LEAKAGE OPTIMIZATION OF WATER DISTRIBUTION NETWORKS BY PRESSURE CONTROL

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ABSTRACT

LEAKAGE OPTIMIZATION OF WATER DISTRIBUTION NETWORKS BY PRESSURE CONTROL

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Excess water losses from drinking water distribution network is a serious problem in many countries all over the world including Turkey where total water losses is around 40% of the distributed water. Total water losses are divided into two parts namely (i) apparent or commercial water loss and (ii) real or physical water loss. Apparent water loss is from sources such as illegal water usage (water theft), inaccuracy in customer water meters, and meter reading handling errors. Real water loss is from sources such as leakage in water mains, leakage from connection to buildings, overflow from distribution reservoirs and from the water lost by pipe bursts. Water losses cause a lot of energy and economic losses and also results in water quality and sustainability problems. Thus, it is important to determine, reduce and manage water loss. It is proven by many studies that excess unnecessary water pressures lead to excess water loss. In this study, it is aimed to optimize pressure in a water distribution system in order to minimize the leakage. In addition, as a new approach, Chance Constraint is applied to cover uncertainties in the system which are resulting from various factors affecting leakage. LSGRG2 code is used for solving non-linear optimization problem and EPANET is used for hydraulic analysis.

Keywords: Leakage, Pressure Control, Non-linear Optimization, LSGRG2, Chance Constraint Programming

ÖZ

SU DAĞITIM ŞEBEKELERİNDEKİ KAÇAKLARIN BASINÇ KONTROLÜ İLE OPTİMİZASYONU

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İçme suyu dağıtım şebekelerinde gözlemlenen aşırı su kayıpları, dünyada pek çok ülke için ciddi bir sorun teşkil etmektedir. Türkiye'de de su kayıplarının oranı, dağıtılan su miktarının %40'ı olarak kaydedilmiştir. Su kayıpları tür olarak ikiye ayrılmaktadır, (i) görünen veya ticari kayıplar ve (ii) gerçek veya fiziki kayıplar. Yasa dışı su kullanımı, hassas alınamayan sayaç ölçümleri ve hatalı sayaç okumaları görünen kayıpların sebepleridir. Gerçek kayıplar ise ana borulardaki sızıntılar, bağlantı noktalarındaki sızıntılar, dağıtım rezervuarlarındaki taşmalar ve boru patlamalarındaki kaçaklardan oluşur. Su kayıpları, enerji ve ekonomik kayıplara sebep olmanın yanı sıra su kalitesinde ve sürdürülebilirliğinde de sorunlara yol açar. Bu sebeplerden ötürü, su kaçaklarının tespit edilmesi, azaltılması ve yönetimi önem taşımaktadır. Geçmişte yapılan birçok çalışma tarafından aşırı su kaybının, aşırı ve gereksiz şebeke içi basıncından kaynaklandığı kanıtlanmıştır. Bu çalışmada, su dağıtım şebekesinde basınç optimizasyonu metoduyla sızıntı azaltımı hedeflenmiştir. Yeni bir yaklaşım olarak, sistemdeki sızıntıyı etkileyen muhtelif etkenleri hesaba katmak için olasılık kısıtlaması çalışılmıştır. Linear olmayan optimizasyon çözücü olarak LSGRG2 kodu ve hidrolik analizler için EPANET kullanılmıştır.

Anahtar Kelimeler: Sızıntı, Basınç Kontrolü, Doğrusal Olmayan Optimizasyon, LSGRG2, Rastlantısal Kısıntılı Programlama

To the ones who live to love

ACKNOWLEDGEMENTS

A long time ago in a galaxy far, far away….

Episode V – Ezgi Strikes Back

It was a dark time for Ezgi. She has been drifting in the thunderstorms of the academic universe to complete her ultimate mission: doctorate degree. While she was struggling in the fight with leakage troops, supreme advisor Burcu Altan Sakarya was lighting the way with her guidance and support. Congress of the thesis, Nuray Tokyay and Önder Koçyiğit believed that she will make it through and have given their full support.

The code was getting strong and she was losing faith in herself. However, she was not alone. Her mom, dad, Ekin, Can, Kürşat and Agah have hold her before falling. They keep her secure until she gained the trust back again.

Gülsüş was there for her every time to keep the dark thoughts away. She knew that nothing is more important than her being safe. Gülsüş and Onurcuk has taken her to long walks to let her complain and clear the mind.

From different universes, Aslıcan and Nilay were sending their continuous support and always believed that she will win the battle.

Another war was going on in another part of the galaxy between Yaprak and her thesis. Although Yaprak was having hard times, she and Binnur have done everything they could to keep Ezgi going.

The final fight with code was near. She was trying to keep her inner peace to succeed. Şule, Disar, Gözde and Müge were helping her enlightment.

Ahmet Nazım was spending hours with her to find a way to defeat the code, but they failed. Emre accompanied her every morning and tried to keep her positive. But for her, all of the hope was gone. All of a sudden, Ersin has given her the ultimate weapon `F11` and tought her to control its power. Ezgi was standing with her all time and trying to protect her from a break down. From the seeds they have planted, a new hope has appeared.

With the new hope, the code has been finally defeated. Now she had to succeed one final step: defeat the emperor.

There were good times and bad times for her before the last battle. However, Belin, Gökhan, Alper and Sema were always trying to bad times to good ones.

Little did she know that the victory was around the corner. With the existence of the loved ones, their belief and protection, the force inside Ezgi awakened. The emperor thesis was beaten, the war was over.

Before getting into the ship, Ezgi looked at all of the ones that she love. They are the reason of this victory. Their love is the force inside her. She knew that there will be more fights, but this love will always protect her. She hold the hand of her beloved Can and with Mahmut on her lap, they headed to their home to rest before the new adventures.

May the love be with you….

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WDN	: **W**ater **D**istribution **N**etwork
IWA	: **I**nternational **W**ater **A**ssociation
NRW	: **N**on-**R**evenue **W**ater
PRV	: **P**ressure **R**educing **V**alve
FCV	: **F**low **C**ontrol **V**alve
TCV	: **T**hrottle **C**ontrol **V**alve
PAT	: **P**umps **O**perating as **T**urbines
DMA	: **D**istrict **M**etering **A**rea
ILI	: **I**nternational **L**evel of **L**eakage
ELL	: **E**conomic **L**evel of **L**eakage
H-W	: **H**azen **W**illiams
N	: Number of junction nodes
M	: Number of pipes
K	: Number of control nodes
S	: Number of tanks
V	: Number of valves
T	: Number of time intervals
$Q_{i,j}$	: Flow rate from junction node i to j

D_i	: Flow demand at node i
H	: Nodal head
h	: Head loss
r	: Resistance coefficient
n	: Flow exponent
m	: Minor loss coefficient
$HP_{k,t}$	: Pressure head at control node k, for time interval t
$HP_{k,t,min}$	: Minimum pressure head for control node k, for time interval t
$y_{s,ft}$	: Water level in the tank s at the initial time interval ft
$y_{s,it}$	: Water level in the tank s at the final time interval it
$y_{s,newmin}$	: Modified minimum tank level for the tank s
$\underline{HP}_{v,t}$	: Minimum pressure head setting for valve v, at time interval t
$\overline{HP}_{v,t}$	: Maximum pressure head setting for valve v, at time interval t
$x_{v,t}$	: Pressure head setting for valve v, at time interval t
$Q_{leak,j,t}$	: Leakage amount for node j and time interval t
C	: Emitter Coefficient
P	: Pressure
α	: Pressure exponent
γ_l	: Half of the length of pipe l connected to node j
γ_j	: Summation of the half lengths of all pipes connected to node j

m_j	: Number of pipes connected to node *j*
Γ_j	: Relative importance of each node *j*
γ_{Net}	: Total sum of the lengths of each pipe
${K_{net}}^{(1)}$	: Initial leakage coefficient for the whole network
$Q_{Net,real}$	: Real total network leakage over a period of 24 hours
$\overline{P}_{Net}$	: Average pressure of all nodes
${K_j}^{(h)}$	: Leak valve coefficient at node *j* at iteration *h*
${K_{net}}^{(h)}$	: Network leakage coefficient at iteration *h*
$Q_{Net,model}$	: Total leakage calculated from the simulation results
ΔQ	: Difference between real and simulated leakages
ε	: Threshold value for ΔQ
$f(x)$	: Probability distribution function of a normal variable
$f_X(x)$	: Probability distribution function of a log- normal variable
μ	: Mean of the normal distribution
λ	: Mean of the log-normal distribution
σ	: Standard deviation of the normal distribution
ξ	: Standard deviation of the log-normal distribution
X	: Random variable
Z	: Standardized variate of a random variable
$\phi(z)$	: Probability distribution function of a standardized variable

$\Phi(z)$: Cumulative distribution function of a standardized variable

φ : Specified reliability of lower pressure head limit

μ_H : Mean of the normally distributed lower limit

λ_H : Mean of the log-normally distributed lower limit

σ_H : Standard deviation of the normally distributed lower limit

ξ_H : Standard deviation of the log-normally distributed lower limit

Z_H : Standardized variate of lower limit

$h(x)$: A generalized non-linear optimization problem

$g(x)$: Constraint of a generalized non-linear optimization problem

x_j : Decision variable of a generalized non-linear optimization problem

$\overline{x}_j$: Upper limit of the bound constraint

$\underline{x}_j$: Lower limit of the bound constraint

x_B : Basic variables

x_N : Nonbasic variables

CHAPTER 1

INTRODUCTION

Water scarcity is currently one of the key problems that the world is facing. While the demand for freshwater is increasing with population growth, sources are diminishing due to climate change, as well as with the acceleration of urbanization and industrialization. The current world population is reported to be 7.4 billion people and it is estimated to reach 9.7 billion till 2050 (Melorose, Perroy, & Careas, 2015). Contrary to this expansion, the volume of lakes with the harmful algal blooms will increase by at least 20% until 2050, significantly impacting one of the main sources of freshwater (United Nations, 2012). Thus, it is essential to maintain sustainability on the water resources for the continuity of life on earth.

What has equal or even higher importance than maintaining sustainability is increasing the efficiency of existing source utilization. Some significant remedies are developing enhanced data acquisition systems for location and identification of the problems; rehabilitating the existing infrastructures to decrease excessive water losses; and raising public awareness by informing about efficient water usage methods.

1.1 Statement of the Problem

The major problem with the usage of the current resources is the loss of usable water within circulation. According to a World Bank study, every year, more than 32 billion m^3 of treated water is lost from the water distribution networks (WDNs) as leakage and approximately 16 billion m^3 are distributed, but are not paid for, constituting unauthorized usage (Kingdom, Liemberger, & Marin, 2006).

Before discussing the precautions, it is vital to define components of the water balance. International Water Association (IWA) has produced an international terminology for Water Balance (Table 1-1) (Lambert & Hirner, 2000).

Table 1-1: Components of the Water Balance by the IWA (Lambert & Hirner, 2000)

<table>
<tr><td rowspan="10">System Input Volume (corrected for known errors)</td><td rowspan="4">Authorized Consumption</td><td rowspan="2">Billed Authorized Consumption</td><td>Billed Metered Consumption (including water exported)</td><td rowspan="2">Revenue Water</td></tr>
<tr><td>Billed Unmetered Consumption</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption</td><td>Unbilled Metered Consumption</td><td rowspan="8">Non-Revenue Water (NRW)</td></tr>
<tr><td>Unbilled Unmetered Consumption</td></tr>
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<tr><td>Leakage on Service Connections up to Point of Customer Metering</td></tr>
</table>

The difference between the total water input to the system and water billed to the customers is called Non-Revenue Water (NRW). Having high amount of NRW in a WDN indicates that a great amount of water is lost through leakage. The level of NRW is increasing significantly for developing countries. A World Bank study reveals that around 45 million m^3 water is lost daily through leakage from WDNs which is roughly equal to the demands of 200 million people (Kingdom et al., 2006). The situation is at a critical stage for Turkey, where NRW amount is around 36% of the total inflow to the system according to a study of the Turkish Statistical Institute (Turkish Statistical Institute, 2017). This rate decreases significantly for developed countries. As an example, the amount of NRW in the Netherlands is estimated to be approximately 6% (Vewin, 2016).

Water leakage from a WDN results in not only the diminishing of the sources but also the waste of energy and money. Consequently, it is vital to reduce the amount of water loss, especially for developing countries where rates are relatively high. Some of the main methods for controlling leakage are improving leak detection systems, repair and replacement of meters, rehabilitation and replacement of infrastructure, pressure reduction and raising public awareness. While the ideal situation would be to administer all of these solutions together, in reality, this would not be possible due to high economic burden it would inflict onto the countries. Among these solutions, the former three would require comparatively higher financial resources and workload than the latter two. Since the problem is more critical for developing countries, the budget allocated for improving water infrastructures would be limited. Focusing on the remaining methods, raising public awareness would be time consuming as well as depending on the people's perceptions. As such, the easiest and the most efficient way to control leakage is to control pressures in the WDNs.

In a WDN, pressures at the consumer nodes must be between a minimum and a maximum limit. The reason for having a minimum limit is that it is not possible to deliver the required demands to the nodes with insufficient pressures. Likewise, a maximum limit is set, as high pressures result in bursts in the pipes and, also, high leakages. For the regulation of pressures, pressure reducing valves (PRVs) can be used in the network. A PRV is basically a control valve, which reduces the input pressure of the fluid to a desired output value. It does not allow back flow and will not be active if the pressure on the line is below the desired setting, which means that it will act as a normal pipe. It is possible to reduce the leakage by adjusting the local pressure of a selected region by mounting the PRV at the beginning of said region. Furthermore, the pressure for the whole network could be reduced by mounting the PRV at the entrance line.

It is known that the demands from the consumer nodes are not constant. They change with time and, in order to satisfy them, so does the pressure. Thus, a constant setting of the PRV for the whole time span is not an efficient method. Considering these, an optimization model is needed to determine the time dependent settings of the PRVs, which will decrease the pressure within the WDN while satisfying the demands and necessary bound requirements on certain variables.

It is known that nothing can be modelled as in real life. So, while constructing the optimization model, it is important to consider that there may be many uncontrollable factors that will increase the difference between the real case and the analysis results. For the leakage modelling, there are additional minor factors that would affect the leakage such as traffic flow, cover depth, temperature fluctuations or pipe material (Puust, Kapelan, Savic, & Koppel, 2010; Shafiqul Islam et al., 2012). Although they are not as effective as pressure, changes in these factors will also affect the leakage amount. As it is not possible to model each individual factor accurately, the probability concept should be introduced to the problem in order to get more realistic results.

As a result, an optimization model for a WDN is developed to minimize the leakage by decreasing the pressure within its limitations while considering uncertainties in the network.

1.2 Literature Review

After previous works related with leakage management are examined, it is seen that the topic can be categorized under three main headings. First, the identification and quantification of the leakage. Second, the determination of the leak areas. Third, the methods for control. Since, the main emphasis of this study is on the control of leakage, a background search for only the leakage assessment and control will be presented in this section.

1.2.1 Leakage Assessment

The modern definition of leakage in terms of pressure is first introduced in 80s. Germanopoulos (1985) developed the commonly used pressure dependent leakage equation for pipes. Moreover, he stated that the pressure exponent and coefficient are both dependent on network characteristics and the type of leak, which is further investigated by many other studies (Al-Ghamdi, 2011; Giustolisi, Savic, & Kapelan, 2008; Jowitt & Xu, 1990; Lambert, 2001; May, 1994; Tucciarelli, Criminisi, & Termini, 1999; Vairavamoorthy & Lumbers, 1998; Walski, Bezts, Posluzny, Weir, & Whitman, 2006). Tucciarelli et al. (1999) modified the leakage definition of pipe to nodal leakage which was later on used by the hydraulic solver EPANET to define leakage on the nodes.

During 1900s, the effects of various operating pressures have been studied. It was modelled by May (1994) using Fixed and Variable Area Discharge (FAVAD) principles. Lambert (2001) made a simplification on the method by modifying the power law in the formulation.

Although the aim is to decrease leakage in a WDN, it is not possible to set it to zero. However, having non/zero leakage in a network can also be advantageous as shown in the study of Colombo & Karney (2002), in which the presence of leakage is suggested to diminish water age and attenuate the hydraulic transients in the network.

The widely used leak index, International level of leakage (ILI), was first introduced in 2003 by the International Water Association Task Force in a special series for Task 21 (Lambert, 2003). The index is, basically, calculated by dividing current annual real losses to unavoidable real losses of the WDN.

In the study of Giustolisi et al. (2008), it was proven that the simulations carried out by assuming a constant nodal leakage percent (a demand driven leakage) give lower leakage results than the realistic values. This is because, nodes with low demands have low leakage values even if they have high nodal pressures. Thus, demand driven leakage description is not realistic.

Shafiqul Islam et al. (2012) conducted a study for estimating the leakage potential in a WDN by analyzing 22 selected leakage influencing factors such as traffic impact, system pressure, pipe age, pipe workmanship, etc. Among all these factors, the system pressure was found to be the most influencing factor, followed by pipe age.

1.2.2 Leakage Control

With the acceptance of the pressure-leakage relationship, minimization of leakage by reducing overpressures in a network began to be studied in mid-80s. In the study of Sterling & Bargiela (1984), the reduction was aimed to be achieved by controlling the settings of flow control valves (FCV) mounted to the network and the objective was to minimize the difference between the targeted and actual pressures. This non-linear optimization problem was, first, simplified by a linearization method and, then solved. The same problem was investigated in many other studies with different solution methods (Germanopoulos & Jowitt, 1989; Jowitt & Xu, 1990; Vairavamoorthy & Lumbers, 1998).

Tucciarelli et al. (1999) suggested a two-step procedure to solve the same method of using FCV to reduce the pressure in the network. The first was the calibration of the network for the leakage parameters estimation and the second was the optimization of the openings of the valves.

Creaco & Pezzinga (2015) studied the usage of isolation valves with FCVs and created a multi objective optimization problem with decision variables of pipe replacement and control valve settings.

In the study of Araujo, Ramos, & Coelho (2006), the usage of throttle control valves (TCV) was proposed. An optimization problem was constructed to determine the number and the locations of the TCVs together with the opening adjustments of the valves.

Apart from FCV and TCV installations, different methods, such as optimal water level variations in storage tanks (Nazif, Karamouz, Tabesh, & Moridi, 2010) and pump schedule optimization (Giustolisi, Laucelli, & Berardi, 2013; Price & Ostfeld, 2013, 2014; Skworcow, Paluszczyszyn, Ulanicki, Rudek, & Belrain, 2014), were also studied in order to reduce leakage.

Eck & Mevissen (2012) conducted a study on valve placement in WDNs. The valves are PRVs and the objective function is to minimize the total pressure in the network. The problem was solved with a quadratic approximation approach to the head loss equation, which was found to be significantly faster than the models solved with the linearization of the head loss.

Similarly, Fontana, Giugni, & Portolano (2012) also worked on the PRV placement problem. The objective function was taken as the penalty term for the pressure variation from a predetermined minimum value. The application of pumps operating as turbines (PAT) were done for comparison purposes and it was proven that PATs were also as much effective as PRVs.

Xu, Chen, Ma, Blanckaert, & Wan (2014) studied the pressure management of the WDNs by mounting PRVs at the entrances of the district metering areas (DMA). The aim was to optimize the constant setting of PRVs and it was shown by the results that the flow into the DMA was sensitive to the inlet water pressure. Also, it was stated that the pressure management reduces the risk of new breaks and extends pipe lifetime.

There are only a limited amount of studies conducted on real cases as access to real data is challenging. Peters & Ben-Ephraim (2012) studied the leakage assessment in the city of Guyana by night flow analysis. For leakage control strategies, target setting in terms of economic level of leakages (ELL), which is an economic indication for each network, was studied for Bangkok by Islam & Babel (2013) and for South Korea by Lim, Savic, & Kapelan (2015). Pressure management with PRV usage for the cities of Kos and Kozani, Greece, was researched by Kanakoudis & Gonelas (2014).

In 2014, Water Distribution Systems Analysis Conference held an event called “Battle of Background Leakage Assessment for Water Networks”. In the event, a design project with the requirement to meet the minimum pressure criteria was needed by the municipality of C-town. The existing structure was not able to meet the performance targets when future demands were considered. The competitors were expected to propose a methodology to reduce water losses by both pipe replacement and pressure adjustment while minimizing cost. Following highlights were selected from the studies of the event.

The winning project belongs to Creaco, Alvisi, & Franchini (2014). A multi objective genetic algorithm methodology was developed to solve the optimization problem. Minimum pressure head and tank level constraints were added to the objective function as penalty. In the study, Tucciarelli et al. (1999)' s leakage formulation was found to be as effective as Germanopoulos (1985)' s formulation. This conclusion was also made by the study of Tolson & Khedr (2014) in the same event.

The second place belongs to B. J. Eck, Arandia, Naoum-Sawaya, & Wirth (2014). A mixed integer non-linear programming formulation was constructed and a new approach based on a fixed-point iteration for networks with background leakage was developed. It was concluded that PRV installment is a more economical solution compared to pipe replacement.

Morley & Tricarico (2014) added a constraint of not having EPANET warnings and applied a differential weighting to constraints by taking the EPANET warning constraint as the most important.

Tricarico et al. (2014) suggested that the usage of PATs are more economical than PRVs. Uncertain futures were integrated into the study by accepting the flow as uncertain with a normal probability distribution.

1.3 Scope of the study

After the background check on the subject, it was found that the dynamic changing of PRV settings and uncertainty effects have not been covered well (Mutikanga, Sharma, & Vairavamoorthy, 2013; Puust et al., 2010). In order to address these issues as well as the shortcomings of the previous studies, the main aim of this study is defined as minimizing leakage in a WDN by decreasing pressures of the consumer nodes without violating pressure limitations with the usage of PRVs. The decision variable of the optimization problem is the hourly PRV settings. The number and the locations of the

PRVs are going to be pre-determined according to the network. The effect of uncertainty concept on the minimization of the leakage problem will be examined. The purpose of introducing uncertainty is to examine the relationship between the reliability and pressures in the network, which directly affects leakage. The uncertainty in WDN leakage analyses may cause the system to not reach the minimum pressure head at the control nodes. Hence, having a more reliable WDN means lower probability of violating pressure head limitation. The main cause of uncertainty in this study is the factors affecting the leakage. Hence, the probabilistic approach is applied to the pressure limitation constraint by assigning different types of probability distributions for comparison.

1.4 Outline of the Thesis

In this thesis, there are six chapters. These are, in order, Introduction, Problem Formulation, Solution Methodology, Program Structure, Application Results, and Conclusions.

The second chapter explains how the problem is formulated. Derivation of different objective functions and corresponding constraints are explained. In addition to these, leakage formulation and mathematical representation of the uncertainty concept are examined.

Chapter three covers the solution methodology of the leakage optimization problem. The reduction method applied to reduce the complexity of the problem, penalty method to handle the constraints and computation of the necessary components for the solution procedure are clarified.

Then, in chapter four, structure of the program is described in detail. Codes used for hydraulic and optimization solvers are introduced. Moreover, the structure of the combined program created for this study is explained.

In chapter five, the application results are presented. The characteristics of three different application networks, tested PRV locations, setting limitations and the analysis results with uncertainty applications are discussed.

Finally, in chapter six, conclusions from this study are discussed and future recommendations are given.

CHAPTER 2

PROBLEM FORMULATION

Among many options, pressure adjustment is found to be the most effective method to control the leakage in water distribution networks. Pressure Reducing Valves (PRV) are used to decrease pressure over selected regions. Lower pressures will result in lower leakage values in the network. However, water must be supplied to the consumer nodes within a maximum and a minimum range of pressure in addition to satisfying demands. Thus, it is important to reduce the pressures without violating the minimum pressure requirement. To overcome this problem, appropriate scheduling of the PRV setup is required. In this chapter, mathematical representation of the pressure control problem will be explained.

2.1 General Formulation

The optimization of pressure control problem aims to minimize the total leakage in the network while maintaining the pressure head within limits at each consumer node. Minimization of leakage can be achieved in a numerous ways such as reducing the pressure heads at the consumer nodes or total leakage in the system. In this study, the objective is to minimize the leakage by adjusting the PRVs settings for each time interval.

Consumer nodes in the network are the nodes that have demands, which means that pressure head for each of them for each time interval had to be checked. The nodes which do not have demand values are the nodes where pressure head check will not be made. Depending on the choice, some part of the consumer nodes may be excluded from the pressure check. All of the nodes that considered for the violation check are called the control nodes.

There are five constraints of the optimization problem formulized. Two of them are the conservation of mass and conservation of energy equations which are known as the hydraulic constraints (Rossman, 2000). Assuming a network with *N* number of junction nodes, *M* number of pipes, *K* number of control nodes, *S* number of tanks, *V* number of valves and *T* number of time intervals. Conservation of mass at each junction node is,

$$\sum_j Q_{i,j} - D_i = 0 \qquad \text{for } i = 1, \dots, N \qquad (2.1)$$

where $Q_{i,j}$ is the flow rate from junction node *i* to *j* and D_i is the flow demand at node *i*. If there exist an external inflow to the node, then it is added as positive.

