000
5.00	1.154.84	94.1	94.29	0.000
6.00	1.154.71	94.0	94.15	0.000
7.00	1.154.48	93.7	93.93	0.000
8.00	1.154.28	93.5	93.72	0.000
9.00	1.154.04	93.3	93.48	0.000
10.00	1.153.75	93.0	93.20	0.000
11.00	1.153.45	92.7	92.89	0.000
12.00	1.153.16	92.4	92.60	0.000
13.00	1.152.88	92.1	92.33	0.000
14.00	1.152.62	91.9	92.07	0.000
15.00	1.152.99	92.2	92.44	0.000
16.00	1.153.18	92.4	92.62	0.000
17.00	1.152.73	92.0	92.17	0.000
18.00	1.152.45	91.7	91.89	0.000
19.00	1.152.17	91.4	91.61	0.000
20.00	1.151.92	91.2	91.36	0.000
21.00	1.151.69	91.0	91.13	0.000
22.00	1.152.25	91.5	91.69	0.000
23.00	1.154.28	93.5	93.73	0.000
24.00	1.154.90	94.2	94.35	0.000

Report Close Help

Since any analysis related to tank T53 has not been made within the scope of this study, worst scenario is considered for JC-0702. It is assumed that HGL value of JC-0702 equals to 1151.69 m while applying sensitivity analysis. JC-0702 is replaced by reservoir, which has a HGL of 1151.69 m.

4.4.2. Linearization of Yayla Neighborhood

HGL values of skeletonized Yayla neighborhood are found by linearization of nodal head equations like Section 3.3.2. In Equation (3.16) Hazen-Williams formula was given according to the discharge Q in meters per second. Values of constant in Hazen-Williams formula are presented in Table 4.10.

Table 4.10 Values of Constant in Hazen-Williams Formula (Bhave, 1991)

	Discharge, in						
Pipe Diameter, in	m^3/s	m^3/min	m^3/hr	m^3/d	L/s	L/min	ML/d
m	10.68	$5.438*10^{-3}$	$2.769*10^{-6}$	$7.694*10^{-9}$	$2.969*10^{-5}$	$1.512*10^{-8}$	$2.768*10^{-3}$
cm	$5.869*10^{10}$	$2.988*10^{7}$	$1.522*10^{4}$	42.28	$1.631*10^{5}$	83.07	$1.521*10^{7}$
mm	$4.351*10^{15}$	$2.215*10^{12}$	$1.128*10^{9}$	$3.134*10^{6}$	$1.209*10^{10}$	$6.158*10^{6}$	$1.128*10^{12}$

Nodal demands of Yayla neighborhood are in meters per hour. Instead of converting pipe discharges to cubic meters per second for the entire network, 10.68 is replaced by an appropriate value, which is $2.769*10^{-6}$ for this study. Equation (3.16) now becomes

$$h_f = \underbrace{\frac{2.769*10^{-6}*L}{{C_{HW}}^{1.852}*D^{4.87}}}_{R_o} * Q^{1.852} \tag{4.3}$$

where,

h_f = frictional loss through pipe (m)

C_{HW} = Hazen-Williams coefficient

L = pipe length (m)

D = pipe diameter (m)

Q = discharge in pipe (m^3/hr)

Iteration is started by assuming discharge through pipes then it is stopped when ε_{max} is less than 0.0001. Iteration values belong to first and second are given in Table 4.11 and Table 4.12 respectively. At the end, HGL values of Linear Theory are compared with HGL values of Watercad results in Table 4.13.

Table 4-11 First Iteration Values of Yayla Neighborhood

					Iteration 1					
Pipe	D (m)	L(m)	C_{HW}	R_o	${}_1Q_x$ (m^3/hr)	${}_1h_x$ (m)	${}_1C_x'$	$h_{x(1)}$ (m)	$Q_{x(1)}$ (m^3/hr)	$C_x'_{(1)}$
1	0.200	6.64	130	0.000006	0.50	0.000002	318438.59	0.000002	0.64	257603.84
2	0.100	8.73	130	0.000218	0.50	0.000060	8282.54	0.000083	0.59	7144.07
3	0.200	15.85	130	0.000014	0.50	0.000004	133402.66	0.000026	1.43	54591.31
4	0.100	23.27	130	0.000581	0.50	0.000161	3107.29	-0.000064	-0.30	4737.69
5	0.125	26.39	130	0.000222	0.50	0.000062	8122.51	0.000120	0.72	5969.04
6	0.100	26.64	130	0.000665	0.50	0.000184	2714.21	0.000399	0.76	1903.10
7	0.200	33.39	130	0.000029	0.50	0.000008	63325.31	-0.000013	-0.66	50053.21
8	0.125	33.80	130	0.000285	0.50	0.000079	6341.80	0.000298	1.02	3440.66
9	0.125	35.63	130	0.000300	0.50	0.000083	6016.08	0.000129	0.63	4918.66
10	0.200	37.79	130	0.000032	0.50	0.000009	55952.16	0.000162	2.39	14746.08
11	0.200	43.49	130	0.000037	0.50	0.000010	48618.81	0.000217	2.59	11956.28
12	0.200	43.99	130	0.000038	0.50	0.000010	48066.20	-0.000012	-0.54	45330.80
13	0.100	44.80	130	0.001118	0.50	0.000310	1613.99	0.001843	1.31	710.64
14	0.125	44.83	130	0.000377	0.50	0.000105	4781.46	0.001045	1.73	1658.53
15	0.125	49.51	130	0.000417	0.50	0.000115	4329.49	0.000485	1.09	2237.20
16	0.100	54.14	130	0.001352	0.50	0.000374	1335.55	0.000362	0.49	1355.99
17	0.200	55.34	130	0.000047	0.50	0.000013	38208.03	0.000431	3.30	7658.24
18	0.100	56.03	130	0.001399	0.50	0.000387	1290.50	0.001373	0.99	721.10
19	0.200	56.70	130	0.000048	0.50	0.000013	37291.57	0.000366	2.98	8147.78
20	0.100	57.20	130	0.001428	0.50	0.000396	1264.10	0.001914	1.17	612.05
21	0.100	57.86	130	0.001444	0.50	0.000400	1249.68	0.000758	0.71	931.24
22	0.100	57.90	130	0.001445	0.50	0.000400	1248.82	0.002213	1.26	568.74
23	0.125	62.14	130	0.000523	0.50	0.000145	3449.52	0.000003	0.06	19914.69
24	0.100	64.86	130	0.001619	0.50	0.000449	1114.81	0.001484	0.95	642.83
25	0.125	78.32	130	0.000660	0.50	0.000183	2736.89	0.000493	0.85	1734.02
26	0.100	79.33	130	0.001980	0.50	0.000549	911.47	0.000456	0.45	992.01
27	0.100	79.72	130	0.001990	0.50	0.000551	907.01	0.001635	0.90	550.09
28	0.100	83.57	130	0.002086	0.50	0.000578	865.22	0.001604	0.87	540.96
29	0.100	83.71	130	0.002090	0.50	0.000579	863.77	0.001594	0.86	541.99
30	0.100	88.98	130	0.002221	0.50	0.000615	812.62	0.000610	0.50	816.11
31	0.125	92.42	130	0.000778	0.50	0.000216	2319.34	0.001662	1.51	906.39
32	0.100	104.02	130	0.002597	0.50	0.000719	695.12	0.000208	0.26	1231.47
33	0.125	108.46	130	0.000913	0.50	0.000253	1976.33	0.001107	1.11	1002.12
34	0.125	62.03	130	0.000522	0.50	0.000145	3455.63	0.000424	0.89	2107.88
35	0.125	71.88	130	0.000605	0.50	0.000168	2982.09	0.000609	1.00	1647.27
36	0.200	135.28	130	0.000115	0.50	0.000032	15630.04	0.000759	2.76	3642.36
37	0.250	53.64	130	0.000015	0.50	0.000004	116857.55	0.000180	3.76	20928.71
38	0.100	76.58	130	0.001912	0.50	0.000530	944.20	0.001086	0.74	678.43
39	0.125	40.18	130	0.000338	0.50	0.000094	5334.82	0.000578	1.34	2310.53
40	0.200	85.35	130	0.000073	0.50	0.000020	24773.66	0.000337	2.29	6787.66
41	0.125	73.60	130	0.000620	0.50	0.000172	2912.40	0.000442	0.83	1884.76
42	0.125	111.90	130	0.000942	0.50	0.000261	1915.58	0.001411	1.24	881.36
43	0.100	84.57	130	0.002111	0.50	0.000585	854.99	0.000202	0.28	1394.52
44	0.100	102.98	130	0.002571	0.50	0.000712	702.14	0.000570	0.44	777.85
45	0.100	126.17	130	0.003150	0.50	0.000872	573.09	0.000322	0.29	906.68
46	0.200	72.46	130	0.000062	0.50	0.000017	29180.68	0.000762	3.88	5090.85
47	0.125	65.65	130	0.000553	0.50	0.000153	3265.09	0.000102	0.40	3936.02
48	0.125	105.49	130	0.000888	0.50	0.000246	2031.97	0.001820	1.47	809.32
49	0.100	115.83	130	0.002891	0.50	0.000801	624.25	0.001897	0.80	419.89
50	0.125	122.16	130	0.001029	0.50	0.000285	1754.69	0.000939	0.95	1013.94
51	0.125	152.84	130	0.001287	0.50	0.000357	1402.47	0.000486	0.59	1216.67
52	0.100	561.57	130	0.014019	0.50	0.003883	128.76	0.007040	0.69	97.93
53	0.100	139.42	130	0.003480	0.50	0.000964	518.62	0.000959	0.50	519.98
54	0.300	189.59	130	0.000022	0.50	0.000006	80342.02	0.000554	5.64	10188.44
55	0.200	175.78	130	0.000150	0.50	0.000042	12028.86	0.000686	2.27	3312.61
56	0.200	539.08	130	0.000460	0.50	0.000127	3922.30	0.004252	3.32	781.30
57	0.300	536.21	130	0.000064	0.50	0.000018	28406.86	0.001799	6.08	3380.47
58	0.125	716.37	130	0.006032	0.50	0.001671	299.22	0.008472	1.20	141.79