Secondly, conservation of energy for each pipe connecting nodes *i* and *j* in the set of all pipes, *M*,

$$H_i - H_j = h_{i,j} = rQ_{i,j}{}^n + mQ_{i,j}{}^2 \qquad (2.2)$$

where *H* is the nodal head, *h* is the head loss, *r* is the resistance coefficient, *n* is the flow exponent and *m* is the minor loss coefficient. The above two equations are satisfied for all time intervals.

Third constraint is the pressure head limitations at the consumer nodes, which can be expressed as,

$$HP_{k,t} \geq HP_{k,t,min} \qquad \text{for } k = 1, \dots, K \text{ and } t = 1, \dots, T \qquad (2.3)$$

where $HP_{k,t}$ is the pressure head at control node *k*, for time interval *t* and $HP_{k,t,min}$ is the pre-determined minimum pressure head for control node *k*, for time interval *t*.

Fourth constraint is the tank level variation limit. Tank level variation is defined as the difference of the tank level at the beginning and at the end of a 24-h period. The aim of having this constraint is to satisfy periodicity for the tanks in the network.

$$y_{s,ft} \geq y_{s,it} \quad \text{for } s = 1, \ldots, S \tag{2.4}$$

where $y_{s,ft}$ is the water level in the tank *s* at the final time interval *ft* and $y_{s,it}$ is the water level in the tank *s* at the initial time interval *it*.

Final constraint is the pressure settings of the PRVs to be between a given upper and lower bound.

$$\underline{HP}_{v,t} \leq x_{v,t} \leq \overline{HP}_{v,t} \qquad \text{for } v = 1, \ldots, V \text{ and } t = 1, \ldots, T \tag{2.5}$$

where $\underline{HP}_{v,t}$ is the minimum pressure head setting for valve *v*, $x_{v,t}$ is the pressure head setting for valve *v* and $\overline{HP}_{v,t}$ is the maximum pressure head setting for valve *v*, at time interval *t*.

In this study, two different objective functions are examined with the goal of minimizing leakage. In the first one, the aim is to decrease the pressure heads at the control nodes as leakage is a function of pressure. In the second one, it is directly the minimization of the leakage in the network. Leakage formulation will be discussed in Section 2.2.

Hence, the pressure optimization formulation becomes a large scale non-linear programming problem with the decision variables of pressure heads at the control nodes, total leakage and the pressure head settings for PRVs. The decision variables, can be partitioned into two groups as dependent and independent terms. Dependent variables, which are pressure heads at the control nodes, total leakage and the water level in the tank, are also called as state variables. Moreover, independent variables, also called as control variables, are the pressure head settings for PRVs. In both of the cases, the pressure head settings for PRVs will be optimized to minimize the leakage.

2.1.1 Case I

The objective function for Case I is to minimize the summation of pressure head at the control points.

$$Minimize\ f = \sum_{k=1}^{K} \sum_{t=1}^{T} HP_{k,t} \tag{2.6}$$

Constraints for the optimization problem are conservation of mass (Equation 2.1), conservation of energy (Equation 2.2), the pressure head limitations at the consumer nodes (Equation 2.3), the tank level variation limit (Equation 2.4) and upper and lower bounds for the valve settings (Equation 2.5).

2.1.2 Case II

The objective function for Case II is to minimize the total leak from the junction points.

$$Minimize\ f = \sum_{j=1}^{N} \sum_{t=1}^{T} Q_{leak,j,t} \tag{2.7}$$

where $Q_{leak,j,t}$ is the leakage amount for node *j* and time interval *t*.

Constraints for the optimization problem are conservation of mass (Equation 2.1), conservation of energy (Equation 2.2), the pressure head limitations at the consumer nodes (Equation 2.3), the tank level variation limit (Equation 2.4) and upper and lower bounds for the valve settings (Equation 2.5).

2.2 Leakage Formulation

As it is already stated, leakage is mostly effected from the pressure and as a result it is mathematically represented as a function of pressure. Explanation of its representation and calculation of the related terms will be explained in this section.

2.2.1 Leakage in EPANET

For the hydraulic analysis of the network, a hydraulic simulation code EPANET will be used in this study. Leakage is defined by usage of emitters in EPANET. Basically, emitters are properties of junctions which help to model the flow through a nozzle or orifice that discharges to the atmosphere (Rossman, 2000). In addition to these, it can also be used to model leakage in a pipe connected to a junction. The flow rate through the emitter is defined as:

$$Q_{leak} = C(P)^{\alpha} \tag{2.8}$$

where Q_{leak} is the leakage flow rate, C is the emitter coefficient, P is the pressure and α is the pressure exponent.

Emitter coefficient, C and pressure exponent, α values are network dependent and input to EPANET as junction properties. In the present study, emitter coefficient values are calculated by a methodology presented by Cobacho, Arregui, Soriano, & Jr (2013) which will be explained in Section 2.2.2.

2.2.2 Emitter Coefficient Calculations

Cobacho et al. (2013) developed a two-staged emitter coefficient calibration process. In the first stage, leakage is distributed to all of the nodes according to the characteristics of the network. In the second stage, leakage is modelled through an emitter at each node. Different factors such as pipe length, the number of repairs per length, etc. can be used as an influencing factor for calibration. In this study, pipe length is used. A step-by step description of the process is:

- **Phase 1 – Distribution**
    1) Initially assume that the known leakage is uniformly distributed to each pipe.

2) Half of the pipe lengths of all the pipes connected to node *j* are assigned to node *j*.

$$\gamma_j = \sum_{i=1}^{m_j} \gamma_l \tag{2.9}$$

where $\gamma_l$is the half of the length of pipe *l* connected to node *j*, γ_j is the summation of the half lengths of all pipes connected to node j and m_j is the number of pipes connected to node j.

3) Relative importance of each node is calculated.

$$\Gamma_j = \frac{\gamma_j}{\Sigma\gamma_l} = \frac{\gamma_j}{\gamma_{Net}} \tag{2.10}$$

where Γ_j is the relative importance of each node j and γ_{Net} is the total sum of the lengths of each pipe.

- **Phase 2 – Calibration**

4) A leakage coefficient for the whole network to be used in the first iteration is calculated.

$$K_{net}{}^{(1)} = \frac{Q_{Net,real}}{\overline{P}_{Net}{}^{\alpha}} \tag{2.11}$$

where $Q_{Net,real}$ is the real total network leakage over a period of 24 hours, $\overline{P}_{Net}$ is the average pressure of all nodes and α is the predefined pressure exponent.

5) Network leakage is distributed to each node by using leak valve coefficient.

$$K_j{}^{(h)} = K_{net}{}^{(h)}\Gamma_j \tag{2.12}$$

where ${K_j}^{(h)}$ is the leak valve coefficient at node *j* at iteration *h* and ${K_{net}}^{(h)}$ is the network leakage coefficient at iteration *h*.

6) Network is simulated with the calculated ${K_j}^{(h)}$ values and total leakage is calculated from the simulation results, ${Q_{Net,model}}^{(h)}$.

7) If the difference between the known and the calculated leakage value, ΔQ, is higher than a threshold value, ε, ${K_{net}}^{(h)}$ is modified in accordance with the difference amount and new average pressure of the network.

$$\Delta Q = {Q_{Net,model}}^{(h)} - Q_{Net,real} \tag{2.13}$$

$$|\Delta Q| \leq \varepsilon \tag{2.14}$$

$$\Delta K_{net} = \frac{\Delta Q}{{\overline{P}_{net}^{(h)}}^{\alpha}} \tag{2.15}$$

$${K_{net}}^{(h)} = {K_{net}}^{(h-1)} + \Delta K_{net} \tag{2.16}$$

8) Same procedure from step 5 to 8 is repeated until the difference is below the threshold, ε.

Calibration process of the emitter coefficients can be summarized with a flow chart in Figure 2.1.

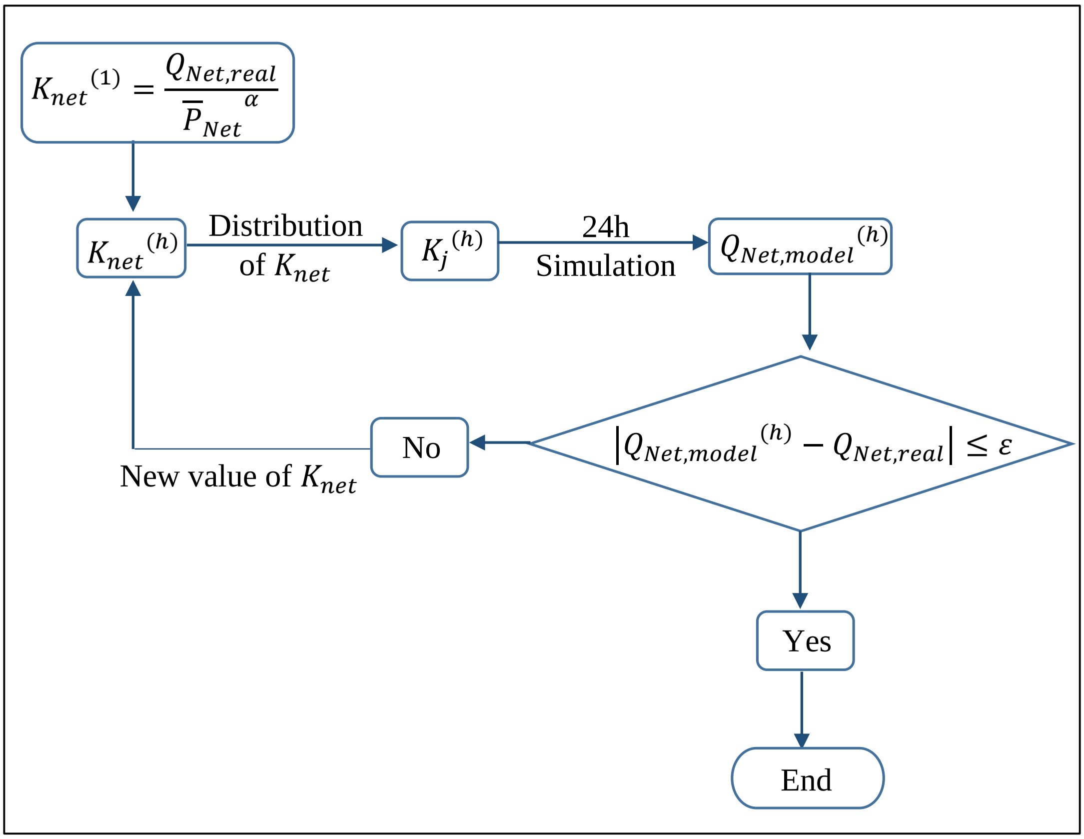

Figure 2-1: Flow chart of emitter coefficient calibration (Cobacho et al., 2013)

2.3 Uncertainty Concept

In every analysis, some assumptions are made for obtaining simpler solvable mathematical models of the existing problems. For a water distribution network analysis, two of the typical assumptions are accepting the demands as not changing for a period of time and suggesting there will be no uncontrolled losses. Due to these assumptions and many uncontrollable factors, the gap between the real case and the analysis results widens.

In order to obtain more realistic and reliable results from the analysis, uncertainties have to be taken into consideration. This can be done by the probabilistic approach. Mathematical representation of the uncertainty within the optimization procedure is the chance constraint application.

2.3.1 Governing Probability Distributions

During the optimization of leakage in a water distribution network, the effects of random factors can be examined from the analysis results. The aim in this study is to reduce the leakage in the network and it is known that the leakage is a function of the pressure at the consumer nodes. Hence, it is proper to associate the uncertain characteristic to the pressure head. This association is made through the probability distribution of the variable.

For the reliability analysis of the continuous random variables, there are various different probability distribution functions (PDF). In this study, Normal and Log-normal distribution will be used as they are the most commonly used ones.

2.3.1.1 Normal Distribution

The normal distribution, which is also known as the Gaussian distribution, is a well-known probability distribution (Ang & Tang, 1975). The probability density function of a normal distribution is given as,

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right], \quad \text{for} \quad -\infty < x < +\infty \tag{2.17}$$

where μ is the mean and σ is the standard deviation. Both are the parameters of the distribution and simple notation for the distribution is $N(\mu, \sigma)$.

In order to make the probability computations, the normal random variable has to be transformed into its standardized varied Z which denotes a distribution with $\mu = 0$ and $\sigma = 1$. X is a normally distributed random variable and since Z is a linear function of X, Z is also normally distributed. This distribution is called the standard normal distribution and denoted as N (0,1). Z can be expressed as,

$$Z = \left(\frac{X-\mu}{\sigma}\right) \tag{2.18}$$

The probability density function of a standard normal distribution is given as,

$$\phi(z) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{z^2}{2}\right], \quad \text{for } -\infty < x < +\infty \tag{2.19}$$

The cumulative distribution function (CDF) tables of Z can be found in statistics textbooks.

Probability of random variable $X \sim N(\mu, \sigma)$ can be described by its CDF, which is

$$P(X \leq x) = P\left[\frac{X-\mu}{\sigma} \leq \frac{x-\mu}{\sigma}\right] = P[Z \leq z] = \Phi(z) \tag{2.20}$$

where x is a value and $\Phi(z)$ is the CDF of standardized variable, Z.

2.3.1.2 Log-Normal Distribution

The logarithmic normal distribution, simply log-normal distribution, is also a commonly used distribution which can be used when the variable cannot be negative (Ang & Tang, 1975). A random variable X has a log-normal probability distribution if $\ln X$ is normal. The probability density function of a log-normal distribution is given as,

$$f_X(x) = \frac{1}{\sqrt{2\pi x\xi}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda}{\xi}\right)^2\right], \quad \text{for } 0 < x < +\infty \tag{2.21}$$

where λ is the mean and ξ is the standard deviation. Both are the parameters of the log-normal distribution. These parameters are related to the mean, μ and the standard deviation, σ as,

$$\lambda = \ln\mu - \frac{1}{2}\xi^2 \tag{2.22}$$

$$\xi = \sqrt{\ln\left(1 + \frac{\sigma^2}{\mu^2}\right)} \tag{2.23}$$

With the logarithmic transformation, log-normal distribution is related with the normal distribution. Thus, the table of standard normal probabilities can be used to determine probabilities associated with the log-normal variable.

2.3.2 Chance Constraint Formulation

In order to obtain chance constrained model, probability concept is applied to the constraints related with the random variable. In this case, random variable is the pressure head and the constraint related with it is the pressure head at the consumer nodes being equal to or higher than the pre-decided minimum. However, as this constraint is embedded to the objective function as a penalty term, chance constraint will be applied to the original constraint first and modified version will be implemented as penalty.

2.3.2.1 The Normal Distribution

In the chance constrained optimization formulation, pressure head constraint will be adjusted by taking the normal probability distribution into consideration (Mays & Tung, 1992).

Replacing the pressure head constraint, Equation (2.3), with a probabilistic statement in the form of chance constraint,

$$P\left\{ HP_{k,t} \geq HP_{k,t,min} \right\} \geq \varphi \tag{2.24}$$

where φ is the specified reliability of lower pressure head limit.

Equation (2.24) is not mathematically operational for algebraic solution. So, deterministic equivalent of this equation can be obtained by the following steps. Lower limit, $HP_{k,t,min}$, is accepted to have a cumulative distribution function (CDF) with mean μ_H and standard deviation σ_H. Equation (2.24) is equivalent to,

$$P\left[\ HP_{k,t,min} \leq HP_{k,t} \right] \geq \varphi \tag{2.25}$$

which can also be expressed in terms of the CDF of $H_{k,t,min}$,

$$F_H\left(HP_{k,t}\right) \geq \varphi \tag{2.26}$$

Using Equation (2.18), standardized versions of random variable $HP_{k,t,min}$ is obtained as,

$$Z_H = \left(\frac{HP_{k,t,min} - \mu_H}{\sigma_H}\right) \tag{2.27}$$

Introducing Equation (2.27) to Equations (2.25) and (2.26), these can be expressed as respectively,

$$P\left[\ Z_H \leq \frac{HP_{k,t} - \mu_H}{\sigma_H}\right] \geq \varphi \tag{2.28}$$

and

$$F_{Z_H}\left(\frac{HP_{k,t} - \mu_H}{\sigma_H}\right) \geq \varphi \tag{2.29}$$

Deterministic equivalent of the original chance constraint, Equation (2.24), is the inverse of Equation (2.29),

$$\frac{HP_{k,t} - \mu_H}{\sigma_H} \geq F_{Z_H}^{-1}(\varphi) \tag{2.30}$$

Equation (2.30) can be rearranged as,

$$HP_{k,t} \geq \mu_H + (z_{H,\ \varphi})\sigma_H \tag{2.31}$$

where the specific value of $z_{H,\varphi}$ is $F_{Z_H}^{-1}(\varphi)$, which is the $(\varphi)^{\text{th}}$ quantile of the standardized $HP_{k,t,min}$. Knowing the PDF of $HP_{k,t,min}$ and the required constraint reliability, φ, the specific value $z_{H,\varphi}$ can be determined. As $HP_{k,t,min}$ is assumed to have a normal distribution, $z_{H,\varphi}$ is referring to the standardized normal variant

$\phi(z_{H,\varphi}) = \varphi$ where $\phi()$ is the standard normal CDF that is expressed in Equation (2.20).

Thus, the pressure head limitation constraints at the consumer nodes, Equation (2.3), is modified into Equation (2.31) for normal probability distribution application.

2.3.2.2 The Log-Normal Distribution

Similarly, pressure head constraint will be adjusted by taking the probability distribution of log-normal in this case. Same procedure with the normal distribution will be applied from Equation (2.24) to Equation (2.26). After Equation (2.26), standardization will be done according to the log-normal distribution of pressure head.

As it is explained in the Log-normal distribution part, 2.3.1.2, table of standard normal probabilities can be used to determine probabilities associated with the log-normal variable; though, its own mean, λ_H and standard deviation, ξ_H must be used. Thus, using Equation (2.18) and corresponding parameters, standardized versions of random variable $HP_{k,t,min}$ is obtained as,

$$Z_H = \left(\frac{ln(HP_{k,t,min}) - \lambda_H}{\xi_H}\right) \tag{2.32}$$

Introducing Equation (2.32) to Equations (2.25) and (2.26), these can be expressed as respectively,

$$P\left[\ Z_H \ \leq \ \frac{ln\left(HP_{k,t}\right) - \lambda_H}{\xi_H}\ \right] \geq \varphi \tag{2.33}$$

and

$$F_{Z_H}\left(\frac{ln\left(HP_{k,t}\right) - \lambda_H}{\xi_H}\right) \geq \varphi \tag{2.34}$$

Deterministic equivalent of the original chance constraint, Equation (2.24), is the inverse of Equation (2.34),

$$\frac{ln\left(HP_{k,t}\right) - \lambda_H}{\xi_H} \geq F_{Z_H}^{-1}(\varphi) \tag{2.35}$$

Equation (2.35) can be rearranged as,

$$HP_{k,t} \geq e^{\left(\lambda_H + (z_{H,\varphi})\xi_{\underline{C}}\right)} \tag{2.36}$$

where the specific value of $z_{H,\varphi}$ is $F_{Z_H}^{-1}(\varphi)$, which is the $(\varphi)^{th}$ quantile of the standardized $HP_{k,t,min}$. Knowing the PDF of $HP_{k,t,min}$ and required constraint reliability, φ the specific value $z_{H,\varphi}$ can be determined. As $HP_{k,t,min}$ is assumed to have a log-normal distribution, $z_{H,\varphi}$ is referring to the standardized normal variant $\phi\left(z_{H,\varphi}\right) = \varphi$ where $\phi()$ is the standard normal CDF that is expressed in Equation (2.20).

Hence, the pressure head limitations constraints at the consumer nodes (Equation 2.3) is modified into Equation (2.36) for log-normal probability distribution application.

CHAPTER 3

SOLUTION METHODOLOGY

Formulation of leakage reduction by pressure optimization in a water distribution network is explained in the previous chapter. Two cases with different objective functions are created with this purpose. The mutual aim is to find the PRV settings for each hour that will minimize leakage while satisfying the hydraulic and bound constraints. Due to the complexity of the water distribution networks with numerous components, the problem becomes a large scale non-linear programming problem. A reduction technique will be applied for simplification of this complex problem (Brion & Mays, 1991; Lansey & Mays, 1990; Sakarya, 1998). The solution will be achieved by the use of a combination of hydraulic simulation code and a non-linear optimization code.

3.1 Basic Solution Approach

The solution procedure of the pressure optimization in a water distribution network for leakage reduction is basically composed of two codes used in a correlative way. The first of them is the hydraulic simulation code, EPANET by Rossman (2000). The second one is the non-linear optimization code, LSGRG2 which is developed by Lasdon, Warren, Smith and Plummer at 1998.

In both of the cases, the independent variable is the PRV setting for each hour. Throughout the procedure, optimization code LSGRG2 will calculate the new values of the control variables and EPANET will calculate the corresponding state variables such as discharge, pressure head and tank level with the new values of the control variables (Figure 3-1). The details of this process will be explained in the following sections.

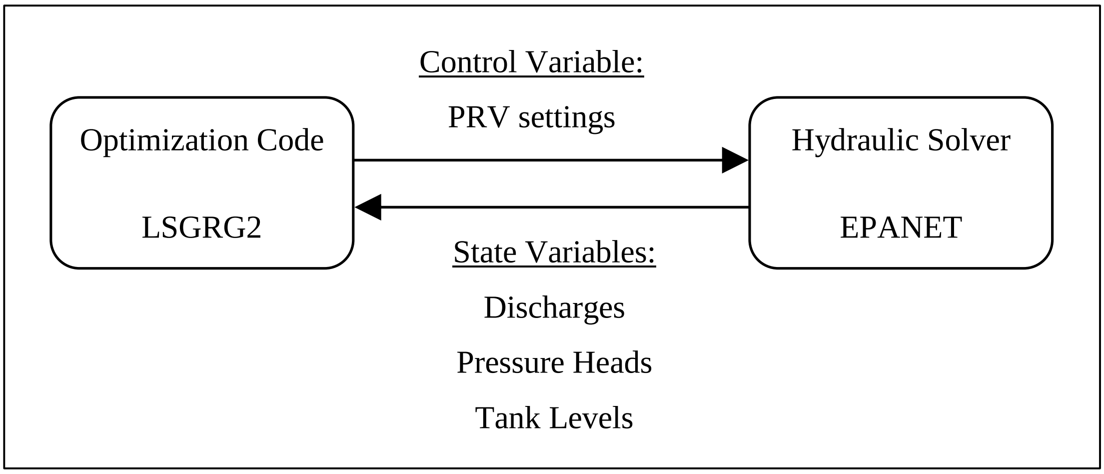

Figure 3-1: Optimization Code – Hydraulic Solver linkage

Moreover, in both of the cases there exists constraints of conservation of mass (Equation 2.1) and conservation of energy (Equation 2.2). EPANET by its simulation method will satisfy both of them. Thus, with the use of this hydraulic solver, these two constraints can be removed from both of the cases.

3.2 The Reduced Problem

The reduced problem is obtained by the use of generalized reduced gradient (GRG) method (Mays & Tung, 1992). The main aim in this method is to convert a constrained non-linear optimization problem to an unconstrained one so that the complexity of the problem will decrease.

A generalized non-linear optimization problem with non-linear objective can be expressed as,

$$Minimize\ h(x) \tag{3.1}$$

subject to

$$g(x) = 0 \qquad i = 1, \ldots, m \tag{3.2}$$

and

$$\underline{x}_j \leq x_j \leq \overline{x}_j \qquad j = 1, \ldots, n \tag{3.3}$$

where Equation (3.3) is a bound constraint for the j^{th} decision variable x_j with an upper limit of $\overline{x}_j$ and lower limit of $\underline{x}_j$.

The decision variables can be divided into two groups as basic, x_B, and nonbasic , x_N, variables. There are m number of basic variables, which are the constraint equations and $(n\text{-}m)$ number of nonbasic variables.

$$x = (x_B, x_N) \tag{3.4}$$

With the new definition of variables, the optimization problem can now be stated as,

$$Minimize\ h(x_B, x_N) \tag{3.5}$$

subject to

$$g(x_B, x_N) = 0 \tag{3.6}$$

and

$$\underline{x}_B \leq x_B \leq \overline{x}_B \tag{3.7}$$

$$\underline{x}_N \leq x_N \leq \overline{x}_N \tag{3.8}$$

In theory, basic variables can be defined as the functions of nonbasic variables $x_B(x_N)$. As a result, the objective function of a reduced problem becomes,

$$Minimize\ H(x_B(x_N), x_N) \tag{3.9}$$

In this way constraints are embedded into the objective function and the problem becomes unconstrained non-linear minimization problem.

$$Minimize\ H(\ x_N\ ) \tag{3.10}$$

subject to

$$\underline{x}_N \leq\ x_N \leq \overline{x}_N \tag{3.11}$$

Hence, by using generalized reduced gradient method, original problem (Equation 3.1, 3.2, 3.3) can be solved by a sequence of reduced problems (Equation 3.10, 3.11).

3.3 The Reduced Problem with the Penalty Method

When the final reduced form of the problem is simulated, non-linear programming solver will try to reduce the objective function value by changing the control variable as it is a minimization formulation. This change in the control variable, which is the step size, is adjusted by the solver so that the variable stays within the limitations. For the determination of the step size, state variables are not taken into consideration although they are implicit functions of control variables. So, if there exists a violation in the state variables, more iterations would be needed for a feasible result. In order to overcome this problem, the penalty method is introduced.

With the penalty method, state variable bounds are incorporated in the objective function as penalty terms. Usage of this method has two main advantages. First one is that it will decrease the number of iterations to have a feasible solution with state variables within their limitations. And also it will decrease the size of the problem as the state boundary constraints are embedded to the objective function.

There are various types of different penalty function forms (Gill, Murray, & Wright, 1981; McCormick, 1983). The Augmented Lagrangian and the Bracket Penalty methods are two different forms of the penalty functions. In this thesis, the Bracket Penalty method (Li & Mays, 1995; Ravindran, Ragsdell, & Reklaitis, 2006; Sakarya, 1998) will be used as it is founded to be similarly effective as the Augmented Lagrangian form (Sakarya, 1998) for water distribution network analysis. And also, it is less complicated than the latter one.

In this study, state variable constraints inserted into the objective function are the pressure head and the tank level limitation. Firstly, violation of the pressure head limitation constraint at the consumer nodes (Equation 2.3) is expressed as, $V_{HP,k,t}$,

$$V_{HP,k,t} = HP_{k,t} - HP_{k,t,min} \quad \text{for } k = 1, \ldots, K \text{ and } t = 1, \ldots, T \quad (3.12)$$

where $V_{HP,k,t}$ is the pressure head violation for time interval t and for each control point k.

The Bracket Penalty function of the pressure violation term can be expressed as,

$$PB_{HP}(V_{HP,k,t}, R_H) = R_H \sum_{k=1}^{K} \sum_{t=1}^{T} \left[min(0, V_{HP,k,t})\right]^2 \quad (3.13)$$

where PB_{HP} defines the bracket penalty function and R_H is the penalty coefficient for the pressure head violation. If there is no violation (i.e. $HP_{k,t} \geq HP_{k,t,min}$) penalty term will be zero.

Similarly, violation of the tank level variation constraint (Equation 2.4) is expressed as, $V_{HP,k,t}$,

$$V_{y,s} = y_{s,ft} - y_{s,it} \quad \text{for } s = 1, \ldots, S \quad (3.14)$$

where $V_{y,s}$ is the tank level violation for tank S. Likewise, if there is no violation (i.e. $y_{s,ft} \geq y_{s,it}$) penalty term will be zero.

The Bracket Penalty function of the tank level violation term can be expressed as,

$$PB_y(V_{y,s}, R_y) = R_y \sum_{s=1}^{S} \left[min(0, V_{y,s})\right]^2 \quad (3.15)$$

where PB_y defines the bracket penalty function and R_y is the penalty coefficient for the tank level violation.

Objective functions for both of the cases will be modified with these penalty terms. Altering of the objective functions and corresponding constraints can be seen in Figure 3-2. The objective function for Case I, Equation (2.6) will be transformed into,

$$Minimize\ f = \sum_{k=1}^{K}\sum_{t=1}^{T} HP_{k,t} + R_H \sum_{k=1}^{K}\sum_{t=1}^{T}\left[min\left(0, V_{HP,k,t}\right)\right]^2 + R_y \sum_{s=1}^{S}\left[min\left(0, V_{y,s}\right)\right]^2 \tag{3.16}$$

And the objective function for Case II, Equation (2.7) will be transformed into,

$$Minimize\ f = \sum_{j=1}^{N}\sum_{t=1}^{T} Q_{leak,j,t} + R_H \sum_{k=1}^{K}\sum_{t=1}^{T}\left[min\left(0, V_{H,k,t}\right)\right]^2 + R_y \sum_{s=1}^{S}\left[min\left(0, V_{y,s}\right)\right]^2 \tag{3.17}$$

For both of the cases, conservation of mass (Equation 2.1) and conservation of energy (Equation 2.2) are satisfied with the use of the hydraulic solver EPANET. Moreover, the constraints for state variables, pressure head limitations (Equation 2.3) and the tank level variations (Equation 2.4) are integrated into the objective functions with the penalty method. The only constraint that is remaining is corresponding to the control variable, the pressure settings of the PRVs, to be between a given upper and lower bounds (Equation 2.5).

Final form of Case I is with the objective function of Equation (3.16) and the boundary constraint Equation (2.5). Likewise, final form of Case II is with the objective function Equation (3.17) and the boundary constraint Equation (2.5). Note that all of the state variables in the modified objective functions, the pressure head values, leakages and the water level in the tank, are all implicit functions of control variables, which is the

PRV settings. These final forms of the optimization problems will be solved with the non-linear optimization code LSGRG2.

Considering the penalty method, if there is no violations of the constraints, violation terms $V_{HP,k,t}$ and $V_{y,s}$ will become positive and penalty function values PB_{HP} and PB_y, will be zero. So, if there is no violations, there will be no penalty. When the violation occurs, penalty term will increase the objective function value which is not desired in a minimization problem. As a result, the program will try to prevent the violation by changing the decision variable in order to reduce the objective function value.

The penalty coefficients, R_H and R_y, must be defined at the beginning and modified throughout the procedure. The aim of this is to adjust the relative importance of the penalty term with respect to the main term of the objective function.

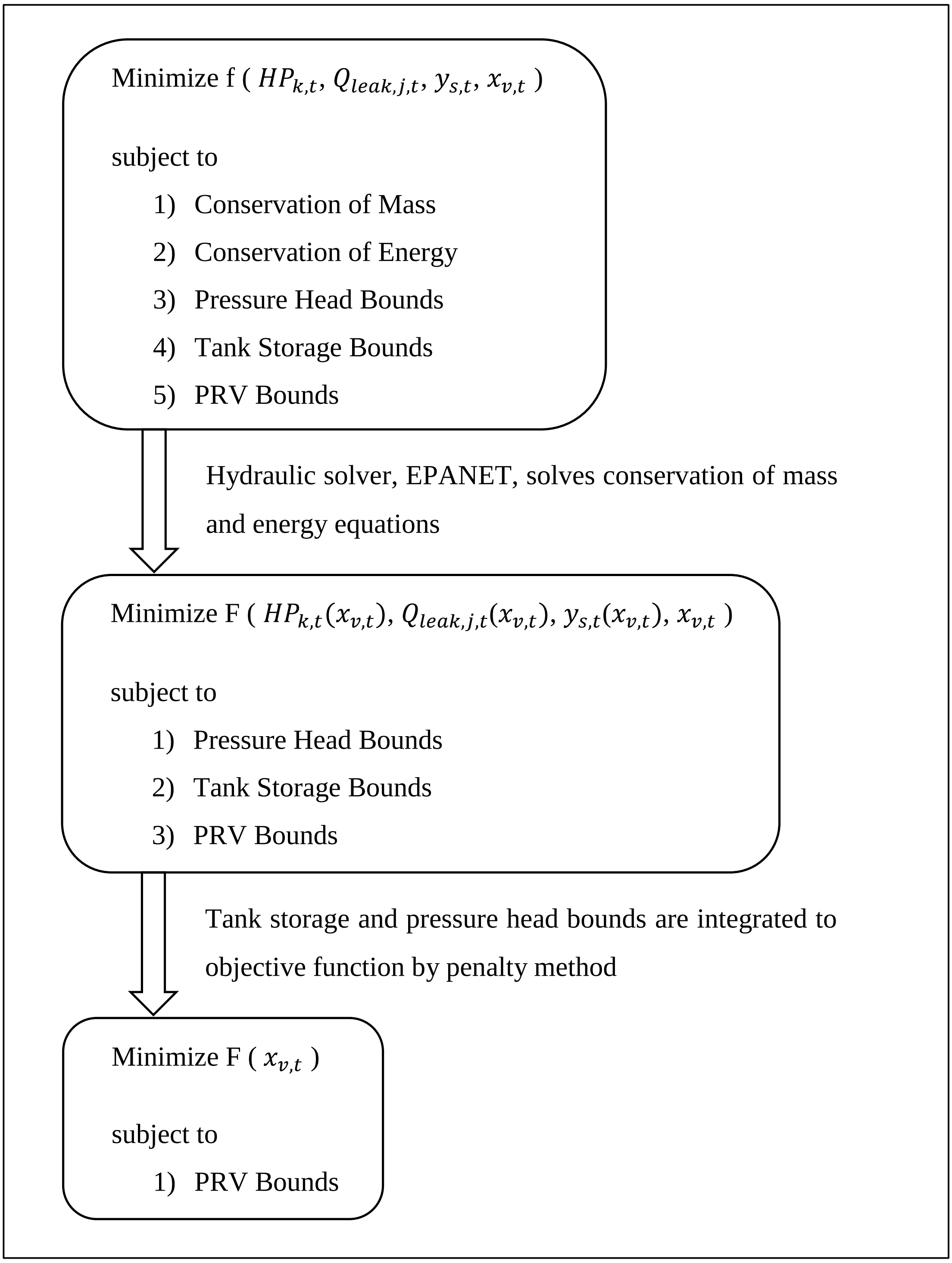

Figure 3-2: Transformation of pressure optimization formulation for leakage reduction problem

3.4 Computation of Reduced Gradients

The non-linear programming optimization code LSGRG2, uses generalized reduced gradient (GRG) method to solve the problems (Lasdon & Waren, 1997). Computation of the reduced gradient is necessary for the method to define the search direction in the optimization process. And this is fundamentally achieved by taking the derivative of the reduced objective function with respect to the control variables. Reduced gradient calculations for each of the cases will be explained in this section.

Gradient of Case I is the derivative of its objective function Equation (3.16) with respect to the control variables, pressure head settings for valve, $x_{v,t}$,

$$\frac{\partial f}{\partial x_{v,t}} = \frac{\partial HP_{k,t}}{\partial x_{v,t}} + \frac{\partial PB_{HP}}{\partial x_{v,t}} + \frac{\partial PB_{y}}{\partial x_{v,t}} \tag{3.18}$$

Using the chain rule, the second term in the Equation (3.18),

$$\frac{\partial PB_{HP}}{\partial x_{v,t}} = \frac{\partial PB_{HP}}{\partial V_{HP,k,t}} \frac{\partial V_{HP,k,t}}{\partial HP_{k,t}} \frac{\partial HP_{k,t}}{\partial x_{v,t}} \tag{3.19}$$

And this derivative is equals to,

$$= \begin{cases} \left(2R_H\left(HP_{k,t} - HP_{k,t,min}\right)\right) \dfrac{\partial HP_{k,t}}{\partial x_{v,t}} & if\ HP_{k,t} < HP_{k,t,min} \\ 0 & if\ HP_{k,t} \geq HP_{k,t,min} \end{cases} \tag{3.20}$$

Similarly, the third term in Equation 3.18,

$$\frac{\partial PB_{y}}{\partial x_{v,t}} = \frac{\partial PB_{y}}{\partial V_{y,s}} \frac{\partial V_{y,s}}{\partial y_{s}} \frac{\partial y_{s}}{\partial x_{v,t}} \tag{3.21}$$

And this derivative is equal to,

$$= \begin{cases} \left(2R_y\left(y_{s,ft} - y_{s,it}\right)\right) \left(\dfrac{\partial y_{s,ft}}{\partial x_{v,t}} - \dfrac{\partial y_{s,it}}{\partial x_{v,t}}\right) & if\ y_{s,ft} < y_{s,it} \\ 0 & if\ y_{s,ft} \geq y_{s,it} \end{cases} \tag{3.22}$$

To summarize, the reduced gradient for Case I is composed of $\frac{\partial HP_{k,t}}{\partial x_{v,t}}$ plus Equation (3.20) and Equation (3.22).

In the same way, gradient of Case II is the derivative of its objective function Equation (3.17) with respect to the control variables, pressure head settings for valve, $x_{v,t}$,

$$\frac{\partial f}{\partial x_{v,t}} = \frac{\partial Q_{leak,j,t}}{\partial x_{v,t}} + \frac{\partial PB_{HP}}{\partial x_{v,t}} + \frac{\partial PB_{y}}{\partial x_{v,t}} \tag{3.23}$$

The derivatives of the second and the third term are same with the Case I. Thus, the reduced gradient for Case II is composed of $\frac{\partial Q_{leak,j,t}}{\partial x_{v,t}}$ plus Equation (3.20) and Equation (3.22).

In order to calculate the reduced gradients, derivatives of the state variables with respect to control variables, $\frac{\partial HP_{k,t}}{\partial x_{v,t}}$, $\frac{\partial Q_{leak,j,t}}{\partial x_{v,t}}$, and $\frac{\partial y_{s,ft/it}}{\partial x_{v,t}}$, are needed. Both of the state variables are implicit functions of the control variables and the derivatives are numerically calculated by using finite difference method. For the pressure head derivative,

$$\frac{\partial HP_{k,t}}{\partial x_{v,t}} = \frac{{HP_{k,t}}^{i} - {HP_{k,t}}^{f}}{\Delta x} \tag{3.24}$$

where ${HP_{k,t}}^{i}$ is the initial pressure head for control point *k*, Δx is the step size for changing control variable and ${HP_{k,t}}^{f}$ is the final pressure head for control point *k* calculated after changing control variable by Δx.

Furthermore, for the leakage derivative,

$$\frac{\partial Q_{leak,j,t}}{\partial x_{v,t}} = \frac{{Q_{leak,j,t}}^{i} - {Q_{leak,j,t}}^{f}}{\Delta x} \tag{3.25}$$

where ${Q_{leak,j,t}}^{i}$ is the total initial leakage in the network, Δx is the step size for changing control variable and ${Q_{leak,j,t}}^{f}$ is the total final leakage in the network calculated after changing control variable by Δx.

Finally, for the tank level derivative,

$$\frac{\partial y_{s,ft/it}}{\partial x_{v,t}} = \frac{{y_{s,ft/it}}^{i} - {y_{s,ft/it}}^{f}}{\Delta x} \tag{3.26}$$

where ${y_{s,ft/it}}^{i}$ is the initial water level in the tank s at time interval *ft/it*, Δx is the step size for changing control variable and ${y_{s,ft/it}}^{f}$ is the final water level in the tank s at time interval *ft/it* calculated after changing control variable by Δx.

These derivative values are calculated for all time intervals and for all PRVs. For each time step, the value of the PRV setting is changed and new state variable values are calculated by EPANET. Hence, the effects of changing each PRV setting at each time interval are calculated.

3.5 Summary of the Solution Algorithm

For the solution of the pressure optimization to reduce leakage in a water distribution network problem, the first step is to apply reduction and penalty methods to the formulation. After the reduced problem with the penalty functions are obtained, one of the two cases is selected and initial values of penalty coefficients, minimum pressure heads for the selected control points and limitations for the PRVs settings are defined.

Before starting the optimization procedure, the emitter coefficients for the selected network are calibrated with Cobacho et al. (2013)’s method and as these coefficients are network dependent, they will not change throughout the procedure. Note that, for the calibration process, analyzed network is used in its non-PRV form. When PRVs are attached to the network, the pressure head and leakage amounts in Equation (2.11) would change in each iteration. Thus, a convergence would not be achieved with this alteration. After the calibration, PRVs are attached to the network for the optimization.

During the calibration procedure, all of the discharge and the pressure values are calculated by EPANET.

While setting limitations for the PRVs, the user defined values are taken as initial values. However, as it is described before, PRVs start to control the pressure when the set value is violated at the node located after the PRV. So, if the upper limit for the PRV, $\overline{HP}_{v,t}$, is defined as 80 m and the pressure head at the node after the PRV is 50 m, the PRV will not be active. While calculating reduced gradients, depending on the value of the step size, Δx, state variable difference of the initial and the final values will not change as can be seen from Equations (3.24) - (3.26). If the step size is 4 m, the initial set will be 80 m and the final set will be 76 m. In both of the settings, PRV will be inactive as it will start to be active at 50 m and the difference will be zero. Thus, within the gradient calculation procedure, the step size value will be increased with a selected increment until the difference has a non-zero value. This increases the amount of calculations performed during one run. Hence, before starting the analysis, a modification is made on the upper limit setting of the PRVs in order to decrease the calculation load. EPANET is called with the initial values and the calibrated network to calculate the pressure head values at the points after PRVs. If the values are lower than the initially entered upper limits, $\overline{HP}_{v,t}$ is modified with the newly calculated values. Final values of the upper limits, $\overline{HP}_{v,t}$, are used as initial values of decision variables in the optimization.

With all of the input, problem is run with the interactive work of optimization solver, LSGRG2 and hydraulic solver EPANET. LSGRG2 uses reduced gradients for the calculations of the step sizes and gives improved values of the control variables, which are the PRVs settings.

Following, if there is any violation penalty coefficients are increased, to increase the importance of the penalty in the objective function. In addition to that, initial values of the control variables are changed to the improved results obtained from the LSGRG2 results. And the program is run once again with the modified values. This improvement loop will be repeated continuously until one or more of the three overall optimum criteria are met. These criteria are, reaching to the pre-defined iteration limit or having no improvement in the objective function or control variable values for a pre-defined number of iterations. Flow chart of the solution algorithm can be seen in Figure 3-3 below.

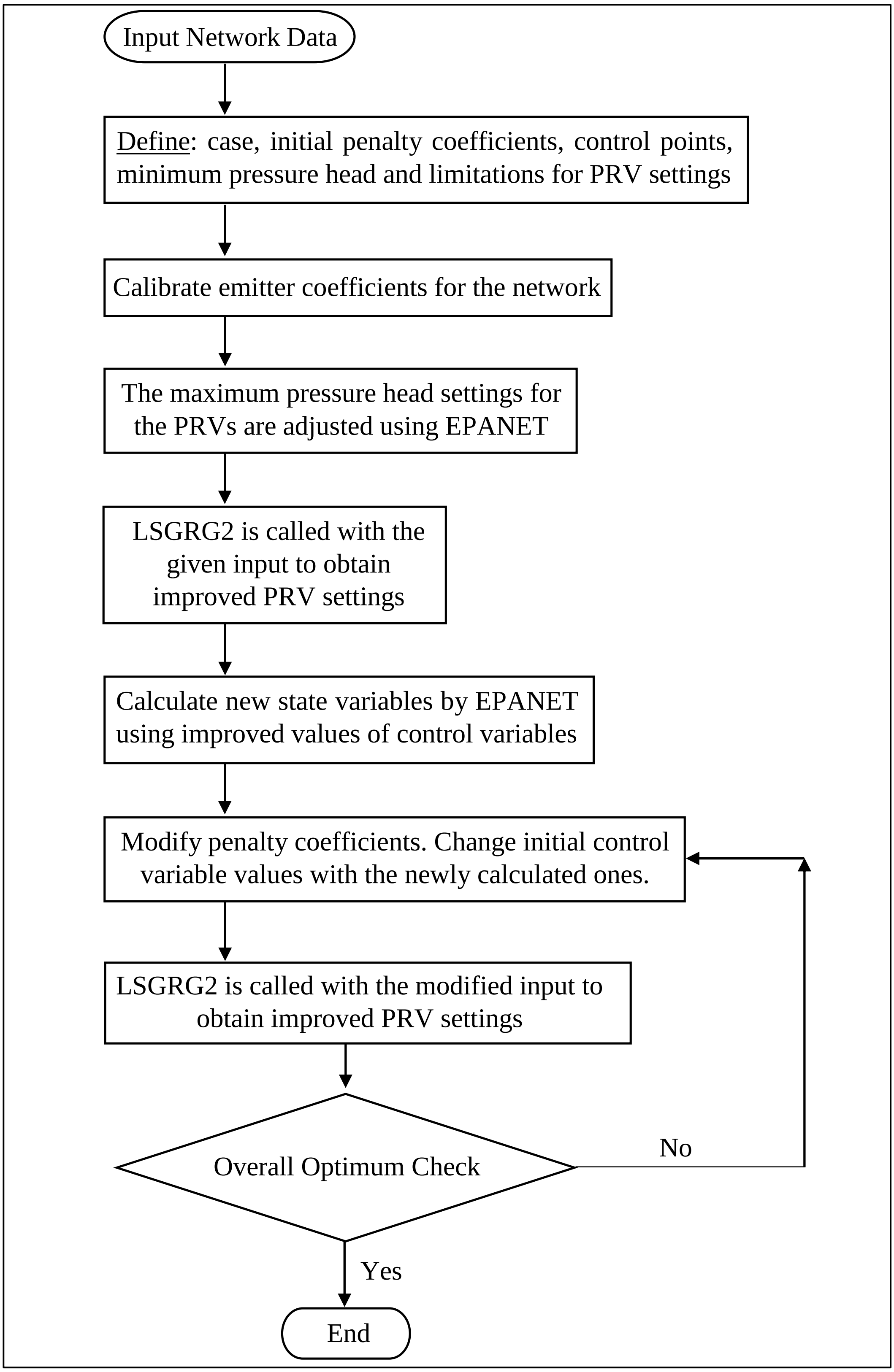

Figure 3-3: Flow chart of the pressure optimization model

CHAPTER 4

PROGRAM STRUCTURE

Formulation and the solution approach of leakage reduction with pressure optimization of PRVs in a water distribution network is explained in Chapter 2 and 3. In this chapter, details of the model and the combined program will be explained.

4.1 Overview of the Model

The main aim in this study is to reduce the leakage in a water distribution network by adjusting pressure settings of PRVs integrated in the selected locations of the network. With this aim, two different objective functions are used for comparison. First one is the minimization of total pressure heads in the control nodes as leakage is pressure dependent. The second one is to minimize total leakage in the network.

The decision variables are divided into two types, which are control and state variables. Control variables are independent variables and they are PRV settings in this formulation. State variables are dependent variables and they are pressure heads at the control nodes, total leakage in the system and the water levels in the tanks. The program calculates the values of the control variables by using the optimization solver, LSGRG2 and uses them as input to hydraulic simulator, EPANET to calculate the corresponding values of the state variables. State variables are implicit functions of control variables as they are depending on the current values of the control variables.

There are five constraints for this problem. Two of them are the mass and energy conservation equations, and the other two are the limitations for state variables and one for the limitations of the control variables. Hydraulic solver, EPANET satisfies the mass and energy conservation equations in its solution methodology; thus, the continuity constraints are always satisfied and can be removed from the constraint list. The constraints corresponding to the state variables are integrated into both of the objective functions as penalty terms. In this study, Bracket Penalty method is used for the penalty definitions. For both of the penalties, there exist penalty coefficients which must be defined before starting the optimization procedure.

With these reduction and penalty method applications, the final form of the optimization problem is obtained. For the solution, a computer program LEAK_PROB is created in MATLAB. The program is mainly composed of three parts which are the optimization, the hydraulic analysis and finally the interfacing part. Optimizations are carried out by the non-linear optimization code, LSGRG2 to calculate the improved values of the control variables. Moreover, the hydraulic analysis are done by the hydraulic simulator, EPANET to calculate the corresponding state variables. Lastly, the interfacing part is handling acquisition and processing of the data and the interaction between these two simulators.

Before starting the optimization, the emitter coefficient calibration on the non-PRV version of the same network is done by using Cobacho et al. (2013)'s method. Also, upper limit of the PRV settings are modified to find PRVs active region in order to decrease the workload. In both of the applications, EPANET is used to calculate the flow rates and the pressure heads.

With the initial input values, LSGRG2 is called to initialize optimization. For improving control variable values, LSGRG2 needs reduced gradients to calculate the step size. And for the calculations of reduced gradients and the value of the objective function, current value of the state variables are needed in each iteration step which can be calculated by EPANET. LSGRG2 code has two user definable subroutines, GCOMP and PARSH that allows the link between LSGRG2, LEAK_PROB and EPANET.

During optimization, LSGRG2 will repeatedly call EPANET in each iteration to calculate the necessary values to improve the control variables accordingly until it reaches an optimum point. After the new set of control variables are obtained, penalty coefficients are modified and new values are taken as the initial values for the next LSGRG2 run. This loop will continue until one or more of the overall optimality criteria are met which are exceeding of the pre-defined iteration limit or having no improvement in the objective function or control variable values for a pre-defined number of consecutive iterations.

The flow chart of the program LEAK_PROB can be seen in Figure 4-1.

4.2 Optimization Model LSGRG2

The optimization solver used in this study is LSGRG2 which is developed by Lasdon, Warren, Smith and Plummer at 1998. It is an extension of GRG (Lasdon & Waren, 1997) that includes sparse matrix calculations and increased size limit of variables and constraints. LSGRG2 is basically a computer code written in both FORTRAN and C languages which can solve large scale non-linear optimization problems by using generalized reduced gradient method (Lasdon & Waren, 1979; Lasdon, Waren, Jain, & Ratner, 1978). There are a lot of different non-linear programming solvers like GAMS, CPLEX and MATLAB non-linear programming solver, fmincon. LSGRG2 is selected for this study depending on the two main advantages which the rest of the solvers do not have. The first one is its capability to handle large scale non-linear problems and the second one is it allows the usage of user defined gradient calculations.