Table 4.12 Second Iteration Values of Yayla Neighborhood

					Iteration 2			
Pipe	D (m)	L(m)	C_{HW}	R_o	$_2C_x'$	$h_{x(2)}$ (m)	$Q_{x(2)}$ (m^3/hr)	$C_x'_{(2)}$
1	0.200	6.64	130	0.000006	288021.21	0.000003	0.77	220490.05
2	0.100	8.73	130	0.000218	7713.30	0.000087	0.61	7014.85
3	0.200	15.85	130	0.000014	93996.99	0.000038	1.74	46035.30
4	0.100	23.27	130	0.000581	3922.49	0.000004	0.06	17886.74
5	0.125	26.39	130	0.000222	7045.77	0.000183	0.90	4920.70
6	0.100	26.64	130	0.000665	2308.65	0.000480	0.84	1746.98
7	0.200	33.39	130	0.000029	56689.26	-0.000006	-0.44	70166.13
8	0.125	33.80	130	0.000285	4891.23	0.000401	1.20	3001.09
9	0.125	35.63	130	0.000300	5467.37	0.000155	0.70	4520.48
10	0.200	37.79	130	0.000032	35349.12	0.000255	3.06	11968.82
11	0.200	43.49	130	0.000037	30287.55	0.000320	3.20	9999.39
12	0.200	43.99	130	0.000038	46698.50	-0.000006	-0.38	61067.62
13	0.100	44.80	130	0.001118	1162.31	0.002621	1.58	604.34
14	0.125	44.83	130	0.000377	3220.00	0.001420	2.05	1439.89
15	0.125	49.51	130	0.000417	3283.34	0.000713	1.34	1873.73
16	0.100	54.14	130	0.001352	1345.77	0.000369	0.50	1344.47
17	0.200	55.34	130	0.000047	22933.14	0.000704	4.30	6107.51
18	0.100	56.03	130	0.001399	1005.80	0.002324	1.32	566.06
19	0.200	56.70	130	0.000048	22719.68	0.000603	3.90	6473.34
20	0.100	57.20	130	0.001428	938.07	0.002783	1.43	515.20
21	0.100	57.86	130	0.001444	1090.46	0.000808	0.73	904.40
22	0.100	57.90	130	0.001445	908.78	0.002997	1.48	494.66
23	0.125	62.14	130	0.000523	11682.10	0.000009	0.11	12349.05
24	0.100	64.86	130	0.001619	878.82	0.001944	1.10	567.78
25	0.125	78.32	130	0.000660	2235.45	0.000591	0.94	1594.63
26	0.100	79.33	130	0.001980	951.74	0.000480	0.47	969.16
27	0.100	79.72	130	0.001990	728.55	0.002043	1.01	496.50
28	0.100	83.57	130	0.002086	703.09	0.001953	0.97	494.08
29	0.100	83.71	130	0.002090	702.88	0.002062	0.99	481.53
30	0.100	88.98	130	0.002221	814.36	0.000521	0.46	877.30
31	0.125	92.42	130	0.000778	1612.86	0.002460	1.86	756.77
32	0.100	104.02	130	0.002597	963.30	0.000319	0.32	1010.33
33	0.125	108.46	130	0.000913	1489.23	0.001494	1.30	873.13
34	0.125	62.03	130	0.000522	2781.76	0.000631	1.11	1754.99
35	0.125	71.88	130	0.000605	2314.68	0.000768	1.14	1481.06
36	0.200	135.28	130	0.000115	9636.20	0.001132	3.43	3030.20
37	0.250	53.64	130	0.000015	68893.13	0.000308	5.03	16334.29
38	0.100	76.58	130	0.001912	811.31	0.001527	0.89	580.15
39	0.125	40.18	130	0.000338	3822.67	0.000879	1.67	1905.39
40	0.200	85.35	130	0.000073	15780.66	0.000471	2.74	5817.35
41	0.125	73.60	130	0.000620	2398.58	0.000566	0.95	1681.63
42	0.125	111.90	130	0.000942	1398.47	0.001656	1.36	818.77
43	0.100	84.57	130	0.002111	1124.76	0.000217	0.29	1349.82
44	0.100	102.98	130	0.002571	740.00	0.000806	0.53	663.20
45	0.100	126.17	130	0.003150	739.89	0.000296	0.28	942.08
46	0.200	72.46	130	0.000062	17135.76	0.001311	5.20	3967.12
47	0.125	65.65	130	0.000553	3600.55	0.000210	0.59	2826.11
48	0.125	105.49	130	0.000888	1420.65	0.002744	1.84	670.06
49	0.100	115.83	130	0.002891	522.07	0.002202	0.86	391.98
50	0.125	122.16	130	0.001029	1384.32	0.001189	1.08	909.29
51	0.125	152.84	130	0.001287	1309.57	0.000546	0.63	1152.34
52	0.100	561.57	130	0.014019	113.34	0.009836	0.83	83.96
53	0.100	139.42	130	0.003480	519.30	0.001563	0.65	415.30
54	0.300	189.59	130	0.000022	45265.23	0.000979	7.67	7841.68
55	0.200	175.78	130	0.000150	7670.73	0.001110	2.95	2654.63
56	0.200	539.08	130	0.000460	2351.80	0.006670	4.24	635.15
57	0.300	536.21	130	0.000064	15893.67	0.003215	8.32	2587.94
58	0.125	716.37	130	0.006032	220.51	0.012438	1.48	118.84

Table 4.13 Comparison of HGL Values

	COMPARISON of HGL VALUES	
Label	Linear Theory Result (m)	Watercad Result (m)
JC-0054	1151.5304	1151.5304
JC-0055	1151.5159	1151.5159
JC-0056	1151.5159	1151.5159
JC-0072	1151.5302	1151.5302
JC-0085	1151.5201	1151.5201
JC-0093	1151.5210	1151.5210
JC-0094	1151.5210	1151.5210
JC-0098	1151.5112	1151.5112
JC-0118	1151.5973	1151.5973
JC-0150	1151.5137	1151.5136
JC-0166	1151.5145	1151.5145
JC-0185	1151.5456	1151.5456
JC-0187	1151.5236	1151.5235
JC-0211	1151.5554	1151.5555
JC-0220	1151.5514	1151.5514
JC-0234	1151.5250	1151.5250
JC-0240	1151.5171	1151.5171
JC-0256	1151.5228	1151.5228
JC-0288	1151.5292	1151.5292
JC-0300	1151.5097	1151.5097
JC-0305	1151.5137	1151.5136
JC-0315	1151.5249	1151.5249
JC-0327	1151.5125	1151.5124
JC-0343	1151.5220	1151.5220
JC-0348	1151.5118	1151.5118
JC-0349	1151.5125	1151.5125
JC-0430	1151.5158	1151.5158
JC-0431	1151.5159	1151.5159
JC-0433	1151.5211	1151.5212
JC-0453	1151.5232	1151.5232
JC-0466	1151.5401	1151.5401
JC-0467	1151.5386	1151.5386
JC-0514	1151.5220	1151.5220
JC-0515	1151.5184	1151.5183
JC-0598	1151.5184	1151.5184
JC-0603	1151.5128	1151.5127
JC-0604	1151.5130	1151.5130
JC-0611	1151.5736	1151.5736
JC-0622	1151.5157	1151.5156
JC-0665	1151.5304	1151.5304

Since results are close to each other in Table 4.13, it can be said that Linear Theory is a good alternative for obtaining HGL values. After obtaining HGL values, SA can be made now. It is difficult to show location of all nodes in Watercad view of Yayla because Yayla DMA consists of 40 nodes. Instead of this, three nodes are selected. Two of them are critical because they are at highest and lowest elevations. The other is selected in between these two nodes. Location of three selected nodes in Yayla neighborhood is presented in Figure 4.21. Moreover, 10 more nodes' results are presented in Appendix A.

Before giving results of junctions, flowchart of the methodology is given in Figure 4.20.

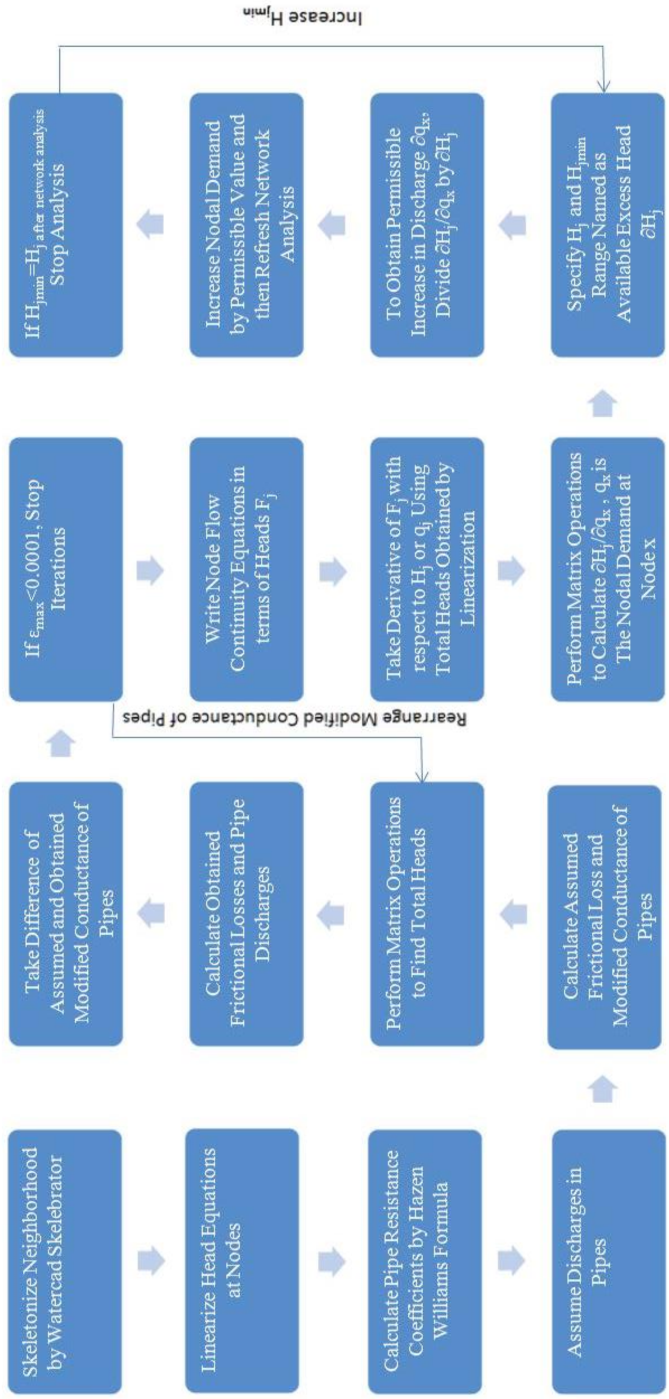

Figure 4.20 Flowchart of the Methodology

4.5. Results of Yayla Neighborhood

The aim of the study is to find maximum possible outflow at the related node without affecting the outflows at all other nodes. H_{jmin} is the main constraint while solving the problem. Δ, which is the difference of H_j obtained by Linear Theory and H_{jmin}, should be selected small. After finding H_j values with the help of Linear Theory, minimum pressure head $(P/\gamma)_{min}$ existing at maximum elevation is read as 40.31 m at JC-0433 in Yayla neighborhood. This value is critical because when any nodal demand is increased, this node will maintain minimum pressure head. In other words, every scenario meets same barrier, which is pressure head of JC-0433. In this study Δ is selected as 0.31 m, which means that pressure head of JC-0433 can drop by 0.31 m after sensitivity analysis. In order to find minimum total head H_{jmin}, 40.00 m $(P/\gamma)_{min}$ is added to topographical elevation of each node Z_i. At the end, permissible increase in discharge value is checked with Watercad by increasing the nodal demand of a particular node.