The code has two subroutines GCOMP and PARSH which allow users to define objective function and gradient calculations. GCOMP is handling the calculations of objective function. In this study, the final form of the objective function with reduction and penalty method application is defined in GCOMP.

Likewise, PARSH is used for calculating reduced gradient values to determine search directions and step sizes. LSGRG2 uses first derivative of the objective function and constraints with respect to each variable which are calculated by finite difference approximations if the subroutine PARSH is not supplied by the user. For this work, reduced gradients are defined in PARSH as partial derivatives of the objective function with respect to control variables.

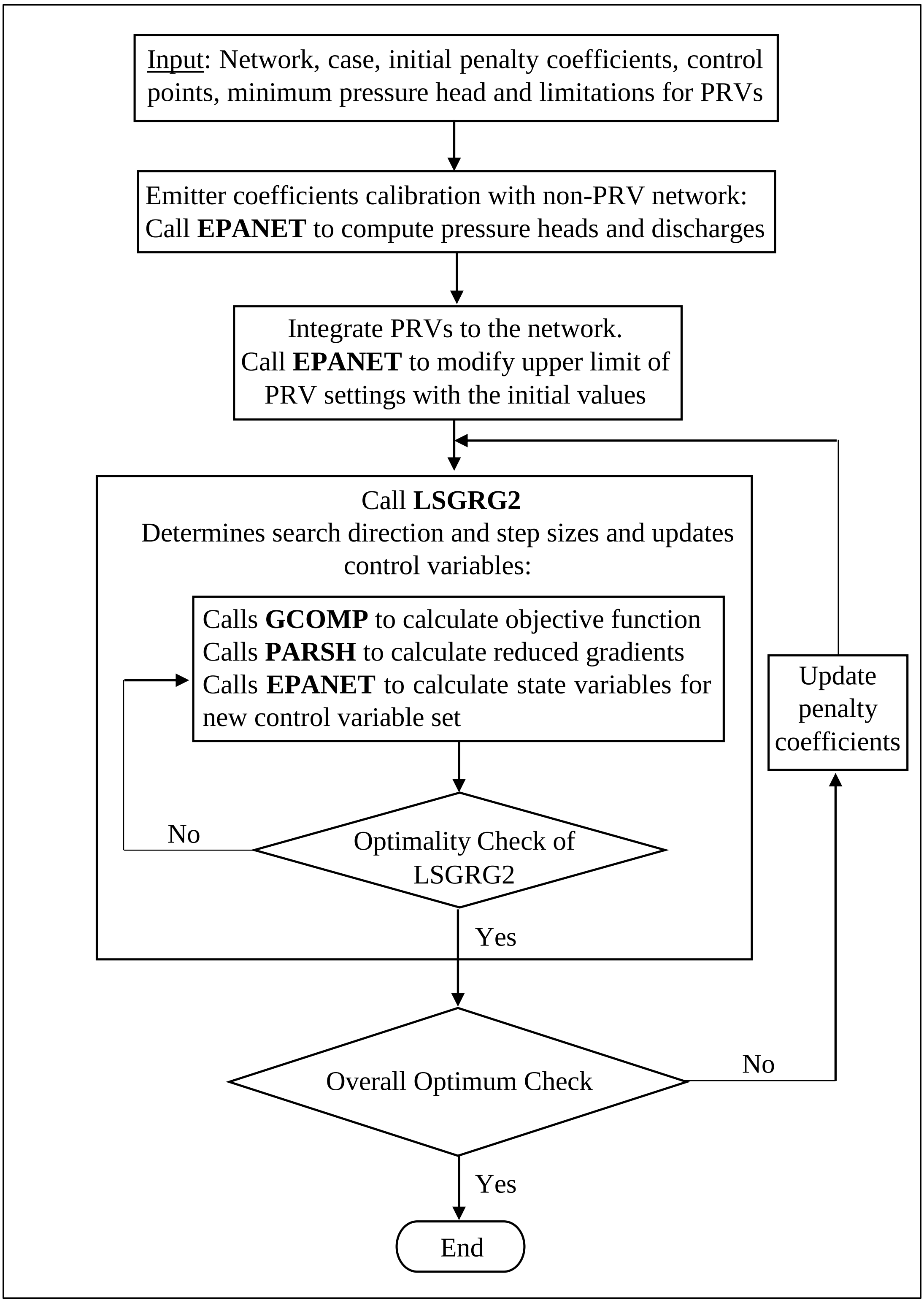

Figure 4-1: The flow chart of the program LEAK_PROB

LSGRG2 calls GCOMP and PARSH multiple times in a loop within its solution procedure until it finds an optimum solution with the given input.

In this study, C code version of LSGRG2 is used in order to be consistent with EPANET, which is also written in C language. For LSGRG2 to be callable from MATLAB, an additional function is added at the end of the C code. This additional function defines that the input values are going to be taken from MATLAB and makes the conversion of the data types, so that they can be consistent with the C code definitions. Also, it allows the C code to use the aforementioned subroutines (PARSH and GCOMP) to be called from MATLAB functions.

4.3 Hydraulic Solver EPANET

In this study, EPANET is used as the hydraulic solver. It is a computer program written in C language which performs extended period simulation on pressurized pipe networks to observe hydraulic and water quality behaviors. The program basically tracks the discharges in pipes, the pressures at nodes, the water levels in tanks and the chemical concentrations throughout the network for whole simulation period of several time steps.

EPANET uses a hybrid node-loop approach developed by Todini & Pilati (1987), which is called the “Gradient Method” (Salgado, Todini, & O’Connell, 1988), to solve mass and energy conservation equations that define the hydraulic state of the network at a given point in time (Rossman, 2000).

EPANET is an open source program and has a toolkit which allows the user to call desired functions from other programs; in the case of this study, from MATLAB. As EPANET is a C language based program, functions have to be converted to a version in which they can be called from MATLAB. KIOS Research Center for Intelligent Systems and Networks (University of Cyprus, www.kios.org.cy) has developed a MATLAB class named EPANET-MATLAB (2013), which includes a list of all C code functions of EPANET in the form of MATLAB callable functions. In order to run the analysis, the user has to supply the input file in the format of EPANET (.inp), order the necessary functions from the class and define which outputs are required.

In this study, EPANET is used to calculate values of the state variables using known control variable values. For each call, the control variables, which are the pressure settings of the PRVs for each time interval, are given from MATLAB as inputs in the form of control statements to EPANET. Then, state variables, which are the pressures at the control nodes, leakages and the tank levels, are calculated by EPANET.

4.4 Combination Code in MATLAB

The computer program LEAK_PROB is created using MATLAB. The main body written in MATLAB is responsible of data gathering, data processing and the interaction between hydraulic simulator, EPANET and optimization solver, LSGRG2. Firstly, initial inputs such as the case, the network, initial penalty coefficients, control points, minimum pressure head and limitations for PRV settings are defined in the code.

The network must be supplied in both non-PRV version and with the desired PRV configurations. The non-PRV version is used for the emitter coefficient calibration. A MATLAB function, EMIT_CALIB, is created for this calibration process which is explained in Section 2.2.2. Within the procedure, function modifies emitter coefficients in each step and send the new calculated ones to EPANET to calculate all discharge and pressure values.

In the main code, initial values are rearranged in the required format and sent to LSGRG2 for optimization. For the objective function and constraint calculations, a function, which is called LEAK_FUNCS, is created in MATLAB to substitute GCOMP subroutine. Every time LSGRG2 needs to compute the objective function value, it calls GCOMP and, since the link is already defined in the C code, GCOMP calls the function LEAK_FUNCS from MATLAB. Within LEAK_FUNCS, hydraulic calculations are carried out by calling EPANET. Thus, the interface between LSGRG2 and EPANET is established through MATLAB.

For the reduced gradient calculations, a function called LEAK_PARSH, is created in MATLAB to substitute PARSH subroutine. The relationship between LEAK_PARSH and PARSH is the same as the one between LEAK_FUNCS and GCOMP.

For EPANET calls during LEAK_PROB runs, a function named RUNEPA_LEAK is built. This function includes the arrangement of all of the input values that need to be sent to EPANET, calling of the necessary functions and arrangement of the required hydraulic outputs.

As the initial LSGRG2 run finishes, LEAK_PROB enters the loop. After each iteration, program makes the check of pressure and tank level violations after the overall optimality check. If violation exists, it modifies the penalty coefficients to increase the significance of the penalty term in the objective function by,

$$R^{k+1} = R^{k} \Delta R \tag{4.1}$$

where R denotes R_H and R_y, ΔR is the pre-determined modification factor and k represents the iteration number in the loop.

Additionally, LEAK_PROB changes the initial values of the control variables to the newly calculated ones after the first run of LSGRG2. With the modified penalty coefficients and initial values, LSGRG2 is called to optimize again. The loop will continue until one or more of the overall optimality conditions are met. The program has three optimality checks that are reaching to the pre-defined iteration limit or having no improvement in the objective function or control variable values for a pre-defined number of iterations.

Final part of the program calculates the leakage reduction with the new control variable set, checks the pressure head conditions at the control points and plots the tank levels for whole simulation period to check the periodicity.

CHAPTER 5

APPLICATION RESULTS

In this chapter, application of the formulated optimization model on three different example networks will be examined in detail. The effects of different PRV configurations, optimization formulations and pressure limitations will be discussed for each of the three networks with different complexity levels.

5.1 General Information

There are some common concepts and parameters which are valid for all applications such as periodicity, values of pressure limitations and exponent, and penalty coefficients.

5.1.1 Periodicity

In all of the applications, the network hydraulic dynamics is done by the daily 24 *h* periodic cycle of both demand and pump patterns. When tanks exist in the network, the 24 *h* simulation time will not be enough to reach a stable hydraulic condition. For these cases, the analyses are carried out with a 168 *h* simulation time in order to reach the periodic cycle of hydraulic dynamics. For each case, this periodic cycle check is done for all the tanks in the network. Hydraulic and pattern time steps are taken as 1 *h*. Once the periodicity is reached, the results are considered as stable and only the last 24 *h* results of the 168 *h* analyses are used for the calculations. An example periodicity check on a tank level variation graph can be seen in Figure 5-1.

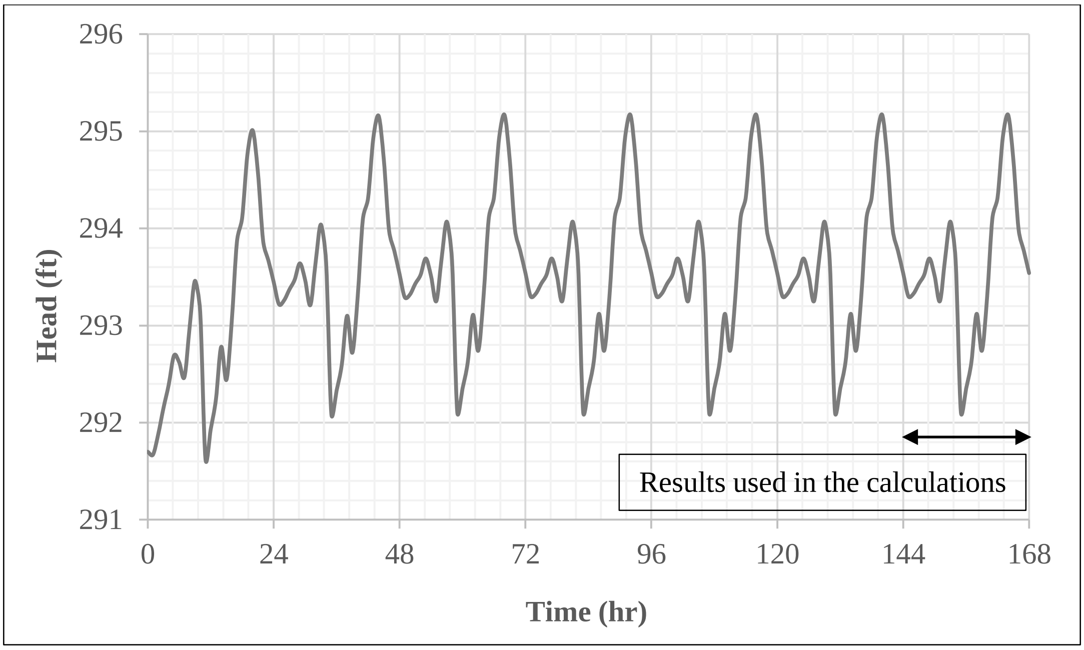

Figure 5-1: An example tank level variation

5.1.2 Pressure Limitations

There are no universally accepted values for pressure head limitations. The regulation in Turkey is a minimum of 20 m for an approximate population of 50000 and 30 m for higher populations. The maximum pressure head is 80 m (Turkish Ministry of Public Works and Settlement, 1985). Similarly, the minimum pressure head requirement is also taken as 20 m in the study of Giustolisi et al. (2008) and as 30 m in many other studies (Germanopoulos & Jowitt, 1989; Jowitt & Xu, 1990; Savic & Walters, 1997; Sterling & Bargiela, 1984; Vairavamoorthy & Lumbers, 1998). Sakarya (1998) stated the minimum and the maximum pressure limit as 20 psi (~14 m) and 100 psi (~70 m), respectively. Aydin, Mays, & Schmitt (2014) used the limits as 40 psi (~28 m) and 80 psi (~56 m). Additional water pressure requirements from different references can be seen in Table 5-1, which is presented by Aydin et al. (2014).

In this study, the minimum allowable pressure, $HP_{k,t,min}$, is set as 30 m but there were also some instances, where the minimum value was set as 20 m for comparison purposes. The minimum, $\underline{HP}_{v,t}$, and the maximum, $\overline{HP}_{v,t}$, values of the pressure head settings of the PRVs are set as 20 m and 80 m, respectively. Since PRV controls only the pressure, a 30 m minimum allowable pressure head can still be obtained with a minimum pressure head setting of 20 m due to the elevation differences of the consumer nodes.

Table 5-1: Water pressure requirements (Aydin et al., 2014)

Reference	**Location**	**Required Pressure**
Chin (2000)	20-story building	120 psi (84.4 m)
	3-story building	42 psi (29.5 m)
U.S. Army Corps of Engineers (1999)	Small WDS	20 - 70 psi (14.1 - 49.2 m)
GLUMB (1992)		35 - 60 psi (24.6 - 42.2 m)
Tabesh et al. (2010)	Complex network with 1533 connections	15 - 30 m
Swamee and Sharma (2008)	High-rise building	Minimum 8 - 20 m

5.1.3 Pressure exponent, α

The pressure exponent is, basically, dependent on the type of leak, pipe material and soil hydraulics (Puust et al., 2010). The most accurate way to obtain its value is from the field studies and experiments. As the opportunity to have a real network data is so scarce, many studies were conducted to standardize it. Dependent on the aforementioned factors, the value ranges between 0.5 and 2.5 (Lambert, 2001). In this study, the pressure exponent, α, is adopted as 1.18 as it was used in many other studies (Creaco et al., 2014; Germanopoulos & Jowitt, 1989; Jowitt & Xu, 1990; Sterling & Bargiela, 1984; Tucciarelli et al., 1999; Vairavamoorthy & Lumbers, 1998).

5.1.4 Penalty Coefficients

The default initial values for the penalty coefficient for the pressure head violation, R_H, and the penalty coefficient for the tank level violation, R_y, are both taken as 1. However, in some of the cases that initial condition is modified to adjust the order of magnitude of the penalty term in the objective function. This will be explicitly stated for the cases, in which the modification was necessary. In addition to that, in all of the cases, the modification factor for penalty coefficients, ΔR, is taken as 10.

5.2 Example Network 1

First example network is a small two-looped network used in Savic & Walters (1997)'s diameter estimation study. The network consists of one source reservoir at a 210 m fixed head and eight pipes arranged in two loops as shown in Figure 5-2. The node and link data for this network can be found in Table 5-2 and 5-3, respectively. Note that H-W in Table 5-3 is corresponding to Hazen-Williams roughness coefficient. There is no demand pattern for the network, meaning that the same base demand will be valid for the entire simulation period.

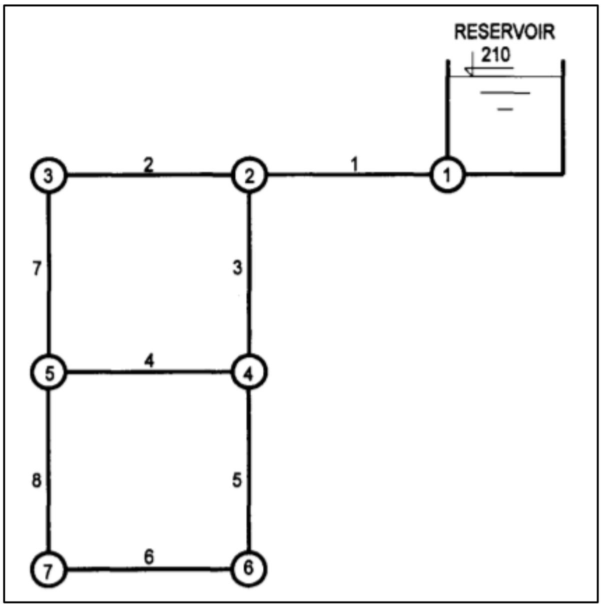

Figure 5-2: Example Network-1

Table 5-2: Nodal data of Example Network-1

Node ID	Elevation (m)	Demand (m^3/h)
1 (Res)	210	-1120
2	150	100
3	160	100
4	155	120
5	150	270
6	165	330
7	160	200

Table 5-3: Link data of the Example Network-1

Link ID	Length (m)	Diameter (mm)	Roughness Coefficient (H-W)
1	1000	609.6	130
2	1000	609.6	130
3	1000	609.6	130
4	1000	609.6	130
5	1000	609.6	130
6	1000	609.6	130
7	1000	609.6	130
8	1000	609.6	130

5.2.1 40% Leakage

Since the WDN in this study is a simple two-looped network, there is no recorded leakage data. In order to apply the procedure, the leakage value is assumed to be 40% of the total base demand, which is slightly higher than the leakage rate in Turkey.

As there is no demand pattern, system hydraulics are constant for 24 hours. Thus, the system is steady and only a single output value will be reported for the pressure head at the control node, HP_k, the modified maximum pressure head setting for PRV, $\overline{HP}_v$, and the pressure head setting for valve, x_v.

5.2.1.1 Emitter Coefficient Calculations for 40% Leakage

The adopted method of Cobacho et al. (2013) starts with the known leakage value. In this case, it is assumed to be 40% of the total base demand, which is 1120 m^3/h (Table 5-2). Thus, the total leakage, $Q_{Net,real}$ in Equation (2.11) becomes 448 m^3/h. The average system pressure head without the emitters is 51.25 m and the pressure exponent α is taken as 1.18 (Section 5.1.3). By using these parameters, ${K_{net}}^{(1)}$ is estimated to be 4.303 $m^3h^{-1}m^{-1.18}$ (= 448 /($51.25^{1.18}$)). After the convergence is met in the iterative process, which is in this case four iterations, the final values of emitter coefficients, ${K_j}^{(4)}$ are calculated and presented in Table 5-4. Note that, the entire length of Pipe 1 will be assigned to Node 2 as it is not possible to assign emitter coefficients to reservoirs.

Table 5-4: Emitter coefficients of Network-1 with 40% leakage for the first and the last iteration

Node ID	**Length γ_j (m)**	$\boldsymbol{\Gamma_j}$	$\boldsymbol{{K_{net}}^{(1)}}$ **($m^3h^{-1}m^{-1.18}$)**	$\boldsymbol{{K_j}^{(1)}}$ **($m^3h^{-1}m^{-1.18}$)**	$\boldsymbol{{K_{net}}^{(4)}}$ **($m^3h^{-1}m^{-1.18}$)**	$\boldsymbol{{K_j}^{(4)}}$ **($m^3h^{-1}m^{-1.18}$)**
2	2000	0.250	4.303	1.076	4.325	1.08123
3	1000	0.125	4.303	0.538	4.325	0.54062
4	1500	0.188	4.303	0.807	4.325	0.81092
5	1500	0.188	4.303	0.807	4.325	0.81092
6	1000	0.125	4.303	0.538	4.325	0.54062
7	1000	0.125	4.303	0.538	4.325	0.54062

5.2.1.2 One-valve Applications

Three different one PRV applications are studied in Network-1. For each case, the PRV is individually attached to the main line, to Pipe 7 and to Pipe 8.

5.2.1.2.1 Valve on Pipe 1

For this case, the valve is attached only to the main line, Pipe 1.The node at the end of the network, Node 7, is selected as the control point. As a result, pressure head check is only made for this specific node. The pressure head of the Node 7, HP_7, without any valve installation is 45.94 m. The overview of the network can be seen in Figure 5-3.

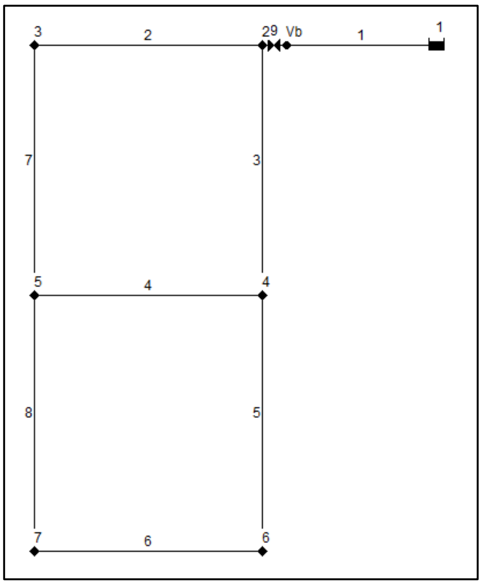

Figure 5-3: View of Network-1 for one PRV on Pipe 1

For comparison purposes, two different minimum pressure head requirements, 30 m and 20 m, are evaluated in this network. In order to modify the maximum pressure setting of the PRV, $\overline{HP}_1$, the pressure head of the node located after the PRV, Node 2, is checked as explained in Section 3.5.

5.2.1.2.1.1 30 m Minimum Pressure

The minimum allowable pressure head at the control point, $HP_{7,min}$, is set as 30 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-5.

Analyzing Table 5.5, cases I and II refers to the optimization formulations of minimizing the total pressure head at the control point (Section 2.1.1) and the total leakage (Section 2.1.2), respectively. Number of iterations indicates the number of penalty coefficient updated before reaching to the overall optimality (Figure 4-1). At the beginning of the analysis the maximum pressure setting of the PRV on Pipe 1, $\overline{HP}_1$, is modified from 80 m to 56.90 m by checking the pressure head of the Node 2 located after it. After the optimization, the following results are obtained as same for both of the cases. The pressure head of the control point, HP_7, in Equation (2.3) is reduced from 45.94 m to 30 m. The final optimum pressure head setting of the PRV on Pipe 1, x_1, is 40.82 m and the total leakage in the network calculated with the PRV setting of 40.82 m, Q_{leak}, is 287.804 m^3/h. The initial leakage amount before the optimization was 448 m^3/h; thus, the leakage reduction for this application is calculated to be 35.76%. The difference between the results of two cases are the objective function values. For Case I, objective function is the summation of pressure head values at the control point, HP_7, which is 30 m. As the value is constant for 24 hours, the objective function value becomes 720 m (=30*24). For Case II, objective function is the total leakage in the network, Q_{leak}, which is 287.804 m^3/h. Same reason with Case I, the objective function value becomes 6907.296 m^3/day (=287.804*24). Note that for both of the cases, there are no violations for pressure head or tank level, so the corresponding penalty terms becomes zero. The run times for the program to give optimum results are very close to each other for both of the cases.

Table 5-5: The results of Network-1 for: 40% leakage, one valve on Pipe 1, $HP_{7,min}$ = 30 m

Case	**Objective Function Value**	**# of iter.**	$\boldsymbol{HP_7}$ **(m)**	$\boldsymbol{\overline{HP}_1}$ **(m)**	$\boldsymbol{x_1}$ **(m)**	$\boldsymbol{Q_{leak}}$ **(m^3/h)**	**Leak Reduction (%)**	**Run time (min)**
I	720.000	6	30.00	56.90	40.82	287.804	35.76	5.75
II	6907.296	7	30.00	56.90	40.82	287.804	35.76	5.78

5.2.1.2.1.2 20 m Minimum Pressure

The $HP_{7,min}$ is set as 20 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-6.

The results show that the leakage decreased from 448 m^3/h to 193.740 m^3/h, resulting in a reduction of 56.75%. Moreover, the pressure head at the control node (Node 7) is reduced from 45.94 m to 20 m for both of the cases.