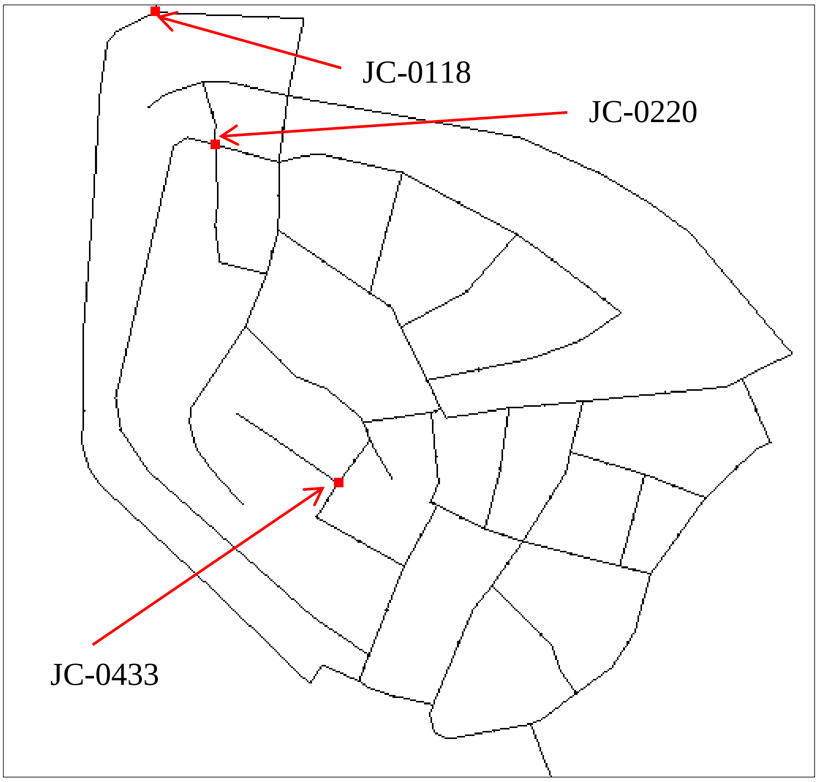

Figure 4.21 Location of Three Selected Nodes in Yayla Neighborhood

4.5.1. JC-0118 Results

Table 4.14 Calculation of Permissible Increase in Discharge at JC-0118

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{10}$	Permissible Increase in q_{10} (m^3/hr)	H_j for Increased q_{10} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00340	167.87	1151.0063
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00338	951.21	1150.9918
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00337	1099.92	1150.9918
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00340	108.82	1151.0061
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00342	959.55	1150.9960
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00338	1487.30	1150.9969
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00343	1649.15	1150.9969
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00344	6543.98	1150.9871
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00337	10818.14	1151.0732
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00339	6437.26	1150.9895
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00345	9521.09	1150.9904
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00342	5377.03	1151.0215
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00339	8388.70	1150.9994
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00341	7635.46	1151.0314
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00337	5645.25	1151.0273
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00343	2346.23	1151.0009
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00344	4382.05	1150.9930
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00343	6633.52	1150.9987
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00338	2771.78	1151.0051
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00338	7660.48	1150.9856
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00340	5567.40	1150.9895
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00338	5306.44	1151.0008
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00337	2955.74	1150.9883
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00337	1910.55	1150.9979
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00339	8219.78	1150.9877
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00343	6693.99	1150.9884
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00339	3263.33	1150.9917
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00342	2344.49	1150.9918
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00342	91.09	1150.9971
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00341	6172.12	1150.9991
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00335	3581.50	1151.0160
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00339	2353.78	1151.0145
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00343	3621.77	1150.9979
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00339	4691.87	1150.9942
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00338	2871.28	1150.9943
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00344	8921.67	1150.9886
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00340	7068.75	1150.9889
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00339	7446.03	1151.0495
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00339	1297.25	1150.9915
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00342	5272.16	1151.0063

JC-0118 is at minimum elevation in Yayla neighborhood and its results are presented in Table 4.14. Column (5) is obtained by adding topographical elevation Z_i with 40 m, which is the minimum pressure head $(P/\gamma)_{min}$ that should be provided by developer after urban renewal. Column (6) has already been calculated by using Linear Theory. Column (7) indicates working range of hydraulic grade line value after increasing demand of particular node, which is JC-0118 in here. Column (7) is obtained by subtracting column (5) from column (6). Column (9) represents hydraulic grade line decrease when nodal demand of JC-0118 (q_{10}) is increased by 1 m^3/hr. For example if q_{10} is increased by 1 m^3/hr, its total head will be

H_{10} = 1151.5973 - 0.0034 = 1151.5939 m

Column (10) can be calculated as

$$\text{permissible increase in } q_{10} = \frac{H_{j,\text{initial (obtained by linear theory)}} - H_{j,\min}}{\frac{\partial H_j}{\partial q_{10}}} \quad (4.4)$$

Minimum permissible increase in q_{10} is found as 91.09 m^3/hr at column (10). It means that nodal demand of JC-0118 can be increased by 91.09 m^3/hr. The maximum possible outflow at node 10 without affecting the outflows at the other nodes is 91.09 + 4.06 = 95.15 m^3/hr. If q_{10} is increased by 91.09 m^3/hr, total heads will be at column (11). To visualize results, Figure 4.22 is given below.

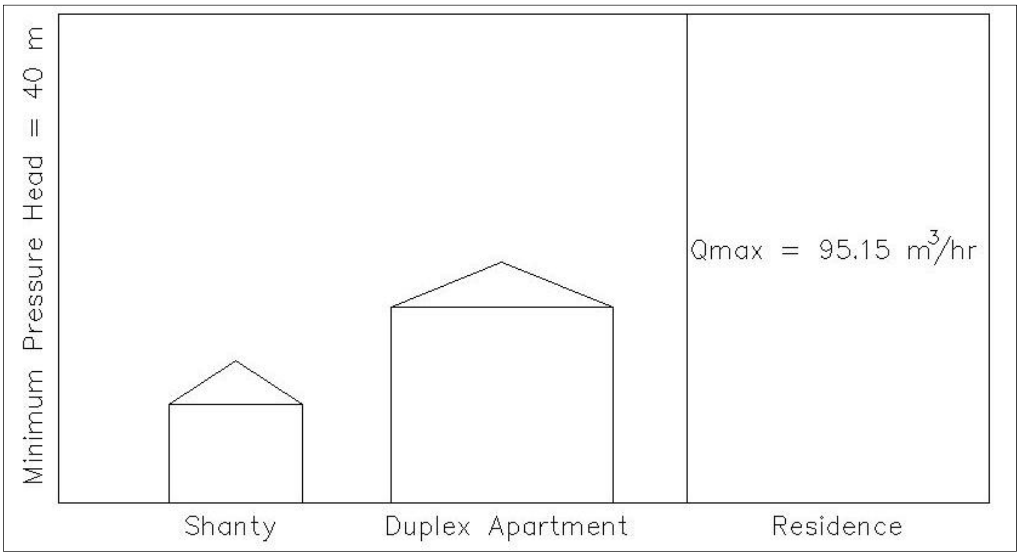

Figure 4.22 Maximum Possible Outflow at JC-0118 without Affecting the Outflows at Other Nodes

4.5.2. JC-0220 Results

Table 4.15 Calculation of Permissible Increase in Discharge at JC-0220

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{16}$	Permissible Increase in q_{16} (m^3/hr)	H_j for Increased q_{16} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00543	105.03	1.151.0392
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00510	631.17	1.151.0427
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00509	727.39	1.151.0427
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00543	68.20	1.151.0392
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00525	624.25	1.151.0387
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00523	962.38	1.151.0398
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00523	1083.17	1.151.0398
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00506	4450.03	1.151.0410
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1.151.3064
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00504	4337.21	1.151.0448
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00504	6510.49	1.151.0487
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00560	3285.86	1.151.0422
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00498	5703.89	1.151.0669
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00550	4731.10	1.151.0716
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00577	3292.27	1.151.0417
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00535	1504.57	1.151.0382
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00508	2963.27	1.151.0468
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00532	4279.75	1.151.0363
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00541	1730.36	1.151.0384
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00506	5115.13	1.151.0396
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00504	3758.84	1.151.0409
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00535	3347.70	1.151.0367
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00507	1966.12	1.151.0414
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00527	1222.16	1.151.0386
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00506	5503.03	1.151.0423
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00507	4528.91	1.151.0427
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00509	2171.61	1.151.0434
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00509	1573.90	1.151.0430
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00528	58.92	1.151.0387
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00533	3954.50	1.151.0363
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00555	2162.70	1.151.0407
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00553	1441.51	1.151.0404
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00528	2351.93	1.151.0365
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00508	3136.19	1.151.0494
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00510	1906.19	1.151.0431
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00506	6074.74	1.151.0442
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00506	4753.12	1.151.0441
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00434	5829.93	1.151.1963
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00511	860.94	1.151.0404
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00544	3317.20	1.151.0381

JC-0220 is at middle elevation in Yayla neighborhood and its results are presented in Table 4.15. Column (5) is obtained by adding topographical elevation Z_i with 40 m, which is the minimum pressure head $(P/\gamma)_{min}$ that should be provided by developer after urban renewal. Column (6) has already been calculated by using Linear Theory. Column (7) indicates working range of hydraulic grade line value after increasing demand of particular node, which is JC-0220 in here. Column (7) is obtained by subtracting column (5) from column (6). Column (9) represents hydraulic grade line decrease when nodal demand of JC-0220 (q_{16}) is increased by 1 m^3/hr. For example if q_{16} is increased by 1 m^3/hr, its total head will be

H_{16} = 1151.5514 - 0.0058 = 1151.5456 m

Column (10) can be calculated as

$$\text{permissible increase in } q_{16} = \frac{H_{j,\text{initial (obtained by linear theory)}} - H_{j,\min}}{\frac{\partial H_j}{\partial q_{16}}} \qquad (4.5)$$

Minimum permissible increase in q_{16} is found as 58.92 m^3/hr at column (10). It means that nodal demand of JC-0220 can be increased by 58.92 m^3/hr. The maximum possible outflow at node 16 without affecting the outflows at the other nodes is 58.92 + 3.16 = 62.08 m^3/hr. If q_{16} is increased by 58.92 m^3/hr, total heads will be at column (11). To visualize results, Figure 4.23 is given below.

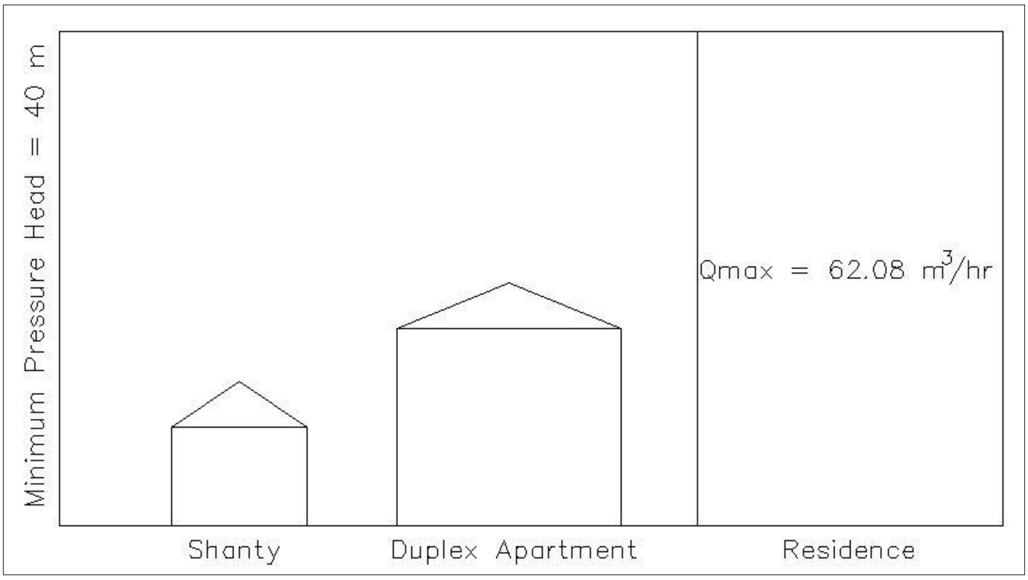

Figure 4.23 Maximum Possible Outflow at JC-0220 without Affecting the Outflows at Other Nodes

4.5.3. JC-0433 Results

Table 4.16 Calculation of Permissible Increase in Discharge at JC-0433

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{30}$	Permissible Increase in q_{30} (m^3/hr)	H_j for Increased q_{30} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00697	81.84	1.151.2512
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00678	474.45	1.151.2437
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00678	546.69	1.151.2437
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00701	52.81	1.151.2473
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00958	342.45	1.150.9705
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00657	766.22	1.151.2531
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00655	864.34	1.151.2563
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00669	3362.78	1.151.2371
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1.151.4665
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00668	3269.25	1.151.2372
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00653	5021.18	1.151.2516
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00560	3284.16	1.151.3263
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00629	4518.29	1.151.2725
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00509	5110.26	1.151.3567
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00528	3600.26	1.151.3451
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00629	1278.38	1.151.2755
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00664	2266.14	1.151.2507
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00635	3580.71	1.151.2711
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00616	1520.74	1.151.2859
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00667	3878.80	1.151.2371
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00670	2830.54	1.151.2266
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00627	2858.50	1.151.2766
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00671	1485.35	1.151.2402
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00645	998.14	1.151.2635
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00664	4196.07	1.151.2431
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00665	3450.69	1.151.2439
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00675	1637.95	1.151.2452
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00676	1185.14	1.151.2447
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.01001	31.09	1.150.9439
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00633	3326.33	1.151.2725
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00597	2011.43	1.151.3061
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00611	1305.24	1.151.2981
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00644	1927.32	1.151.2657
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00657	2422.47	1.151.2549
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00658	1477.03	1.151.2543
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00660	4650.09	1.151.2461
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00662	3632.42	1.151.2461
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00429	5891.08	1.151.4062
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00713	616.18	1.151.1821
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00607	2968.42	1.151.2911

JC-0433 is at max elevation in Yayla neighborhood and its results are presented in Table 4.16. Column (5) is obtained by adding topographical elevation Z_i with 40 m, which is the minimum pressure head $(P/\gamma)_{min}$ that should be provided by developer after urban renewal. Column (6) has already been calculated by using Linear Theory. Column (7) indicates working range of hydraulic grade line value after increasing demand of particular node, which is JC-0433 in here. Column (7) is obtained by subtracting column (5) from column (6). Column (9) represents hydraulic grade line decrease when nodal demand of JC-0433 (q_{30}) is increased by 1 m^3/hr. For example if q_{30} is increased by 1 m^3/hr, its total head will be

H_{30} = 1151.5211 - 0.0100 = 1151.5111 m

Column (10) can be calculated as

$$\text{permissible increase in } q_{30} = \frac{H_{j,\text{initial (obtained by linear theory)}} - H_{j,\min}}{\frac{\partial H_j}{\partial q_{30}}} \qquad (4.6)$$

Minimum permissible increase in q_{30} is found as 31.09 m^3/hr at column (10). It means that nodal demand of JC-0433 can be increased by 31.09 m^3/hr. The maximum possible outflow at node 30 without affecting the outflows at the other nodes is 31.09 + 1.09 = 32.18 m^3/hr. If q_{30} is increased by 31.09 m^3/hr, total heads will be at column (11). To visualize results, Figure 4.24 is given below.

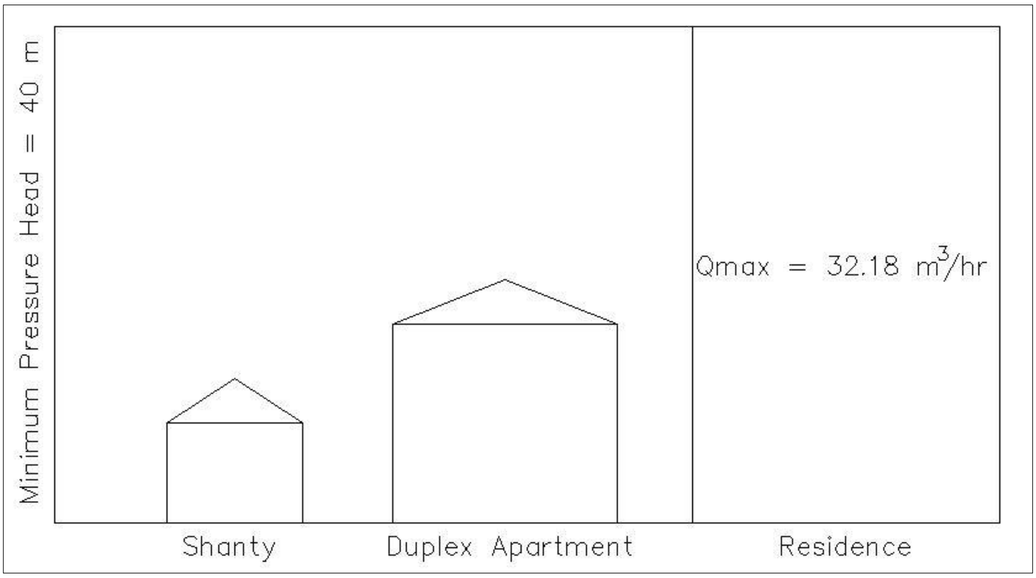

Figure 4.24 Maximum Possible Outflow at JC-0433 without Affecting the Outflows at Other Nodes

4.5.4. Permissible Increase in Discharge Values of All Nodes in Yayla Neighborhood

Since skeletonized Yayla neighborhood consists of 40 nodes, it is necessary to repeat Table 4.13 40 times. Instead of this, permissible increase in discharge values for each node is given in Table 4.17.

Table 4.17 Permissible Increase in Discharge Values of All Nodes in Yayla Neighborhood

Label	H_i	q_i	Permissible Increase in Discharge q_i(m^3/hr)
JC-0054	H_2	q_2	44.64
JC-0055	H_3	q_3	45.90
JC-0056	H_4	q_4	45.90
JC-0072	H_5	q_5	44.38
JC-0085	H_6	q_6	32.48
JC-0093	H_7	q_7	47.39
JC-0094	H_8	q_8	47.51
JC-0098	H_9	q_9	46.50
JC-0118	H_{10}	q_{10}	91.09
JC-0150	H_{11}	q_{11}	46.57
JC-0166	H_{12}	q_{12}	47.63
JC-0185	H_{13}	q_{13}	55.52
JC-0187	H_{14}	q_{14}	49.50
JC-0211	H_{15}	q_{15}	61.12
JC-0220	H_{16}	q_{16}	58.92
JC-0234	H_{17}	q_{17}	49.44
JC-0240	H_{18}	q_{18}	46.83
JC-0256	H_{19}	q_{19}	48.97
JC-0288	H_{20}	q_{20}	50.50
JC-0300	H_{21}	q_{21}	46.62
JC-0305	H_{22}	q_{22}	46.47
JC-0315	H_{23}	q_{23}	49.62
JC-0327	H_{24}	q_{24}	46.34
JC-0343	H_{25}	q_{25}	48.21
JC-0348	H_{26}	q_{26}	46.88
JC-0349	H_{27}	q_{27}	46.80
JC-0430	H_{28}	q_{28}	46.10
JC-0431	H_{29}	q_{29}	46.00
JC-0433	H_{30}	q_{30}	31.09
JC-0453	H_{31}	q_{31}	49.14
JC-0466	H_{32}	q_{32}	52.15
JC-0467	H_{33}	q_{33}	50.90
JC-0514	H_{34}	q_{34}	48.31
JC-0515	H_{35}	q_{35}	47.35
JC-0598	H_{36}	q_{36}	47.29
JC-0603	H_{37}	q_{37}	47.11
JC-0604	H_{38}	q_{38}	46.97
JC-0611	H_{39}	q_{39}	72.53
JC-0622	H_{40}	q_{40}	43.62
JC-0665	H_{41}	q_{41}	51.23

Three selected nodes' results are highlighted in yellow in Table 4.17.