Table 5-6: The results of Network-1 for: 40% leakage, one valve on Pipe 1, $HP_{7,min}$ = 20 m

Case	Objective Function Value	# of iter.	HP_7 (m)	$\overline{HP}_1$ (m)	x_1 (m)	Q_{leak} (m³/h)	Leak Reduction (%)	Run time (min)
I	480.000	6	20.00	56.90	30.74	193.740	56.75	6.22
II	4649.760	7	20.00	56.90	30.74	193.740	56.75	6.43

5.2.1.2.2 *Valve on Pipe 8*

In this case, the valve is on Pipe 8. Similar to the previous configuration, the control point is selected as Node 7 and as such, it is the only node in the network that undergoes pressure head check. The HP_7 without any valve installation is 45.94 m. The overview of this configuration of the network can be seen in Figure 5-4.

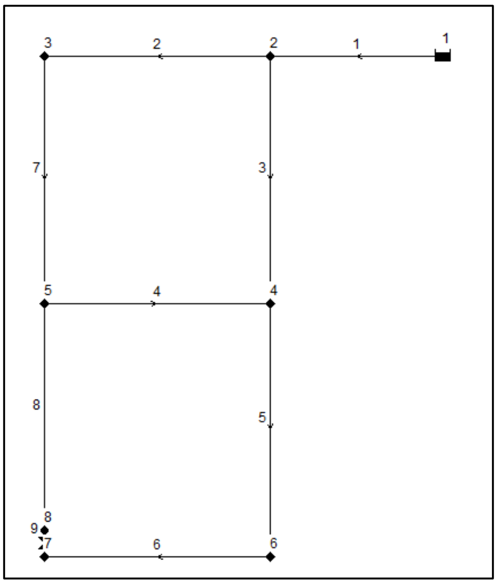

Figure 5-4: View of Network-1 for one PRV on Pipe 8

The maximum value of $\overline{HP}_1$ is modified by checking the pressure head of the node located after the PRV (Node 7). The $HP_{7,min}$ is set as 30 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-7.

As can be seen from Table 5-7, the final PRV settings, x_1, is 20 m while HP_7 is 45.44 m for both of the cases. This means that the valve cannot further decrease the pressure head at the Node 7, because the hydraulic conditions within the loop cannot be met. Therefore, the system closes the Pipe 8 and starts supplying the demand of Node 7 from Pipe 6 without decreasing the pressure. So, there is no flow in the Pipe 8 which is evident from the flow arrows in Figure 5-4.

Table 5-7: The results of Network-1 for: 40% leakage, one valve on Pipe 8, $HP_{7,min}$ = 30 m

Case	Objective Function Value	# of iter.	HP_7 (m)	$\overline{HP_1}$ (m)	x_1 (m)	Q_{leak} (m^3/h)	Leak Reduction (%)	Run time (min)
I	1090.560	4	45.44	45.94	20.00	446.970	0.23	1.11
II	10727.280	4	45.44	45.94	20.00	446.970	0.23	1.11

Based on these results, it can be concluded that the usage of PRV on Pipe 8 is pointless. Hence, the minimum pressure condition of 20 m is not analyzed for this valve setup.

5.2.1.2.3 Valve on Pipe 7

In this case, the valve is on Pipe 7. For this configuration, Node 5 is selected as the control point, so the pressure head check is only made for that specific node. The pressure head of the Node 5, HP_5, without any valve installation is 56.07 m. The overview of the network can be seen in Figure 5-5.

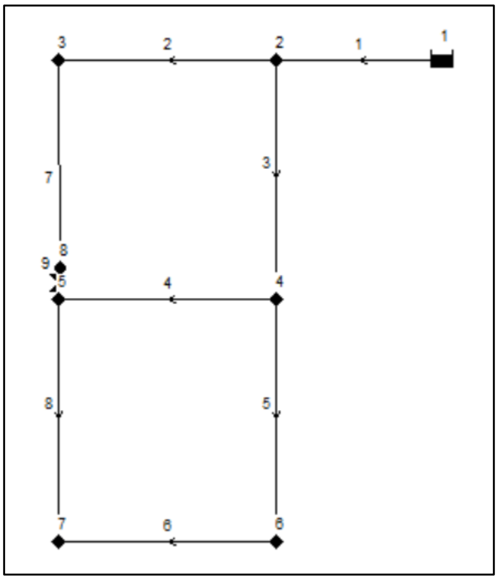

Figure 5-5: View of Network-1 for one PRV on Pipe 7

In order to modify the maximum value of $\overline{HP}_1$, the pressure head of the node located after PRV, Node 5, is checked. The $HP_{5,min}$ is set as 30 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-8.

As can be seen from Table 5-8, the final PRV settings, x_1, is 20 m, whereas the HP_5 is 54.73 m for both of the cases. This suggest that the valve cannot decrease the pressure head of the node located after the PRV (Node 5) any further, because the hydraulic conditions within the loop cannot be met. Therefore, the system closes Pipe 7 and starts providing the demand of Node 5 from Pipe 4 without decreasing the pressure. This can be seen from the flow arrows in Figure 5-5.

Table 5-8: The results of Network-1 for: 40% leakage, one valve on Pipe 7, $HP_{5,min}$ = 30 m

Case	Objective Function Value	# of iter.	HP_5 (m)	$\overline{HP}_1$ (m)	x_1 (m)	Q_{leak} (m^3/h)	Leak Reduction (%)	Run time (min)
I	1313.520	4	54.73	56.07	20.00	440.967	1.57	1.08
II	10583.208	4	54.73	56.07	20.00	440.967	1.57	1.08

Similar to placing a valve on Pipe 8, it can be concluded from the results that the usage of PRV on Pipe 7 is pointless. Hence, the 20 m minimum pressure head condition is not analyzed for this valve setup.

5.2.1.3 Two-valve Applications

Two different double PRV applications are studied in Network-1. The first configuration represents placing PRVs on Pipe 1 and Pipe 7, while the second one corresponds to placing PRVs on Pipe 1, plus on an additional line labeled as Pipe 9.

5.2.1.3.1 Valves on Pipe 1 and Pipe 7

In this case, the valves are placed on the main line, Pipe 1 (PRV-1), and Pipe 7 (PRV-2). As a control point, Node 5 is selected. The overview of this network can be seen in Figure 5-6.

To modify the maximum value of $\overline{HP}_1$ the pressure head of the node that comes after the PRV, Node 2, is checked. Likewise, the maximum pressure head setting of the PRV-2, $\overline{HP}_2$, is modified by checking Node 5.

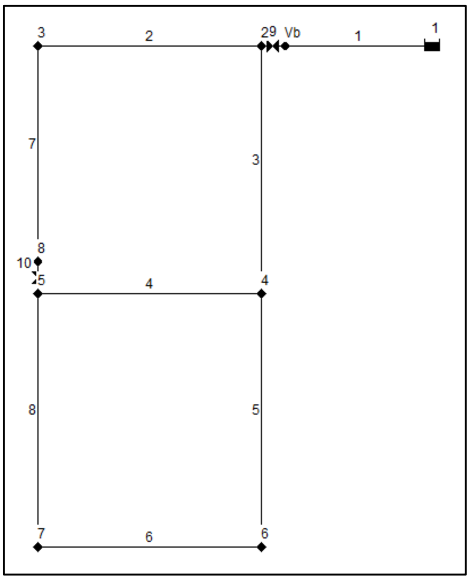

Figure 5-6: View of Network-1 for two PRVs on Pipe 1 and Pipe 7

5.2.1.3.1.1 30 m Minimum Pressure

The $HP_{5,min}$ is set as 30 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-9.

Table 5-9: The results of Network-1 for: 40% leakage, two PRVs on Pipe 1 and Pipe 7, $HP_{5,min}$ = 30 m

Case	Objective Function Value	# of iter.	HP_5 (m)	PRV	$\overline{HP}$ (m)	x (m)	Q_{leak} (m^3/h)	Leak Reduc. (%)	Run time (min)
I	720.000	6	30.00	1	56.90	30.64	192.838	56.96	101.47
				2	56.07	56.07			
II	4628.112	6	30.00	1	56.90	30.64	192.838	56.96	34.78
				2	56.07	56.07			

It can be seen from the results that the PRV-2 is not working in this case also, as the initial value remains constant throughout the optimization. Hence, although there are two PRVs in the network, the pressure head control for Node 5 is maintained by using PRV-1. The total system leakage is reduced by 56.96% and the pressure head at the control node (Node 5) decreases from 56.07 m to 30 m for both of the cases.

5.2.1.3.1.2 20 m Minimum Pressure

The $HP_{5,min}$ is set as 20 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-10.

Table 5-10: The results of Network-1 for: 40% leakage, two PRVs on Pipe 1 and Pipe 7, $HP_{5,min}$ = 20 m

Case	Objective Function Value	# of iter.	HP_5 (m)	PRV	$\overline{HP}$ (m)	x (m)	Q_{leak} (m^3/h)	Leak Reduc. (%)	Run time (min)
I	480.000	6	20.00	1	56.90	20.57	106.003	76.34	114.35
				2	56.07	56.07			
II	2544.072	7	20.00	1	56.90	20.57	106.003	76.34	100.88
				2	56.07	56.07			

Similar to the 30 m condition, it can be seen from the results that PRV-2 is not working and the pressure head regulation is done by PRV-1 on the main line. Leakage is reduced by 76.34%, decreasing from 448 m^3/h to 106.003 m^3/h. Moreover, the pressure head at the control node (Node 5) is reduced from 56.07 m to 20 m for both of the cases.

5.2.1.3.2 Valves on Pipe 1 and Pipe 9

In this case, the valves are placed on the main line, Pipe 1 (PRV-1), and on the newly added Pipe 9 (PRV-2). As it is shown in Section 5.2.1.2.2, when a PRV is attached before Node 7, it closes the pipe and delivers the water from another line without adjusting the pressure head. So, in order to see the effect of second valve without closing any line, Pipe 9, a pipe with no length, is added to the network. The characteristics of Node 7 is carried to Node 8. As a result Node 7 has no base demand or emitter coefficient for this network. As control point, Node 8 is selected. The pressure head of Node 8, HP_8, without any valve installation is 45.94 m. The maximum values of $\overline{HP}_1$ and $\overline{HP}_2$ are modified by checking Nodes 2 and 8, respectively. The overview of the network can be seen in Figure 5-7.

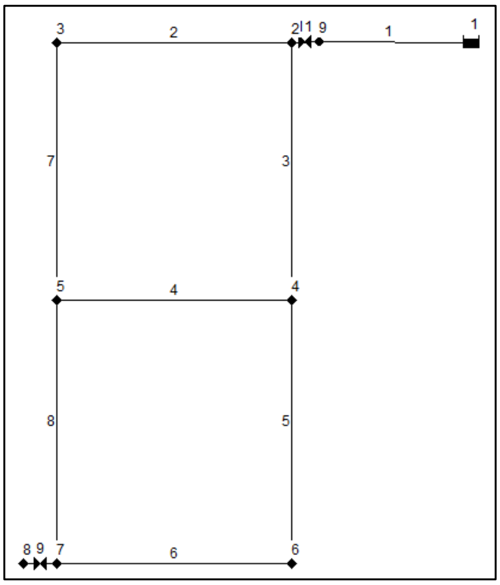

Figure 5-7: View of Network-1 for two PRVs on Pipe 1 and Pipe 9

5.2.1.3.2.1 30 m Minimum Pressure

The $HP_{8,min}$ is set as 30 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-11.

The results suggest that for Case I, PRV-1 is not active on the pressure head of the control node. As such, the reduction is obtained by adjusting PRV-2. Contrary to this, for Case II, the control is on PRV-1, while the initial setting of PRV-2 remains constant. This difference between the two cases is due to the variations in their formulations. In Case I, the objective is to minimize the summation of the pressure head at the control point. Since PRV-2 has a bigger influence on the pressure reduction of the control point compared to PRV-1, only PRV-2 contributes to leakage reduction in the network. On the other hand, for Case II, the objective is to minimize the total leak in the WDN. To that end, reducing pressure head from the main line results in an overall pressure decrease at all junction points, while adjusting PRV-2 affects only the pressure head of Node 8. This is why a leakage reduction of 35.76% can be achieved in Case II while only 4.33% can be achieved in Case I.

Table 5-11: The results of Network-1 for: 40% leakage, two PRVs on Pipe 1 and Pipe 9, $HP_{8,min}$ = 30 m

Case	Objective Function Value	# of iter.	HP_8 (m)	PRV	$\overline{HP}$ (m)	x (m)	Q_{leak} (m³/h)	Leak Reduc. (%)	Run time (min)
I	720.000	6	30.00	1	56.90	56.90	428.609	4.33	61.27
				2	45.94	31.04			
II	6907.296	7	30.00	1	56.90	40.82	287.804	35.76	53.27
				2	45.94	45.94			

5.2.1.3.2.2 20 m Minimum Pressure

The $HP_{8,min}$ is set as 20 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-12.

Table 5-12: The results of Network-1 for: 40% leakage, two PRVs on Pipe 1 and Pipe 9, $HP_{8,min}$ = 20 m

Case	Objective Function Value	# of iter.	HP_8 (m)	PRV	$\overline{HP}$ (m)	x (m)	Q_{leak} (m^3/h)	Leak Reduc. (%)	Run time (min)
I	480.000	5	20.00	1	56.90	30.74	193.740	56.75	29.10
				2	45.94	20.00			
II	4649.760	8	20.00	1	56.90	30.74	193.740	56.75	62.80
				2	45.94	45.94			

For Case II, the behavior of the system is similar to the 30 m minimum pressure head application. PRV-2 is not active and the pressure head of the control node, Node 8, is controlled by PRV-1 on the main line. But for Case I, the results show a different trend. With the current configuration, both of the PRVs are active; whereas, for the 30 m minimum pressure head condition, only PRV-2 was working. This difference results from the gradient calculations. In both of the minimum pressure head settings, initially, the PRV-2 setting is reduced in the iteration steps. After reducing the pressure head of the control node without violating the minimum limit with PRV-2, the gradient value for changing the PRV-1 setting starts to give relatively small values for the 30 m case. Thus, the optimization does not decrease the setting of PRV-1 any further. Contrary to this, for the 20 m case, the gradient value for changing PRV-1 is comparatively higher. So the optimization continues to decrease the setting of PRV-1.

With these current conditions, the leakage is reduced by 56.75%, decreased from 448 m^3/h to 193.740 m^3/h. Moreover, the pressure at the control node (Node 8) is reduced from 45.94 m to 20 m for both of the cases.

5.2.1.4 Discussion of 40% Leakage

A summary of all the cases for 40% leakage can be seen in Table 5-13. In light of these results, the following conclusions can be made:

- Setting a lower minimum pressure head requirement results in higher leakage reductions. For example, for the one-valve application on Pipe 1, setting a 30 m minimum pressure head requirement results in a 35.76% leakage reduction, while the 20 m case results in a decrease of 56.75%. This is as expected since a higher pressure drop results in a higher leakage drop.
- Reducing the pressure heads of the control nodes with higher initial pressures results in higher leakage reductions compared to reducing the pressure heads of the nodes with lower initial pressures. For the one-valve application on Pipe 1, the control point of Node 7 has a 45.94 m pressure without PRV control, and the leakage is reduced by 35.76% for the 30 m minimum pressure head requirement. For the two-valve application, in which the valves are located on the Pipe 1 and Pipe 7, the PRV on Pipe-7 is not active and the system pressure is controlled by the PRV on Pipe 1. This makes it the same with the one-valve application on Pipe 1. The control point for the two-valve case is Node 5, which has a 56.07 m pressure head without PRV control, and the leakage is reduced by 56.96% for the 30 m minimum pressure head requirement.
- Different formulations may affect the active usage of PRVs, so the number and the locations of both PRVs and control points must be decided accordingly. For the two-valve application, in which the valves are placed on Pipe 1 and Pipe 9, with the minimum pressure head requirement of 30 m, the PRV on Pipe 1 is not working for Case I and the PRV on Pipe 9 is not active for Case II. This results from the differences in the objective functions of two cases.
- Usage of a PRV to adjust the pressure head of a node within a loop is not efficient as the network closes the PRV attached to the line and delivers the flow from other lines (valve on Pipe 8 and valve on Pipe 7).
- Initially calculated emitter coefficient values are taken as constant throughout the optimization procedure. For an example check, emitter coefficient values are recalculated with the optimized results of Pipe 1 with 30 m minimum pressure requirement. The maximum difference is observed with a rate of 0.01% at Node 5. The emitter coefficient value for the non- PRV network was

0.81092 (Table 5.4) while 0.81091 is obtained with the optimized PRV settings.

Table 5-13: Results of Network-1 for 40% Leakage

Valve Location	**Control Point**	$HP_{k,min}$ **(m)**	**Case**	Q_{leak} **(m^3/h)**	**Leak Reduction (%)**
Pipe 1	7	30	I	287.804	35.76
			II	287.804	35.76
		20	I	193.740	56.75
			II	193.740	56.75
Pipe 8	7	30	I	446.970	0.23
			II	446.970	0.23
Pipe 7	5	30	I	440.967	1.57
			II	440.967	1.57
Pipe 1 + Pipe 7	5	30	I	192.838	56.96
			II	192.838	56.96
		20	I	106.003	76.34
			II	106.003	76.34
Pipe 1 + Pipe 9	8	30	I	428.609	4.33
			II	287.804	35.76
		20	I	193.740	56.75
			II	193.740	56.75

5.2.2 20% Leakage

In this section, the assumed leakage value is changed to 20% of the total base demand. As PRV does not work on the one-valve application cases, in which the valve is placed on either Pipe 8 or Pipe 7, these will not be analyzed. Similarly, the two-valve application case, in which the valves are placed on Pipe 1 and Pipe 7 will not be analyzed as one of the valves is not active.

5.2.2.1 Emitter Coefficient Calculations for 20% Leakage

For this part of the study, the leakage value is assumed to be 20% of the total base demand, which is 1120 m^3/h as can be seen from Table 5-2. Thus, the total leakage, $Q_{Net,real}$ is calculated from Equation (2.11) as 224 m^3/h. The average system pressure head without the emitters is 51.25 m and the pressure exponent α is, again, taken as 1.18 as explained in Section 5.1.3. By using these parameters, ${K_{net}}^{(1)}$ is estimated to be 2.152 $m^3h^{-1}m^{-1.18}$ (= 224/(51.25$^{1.18}$)). After the convergence is met in the iterative process, which is in this case five iterations, the final values of emitter coefficients, ${K_j}^{(5)}$ are found as in Table 5-14. Note that the whole length of Pipe 1 will be assigned to Node 2 as it is not possible to assign emitter coefficients to reservoirs.

Table 5-14: Emitter coefficients of Network-1 with 20% leakage for the first and the last iteration

Node ID	Length γ_j (m)	Γ_j	${K_{net}}^{(1)}$ ($m^3h^{-1}m^{-1.18}$)	${K_j}^{(1)}$ ($m^3h^{-1}m^{-1.18}$)	${K_{net}}^{(5)}$ ($m^3h^{-1}m^{-1.18}$)	${K_j}^{(5)}$ ($m^3h^{-1}m^{-1.18}$)
2	2000	0.250	2.152	0.538	2.119	0.52968
3	1000	0.125	2.152	0.269	2.119	0.26484
4	1500	0.188	2.152	0.403	2.119	0.39726
5	1500	0.188	2.152	0.403	2.119	0.39726
6	1000	0.125	2.152	0.269	2.119	0.26484
7	1000	0.125	2.152	0.269	2.119	0.26484

5.2.2.2 Applications

Due to reasons previously explained in Section 5.2.1.4, only two cases will be analyzed for the 20% leakage condition. The first is a one PRV application case, in which the valve is placed on Pipe-1, and the second is a two PRV application case, in which the valves are simultaneously placed on Pipe-1 and Pipe-9.

5.2.2.2.1 Valve on Pipe 1

In this case, the valve is located on the main line, Pipe 1 (Figure 5-3). To be consistent with the 40% leakage analyses, the control point is selected as Node 7 and two different minimum pressure head settings are evaluated. The maximum value of $\overline{HP}_1$ is modified by checking Node 2, which is located after the PRV.

5.2.2.2.1.1 30 m Minimum Pressure

The $HP_{7,min}$ is set as 30 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-15.

Table 5-15: The results of Network-1 for: 20% leakage, one valve on Pipe 1, $HP_{7,min}$ = 30 m

Case	**Objective Function Value**	**# of iter.**	$\boldsymbol{HP_7}$ **(m)**	$\boldsymbol{\overline{HP}_1}$ **(m)**	$\boldsymbol{x_1}$ **(m)**	$\boldsymbol{Q_{leak}}$ **(m^3/h)**	**Leak Reduction (%)**	**Run time (min)**
I	720.000	6	30.00	57.67	40.70	140.773	37.15	6.20
II	3378.552	7	30.00	57.67	40.70	140.773	37.15	6.47

The leakage is reduced by 37.15%, decreased from 224 m^3/h to 140.773 m^3/h, and the pressure head at the control node (Node 7) is reduced from 45.94 m to 30 m for both of the cases.

5.2.2.2.1.2 20 m Minimum Pressure

The $HP_{7,min}$ is set as 20 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-16.

Table 5-16: The results of Network-1 for: 20% leakage, one valve on Pipe 1, $HP_{7,min}$ = 20 m

Case	**Objective Function Value**	**# of iter.**	$\boldsymbol{HP_7}$ **(m)**	$\boldsymbol{\overline{HP}_1}$ **(m)**	$\boldsymbol{x_1}$ **(m)**	$\boldsymbol{Q_{leak}}$ **(m^3/h)**	**Leak Reduction (%)**	**Run time (min)**
I	480.000	6	20.00	57.67	30.67	94.806	57.68	5.92
II	2275.344	7	20.00	57.67	30.67	94.806	57.68	5.35

The reduction in leakage increases to 57.68%, decreased from 224 m^3/h to 94.806 m^3/h, while satisfying the minimum pressure head at the control node.

5.2.2.2.2 Valves on Pipe 1 and Pipe 9

In this case, the valves are located on Pipe 1 (PRV-1) and on the newly added Pipe 9 (PRV-2) (Figure 5-7). In line with the 40% leakage analyses, the control point is selected as Node 8. The maximum value of $\overline{HP}_1$ and $\overline{HP}_2$ are modified by checking Node 2 and Node 8, respectively.

5.2.2.2.2.1 30 m Minimum Pressure

The $HP_{8,min}$ is set as 30 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-17.

Table 5-17: The results of Network-1 for: 20% leakage, two PRVs on Pipe 1 and Pipe 9, $HP_{8,min}$ = 30 m

Case	Objective Function Value	# of iter.	HP_8 (m)	PRV	$\overline{HP}$ (m)	x (m)	Q_{leak} (m^3/h)	Leak Reduc. (%)	Run time (min)
I	720.000	5	30.00	1	57.67	57.67	213.866	4.52	43.27
				2	46.90	30.00			
II	30258.552	6	30.00	1	57.67	40.70	140.773	37.15	71.73
				2	46.90	46.90			

The results show that for Case II, PRV-2 does not work and the pressure head of Node 8 is controlled by PRV-1. On the other hand, for Case I, both of the PRVs are active. At the end of the analysis, 37.15% leakage reduction is obtained by reducing the leakage from 224 m^3/h to 140.773 m^3/h.

5.2.2.2.2.2 20 m Minimum Pressure

The $HP_{8,min}$ is set as 20 m. The analyses are carried out for both Case I and Case II and the results can be seen in Table 5-18.

Table 5-18: The results of Network-1 for: 20% leakage, two PRVs on Pipe 1 and Pipe 9, $HP_{8,min}$ = 20 m

<table>
<tr><th>Case</th><th>Objective Function Value</th><th># of iter.</th><th>HP_8 (m)</th><th>PRV</th><th>$\overline{HP}$ (m)</th><th>x (m)</th><th>Q_{leak} (m^3/h)</th><th>Leak Reduc. (%)</th><th>Run time (min)</th></tr>
<tr><td rowspan="2">I</td><td rowspan="2">480.000</td><td rowspan="2">5</td><td rowspan="2">20.00</td><td>1</td><td>57.67</td><td>30.67</td><td rowspan="2">94.805</td><td rowspan="2">57.68</td><td rowspan="2">12.52</td></tr>
<tr><td>2</td><td>46.90</td><td>20.00</td></tr>
<tr><td rowspan="2">II</td><td rowspan="2">29155.344</td><td rowspan="2">6</td><td rowspan="2">20.00</td><td>1</td><td>57.67</td><td>30.67</td><td rowspan="2">94.806</td><td rowspan="2">57.68</td><td rowspan="2">66.47</td></tr>
<tr><td>2</td><td>46.90</td><td>46.90</td></tr>
</table>

The active PRV status for this case is the same as the 30 m minimum pressure head application. Both of the PRVs are working in Case I, while only PRV-1 is active on Case II. It can be seen from the results that the leakage is reduced by 57.68%, decreased from 224 m^3/h to 94.806 m^3/h. Moreover, the pressure at the control node is reduced from 45.94 m to 20 m for both of the cases.

5.2.2.3 Discussion of 20% Leakage

A table summarizing all the cases of the 20% leakage configuration is provided (Table 5-19). The following conclusions can be made from the results:

- Same as the 40% case, setting a lower minimum pressure requirement results in higher leakage reductions.
- Comparing the 40% and the 20% leakage results, the percentages of the final leakage reduction after the optimization are approximately equal to each other; however, the amount of reduced leakage is different. This difference can only be seen in the two-valve application with 30 m minimum pressure requirement of Case I. For the 40%, PRV 1 does not work, thus the overall system cannot be decreased. But for the 20%, both of the PRVs are active, so a higher amount of leakage is obtained. This difference results from the gradient values of the corresponding cases.