4.6. Influence Area of Selected Nodes

In this study each node represents an area and its unit is hectare (ha). Neighborhood area is the summation of these areas. Weight of node reflects influence area of particular node. Since municipality may want to see how much area will be influenced due to change in nodal demand, weight of nodes has been calculated to obtain influence area of each node. After obtaining area value of Yayla neighborhood at Section 4.1, demand distributor macro, in which weight of each node can be obtained, is applied to Yayla. Logic behind the macro is simple and it is given below (Figure 4.25).

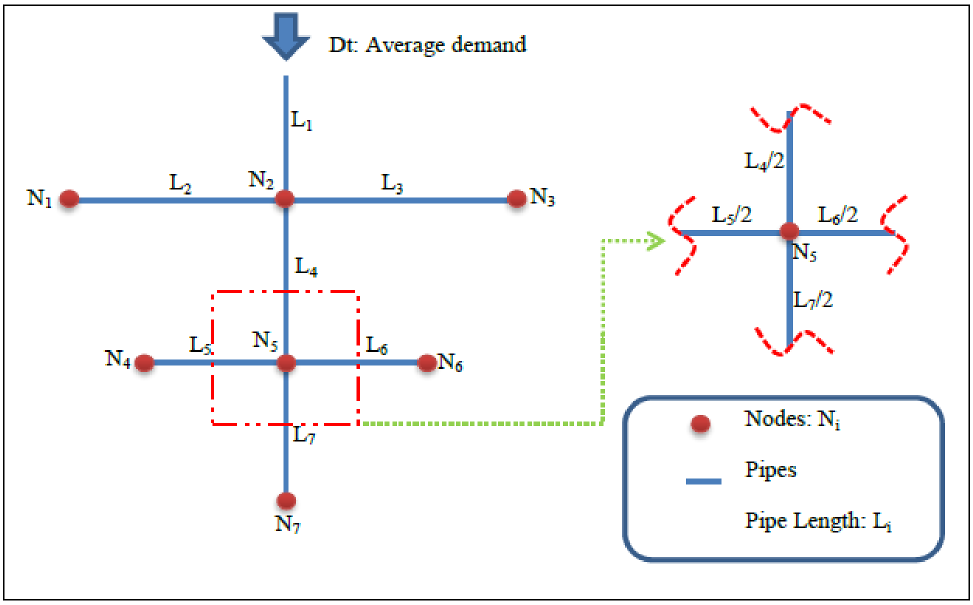

Figure 4.25 Spatial Distribution of Average Demand (Şendil, 2013)

$$w_5 = \frac{\sum(0.5*l_4+0.5*L_5+0.5*L_6+0.5*l_7)}{L_{loop}} \qquad (4.7)$$

where,

w : weight of junction

L_i : length of pipe

In order to run demand distributor macro, label, length of pipe, start and stop node of pipes are needed. These are taken from Watercad and entered as an input to the Excel. Total demand is needed to run the program, 1000 is entered as a total demand. Since aim is obtaining weight of nodes by using pipe lengths, any total demand value does not change weight results. Input page and weight of junctions are given at Figure 4.26 and 4.27 respectively.

Label	Length (m)	Start Node	Stop Node
PP-0647	6.64	JC-0055	JC-0056
PP-0193	8.73	JC-0093	JC-0094
PP-0642	15.85	JC-0072	JC-0054
PP-0249	23.27	JC-0150	JC-0305
PP-0429	26.39	JC-0094	JC-0343
PP-0247	26.64	JC-0348	JC-0349
PP-0713	33.39	JC-0430	JC-0431
PP-0406	33.8	JC-0433	JC-0085
PP-0431	35.63	JC-0256	JC-0453
PP-0680	37.79	JC-0466	JC-0467
PP-0726	43.49	JC-0515	JC-0240
PP-0728	43.99	JC-0056	JC-0431
PP-0016	44.8	JC-0072	JC-0433
PP-0372	44.83	JC-0430	JC-0327
PP-0449	49.51	JC-0343	JC-0234
PP-0113	54.14	JC-0603	JC-0604
PP-0644	55.34	JC-0220	JC-0185
PP-0115	56.03	JC-0185	JC-0611
PP-0676	56.7	JC-0185	JC-0466
PP-0075	57.2	JC-0054	JC-0093
PP-0080	57.86	JC-0622	JC-0056
PP-0070	57.9	JC-0187	JC-0166

Total Demand = 1000.00

RUN

Total Length = 6312.06 m

# of Junction = 41

Clear INPUT Table

INPUT MID OUTPUT

Hazır

Figure 4.26 Input Page of Demand Distributor Macro

Nodes	N. Length	Node	Total N.Length	Weight
JC-0054	57.2	JC-0054	248.83	0.0197
JC-0054	15.85	JC-0055	83.22	0.0066
JC-0054	175.78	JC-0056	108.49	0.0086
JC-0055	6.64	JC-0072	60.65	0.0048
JC-0055	76.58	JC-0085	117.51	0.0093
JC-0056	43.99	JC-0093	142.51	0.0113
JC-0056	6.64	JC-0094	97.15	0.0077
JC-0056	57.86	JC-0098	330.39	0.0262
JC-0072	15.85	JC-0118	1442.17	0.1142
JC-0072	44.8	JC-0150	805.29	0.0638
JC-0085	83.71	JC-0166	129.78	0.0103
JC-0085	33.8	JC-0185	273.56	0.0217
JC-0093	8.73	JC-0187	732.26	0.0580
JC-0093	57.2	JC-0211	126.1	0.0100
JC-0093	76.58	JC-0220	809.97	0.0642
JC-0094	26.39	JC-0234	215.86	0.0171
JC-0094	8.73	JC-0240	193.7	0.0153
JC-0094	62.03	JC-0256	120.2	0.0095
JC-0098	111.9	JC-0288	236.62	0.0187
JC-0098	65.65	JC-0300	390.83	0.0310
JC-0098	152.84	JC-0305	664.56	0.0526
JC-0118	189.59	JC-0315	308.23	0.0244

INPUT MID OUTPUT

Figure 4.27 Weight Results Page

Table 4.18 Influence Area of Nodes in Yayla

Node (1)	Weight (2)	Affected Area Due To Related Junction (ha) (3)	Max. Possible Outflow Without Disturbing Other Nodes (m^3/hr) (4)	(4)/(3) (m3/hr/ha)
JC-0054	0.0197	0.93	46.99	50.54
JC-0055	0.0066	0.31	46.14	148.37
JC-0056	0.0086	0.41	46.31	114.25
JC-0072	0.0048	0.23	44.89	198.11
JC-0085	0.0093	0.44	33.00	75.15
JC-0093	0.0113	0.53	48.09	90.31
JC-0094	0.0077	0.36	47.71	131.43
JC-0098	0.0262	1.23	48.86	39.57
JC-0118	0.1142	5.39	95.15	17.66
JC-0150	0.0638	3.01	48.57	16.14
JC-0166	0.0103	0.48	48.57	100.16
JC-0185	0.0217	1.02	56.40	55.18
JC-0187	0.0580	2.74	51.55	18.84
JC-0211	0.0100	0.47	62.35	132.33
JC-0220	0.0642	3.03	62.08	20.51
JC-0234	0.0171	0.81	50.24	62.29
JC-0240	0.0153	0.72	47.38	65.47
JC-0256	0.0095	0.45	49.57	110.37
JC-0288	0.0187	0.88	51.42	58.16
JC-0300	0.0310	1.46	50.13	34.33
JC-0305	0.0526	2.48	49.06	19.76
JC-0315	0.0244	1.15	50.70	44.03
JC-0327	0.0216	1.02	47.45	46.59
JC-0343	0.0131	0.62	48.84	79.27
JC-0348	0.0180	0.85	47.66	56.16
JC-0349	0.0150	0.71	47.52	67.10
JC-0430	0.0196	0.92	47.22	51.14
JC-0431	0.0143	0.67	46.67	69.25
JC-0433	0.0062	0.29	32.18	109.55
JC-0453	0.0087	0.41	49.65	121.65
JC-0466	0.0148	0.70	52.87	75.70
JC-0467	0.0280	1.32	52.23	39.60
JC-0514	0.0137	0.65	48.98	75.54
JC-0515	0.0191	0.90	48.67	54.07
JC-0598	0.0180	0.85	48.34	56.96
JC-0603	0.0162	0.76	48.06	62.95
JC-0604	0.0157	0.74	47.72	64.40
JC-0611	0.0679	3.20	76.33	23.83
JC-0622	0.0175	0.83	44.46	53.77
JC-0665	0.0252	1.19	52.59	44.27

Total Area of Yayla 47.17 ha

Column (2) is obtained by demand distributor macro in Table 4.18. Then each weight is multiplied by area of Yayla neighborhood to calculate column (3). Column (4) has already been found by sensitivity analysis. Final column is obtained by dividing column (4) by column (3) to find affected area due to related junction in terms of $m^3/hr/ha$. Three selected nodes' results are highlighted in yellow in Table 4.18.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1. Summary

Urban renewal firstly started in England in 19th century and eventually spread to the world. There are various reasons for urban renewal in today's world. Firstly, it is believed that better housing conditions have positive effects on residents morally and economically. Secondly, in order to decrease crime rates government/municipality can apply gentrification "where elderly and lower class households were replaced by younger and wealthier families" like Çinçin, Sulukule (Web 8). Finally, shanties and abandoned regions can disrupt urban aesthetic. Today, according to the article 73th of Municipalities Law No.5393, many neighborhoods like Yayla in Keçiören are subject to urban renewal in Turkey. Article 73 states that "the municipality, may adopt urbanization and development projects in order to reconstruct and restore the ruined parts of the city; to create housing areas, industrial and commercial zones, technology parks, and social facilities; to take measures against the earthquake risk or to protect the historical and cultural structure of the city". Unification of parcels based on the article 15th and 16th of construction law is the methodology of Housing Development Administration (TOKİ) and municipalities acting together while implementing urban renewal in Turkey (Web 9).

Shanties and abandoned regions have been replaced by residences; this brings consumption increase at existing nodes. This study underlines two important points. One of them is that it should be investigated that whether existing water distribution system is suitable for demand increase within the scope of urban renewal. In Section 4.3, it was mentioned that maximum discharge drawn from existing system is 650 m^3/hr. Combined pump curve given in Figure 4.17 illustrates that extra

150 m^3/hr can be drawn from N8.3 pressure zone without adding new pump to the current system. Another important point is minimum pressure head, which should be guaranteed by the developer after urban renewal. Demand increase at particular node will decrease pressure head of all nodes in the neighborhood. Municipality should specify minimum pressure head value before the developer puts a plan into action. In this study, Yayla neighborhood with peak discharge values was hydraulically solved by Linear Theory initially. Then it was observed that minimum pressure head is 40.31 m at JC-0433. This value was allowed to decrease 40.00 m after urban renewal. Analysis proposed by Bhave (1991) was made to obtain maximum possible outflow at a single node. To check accuracy of minimum pressure head value of 40.00 m obtained by sensitivity analysis method, nodal demands were increased by permissible amount and network analysis was refreshed by Watercad 40 times. Results show that minimum pressure heads range between 39.75 m and 39.90 m after demand increases. This confirms Bhave's words "results taken from sensitivity analysis are not exact because they are derivatives at a point but it is a fast way for comparing possible changes".

5.2. Conclusions

As it can be seen from Table 4.17, JC-0118 represents most suitable region for urban renewal because permissible increase in discharge without disturbing other nodes is maximum at this node. Reasons behind this are the closest node to the source and located at minimum elevation. On the other hand, permissible increase in discharge without disturbing other nodes is minimum at JC-0433 because it is located at maximum elevation in Yayla neighborhood. Therefore, it is most unsuitable region for urban renewal. To visualize effect of all junctions, influence areas are given in terms of hectare (ha) in Table 4.18. Based on the work conducted following conclusions can be stated:

- Determining pump capacity of existing WDN is crucial because designer should know limit of pumps before carrying out sensitivity analysis. Otherwise, it is senseless to make this analysis.

- To deal with nonlinear equations in WDNs, Linear Theory can be applied even to the neighborhood with 40 nodes and 58 pipes.
- Sensitivity analysis is conducted after the optimal solution, which is obtained by Linear Theory. It looks for maximum increase in discharge for a single node without disturbing other nodes. At the end of the analysis, the developer will understand suitable regions for urban renewal. In other words, it enables him/her to compare capacity of nodes.
- To find maximum possible outflow at a single node, H_{jmin} summation of topographical elevation and minimum pressure head should be initially specified. Node located at maximum elevation in any neighborhood dictates its pressure head as minimum pressure head. If demand is increased at a single node, pressure head of node at maximum elevation will decrease. Decrement of pressure head of node at maximum elevation Δ, which should be selected small, is subtracted from initial pressure head of node at maximum elevation to obtain minimum pressure head value.
- It can be stated that the method proposed by Bhave (1991) is searching a solution near Node Head Analysis (NHA). If Δ value is chosen a large value, permissible increase in discharge value obtained by sensitivity analysis will get away from the real value.
- Each node represents an influence area. With the help of Mapinfo and demand distributor macro Şendil (2013), the municipality can see the magnitude of the influence area for each node within the scope of urban renewal.
- Before replacing shanties by residences, municipality should make analysis used in this study. Otherwise, unplanned urban renewal would result in low pressure head problem.

As a consequence, this study is a preliminary work for determining maximum discharge that can be drawn from selected node without affecting other nodes in the network. All calculations have been made according to the nodal demands. Any developer can benefit from results of selected nodes used in this study. For future studies, 2 or 3 nodes could be selected at the same time and their effects on system could be investigated. Moreover, calculations could be made according to the parcels instead of nodes to approximate real life scenario.

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APPENDIX A

CALCULATION OF PERMISSIBLE INCREASE IN DISCHARGE AT 10 NODES

Table A.1 Calculation of Permissible Increase in Discharge at JC-0054

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_2$	Permissible Increase in q_2 (m^3/hr)	H_j for Increased q_2 (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00765	74.59	1151.0313
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00611	526.38	1151.1207
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00611	606.64	1151.1207
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00764	48.48	1151.0314
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00685	478.73	1151.0529
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00636	791.47	1151.1128
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00633	894.26	1151.1217
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00601	3744.54	1151.1210
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3935
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00596	3666.03	1151.1252
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00596	5500.00	1151.1309
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00581	3167.47	1151.1905
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00582	4880.67	1151.1530
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00522	4987.92	1151.2382
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00543	3500.96	1151.2208
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00624	1288.73	1151.1358
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00606	2483.11	1151.1276
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00626	3635.67	1151.1327
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00621	1508.25	1151.1432
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00602	4299.66	1151.1195
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00597	3176.87	1151.1214
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00623	2879.10	1151.1375
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00605	1648.60	1151.1211
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00630	1023.06	1151.1268
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00602	4626.43	1151.1224
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00603	3803.69	1151.1227
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00610	1813.24	1151.1227
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00610	1313.40	1151.1219
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00697	44.64	1151.0469
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00625	3370.28	1151.1339
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00626	1915.98	1151.1550
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00647	1233.52	1151.1371
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00629	1972.84	1151.1283
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00604	2634.09	1151.1311
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00609	1596.31	1151.1239
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00601	5113.31	1151.1250
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00602	3995.48	1151.1247
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00431	5864.05	1151.3113
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00618	711.35	1151.1058
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00613	2943.25	1151.1518

Table A.2 Calculation of Permissible Increase in Discharge at JC-0085

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_6$	Permissible Increase in q_6 (m^3/hr)	H_j for Increased q_6 (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00685	83.24	1151.2384
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00689	466.44	1151.2263
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00690	537.45	1151.2263
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00689	53.74	1151.2347
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.01005	326.29	1150.8749
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00660	761.99	1151.2388
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00659	859.34	1151.2417
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00681	3304.16	1151.2188
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.4594
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00681	3208.82	1151.2188
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00663	4946.26	1151.2352
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00557	3305.35	1151.3152
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00637	4460.66	1151.2574
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00507	5132.17	1151.3464
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00525	3618.12	1151.3344
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00630	1276.59	1151.2623
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00675	2232.20	1151.2343
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00637	3571.31	1151.2578
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00615	1522.94	1151.2732
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00679	3813.84	1151.2190
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00682	2777.84	1151.2056
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00628	2854.94	1151.2636
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00683	1460.19	1151.2225
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00648	993.93	1151.2495
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00675	4129.23	1151.2260
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00676	3395.86	1151.2268
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00686	1610.85	1151.2280
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00688	1165.34	1151.2274
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00958	32.48	1150.9421
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00635	3318.80	1151.2593
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00591	2029.01	1151.2944
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00605	1318.58	1151.2864
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00647	1919.61	1151.2519
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00666	2389.07	1151.2389
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00667	1458.07	1151.2387
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00671	4577.93	1151.2293
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00673	3575.88	1151.2293
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00429	5895.81	1151.3973
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00730	602.16	1151.1484
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00607	2972.84	1151.2787

Table A.3 Calculation of Permissible Increase in Discharge at JC-0098

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_9$	Permissible Increase in q_9 (m^3/hr)	H_j for Increased q_9 (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00601	94.92	1151.1513
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00743	432.94	1151.0090
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00743	498.78	1151.0087
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00602	61.51	1151.1505
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00681	481.66	1151.0795
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00672	748.55	1151.0864
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00672	842.55	1151.0864
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00897	2508.77	1150.7234
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3827
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00819	2667.90	1150.8637
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00745	4406.05	1151.0065
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00529	3477.68	1151.2127
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00684	4152.85	1151.0645
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00490	5307.40	1151.2460
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00506	3759.85	1151.2326
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00627	1283.86	1151.1320
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00729	2066.45	1151.0222
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00638	3565.84	1151.1256
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00601	1557.73	1151.1528
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00836	3097.47	1150.8597
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00814	2327.42	1150.9113
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00624	2873.56	1151.1355
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00821	1214.12	1150.8950
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00655	983.31	1151.1048
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00779	3573.07	1150.9630
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00768	2988.36	1150.9800
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00744	1485.71	1151.0065
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00743	1078.32	1151.0080
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00669	46.50	1151.0913
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00634	3320.64	1151.1283
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00552	2172.26	1151.1930
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00559	1426.83	1151.1871
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00653	1901.50	1151.1128
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00715	2225.46	1151.0352
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00711	1367.32	1151.0460
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00762	4030.06	1150.9878
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00759	3169.08	1150.9911
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00425	5948.19	1151.3032
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00749	587.04	1151.0041
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00593	3040.11	1151.1602

Table A.4 Calculation of Permissible Increase in Discharge at JC-0187

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{14}$	Permissible Increase in q_{14} (m^3/hr)	H_j for Increased q_{14} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00582	98.01	1151.1252
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00697	461.38	1150.9781
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00697	531.59	1150.9779
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00583	63.55	1151.1246
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00637	515.13	1151.0669
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00656	766.49	1151.0478
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00657	861.49	1151.0477
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00684	3289.87	1150.9767
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3650
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00667	3276.91	1151.0070
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00728	4507.78	1150.9523
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00520	3540.99	1151.1866
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00773	3675.08	1150.9470
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00485	5366.59	1151.2206
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00498	3817.79	1151.2074
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00613	1311.96	1151.0992
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00709	2122.93	1150.9656
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00624	3644.27	1151.0925
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00589	1591.47	1151.1222
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00695	3725.33	1150.9628
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00667	2843.11	1151.0084
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00610	2936.10	1151.1034
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00692	1440.56	1150.9708
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00641	1005.20	1151.0687
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00708	3934.98	1150.9596
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00708	3240.72	1150.9605
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00699	1581.22	1150.9708
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00698	1148.10	1150.9744
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00629	49.50	1151.0762
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00621	3393.48	1151.0955
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00540	2220.21	1151.1664
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00546	1460.71	1151.1607
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00639	1943.76	1151.0780
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00716	2222.59	1150.9640
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00707	1375.30	1150.9920
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00715	4297.61	1150.9566
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00712	3380.95	1150.9601
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00429	5890.49	1151.2764
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00683	643.46	1151.0084
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00581	3103.95	1151.1302

Table A.5 Calculation of Permissible Increase in Discharge at JC-0240

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{18}$	Permissible Increase in q_{18} (m^3/hr)	H_j for Increased q_{18} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00606	94.06	1151.1419
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00750	428.86	1150.9843
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00750	494.10	1150.9841
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00607	60.97	1151.1413
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00675	486.27	1151.0805
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00690	728.70	1151.0625
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00691	819.42	1151.0625
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00729	3088.09	1150.9858
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3808
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00710	3075.69	1151.0167
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00735	4460.70	1150.9886
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00533	3450.46	1151.2052
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00709	4004.68	1151.0252
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00493	5279.65	1151.2400
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00508	3741.48	1151.2265
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00641	1255.86	1151.1157
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00771	1951.76	1150.9648
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00653	3482.56	1151.1090
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00613	1529.46	1151.1393
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00737	3514.70	1150.9757
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00710	2668.12	1151.0181
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00637	2811.81	1151.1201
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00740	1346.86	1150.9768
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00672	958.27	1151.0843
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00743	3748.60	1150.9757
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00746	3075.16	1150.9749
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00753	1468.16	1150.9758
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00751	1066.73	1150.9802
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00664	46.83	1151.0904
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00649	3244.69	1151.1120
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00558	2152.27	1151.1845
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00564	1413.88	1151.1786
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00670	1853.63	1151.0940
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00751	2119.32	1150.9849
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00742	1308.90	1151.0077
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00743	4133.67	1150.9776
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00748	3217.32	1150.9726
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00428	5906.92	1151.2972
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00732	600.31	1151.0181
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00604	2987.38	1151.1476