Table 5-19: Results of Network-1 for 20% Leakage

Valve Location	Control Point	$HP_{k,min}$ (m)	Case	Q_{leak} (m^3/h)	Leak Reduction (%)
Pipe 1	7	30	I	140.773	37.15
			II	140.773	37.15
		20	I	94.806	57.68
			II	94.806	57.68
Pipe 1 + Pipe 9	8	30	I	213.866	4.52
			II	140.773	37.15
		20	I	94.805	57.68
			II	94.806	57.68

5.2.3 Chance Constraint Application

The chance constrained model is obtained by applying the probability concept to the constraint related with the random variable, as explained in Section 2.3.2. In this study, the random variable is the minimum pressure head for control node k, $HP_{k,t,min}$. The uncertain nature of this variable is represented with two different probability distributions, which are Normal and Log-Normal Distributions.

Based on the results of the analyses conducted on Network-1, the following configuration is selected for chance constraint application. For the model, the one-valve case of PRV on Pipe 1 is used as this valve is the most effective one considering overall leakage reduction. Node 5 is chosen to be the control node since a higher leakage reduction can be obtained compared to the other control points. The minimum pressure requirement is selected as 30 m and for the initial leakage assumption 40% of the base demand is used.

In this work, the uncertainty concept is associated with the pressure head in the WDN. This uncertain characteristic results in the possibility of not satisfying the required minimum pressure head at the control nodes. Thus, increasing the reliability means decreasing the probability of not satisfying the required minimum pressure heads.

Different levels of reliabilities varying from 60% to 99% are analyzed for both of the distribution types.

The results of the optimization to which chance constraint is not applied corresponds to the 50% probability of occurrence for normal and log-normal distributions (Das, 2004; Lansey, Duan, Mays, & Tung, 1989). Thus, it is advantageous to use these distribution types as they enable comparisons between the non-probability cases and different reliability levels.

For different probability distributions, the pressure head at the consumer nodes being equal to or higher than the pre-decided minimum constraint, Equation (2.3), will be modified by taking different reliability levels and standard deviations into consideration. Then, the modified version of the constraint will be implemented to the objective function as penalty.

For both of the distribution types, the mean value of the minimum pressure is taken as μ_H = 30 m and the standardized normal variant is calculated for the φ values ranging from 0.60 to 0.99. Increments are set constant to 0.10 until the reliability level of 0.90. As higher reliability values are favorable, increment selected for the values of φ ranging from 0.95 to 0.99 is 0.02. This lower increment value would help to observe the effects of higher φ values more precisely. Moreover, the standard deviation values range between 0 and 10, increasing with an increment of 2, for each reliability level.

5.2.3.1 The Normal Distribution

The minimum pressure requirement constraint is reformed according to the Equation (2.31) using the normal probability distribution (Section 2.3.2.1). The analyses results of Case I and II can be seen in Table 5-20. In this table, φ is the specified reliability of lower pressure head limit, σ is the standard deviation, $HP_{5,min}$ is the modified value of the minimum pressure head requirement, HP_5 is the pressure head value at the control point after the optimization, Q_{leak} is the total system leakage calculated with the optimized PRV settings, and the final column corresponds to the total leakage reduction from the initial value of 448 m^3/h. The optimization results of Case I and Case II for the same reliability and standard deviation values are the same. Thus, only one single leakage reduction percentage is represented in the table.

Table 5-20: Results of the chance constraint application with normal probability distribution for Case I and Case II

			Case I		Case II		
φ	**σ**	**$HP_{5,min}$ (m)**	**HP_5 (m)**	**Q_{leak} (m^3/h)**	**HP_5 (m)**	**Q_{leak} (m^3/h)**	**Leak Reduc. (%)**
0.99	0.00	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	34.65	34.65	235.754	34.65	235.754	47.38
	4.00	39.31	39.31	280.039	39.31	280.039	37.49
	6.00	43.96	43.96	325.444	43.96	325.444	27.36
	8.00	48.61	48.61	371.750	48.61	371.750	17.02
	10.00	53.26	53.26	419.061	53.26	419.061	6.46
	11.20	56.07	56.07	448.000	56.07	448.000	0.00
0.97	0.00	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	33.76	33.76	227.397	33.76	227.397	49.24
	4.00	37.52	37.52	262.902	37.52	262.902	41.32
	6.00	41.28	41.28	299.078	41.28	299.078	33.24
	8.00	45.05	45.05	336.143	45.05	336.143	24.97
	10.00	48.81	48.81	373.749	48.81	373.749	16.57
	13.86	56.07	56.07	448.000	56.07	448.000	0.00
0.95	0.00	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	33.29	33.29	223.051	33.29	223.051	50.21
	4.00	36.58	36.58	253.927	36.58	253.927	43.32
	6.00	39.87	39.87	285.404	39.87	285.404	36.29
	8.00	43.16	43.16	317.527	43.16	317.527	29.12
	10.00	46.45	46.45	350.062	46.45	350.062	21.86
	15.85	56.07	56.07	448.000	56.07	448.000	0.00
0.90	0.00	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	32.56	32.56	216.236	32.56	216.236	51.73
	4.00	35.13	35.13	240.231	35.13	240.231	46.38
	6.00	37.69	37.69	264.514	37.69	264.514	40.96
	8.00	40.25	40.25	289.150	40.25	289.150	35.46
	10.00	42.82	42.82	314.214	42.82	314.214	29.86
	20.34	56.07	56.07	448.000	56.07	448.000	0.00

(continued)

Table 5-20 (continued): Results of the chance constraint application with normal probability distribution for Case I and Case II

			Case I		Case II		
φ	**σ**	**$HP_{5,min}$ (m)**	**HP_5 (m)**	**Q_{leak} (m³/h)**	**HP_5 (m)**	**Q_{leak} (m³/h)**	**Leak Reduc. (%)**
0.80	0.00	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	31.68	31.68	208.177	31.68	208.177	53.53
	4.00	33.37	33.37	223.790	33.37	223.790	50.05
	6.00	35.05	35.05	239.484	35.05	239.484	46.54
	8.00	36.73	36.73	255.341	36.73	255.341	43.00
	10.00	38.42	38.42	271.450	38.42	271.450	39.41
	30.97	56.07	56.07	448.000	56.07	448.000	0.00
0.70	0.00	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	31.05	31.05	202.346	31.05	202.346	54.83
	4.00	32.10	32.10	212.017	32.10	212.017	52.67
	6.00	33.15	33.15	221.759	33.15	221.759	50.50
	8.00	34.20	34.20	231.477	34.20	231.477	48.33
	10.00	35.24	35.24	241.259	35.24	241.259	46.15
	49.70	56.07	56.07	448.000	56.07	448.000	0.00
0.60	0.00	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	30.51	30.51	197.447	30.51	197.447	55.93
	4.00	31.01	31.01	201.982	31.01	201.982	54.91
	6.00	31.52	31.52	206.716	31.52	206.716	53.86
	8.00	32.03	32.03	211.376	32.03	211.376	52.82
	10.00	32.53	32.53	215.961	32.53	215.961	51.79
	102.88	56.07	56.07	448.000	56.07	448.000	0.00

Table 5-20 shows that as the standard deviation increases, so does the minimum pressure requirement. There is also an additional standard deviation value after 10. It is the highest standard deviation that can be analyzed with the current reliability level, where the minimum pressure requirement, $HP_{5,min}$, increases to 56.07 m. This 56.07 m is the pressure level of Node 5 without any PRV control on the system and it is not possible to obtain higher pressure values for the control node.

The change of total leakage versus reliability level for each standard deviation is presented in Figure 5-8. Similarly, the change of total leakage versus standard deviation for each reliability level is shown in Figure 5-9. As stated before, Case I and Case II results are the same; thus, Figure 5-8 and Figure 5-9 are valid for both cases.

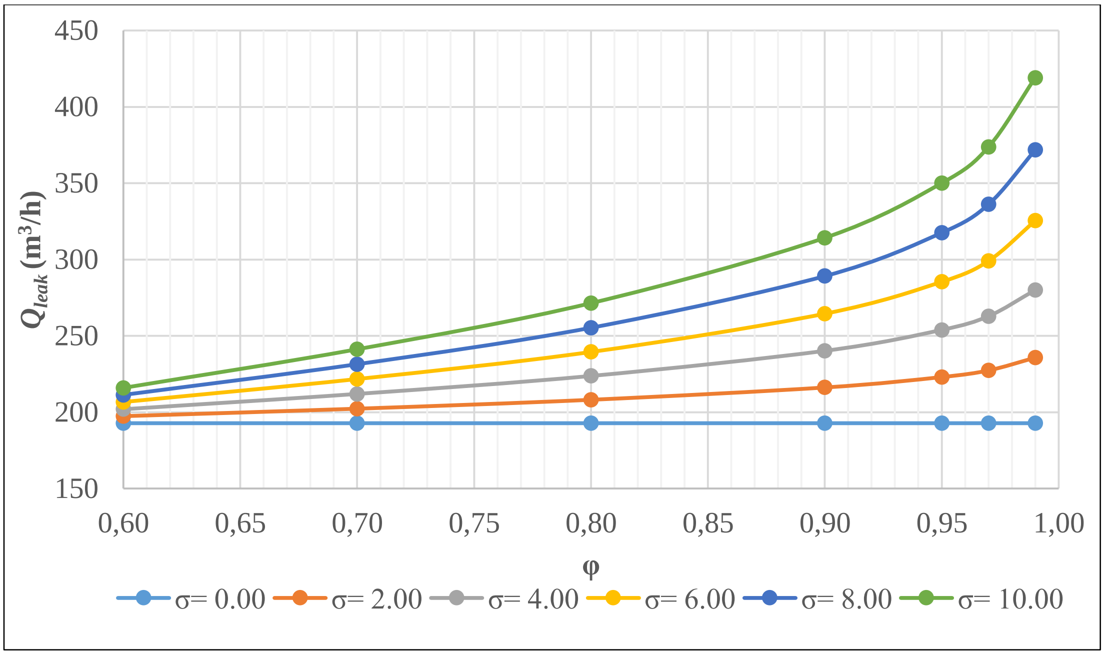

Figure 5-8: The total leakage versus reliability level for normal distribution

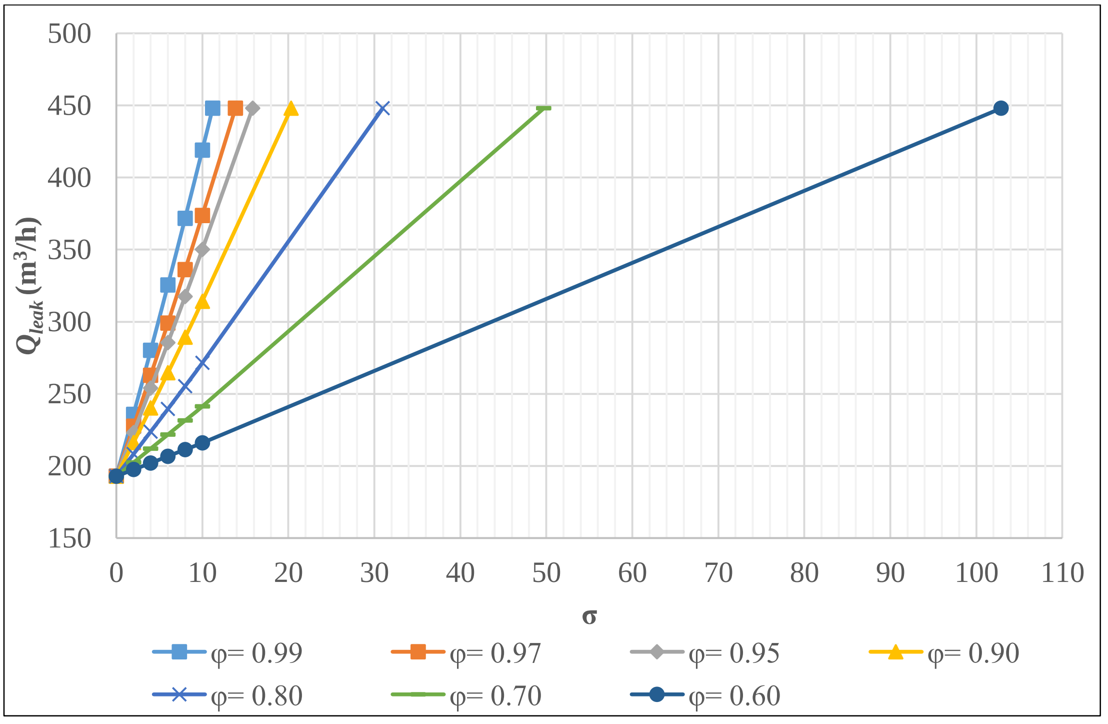

Figure 5-9: The total leakage versus standard deviation for normal distribution

It can be seen from Figure 5-8 that increasing the reliability level results in an increase in the total system leakage for the same standard deviation. The rate of increase especially accelerates after the reliability level of 90%. For zero standard deviation, the minimum pressure requirement value stays constant for any φ; hence, the results are the same with the no-probability case for all reliability levels.

Likewise, it is shown in Figure 5-9 that the total system leakage increases with the increase of standard deviation for the same reliability level. For the reliability levels higher than 90%, the gradually increasing behavior becomes more rapid. In addition, it can also be concluded that as the reliability increases, the highest standard deviation value that can be reached also increases for the corresponding reliability level.

5.2.3.2 The Log-Normal Distribution

As clarified in Section 2.3.2.2, the minimum pressure requirement constraint is modified according to the Equation (2.36) using log-normal probability distribution. λ_H, ξ_H values are calculated for each standard deviation level by using the Equations (2.22) and (2.23), respectively. The analyses results of Case I and II can be seen in Table 5-21.

Similar to the normal distribution application, increasing the standard deviation leads to an increase in the minimum pressure requirement. For 99% to 90% reliability levels, the final analyzed standard deviation for each reliability, corresponds to the highest value of $HP_{5,min}$, which is 56.07 m. For the reliability levels lower than 90%, it is not possible to reach the same limit by increasing the standard deviation. This is due to the definitions of the terms in the log-normal distribution. An increase in the standard deviation, σ, leads to an increase in the term ξ (Equation 2.23) which decreases the value of the term λ (Equation 2.22). After a point, the decrease in the term λ starts to alter the increase in the term ξ in the modified constraint (Equation 2.36). As a result, increasing the standard deviation after this limiting point results in a decrease of the value of $HP_{5,min}$. So, for the reliability levels lower than 90%, the last value of the standard deviation for each reliability level indicates the limiting point. Additional values are analyzed between the standard deviation values of 10 and the limiting point to see the trend of this increase. For example, for the 70% reliability level, the limiting point is 16 and, additionally, the values of 12 and 14 are analyzed.

Table 5-21: Results of the chance constraint application with log-normal probability distribution for Case I and Case II

					Case I		Case II		
φ	**σ**	**ζ**	**λ**	$HP_{5,min}$ **(m)**	HP_5 **(m)**	Q_{leak} **(m^3/h)**	HP_5 **(m)**	Q_{leak} **(m^3/h)**	**Leak Reduc. (%)**
0.99	0.00	0.00	3.40	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	0.07	3.40	34.95	34.95	238.551	34.95	238.551	46.75
	4.00	0.13	3.39	40.50	40.50	291.555	40.50	291.555	34.92
	6.00	0.20	3.38	46.63	46.63	351.944	46.63	351.944	21.44
	8.00	0.26	3.37	53.33	53.33	419.774	53.33	419.774	6.30
	8.77	0.29	3.36	56.07	56.07	448.000	56.07	448.000	0.00
0.97	0.00	0.00	3.40	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	0.07	3.40	33.93	33.93	228.972	33.93	228.972	48.89
	4.00	0.13	3.39	38.17	38.19	269.261	38.17	269.071	39.94
	6.00	0.20	3.38	42.69	42.69	312.948	42.69	312.948	30.15
	8.00	0.26	3.37	47.46	47.46	360.185	47.46	360.185	19.60
	10.00	0.32	3.35	52.41	52.41	410.321	52.41	410.321	8.41
	11.44	0.37	3.33	56.07	56.07	448.000	56.07	448.000	0.00
0.95	0.00	0.00	3.40	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	0.07	3.40	33.40	33.40	224.067	33.40	224.067	49.99
	4.00	0.13	3.39	36.99	36.99	257.795	36.99	257.795	42.46
	6.00	0.20	3.38	40.75	40.75	293.963	40.75	293.963	34.38
	8.00	0.26	3.37	44.61	44.61	331.818	44.61	331.818	25.93
	10.00	0.32	3.35	48.54	48.54	371.050	48.54	371.050	17.18
	13.82	0.44	3.30	56.07	56.07	448.000	56.07	448.000	0.00
0.90	0.00	0.00	3.40	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	0.07	3.40	32.60	32.60	216.604	32.60	216.604	51.65
	4.00	0.13	3.39	35.25	35.25	241.352	35.25	241.352	46.13
	6.00	0.20	3.38	37.92	37.92	266.696	37.92	266.696	40.47
	8.00	0.26	3.37	40.56	40.56	292.132	40.56	292.132	34.79
	10.00	0.32	3.35	43.14	43.16	317.527	43.14	317.332	29.17
	21.99	0.66	3.19	56.07	56.07	448.000	56.07	448.000	0.00

(continued)

Table 5-21 (continued): Results of the chance constraint application with log-normal probability distribution for Case I and Case II

φ	σ	ζ	λ	$HP_{5,min}$ (m)	Case I HP_5 (m)	Case I Q_{leak} (m³/h)	Case II HP_5 (m)	Case II Q_{leak} (m³/h)	Leak Reduc. (%)
0.80	0.00	0.00	3.40	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	0.07	3.40	31.66	31.67	208.085	31.66	207.994	53.57
	4.00	0.13	3.39	33.25	33.25	222.682	33.25	222.682	50.29
	6.00	0.20	3.38	34.75	34.75	236.686	34.75	236.686	47.17
	8.00	0.26	3.37	36.14	36.14	249.787	36.14	249.787	44.24
	10.00	0.32	3.35	37.40	37.40	261.766	37.40	261.766	41.57
	15.00	0.47	3.29	39.93	39.93	285.980	39.93	285.980	36.17
	20.00	0.61	3.22	41.58	41.58	302.077	41.58	302.077	32.57
	25.00	0.73	3.14	42.47	42.47	310.711	42.47	310.711	30.64
	30.00	0.83	3.05	42.75	42.75	313.532	42.75	313.532	30.02
0.70	0.00	0.00	3.40	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	0.07	3.40	31.00	31.01	201.982	31.00	201.891	54.94
	4.00	0.13	3.39	31.88	31.88	210.004	31.88	210.004	53.12
	6.00	0.20	3.38	32.64	32.64	216.972	32.64	216.972	51.57
	8.00	0.26	3.37	33.26	33.26	222.774	33.26	222.774	50.27
	10.00	0.32	3.35	33.74	33.74	227.211	33.74	227.211	49.28
	12.00	0.39	3.33	34.09	34.09	230.456	34.09	230.456	48.56
	14.00	0.44	3.30	34.31	34.31	232.498	34.31	232.498	48.10
	16.00	0.50	3.28	34.41	34.41	233.521	34.41	233.521	47.87
0.60	0.00	0.00	3.40	30.00	30.00	192.838	30.00	192.838	56.96
	2.00	0.07	3.40	30.44	30.44	196.813	30.44	196.813	56.07
	4.00	0.13	3.39	30.75	30.75	199.622	30.75	199.622	55.44
	6.00	0.20	3.38	30.93	30.93	201.255	30.93	201.255	55.08
	8.00	0.26	3.37	30.98	30.98	201.710	30.98	201.710	54.98

The change of total leakage versus reliability level for each standard deviation and the change of total leakage versus standard deviation for each reliability level can be seen in Figures 5-10 and 5-11, respectively. Similar to the normal distribution application, the results for Case I and Case II are the same with each other. Hence, Figure 5-10 and Figure 5-11 are valid for both cases.

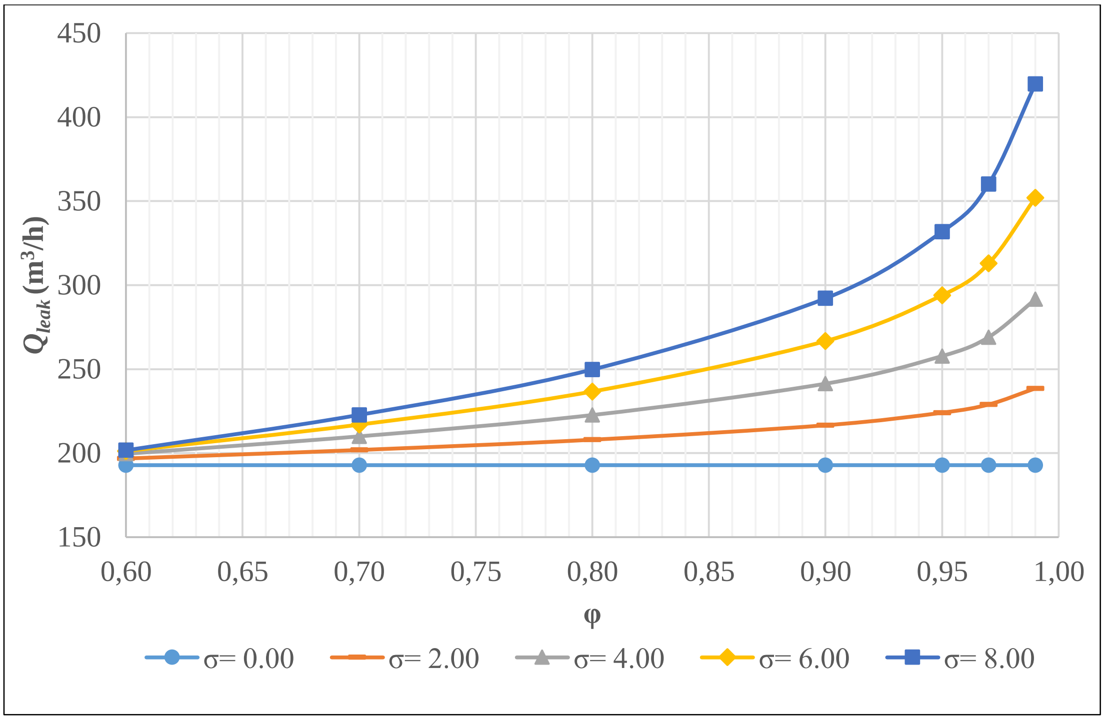

Figure 5-10: The total leakage versus reliability level for log-normal distribution

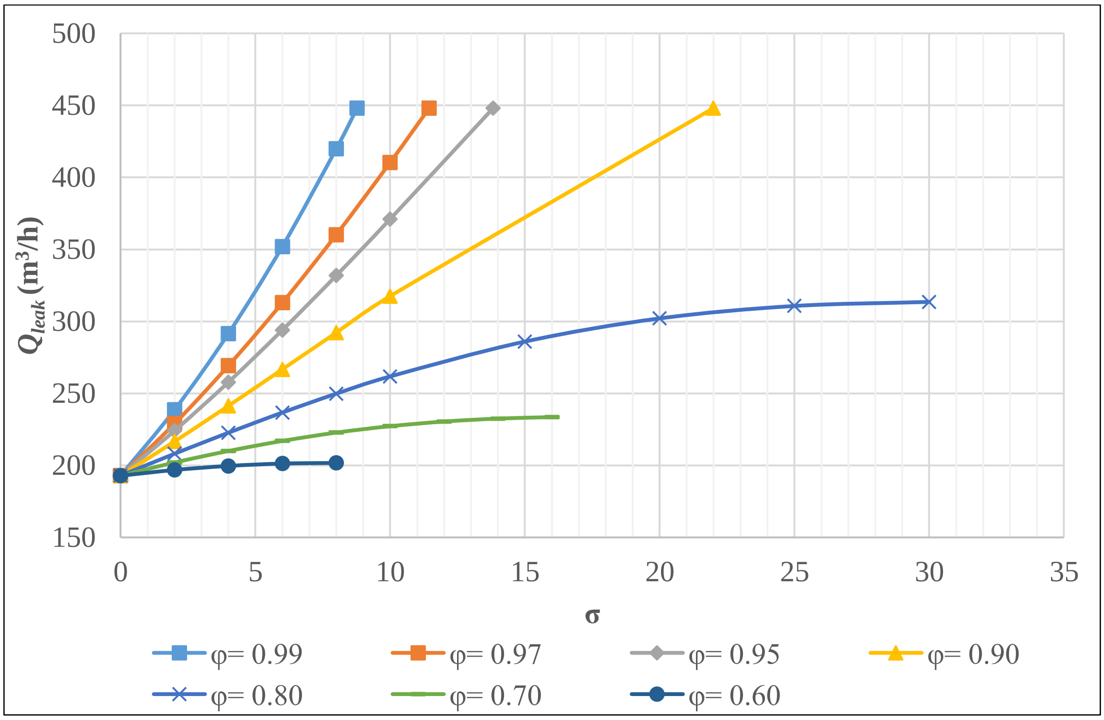

Figure 5-11: The total leakage versus standard deviation for log-normal distribution

Figure 5-10 shows that for the same standard deviation, the total system leakage increases as the reliability increases. For higher reliabilities, especially after 90%, the rate of increase becomes exponential. For zero standard deviation, the total leakage is constant as the minimum pressure requirement value is not changing for any of the reliability levels.