Table A.6 Calculation of Permissible Increase in Discharge at JC-0305

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{22}$	Permissible Increase in q_{22} (m^3/hr)	H_j for Increased q_{22} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00597	95.60	1151.1499
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00727	442.33	1151.0386
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00727	509.60	1151.0384
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00598	61.95	1151.1489
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00682	480.73	1151.0568
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00660	762.52	1151.1015
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00659	858.41	1151.1016
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00814	2763.04	1150.9157
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3829
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00889	2456.08	1150.8275
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00715	4587.33	1151.0480
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00527	3495.47	1151.2112
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00667	4260.61	1151.0917
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00489	5323.70	1151.2438
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00504	3770.29	1151.2296
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00617	1302.92	1151.1394
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00710	2119.59	1151.0534
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00628	3622.62	1151.1335
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00594	1576.93	1151.1573
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00777	3332.20	1150.9689
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00898	2109.95	1150.6027
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00615	2915.56	1151.1422
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00770	1294.45	1150.9874
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00644	1000.43	1151.1167
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00741	3757.28	1151.0201
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00735	3122.30	1151.0279
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00726	1522.56	1151.0387
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00727	1103.35	1151.0387
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00670	46.47	1151.0724
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00625	3372.39	1151.1358
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00549	2186.09	1151.1921
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00556	1436.01	1151.1861
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00642	1934.23	1151.1228
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00698	2281.20	1151.0645
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00694	1400.24	1151.0712
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00729	4212.10	1151.0344
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00728	3303.56	1151.0354
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00423	5975.35	1151.3042
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00755	582.32	1150.9540
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00586	3075.73	1151.1639

Table A.7 Calculation of Permissible Increase in Discharge at JC-0348

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{26}$	Permissible Increase in q_{26} (m^3/hr)	H_j for Increased q_{26} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00602	94.74	1151.1439
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00746	430.96	1150.9931
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00746	496.50	1150.9929
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00603	61.41	1151.1431
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00675	486.30	1151.0782
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00680	740.26	1151.0702
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00680	832.86	1151.0701
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00779	2886.64	1150.9499
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3805
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00743	2941.80	1150.9977
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00831	3948.23	1150.8613
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00530	3469.91	1151.2065
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00708	4012.93	1151.0238
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00491	5298.92	1151.2407
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00506	3756.32	1151.2274
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00632	1272.60	1151.1204
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00743	2026.55	1150.9913
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00644	3531.90	1151.1138
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00606	1546.83	1151.1429
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00832	3113.50	1150.8375
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00741	2556.90	1151.0043
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00629	2848.79	1151.1245
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00775	1287.53	1150.9547
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00662	972.95	1151.0907
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00915	3045.47	1150.6816
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00870	2637.55	1150.7944
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00749	1476.10	1150.9863
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00748	1072.31	1150.9899
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00664	46.88	1151.0888
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00640	3289.81	1151.1167
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00554	2166.55	1151.1861
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00561	1423.33	1151.1803
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00660	1881.73	1151.0997
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00730	2179.26	1151.0027
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00724	1341.94	1151.0208
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00867	3544.32	1150.8022
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00851	2829.12	1150.8367
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00427	5919.15	1151.2973
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00736	597.35	1151.0105
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00597	3019.89	1151.1509

Table A.8 Calculation of Permissible Increase in Discharge at JC-0431

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{29}$	Permissible Increase in q_{29} (m^3/hr)	H_j for Increased q_{29} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00610	93.45	1151.1468
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00774	415.41	1150.9688
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00774	478.57	1150.9685
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00611	60.57	1151.1461
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00688	476.86	1151.0817
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00691	727.94	1151.0686
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00691	819.47	1151.0687
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00743	3026.92	1150.9884
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3856
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00726	3008.13	1151.0156
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00733	4472.88	1151.0064
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00535	3440.96	1151.2109
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00698	4068.21	1151.0494
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00494	5270.39	1151.2460
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00509	3732.85	1151.2324
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00641	1254.70	1151.1216
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00751	2003.75	1150.9994
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00654	3480.32	1151.1149
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00614	1526.99	1151.1451
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00748	3462.70	1150.9818
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00727	2608.89	1151.0161
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00638	2809.11	1151.1260
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00757	1317.63	1150.9793
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00672	958.00	1151.0904
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00748	3725.85	1150.9857
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00751	3055.33	1150.9851
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00773	1430.17	1150.9760
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00776	1032.78	1150.9633
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00676	46.00	1151.0922
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00650	3242.34	1151.1180
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00560	2144.65	1151.1901
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00567	1408.19	1151.1841
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00670	1853.01	1151.1000
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00736	2161.46	1151.0141
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00732	1327.06	1151.0231
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00744	4130.18	1150.9931
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00747	3220.99	1150.9926
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00427	5912.94	1151.3037
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00753	583.37	1151.0147
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00605	2982.62	1151.1534

Table A.9 Calculation of Permissible Increase in Discharge at JC-0514

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{34}$	Permissible Increase in q_{34} (m^3/hr)	H_j for Increased q_{34} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00629	90.66	1151.1056
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00670	479.84	1151.0680
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00670	553.10	1151.0681
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00629	58.83	1151.1054
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00647	507.29	1151.0889
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00736	683.11	1151.0340
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00741	763.77	1151.0113
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00653	3447.16	1151.0705
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3721
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00641	3406.37	1151.0821
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00654	5013.76	1151.0777
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00561	3278.83	1151.1558
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00639	4448.10	1151.1010
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00509	5111.45	1151.2074
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00528	3602.45	1151.1893
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00742	1084.22	1150.9533
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00670	2248.65	1151.0724
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00783	2907.43	1150.5368
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00693	1352.93	1150.9979
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00657	3940.58	1151.0676
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00642	2953.66	1151.0817
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00742	2414.60	1150.8300
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00661	1509.51	1151.0690
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00789	816.16	1150.9421
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00660	4222.51	1151.0692
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00662	3468.17	1151.0692
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00669	1651.37	1151.0692
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00670	1196.71	1151.0683
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00644	48.31	1151.0909
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00772	2728.48	1150.6297
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00589	2036.17	1151.1317
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00594	1342.46	1151.1286
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00824	1506.56	1149.9154
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00670	2374.70	1151.0747
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00680	1428.21	1151.0491
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00659	4661.57	1151.0714
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00661	3639.28	1151.0708
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00430	5881.00	1151.2838
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00661	664.65	1151.0783
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00681	2649.13	1150.9940

Table A.10 Calculation of Permissible Increase in Discharge at JC-0604

Label	Nodal Demand, q_i (m^3/hr)	Elevation, Z_i (m)	Minimum Pressure Head, $(P/\gamma)_{min}$ (m)	$Z_i+(P/\gamma)_{min}$ $=H_{jmin}$ (m)	H_j Obtained by Linear Theory (m)	Available Excess Head, Δ (m)	Free Variable, V_f	$\partial V_f/\partial q_{38}$	Permissible Increase in q_{38} (m^3/hr)	H_j for Increased q_{38} (m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Reservoir	-	-		1151.69	1151.6900	-	q_1	1.00000	-	
JC-0054	2.34	1110.96	40.00	1150.96	1151.5304	0.57	H_2	-0.00602	94.70	1151.1428
JC-0055	0.23	1108.30	40.00	1148.30	1151.5159	3.22	H_3	-0.00746	431.28	1150.9899
JC-0056	0.41	1107.81	40.00	1147.81	1151.5159	3.71	H_4	-0.00746	496.88	1150.9897
JC-0072	0.51	1111.16	40.00	1151.16	1151.5302	0.37	H_5	-0.00603	61.39	1151.1420
JC-0085	0.51	1108.24	40.00	1148.24	1151.5201	3.28	H_6	-0.00673	487.44	1151.0791
JC-0093	0.70	1106.49	40.00	1146.49	1151.5210	5.03	H_7	-0.00681	738.39	1151.0671
JC-0094	0.20	1105.86	40.00	1145.86	1151.5210	5.66	H_8	-0.00682	830.64	1151.0670
JC-0098	2.36	1089.01	40.00	1129.01	1151.5112	22.50	H_9	-0.00759	2963.39	1150.9691
JC-0118	4.06	1075.18	40.00	1115.18	1151.5973	36.42	H_{10}	-0.00336	10847.72	1151.3801
JC-0150	2.00	1089.67	40.00	1129.67	1151.5137	21.84	H_{11}	-0.00729	2995.84	1151.0083
JC-0166	0.95	1078.71	40.00	1118.71	1151.5145	32.80	H_{12}	-0.00836	3922.86	1150.8736
JC-0185	0.89	1093.14	40.00	1133.14	1151.5456	18.41	H_{13}	-0.00531	3468.04	1151.2054
JC-0187	2.06	1083.12	40.00	1123.12	1151.5236	28.40	H_{14}	-0.00712	3990.82	1151.0192
JC-0211	1.23	1085.54	40.00	1125.54	1151.5554	26.02	H_{15}	-0.00491	5296.95	1151.2397
JC-0220	3.16	1092.54	40.00	1132.54	1151.5514	19.01	H_{16}	-0.00506	3755.28	1151.2264
JC-0234	0.80	1103.48	40.00	1143.48	1151.5250	8.05	H_{17}	-0.00633	1270.00	1151.1182
JC-0240	0.55	1096.46	40.00	1136.46	1151.5171	15.06	H_{18}	-0.00748	2013.19	1150.9832
JC-0256	0.60	1088.77	40.00	1128.77	1151.5228	22.75	H_{19}	-0.00646	3524.07	1151.1116
JC-0288	0.92	1102.16	40.00	1142.16	1151.5292	9.37	H_{20}	-0.00607	1544.30	1151.1411
JC-0300	3.51	1085.62	40.00	1125.62	1151.5097	25.89	H_{21}	-0.00795	3255.18	1150.9072
JC-0305	2.59	1092.56	40.00	1132.56	1151.5137	18.95	H_{22}	-0.00728	2602.11	1151.0121
JC-0315	1.09	1093.60	40.00	1133.60	1151.5249	17.92	H_{23}	-0.00630	2843.06	1151.1224
JC-0327	1.11	1101.54	40.00	1141.54	1151.5125	9.97	H_{24}	-0.00760	1311.54	1150.9692
JC-0343	0.63	1105.08	40.00	1145.08	1151.5220	6.44	H_{25}	-0.00664	970.56	1151.0879
JC-0348	0.78	1083.66	40.00	1123.66	1151.5118	27.85	H_{26}	-0.00851	3274.58	1150.8366
JC-0349	0.72	1088.57	40.00	1128.57	1151.5125	22.94	H_{27}	-0.00858	2674.23	1150.8296
JC-0430	1.12	1100.46	40.00	1140.46	1151.5158	11.06	H_{28}	-0.00749	1476.89	1150.9824
JC-0431	0.67	1103.50	40.00	1143.50	1151.5159	8.02	H_{29}	-0.00747	1072.98	1150.9863
JC-0433	1.09	1111.21	40.00	1151.21	1151.5211	0.31	H_{30}	-0.00662	46.97	1151.0893
JC-0453	0.51	1090.46	40.00	1130.46	1151.5232	21.06	H_{31}	-0.00642	3282.69	1151.1146
JC-0466	0.71	1099.54	40.00	1139.54	1151.5401	12.00	H_{32}	-0.00554	2165.20	1151.1850
JC-0467	1.32	1103.56	40.00	1143.56	1151.5386	7.98	H_{33}	-0.00561	1422.51	1151.1791
JC-0514	0.67	1099.11	40.00	1139.11	1151.5220	12.41	H_{34}	-0.00661	1877.18	1151.0971
JC-0515	1.32	1095.60	40.00	1135.60	1151.5184	15.92	H_{35}	-0.00735	2166.71	1150.9959
JC-0598	1.05	1101.80	40.00	1141.80	1151.5184	9.72	H_{36}	-0.00728	1335.30	1151.0157
JC-0603	0.95	1080.80	40.00	1120.80	1151.5128	30.71	H_{37}	-0.00872	3520.78	1150.8212
JC-0604	0.76	1087.45	40.00	1127.45	1151.5130	24.06	H_{38}	-0.00914	2633.84	1150.6010
JC-0611	3.81	1086.30	40.00	1126.30	1151.5736	25.27	H_{39}	-0.00427	5914.07	1151.2963
JC-0622	0.84	1107.12	40.00	1147.12	1151.5157	4.40	H_{40}	-0.00733	599.89	1151.0139
JC-0665	1.37	1093.50	40.00	1133.50	1151.5304	18.03	H_{41}	-0.00598	3015.19	1151.1491