Likewise, for the same reliability level, increasing the standard deviation results in an increase in the total system leakage (Figure 5-11). For the reliability levels of 90% and higher, the behavior of the increase in the total system leakage becomes rapid and the maximum standard deviation that can be reached increases. For the reliability levels lower than 90%, as the standard deviation gets closer to the limiting point, the total system leakage starts to asymptotically reach its limiting value.

5.2.3.3 Discussion of Chance Constraint Applications

Based on the results of the chance constraint applications, the following conclusions can be made:

- In a more reliable network, the probability of not satisfying the pressure requirement decreases and this is mathematically represented as an increase in the minimum pressure limit. Thus, increasing the reliability level of the network for constant standard deviation leads to an increase in the total system leakage.
- In the same manner, higher standard deviations cause higher minimum pressure requirement values. Hence, increasing the standard deviation for the same reliability level results in an increase in the total system leakage.
- Changes in both reliability level and standard deviation starts to affect the changes in the total system leakage more drastically after the reliability level of 90%.
- The results are the same for the solutions that are obtained from the optimization problem formulated with Case I and Case II. This results from the location of the valve. As the PRV is on the main line, it adjusts the pressure of

not only the control point, but of the whole network. Thus, minimizing the total pressure head of the control point or the total system leakage gives the same results.

- The maximum standard deviation value, which can be analyzed for a constant reliability level is higher for the normal distribution. For example, with the 97% reliability level, the highest standard deviation that can be obtained is 13.86 for the normal distribution, while the value of the same parameter is 11.44 for the log-normal distribution.
- The leakage reduction comparison for the normal and log-normal distributions can be seen in Table 5-22. For the reliability levels of 90% and above, higher leakage reductions are obtained for the normal distribution compared to the log-normal case. However, below 90% reliability, the log-normal distribution results in higher reductions than the normal distribution. This is due to the outcome of the formulation of the log-normal distribution, which is explained in Section 5.2.3.3.

Table 5-22: The comparison of normal and log-normal distributions

		Leakage Reduction (%)				Leakage Reduction (%)	
φ	**σ**	**Normal Dist.**	**Log-normal Dist.**	**φ**	**σ**	**Normal Dist.**	**Log-normal Dist.**
0.99	0.00	56.96	56.96	0.80	0.00	56.96	56.96
	2.00	47.38	46.75		2.00	53.53	53.57
	4.00	37.49	34.92		4.00	50.05	50.29
	6.00	27.36	21.44		6.00	46.54	47.17
	8.00	17.02	6.30		8.00	43.00	44.24
	10.00	6.46	-		10.00	39.41	41.57
0.97	0.00	56.96	56.96	0.70	0.00	56.96	56.96
	2.00	49.24	48.89		2.00	54.83	54.94
	4.00	41.32	39.94		4.00	52.67	53.12
	6.00	33.24	30.15		6.00	50.50	51.57
	8.00	24.97	19.60		8.00	48.33	50.27
	10.00	16.57	8.41		10.00	46.15	49.28
0.95	0.00	56.96	56.96	0.60	0.00	56.96	56.96
	2.00	50.21	49.99		2.00	55.93	56.07
	4.00	43.32	42.46		4.00	54.91	55.44
	6.00	36.29	34.38		6.00	53.86	55.08
	8.00	29.12	25.93		8.00	52.82	54.98
	10.00	21.86	17.18		10.00	51.79	-
0.90	0.00	56.96	56.96	-			
	2.00	51.73	51.65				
	4.00	46.38	46.13				
	6.00	40.96	40.47				
	8.00	35.46	34.79				
	10.00	29.86	29.17				

5.3 Example Network-2

The second example network is a modified version of the example network in EPANET version 2.0, which is studied by Köker & Altan-Sakarya (2015). The name of the network is The Brushy Plain WDN and it consists of 1 reservoir, 34 consumer nodes, 1 storage tank and 47 pipes as shown in Figure 5-12. For this study, the pumping station at Node 1 in the original network is replaced by a reservoir, as the pumping station is inadequate for satisfying the summation of the base demand and the leakage.

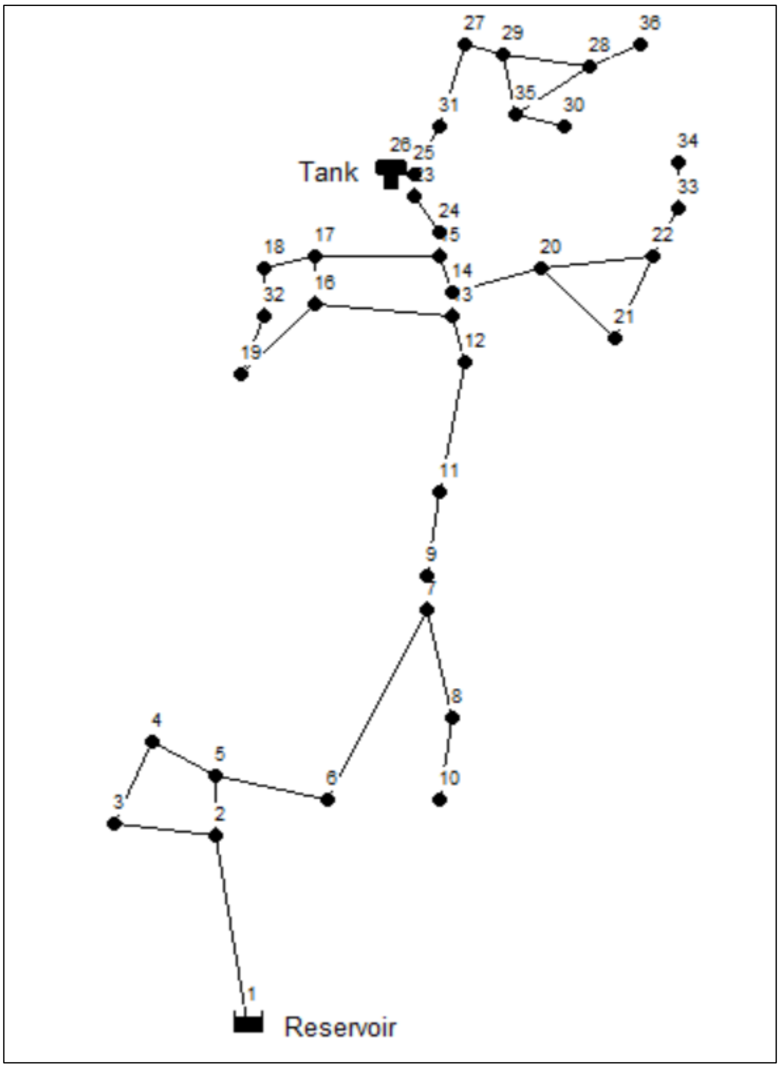

Figure 5-12: Example Network-2

The total head of the newly added reservoir is adjusted as 300 ft by considering two main factors. Firstly, it must be enough to deliver the required demands, while keeping the pressures positive at the consumer nodes. Secondly, the tank in the network must be active, meaning it will not be empty or full for the entire simulation period.

At Node 26, there is a cylindrical storage tank with a diameter of 50 ft. Measuring from the bottom of the tank, the minimum and the maximum water levels for the tank are 50 ft and 70 ft, respectively. The node, link and demand pattern data for this network can be found in Table 5-23, 5-24 and 5-25, respectively.

Table 5-23: Nodal data of Example Network-2

Node ID	Elevation (ft)	Base Demand (gpm)	Node ID	Elevation (ft)	Base Demand (gpm)
1 (Res)	300	-	19	150	5
2	100	8	20	170	19
3	60	14	21	150	16
4	60	8	22	200	10
5	100	8	23	230	8
6	125	5	24	190	11
7	160	4	25	230	6
8	110	9	27	130	8
9	180	14	28	110	0
10	130	5	29	110	7
11	185	34.78	30	130	3
12	210	16	31	190	17
13	210	2	32	110	17
14	200	2	33	180	1.5
15	190	2	34	190	1.5
16	150	20	35	110	0
17	180	20	36	110	1
18	100	20	Tank 26	235	-

Table 5-24: Link data of the Example Network-2

Link ID	Length (ft)	Diameter (in)	Roughness Coefficient (H-W)	Link ID	Length (ft)	Diameter (in)	Roughness Coefficient (H-W)
1	2400	12	100	21	1400	8	100
2	800	12	100	22	1100	12	100
3	1300	8	100	23	1300	8	100
4	1200	8	100	24	1300	8	100
5	1000	12	100	25	1300	8	100
6	1200	12	100	26	600	12	100
7	2700	12	100	27	250	12	100
8	1200	12	140	28	300	12	100
9	400	12	100	29	200	12	100
10	1000	8	140	30	600	12	100
11	700	12	100	31	400	8	100
12	1900	12	100	32	400	8	100
13	600	12	100	34	700	8	100
14	400	12	100	35	1000	8	100
15	300	12	100	36	400	8	100
16	1500	8	100	37	500	8	100
17	1500	8	100	38	500	8	100
18	600	8	100	39	1000	8	100
19	700	12	100	40	700	8	100
20	350	12	100	41	300	8	100

Table 5-25: Demand pattern data of the Example Network-2

Time Period	Demand Multipliers	Time Period	Demand Multipliers
1	1.19	13	0.85
2	0.97	14	0.61
3	0.90	15	1.36
4	0.90	16	0.54
5	0.82	17	0.24
6	1.12	18	0.71
7	1.21	19	0.30
8	0.60	20	0.60
9	0.60	21	1.19
10	1.27	22	1.49
11	2.39	23	1.12
12	0.90	24	1.16

5.3.1 Emitter Coefficient Calculations

The 40% leakage assumption is also valid for this case. However, the calculation of the total base demand varies from Network-1. In Network-1, the hourly base demand is constant for the entire simulation time as there is no demand pattern. In this case, there is a demand pattern and the base demand value changes for each time interval. Thus, in order to calculate the total base demand with the flow unit of gpm (gallons per minute), at first, the total demand for the whole day and for all nodes is calculated as gpd (gallons per day). The demand for a consumer node is constant for a single time period, which is 1 hour; so, gpm is converted to gph (gallons per hour) by multiplying it with 60. This is done for each consumer node and each hourly time interval for the entire 24 hours. The summation of these terms gives the total system as gpd. Then, the average total base demand for a single time period in the unit of gpm is calculated as dividing the total sum by 24 hours and 60 minutes. After making the necessary calculations, the total base demand is found as 309.87 gpm. With the 40% leakage assumption, $Q_{Net,real}$ in Equation (2.11) becomes 123.95 gpm.

The average system pressure is calculated by taking the pressure values of each node for each time interval for the duration of 24 hours into consideration. The average system pressure without the emitters is 63.04 psi and the pressure exponent α is taken as 1.18 (Section 5.1.3). By using these parameters, ${K_{net}}^{(1)}$ is estimated to be 0.933 gpm.psi$^{-1.18}$ (= 123.95 /(63.04$^{1.18}$)). After the iterative process, which in this case is five iterations, the final values of emitter coefficients, ${K_j}^{(5)}$ are calculated and presented in Table 5-26. Note that, the entire length of Pipe 1 and Pipe 29 will be assigned to Node 2 and Node 25, respectively, as it is not possible to assign emitter coefficients to reservoirs or tanks.

Table 5-26: Emitter coefficients of Network-2 for the first and the last iteration

Node ID	Length γ_j (ft)	Γ_j	$K_{net}^{(1)}$ (gpm.psi$^{-1.18}$)	$K_j^{(1)}$ (gpm.psi$^{-1.18}$)	$K_{net}^{(5)}$ (gpm.psi$^{-1.18}$)	$K_j^{(5)}$ (gpm.psi$^{-1.18}$)
2	3450	0.096	0.933	0.089	0.908	0.08703
3	1250	0.035	0.933	0.032	0.908	0.03153
4	1100	0.031	0.933	0.028	0.908	0.02775
5	1500	0.042	0.933	0.039	0.908	0.03784
6	1950	0.054	0.933	0.051	0.908	0.04919
7	2150	0.060	0.933	0.056	0.908	0.05423
8	1100	0.031	0.933	0.028	0.908	0.02775
9	550	0.015	0.933	0.014	0.908	0.01387
10	500	0.014	0.933	0.013	0.908	0.01261
11	1300	0.036	0.933	0.034	0.908	0.03279
12	1250	0.035	0.933	0.032	0.908	0.03153
13	1250	0.035	0.933	0.032	0.908	0.03153
14	900	0.025	0.933	0.023	0.908	0.02270
15	1025	0.028	0.933	0.027	0.908	0.02586
16	1750	0.049	0.933	0.045	0.908	0.04414
17	1400	0.039	0.933	0.036	0.908	0.03532
18	525	0.015	0.933	0.014	0.908	0.01324
19	950	0.026	0.933	0.025	0.908	0.02396
20	1850	0.051	0.933	0.048	0.908	0.04667
21	1300	0.036	0.933	0.034	0.908	0.03279
22	1800	0.050	0.933	0.047	0.908	0.04541
23	450	0.013	0.933	0.012	0.908	0.01135
24	425	0.012	0.933	0.011	0.908	0.01072
25	650	0.018	0.933	0.017	0.908	0.01640
27	400	0.011	0.933	0.010	0.908	0.01009
28	850	0.024	0.933	0.022	0.908	0.02144
29	800	0.022	0.933	0.021	0.908	0.02018
30	500	0.014	0.933	0.013	0.908	0.01261
31	500	0.014	0.933	0.013	0.908	0.01261
32	425	0.012	0.933	0.011	0.908	0.01072
33	700	0.019	0.933	0.018	0.908	0.01766
34	200	0.006	0.933	0.005	0.908	0.00505
35	1100	0.031	0.933	0.028	0.908	0.02775
36	150	0.004	0.933	0.004	0.908	0.00378

5.3.2 Analyses Configurations

In this network, one-valve, two-valve and three valve applications will be studied. There are three common properties, which will be same for all cases. The first one is the limitation of pressure. The minimum pressure head for the control nodes is set as 30 m. As the pressure unit of the network is psi, the limit is converted to 42.66 psi. In addition to that, the minimum, $\underline{HP}_{v,t}$, and the maximum, $\overline{HP}_{v,t}$, values of the pressure head settings of the PRVs are set as 30 m and 80 m, which are 42.66 psi and 114 psi, respectively.

The second one is the control nodes. In order to decide on the control nodes, the network is solved with emitters but without any valve installation. The results show that the pressure for six nodes are below 42.66 psi. That means that it is not possible to maintain the minimum pressure requirement for those points. The rest of the 28 consumer points are selected as control nodes. The status of all the nodes are summarized in Table 5-27.

The third one is the penalty coefficients. Initial values of both minimum pressure head and tank violation penalty coefficients, R_H and R_y, are taken as 100, in order to adjust the order of magnitude of the penalties in the objective function. It should be noted that, initially, the values 1 and 10 were applied for the penalty coefficients, but the optimality condition could not be met with these. Thus, both values were increased to 100.

Table 5-27: Control node check for Network-2

Node ID	Control Node Check	Node ID	Control Node Check
1 (Res)	-	19	Yes
2	Yes	20	Yes
3	Yes	21	Yes
4	Yes	22	No
5	Yes	23	No
6	Yes	24	Yes
7	Yes	25	No
8	Yes	27	Yes
9	Yes	28	Yes
10	Yes	29	Yes
11	Yes	30	Yes
12	No	31	Yes
13	No	32	Yes
14	No	33	Yes
15	Yes	34	Yes
16	Yes	35	Yes
17	Yes	36	Yes
18	Yes	Tank 26	-

5.3.3 One-valve Applications

Five different one PRV applications are studied in Network-2. They are individually placed on Pipe 1 before Node 2, Pipe 31 before Node 27, Pipe 22 before Node 20, Pipe 8 before Node 8, and Pipe 6 before Node 6. Locations of the five different one-valve installations are marked with circles in Figure 5-13.

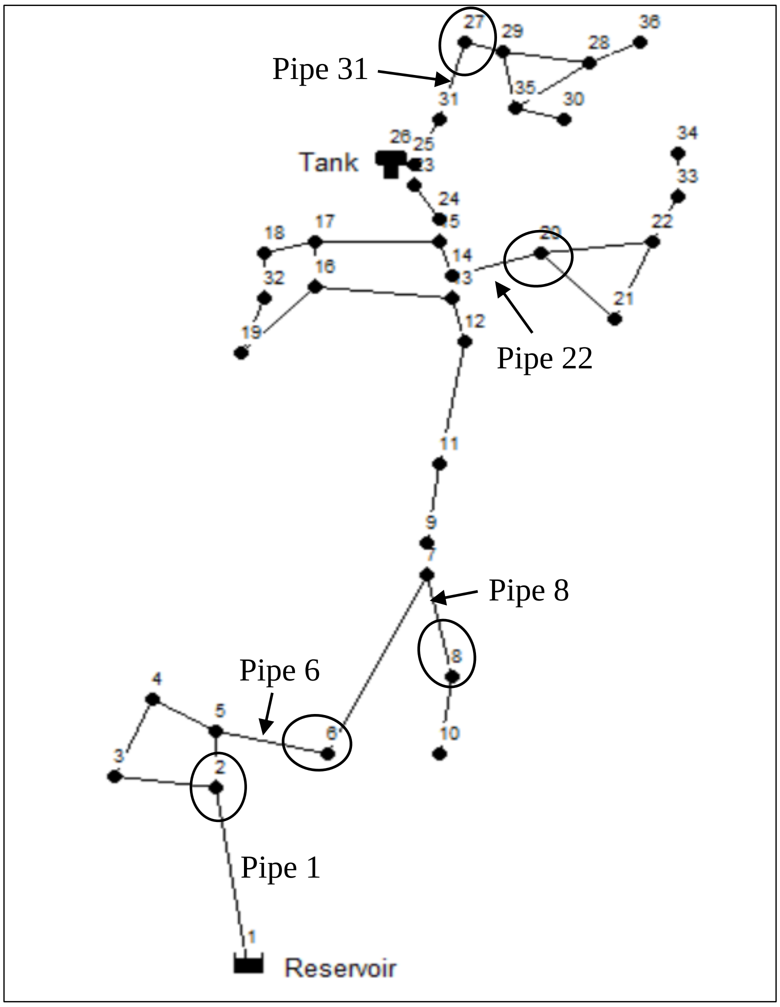

Figure 5-13: Locations of one-valve applications in Network-2

The PRV on Pipe 1 is analyzed in order to see the effect of pressure control from the main supply line. The locations of the PRVs on Pipe 8, Pipe 22 and Pipe 31 are selected by considering the entrance lines of the branches, which will enable the pressure management of the whole branch. Finally, the PRV on Pipe 6 is placed to compare its effectiveness with the PRV on Pipe 1.

In addition to these, placing the PRV before Node 3 (between Nodes 2 and 3), before Node 16 (between Nodes 13 and 16) and Node 17 (between Nodes 15 and 17) are also tested. However, as it is explained in Sections 5.2.1.2.2 and 5.2.1.2.3, a PRV located within a loop stops the flow on the attached line and starts to deliver the flow from the other lines of the loop as it cannot decrease the pressure of the node located after it. Thus, the results for these analyses are not represented.

For each one-valve case, the maximum pressure head setting of the PRV, $\overline{HP}_v$, is modified by checking the pressure of the node located after the PRV. The results of the analyses are summarized for Case I and Case II in Tables 5-28 and 5-29, respectively. In both of the tables, $\overline{HP}_v$ indicates the modified maximum pressure head setting for the PRV and x_v is the optimized PRV settings.

As it can be seen from the results of both cases, the lowest leakage reduction (~0.6 %) is obtained from the PRV located in Pipe 22 before Node 20. The pressures of the nodes in that branch without any valve installation are around 45 psi. Consequently, high pressure reductions cannot be obtained with the minimum pressure requirement of 42.66 psi.

Approximately 2% leakage reduction can be obtained by placing the PRV on Pipe 8 as the pressures of Nodes 8 and 10 are both around 75 psi without any valve installation. However, the percentage is still low as the pressure is reduced for only two nodes.

Comparing the results of PRV on Pipe 1 and Pipe 6, the Pipe 6 application reduced the leakage nearly as half of the PRV on Pipe 1. This is due to the pressures of the nodes located between the PRVs. Nodes 3, 4 and 5 have the highest pressures in the network, which are around 90 - 100 psi without any valve control. Thus, placing a PRV after these points diminishes the majority of the reduction. The amount was around 3% for the PRV in Pipe 1 as the pressures on the Nodes 9, 11 and 15 are around 45 psi without any valve control.

The highest reduction rate of 5.31% is obtained from the PRV located in Pipe 31 as the pressure is decreased from approximately 75 psi to 45 psi within the branch.

Table 5-28: The results of Network-2 for: one-valve applications, Case I

	Case I									
	Pipe 1		Pipe 31		Pipe 22		Pipe 8		Pipe 6	
Time Interval	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)
1	85.69	85.69	70.84	42.67	53.52	51.34	80.12	51.35	74.32	72.23
2	85.71	83.00	70.74	42.66	53.44	51.34	80.11	51.35	74.33	42.66
3	85.72	83.22	70.76	42.66	53.47	51.34	80.15	51.36	74.36	74.36
4	85.74	85.74	70.80	42.66	53.51	51.34	80.18	51.37	74.38	74.38
5	85.76	85.76	70.84	42.66	53.56	51.34	80.23	51.36	74.42	74.42
6	85.72	82.26	70.91	42.67	53.59	51.34	80.19	51.37	74.37	74.27
7	85.68	83.76	70.83	42.67	53.51	51.34	80.11	51.38	74.31	42.66
8	85.79	85.79	70.73	42.66	53.49	51.33	80.24	51.37	74.44	74.44
9	85.83	84.06	70.92	42.66	53.67	51.33	80.36	51.38	74.51	74.51
10	85.73	84.45	71.07	42.67	53.74	51.34	80.26	51.36	74.40	74.40
11	85.42	85.28	70.81	42.67	53.32	51.37	79.74	51.37	73.98	73.98
12	85.59	83.73	70.23	42.66	52.96	51.34	79.80	51.38	74.14	74.14
13	85.63	83.28	70.34	42.66	53.07	51.34	79.89	51.35	74.20	74.20
14	85.72	82.67	70.46	42.66	53.24	51.33	80.06	51.33	74.32	74.32
15	85.60	84.04	70.65	42.67	53.33	51.34	79.94	51.33	74.19	74.19
16	85.75	85.68	70.51	42.66	53.30	51.33	80.12	51.33	74.37	74.37
17	85.88	85.81	70.77	42.66	53.60	51.33	80.40	51.33	74.57	74.57
18	85.85	83.05	71.09	42.66	53.81	51.33	80.43	51.33	74.55	74.43
19	85.97	79.75	71.20	42.66	53.99	51.33	80.65	51.33	74.72	74.58
20	85.97	81.98	71.46	42.66	54.18	51.33	80.71	51.33	74.74	74.63
21	85.88	84.81	71.54	42.67	54.21	51.34	80.62	51.36	74.64	74.54
22	85.77	85.77	71.33	42.67	53.98	51.35	80.39	51.36	74.47	72.90
23	85.75	85.75	71.04	42.67	53.72	51.34	80.28	51.34	74.42	72.71
24	85.72	82.93	70.94	42.67	53.62	51.34	80.20	51.34	74.37	72.47
Leak Reduc. (%)	3.43		5.31		0.62		2.29		1.72	
Runtime (min)	45.1		10.3		21.1		30.5		30.7	

Table 5-29: The results of Network-2 for: one-valve applications, Case II

	Case II									
	Pipe 1		Pipe 31		Pipe 22		Pipe 8		Pipe 6	
Time Interval	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)
1	85.69	85.69	70.84	42.67	53.52	51.37	80.12	64.28	74.32	74.30
2	85.71	83.25	70.74	42.66	53.44	51.34	80.11	64.27	74.33	74.31
3	85.72	83.09	70.76	42.66	53.47	51.34	80.15	64.31	74.36	74.34
4	85.74	83.79	70.80	42.66	53.51	51.34	80.18	64.34	74.38	74.33
5	85.76	83.54	70.84	42.66	53.56	51.38	80.23	64.39	74.42	74.36
6	85.72	83.37	70.91	42.67	53.59	51.37	80.19	64.35	74.37	74.31
7	85.68	84.61	70.83	42.67	53.51	51.34	80.11	64.27	74.31	74.25
8	85.79	83.59	70.73	42.66	53.49	51.36	80.24	51.56	74.44	74.42
9	85.83	84.12	70.92	42.66	53.67	51.45	80.36	51.68	74.51	74.49
10	85.73	85.49	71.07	42.67	53.74	51.43	80.26	51.58	74.40	71.76
11	85.42	85.42	70.81	42.67	53.32	51.38	79.74	51.36	73.98	73.96
12	85.59	83.59	70.23	42.66	52.96	51.34	79.80	51.38	74.14	74.13
13	85.63	83.20	70.34	42.66	53.07	51.37	79.89	52.14	74.20	74.19
14	85.72	82.84	70.46	42.66	53.24	51.36	80.06	51.38	74.32	72.23
15	85.60	84.14	70.65	42.67	53.33	51.34	79.94	52.14	74.19	71.27
16	85.75	83.29	70.51	42.66	53.30	51.55	80.12	51.44	74.37	71.17
17	85.88	81.88	70.77	42.66	53.60	51.33	80.40	51.72	74.57	74.56
18	85.85	85.85	71.09	42.66	53.81	51.51	80.43	51.75	74.55	74.53
19	85.97	85.97	71.20	42.66	53.99	51.68	80.65	51.97	74.72	74.70
20	85.97	81.15	71.46	42.66	54.18	51.33	80.71	53.87	74.74	74.72
21	85.88	85.88	71.54	42.67	54.21	51.37	80.62	51.33	74.64	74.62
22	85.77	83.65	71.33	42.67	53.98	51.44	80.39	53.19	74.47	74.46
23	85.75	85.75	71.04	42.67	53.72	51.35	80.28	51.39	74.42	71.79
24	85.72	82.74	70.94	42.67	53.62	51.38	80.20	51.33	74.37	71.16
Leak Reduc. (%)	3.58		5.31		0.61		1.97		1.98	
Runtime (min)	39.8		15.0		35.8		76.0		30.5	

5.3.4 Two-valve Applications

In this network, five different two-valve applications are analyzed. The first three of them are PRVs located on Pipe 1 and Pipe 31, Pipe 1 and Pipe 8, and Pipe 31 and Pipe 8. For the last two cases, PRVs are again placed on Pipe 1 and Pipe 31, as well as on

Pipe 1 and Pipe 8. However, this time, the settings of the PRV on Pipe 1 are accepted as the same with the values of the 24 hour configuration results for Case II (Table 5-29) and will not be optimized. The optimization will be applied only to the second PRVs. The locations of the PRVs are selected based on the results of the one-valve applications.