APPENDIX B

WORKING RANGE OF THE TECHNIQUE

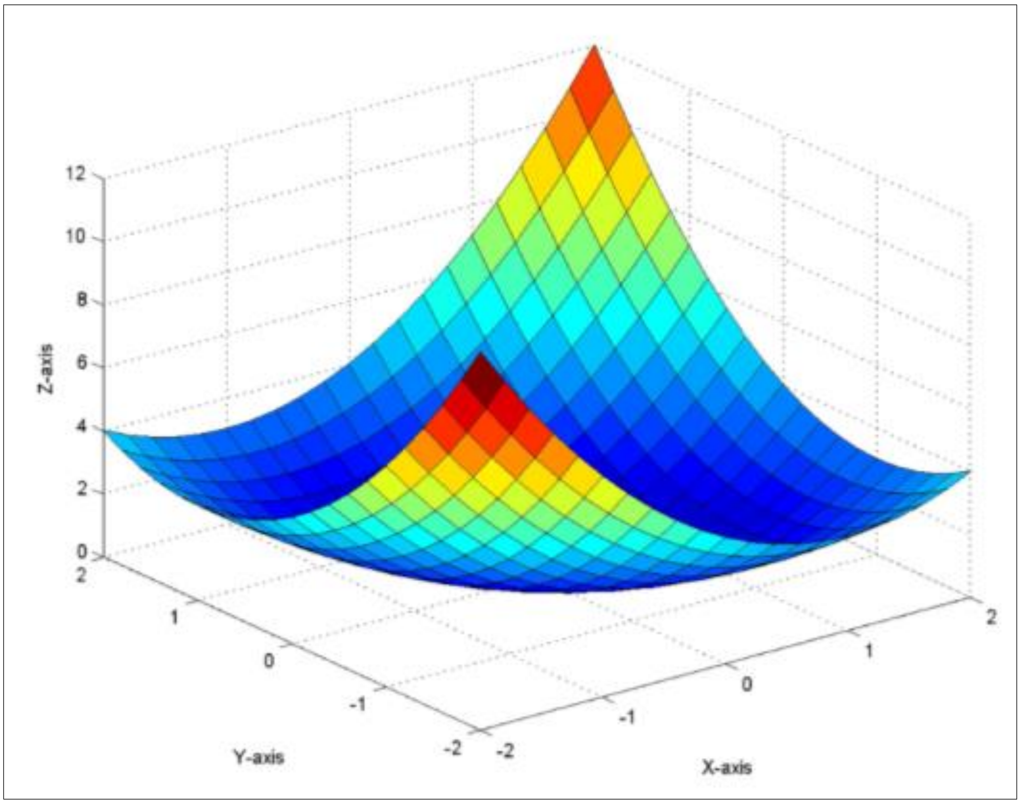

Figure B.1 A graph of $z = x^2 + xy + y$

A graph of $z = x^2 + xy + y$ is given in Figure B.1. This graph is given because it gives an idea about visualization of simple nonlinear equation in space. To relate total head of node 5 H_5 and nodal demand at node 3 q_3, head loss through pipe 5 and pipe 4 are given at Equations (B.1) and (B.2) respectively.

$$H_4 - H_5 = R_5 Q_5^{1.852} \tag{B.1}$$

$$H_4 - H_3 = R_4 Q_4^{1.852} \tag{B.2}$$

Subtracting Equation (B.1) from (B.2) gives Equation (B.3)

$$H_5 - H_3 = R_4 Q_4^{1.852} - R_5 Q_5^{1.852} \qquad (B.3)$$

Node flow continuity equation at node 3 is given below.

$$Q_3 + Q_4 - Q_6 - q_3 = 0 \qquad (B.4)$$

Rearranging Equations (B.3) and (B.4)

$$H_5 = H_3 + R_4 (Q_6 + q_3 - Q_3)^{1.852} - R_5 Q_5^{1.852} \qquad (B.5)$$

By looking Equation (B.5), this is more complex equation than $z = x^2 + xy + y$. Since permissible in q_3 is found minimum at node 5, relation between H_5 and q_3 is given in Equation (B.5). Blue curve represents slice of z equation at y=1 in Figure B.2. Shape of H_5 is similar to blue curve in Figure B.2.

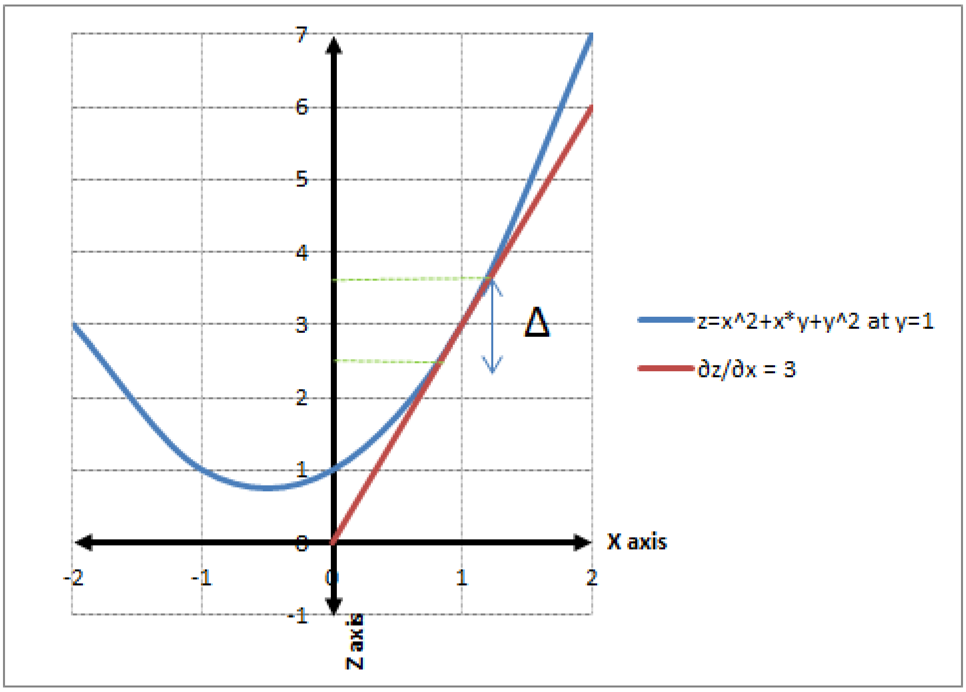

Figure B.2 A slice of $z = x^2 + xy + y$ at y=1 and $\partial z/\partial x=3$

For the partial derivative at (1, 1, 3) that leaves y constant, the corresponding tangent line is parallel to the xz-plane. By finding the derivative of the equation while assuming y is a constant, the slope of f at the point (x, y, z) is found to be:

$$\frac{\partial z}{\partial x} = 2x + y \tag{B.6}$$

So at (1, 1, 3), by substitution, the slope is 3. Therefore

$$\frac{\partial z}{\partial x} = 3 \tag{B.7}$$

at the point (1,1,3). That is, the partial derivative of z with respect to x at (1,1,3).

$$\text{permissible increase in } q_3 = \frac{H_{5,\text{initial (obtained by linear theory)}} - H_{5,\min}}{\frac{\partial H_5}{\partial q_3}} \tag{B.8}$$

Rate of change of z with respect to x is indicated by red line in Figure B.2. Similarly, $\partial H_5/\partial q_3$ is a slope and thus it is a straight line. Straight line coming from derivative intersects H_5 equation like intersection of $z= x^2 + xy + y$ at $y=1$ and $(\partial z)/(\partial x)=3$. As it can be seen from Figure B.2, this method allows working range named as Δ. If Δ value ($H_{5, \text{initial(obtained by linear theory)}} - H_{5,\min}$) is chosen a large value like 2, straight line can not fit nonlinear equation.