The results of the first three cases for Case I and Case II can be seen in Tables 5-30 and 5-31, respectively. Similarly, the results of the last two cases are shown in Tables 5-32 and 5-33. In all of the tables, PRV-1 is the valve on the first pipe and the PRV-2 is the valve on the second pipe, written at the top of the corresponding results column.

Table 5-30: The results of Network-2 for: first three cases of two-valve applications, Case I

		Pipe 1 + Pipe 31		Pipe 1 + Pipe 8		Pipe 31 + Pipe 8	
PRV	**Time Interval**	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)
1	1	85.69	85.69	85.69	84.97	70.84	42.69
	2	85.71	83.23	85.71	82.85	70.74	42.66
	3	85.72	83.17	85.72	83.19	70.76	42.66
	4	85.74	85.74	85.74	84.70	70.80	42.66
	5	85.76	85.76	85.76	85.03	70.84	42.66
	6	85.72	82.32	85.72	84.15	70.91	42.69
	7	85.68	83.33	85.68	82.61	70.83	42.69
	8	85.79	85.79	85.79	85.47	70.73	42.66
	9	85.83	83.44	85.83	83.06	70.92	42.66
	10	85.73	85.45	85.73	85.61	71.07	42.69
	11	85.42	85.42	85.42	85.36	70.81	42.69
	12	85.59	84.37	85.59	83.91	70.23	42.66
	13	85.63	83.39	85.63	83.37	70.34	42.66
	14	85.72	83.01	85.72	82.88	70.46	42.66
	15	85.60	85.28	85.60	83.89	70.65	42.69
	16	85.75	85.41	85.75	85.74	70.51	42.66
	17	85.88	85.61	85.88	85.87	70.77	42.66
	18	85.85	79.43	85.85	82.20	71.09	42.66
	19	85.97	83.34	85.97	80.27	71.20	42.66
	20	85.97	81.37	85.97	83.19	71.46	42.66
	21	85.88	84.45	85.88	83.81	71.54	42.69
	22	85.77	85.77	85.77	85.67	71.33	42.69
	23	85.75	85.75	85.75	85.72	71.04	42.69
	24	85.72	83.35	85.72	83.61	70.94	42.69

(continued)

Table 5-30 (continued): The results of Network-2 for: first three cases of two-valve applications, Case I

		Pipe 1 + Pipe 31		Pipe 1 + Pipe 8		Pipe 31 + Pipe 8	
PRV	**Time Interval**	$\overline{HP}_v$ **(ft)**	x_v **(ft)**	$\overline{HP}_v$ **(ft)**	x_v **(ft)**	$\overline{HP}_v$ **(ft)**	x_v **(ft)**
2	1	70.84	70.84	80.12	80.12	80.12	51.33
	2	70.74	70.55	80.11	80.11	80.11	51.33
	3	70.76	70.76	80.15	80.15	80.15	51.33
	4	70.80	70.80	80.18	80.18	80.18	51.33
	5	70.84	70.84	80.23	80.23	80.23	51.33
	6	70.91	70.91	80.19	80.19	80.19	51.33
	7	70.83	70.83	80.11	80.11	80.11	51.33
	8	70.73	70.26	80.24	80.24	80.24	51.34
	9	70.92	70.87	80.36	80.36	80.36	51.34
	10	71.07	70.97	80.26	80.26	80.26	51.33
	11	70.81	70.81	79.74	79.74	79.74	51.34
	12	70.23	70.23	79.80	79.80	79.80	51.33
	13	70.34	70.34	79.89	79.89	79.89	51.33
	14	70.46	70.46	80.06	80.06	80.06	51.33
	15	70.65	70.08	79.94	79.94	79.94	51.34
	16	70.51	70.51	80.12	80.12	80.12	51.33
	17	70.77	70.77	80.40	80.40	80.40	51.33
	18	71.09	71.09	80.43	80.43	80.43	51.33
	19	71.20	70.76	80.65	80.65	80.65	51.33
	20	71.46	71.46	80.71	80.71	80.71	51.34
	21	71.54	71.54	80.62	80.62	80.62	51.33
	22	71.33	71.33	80.39	80.39	80.39	51.34
	23	71.04	71.04	80.28	80.28	80.28	51.33
	24	70.94	70.42	80.20	80.20	80.20	51.34
	Leak Reduc. (%)	3.27		3.47		7.61	
	Runtime (min)	76.2		76.8		70.0	

Table 5-31: The results of Network-2 for: first three cases of two-valve applications, Case II

		Pipe 1 + Pipe 31		Pipe 1 + Pipe 8		Pipe 31 + Pipe 8	
PRV	**Time Interval**	$\overline{HP}_v$ **(ft)**	x_v **(ft)**	$\overline{HP}_v$ **(ft)**	x_v **(ft)**	$\overline{HP}_v$ **(ft)**	x_v **(ft)**
1	1	85.69	85.69	85.69	85.69	70.84	42.67
	2	85.71	83.25	85.71	83.25	70.74	42.66
	3	85.72	83.09	85.72	83.09	70.76	42.66
	4	85.74	83.79	85.74	83.79	70.80	42.66
	5	85.76	83.54	85.76	83.54	70.84	42.67
	6	85.72	83.37	85.72	83.37	70.91	42.74
	7	85.68	84.61	85.68	84.61	70.83	42.78
	8	85.79	83.59	85.79	83.59	70.73	42.66
	9	85.83	84.12	85.83	84.12	70.92	42.75
	10	85.73	85.49	85.73	85.49	71.07	42.68
	11	85.42	85.42	85.42	85.42	70.81	42.68
	12	85.59	83.59	85.59	83.59	70.23	42.66
	13	85.63	83.20	85.63	83.20	70.34	42.66
	14	85.72	82.84	85.72	82.84	70.46	42.66
	15	85.60	84.14	85.60	84.14	70.65	42.68
	16	85.75	83.29	85.75	83.29	70.51	42.66
	17	85.88	81.88	85.88	81.88	70.77	42.66
	18	85.85	85.85	85.85	85.85	71.09	42.66
	19	85.97	85.97	85.97	85.97	71.20	42.66
	20	85.97	81.15	85.97	81.15	71.46	42.66
	21	85.88	85.88	85.88	85.88	71.54	42.68
	22	85.77	83.65	85.77	83.65	71.33	42.68
	23	85.75	85.75	85.75	85.75	71.04	42.68
	24	85.72	82.74	85.72	82.74	70.94	42.77

(continued)

Table 5-31 (continued): The results of Network-2 for: first three cases of two-valve applications, Case II

		Pipe 1 + Pipe 31		Pipe 1 + Pipe 8		Pipe 31 + Pipe 8	
PRV	**Time Interval**	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)	$\overline{HP}_v$ (ft)	x_v (ft)
2	1	70.84	70.84	80.12	80.12	80.12	64.15
	2	70.74	70.74	80.11	80.11	80.11	64.13
	3	70.76	70.76	80.15	80.15	80.15	64.17
	4	70.80	70.80	80.18	80.18	80.18	64.21
	5	70.84	70.84	80.23	80.23	80.23	64.26
	6	70.91	70.91	80.19	80.19	80.19	64.22
	7	70.83	70.83	80.11	80.11	80.11	64.14
	8	70.73	70.73	80.24	80.24	80.24	51.43
	9	70.92	70.92	80.36	80.36	80.36	51.55
	10	71.07	71.07	80.26	80.26	80.26	51.70
	11	70.81	70.81	79.74	79.74	79.74	51.44
	12	70.23	70.23	79.80	79.80	79.80	51.57
	13	70.34	70.34	79.89	79.89	79.89	51.33
	14	70.46	70.46	80.06	80.06	80.06	51.50
	15	70.65	70.65	79.94	79.94	79.94	52.62
	16	70.51	70.51	80.12	80.12	80.12	51.64
	17	70.77	70.77	80.40	80.40	80.40	51.59
	18	71.09	71.09	80.43	80.43	80.43	51.62
	19	71.20	71.20	80.65	80.65	80.65	51.84
	20	71.46	71.46	80.71	80.71	80.71	59.49
	21	71.54	71.54	80.62	80.62	80.62	66.55
	22	71.33	71.33	80.39	80.39	80.39	59.42
	23	71.04	71.04	80.28	80.28	80.28	62.42
	24	70.94	70.94	80.20	80.20	80.20	80.18
	Leak Reduc. (%)	3.58		3.58		7.07	
	Runtime (min)	107.8		159.0		114.3	

The leakage reduction rate using PRV-1 on Pipe 1 as a one-valve application was around 3.5% (Tables 5-28 and 5-29). When it is combined with another PRV, the rate is still around 3.5% for both Case I and Case II (Tables 5-30 and 5-31). Hence, it is not effective to use PRV-1 with a second valve as PRV-2 becomes inactive. For both combinations with PRV-2 on Pipes 31 and 8, the pressure setting of the PRV-1 is reduced, while the settings of PRV-2 stay constant. This results from the differences in the gradient values. Reducing the pressure settings of PRV-1 affects the whole network pressure, while both PRV-2s affect only a branch of the network. Thus, the gradients corresponding to PRV-1 give higher values compared to the gradients of PRV-2s. As this is a non-linear optimization problem for both Case I and Case II, the solver stops when it reaches a local optimum with the calculated gradient values and so, the global optimum is not reached.

Using valves together on Pipes 31 and 8 gives the highest leakage reduction rate of 7.61% for Case I. Both of the valves are actively working and they are controlling the pressures of two different branches. So, the leakage rate becomes the summation of the individual results of valve on Pipe 31 (5.31%) and valve on Pipe 8 (2.29%) (Table 5-28).

The active usage of the second valve, which is combined with the first valve on Pipe 1, can be obtained by optimizing the valves separately. Optimization results of the one-valve application on Pipe-1 for Case II (Table 5-29) are used as constant settings and the valves on Pipes 31 and 8 are optimized separately. For example, for Case II, the combination of Pipe 1 and 31 results in the leakage reduction rate of 8.66% (Tables 5-33), which is the approximate summation of the individual reduction rates of 3.58% and 5.31% (Table 5-29). Similarly, Pipe 1 and 8 arrangement reduce the leakage by 5.23% (Table 5-33) which is the approximate summation of their separate rates of 3.58% and 1.97% (Table 5-29). Thus, it can be concluded that, if one of the valves is on the main supply line, it should be optimized separately in order to achieve better results.

Table 5-32: The results of Network-2 for: last two cases of two-valve applications, Case I

	Pipe 1 (c)	Pipe 1 (c) + Pipe 31		Pipe 1 (c) + Pipe 8	
Time Interval	x_1 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)
1	85.69	68.93	42.67	78.41	51.34
2	83.25	68.91	42.66	78.09	51.34
3	83.09	68.85	42.66	77.98	51.34
4	83.79	68.80	42.66	77.93	51.33
5	83.54	68.75	42.66	77.98	51.34
6	83.37	68.76	42.67	78.04	51.34
7	84.61	68.69	42.67	78.16	51.34
8	83.59	68.67	42.66	78.10	51.33
9	84.12	68.84	42.66	78.64	51.34
10	85.49	69.10	42.67	78.91	51.34
11	85.42	69.08	42.67	78.47	51.34
12	83.59	68.64	42.66	78.03	51.34
13	83.20	68.69	42.66	77.81	51.34
14	82.84	68.66	42.66	78.08	51.35
15	84.14	68.80	42.67	78.13	51.34
16	83.29	68.67	42.66	77.66	51.34
17	81.88	68.69	42.66	77.58	51.33
18	85.85	68.75	42.66	77.80	51.34
19	85.97	68.74	42.66	77.62	51.35
20	81.15	68.78	42.66	78.35	51.34
21	85.88	68.97	42.67	78.56	51.34
22	83.65	68.98	42.67	78.69	51.34
23	85.75	68.92	42.67	78.52	51.34
24	82.74	68.96	42.67	78.39	51.33
	Leak Reduc. (%)	8.66		5.85	
	Runtime (min)	10.1		33.3	

Table 5-33: The results of Network-2 for: last two cases of two-valve applications, Case II

	Pipe 1 (c)	Pipe 1 (c) + Pipe 31		Pipe 1 (c) + Pipe 8	
Time Interval	x_1 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)
1	85.69	68.93	42.67	78.41	63.64
2	83.25	68.91	42.66	78.09	63.32
3	83.09	68.85	42.66	77.98	63.21
4	83.79	68.80	42.66	77.93	63.16
5	83.54	68.75	42.66	77.98	63.21
6	83.37	68.76	42.67	78.04	63.27
7	84.61	68.69	42.67	78.16	63.39
8	83.59	68.67	42.66	78.10	51.92
9	84.12	68.84	42.66	78.64	70.05
10	85.49	69.10	42.67	78.91	52.58
11	85.42	69.08	42.67	78.47	64.95
12	83.59	68.64	42.66	78.03	51.45
13	83.20	68.69	42.66	77.81	64.29
14	82.84	68.66	42.66	78.08	64.56
15	84.14	68.80	42.67	78.13	64.61
16	83.29	68.67	42.66	77.66	51.33
17	81.88	68.69	42.66	77.58	64.06
18	85.85	68.75	42.66	77.80	64.28
19	85.97	68.74	42.66	77.62	51.33
20	81.15	68.78	42.66	78.35	51.43
21	85.88	68.97	42.67	78.56	51.56
22	83.65	68.98	42.67	78.69	53.54
23	85.75	68.92	42.67	78.52	53.14
24	82.74	68.96	42.67	78.39	52.34
	Leak Reduc. (%)	8.66		5.23	
	Runtime (min)	9.2		61.7	

5.3.5 Three-valve Applications

Based on the results of all the analyses conducted on this network, only one configuration is selected for the three valve application: valves on Pipes 1, 31 and 8.

Two different alternatives are analyzed by taking the settings of valve on Pipe 1 as variable and constant. The results of optimizing both three valves together for Case I and Case II can be seen in Tables 5-34 and 5-35, respectively. Likewise, optimizing two valves by taking the pre-optimized settings of the valve on the main line for Case I and Case II can be seen in Tables 5-36 and 5-37, respectively.

Similar to the two-valve applications, it can be concluded from the results that it is not effective to optimize PRV-1 with other valves as they become inactive. The amount of leakage reduction is again around 3.5% when three of the valves are optimized together. This is equal to the amount when the valve on the main line is optimized individually.

The reduction amount increased to 10.8% when the settings of the PRV on Pipe 1 are used as the pre-optimized results from Case II (Table 5-29) and valves on Pipes 31 and 8 are optimized. This 10.8% reduction is approximately the summation of individual reduction rate results of the three valves.

Table 5-34: The results of Network-2 for: three-valve application optimized together, Case I

	Pipe 1 + Pipe 31 + Pipe 8					
	PRV-1		PRV-2		PRV-3	
Time Interval	$\overline{HP}_1$ (ft)	x_1 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)	$\overline{HP}_3$ (ft)	x_3 (ft)
1	85.69	84.11	80.12	79.72	70.84	70.02
2	85.71	83.75	80.11	79.94	70.74	69.70
3	85.72	83.69	80.15	79.87	70.76	70.09
4	85.74	83.28	80.18	79.80	70.80	70.26
5	85.76	85.62	80.23	79.61	70.84	69.84
6	85.72	82.77	80.19	79.78	70.91	69.58
7	85.68	83.80	80.11	79.91	70.83	69.55
8	85.79	83.46	80.24	79.86	70.73	69.91
9	85.83	84.59	80.36	79.97	70.92	70.23
10	85.73	85.69	80.26	79.86	71.07	70.12
11	85.42	85.42	79.74	79.23	70.81	70.39
12	85.59	83.51	79.80	79.52	70.23	69.22
13	85.63	83.36	79.89	79.56	70.34	69.25
14	85.72	82.45	80.06	79.63	70.46	69.87
15	85.60	85.60	79.94	79.63	70.65	70.39
16	85.75	82.32	80.12	79.83	70.51	69.90
17	85.88	82.32	80.40	80.04	70.77	70.24
18	85.85	82.76	80.43	79.95	71.09	70.49
19	85.97	85.15	80.65	80.29	71.20	70.36
20	85.97	79.86	80.71	80.46	71.46	70.40
21	85.88	84.94	80.62	80.23	71.54	70.69
22	85.77	84.85	80.39	80.29	71.33	70.22
23	85.75	83.73	80.28	79.93	71.04	69.53
24	85.72	84.03	80.20	79.83	70.94	69.88
Leak Reduc. (%)	3.7					
Runtime (min)	141.1					

Table 5-35: The results of Network-2 for: three-valve application optimized together, Case II

	Pipe 1 + Pipe 31 + Pipe 8					
	PRV-1		PRV-2		PRV-3	
Time Interval	$\overline{HP}_1$ (ft)	x_1 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)	$\overline{HP}_3$ (ft)	x_3 (ft)
1	85.69	85.69	80.12	80.12	70.84	70.84
2	85.71	83.25	80.11	80.11	70.74	70.74
3	85.72	83.09	80.15	80.15	70.76	70.76
4	85.74	83.79	80.18	80.18	70.80	70.80
5	85.76	83.54	80.23	80.23	70.84	70.84
6	85.72	83.37	80.19	80.19	70.91	70.91
7	85.68	84.61	80.11	80.11	70.83	70.83
8	85.79	83.59	80.24	80.24	70.73	70.73
9	85.83	84.12	80.36	80.36	70.92	70.92
10	85.73	85.49	80.26	80.26	71.07	71.07
11	85.42	85.42	79.74	79.74	70.81	70.81
12	85.59	83.59	79.80	79.80	70.23	70.23
13	85.63	83.20	79.89	79.89	70.34	70.34
14	85.72	82.84	80.06	80.06	70.46	70.46
15	85.60	84.14	79.94	79.94	70.65	70.65
16	85.75	83.29	80.12	80.12	70.51	70.51
17	85.88	81.88	80.40	80.40	70.77	70.77
18	85.85	85.85	80.43	80.43	71.09	71.09
19	85.97	85.97	80.65	80.65	71.20	71.20
20	85.97	81.15	80.71	80.71	71.46	71.46
21	85.88	85.88	80.62	80.62	71.54	71.54
22	85.77	83.65	80.39	80.39	71.33	71.33
23	85.75	85.75	80.28	80.28	71.04	71.04
24	85.72	82.74	80.20	80.20	70.94	70.94
Leak Reduc. (%)	3.58					
Runtime (min)	238.7					

Table 5-36: The results of Network-2 for: three-valve application, PRV-1 used from pre-optimized results, Case I

	Pipe 1 (c) + Pipe 31 + Pipe 8				
	PRV-1 (c)	PRV-2		PRV-3	
Time Interval	$\overline{HP}_1$ (ft)	x_1 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)	$\overline{HP}_3$ (ft)
1	85.69	78.41	51.36	68.93	42.67
2	83.25	78.09	51.36	68.91	42.66
3	83.09	77.98	51.35	68.85	42.66
4	83.79	77.93	51.36	68.80	42.66
5	83.54	77.98	51.36	68.75	42.66
6	83.37	78.04	51.37	68.76	42.67
7	84.61	78.16	51.36	68.69	42.67
8	83.59	78.10	51.35	68.67	42.66
9	84.12	78.64	51.35	68.84	42.66
10	85.49	78.91	51.37	69.10	42.67
11	85.42	78.47	51.36	69.08	42.67
12	83.59	78.03	51.36	68.64	42.66
13	83.20	77.81	51.36	68.69	42.66
14	82.84	78.08	51.34	68.66	42.66
15	84.14	78.13	51.34	68.80	42.67
16	83.29	77.66	51.36	68.67	42.66
17	81.88	77.58	51.35	68.69	42.66
18	85.85	77.80	51.35	68.75	42.66
19	85.97	77.62	51.34	68.74	42.66
20	81.15	78.35	51.35	68.78	42.66
21	85.88	78.56	51.35	68.97	42.67
22	83.65	78.69	51.35	68.98	42.67
23	85.75	78.52	51.35	68.92	42.67
24	82.74	78.39	51.35	68.96	42.67
Leak Reduc. (%)	10.8				
Runtime (min)	70.4				

Table 5-37: The results of Network-2 for: three-valve application, PRV-1 used from pre-optimized results, Case II

	Pipe 1 (c) + Pipe 31 + Pipe 8				
	PRV-1 (c)	PRV-2		PRV-3	
Time Interval	$\overline{HP}_1$ (ft)	x_1 (ft)	$\overline{HP}_2$ (ft)	x_2 (ft)	$\overline{HP}_3$ (ft)
1	85.69	78.41	52.21	68.93	42.67
2	83.25	78.09	51.89	68.91	42.66
3	83.09	77.98	51.78	68.85	42.66
4	83.79	77.93	51.73	68.80	42.66
5	83.54	77.98	51.78	68.75	42.66
6	83.37	78.04	51.84	68.76	42.67
7	84.61	78.16	51.96	68.69	42.67
8	83.59	78.10	51.90	68.67	42.66
9	84.12	78.64	52.44	68.84	42.66
10	85.49	78.91	52.71	69.10	42.67
11	85.42	78.47	52.27	69.08	42.67
12	83.59	78.03	51.83	68.64	42.66
13	83.20	77.81	51.61	68.69	42.66
14	82.84	78.08	51.88	68.66	42.66
15	84.14	78.13	51.93	68.80	42.67
16	83.29	77.66	51.46	68.67	42.66
17	81.88	77.58	51.38	68.69	42.66
18	85.85	77.80	51.60	68.75	42.66
19	85.97	77.62	51.42	68.74	42.66
20	81.15	78.35	52.15	68.78	42.66
21	85.88	78.56	52.36	68.97	42.67
22	83.65	78.69	52.49	68.98	42.67
23	85.75	78.52	52.32	68.92	42.67
24	82.74	78.39	52.19	68.96	42.67
Leak Reduc. (%)	10.8				
Runtime (min)	41.6				

5.3.6 Discussion of Network-2

A summary of the results for Network-2 can be seen in Table 5-38. Considering the outcomes, the following conclusions can be made:

- Placing PRVs at the entrances of the branches, in which the pressure heads of the consumer nodes are higher, results in higher leakage reductions. For example, it can be seen from Tables 5-28 and 5-29 that when the PRV is placed on Pipe 22, the leakage reduction that can be obtained is 0.62%, whereas when it is placed on Pipe 31, the reduction rate increases to 5.31%. This is due to the pressure heads of the consumer nodes within the branch starting with Pipe 31 being much higher compared to the values within the branch starting with Pipe 22.
- For a more effective leakage reduction, it is better to optimize multiple PRVs separately, if a PRV on Pipe 1 (main line) is coupled with other PRVs. For a separate optimization, the first step is to only place a valve on Pipe 1 and optimize it. In the second step, additional valves are installed on the same network. Finally, the optimization is carried out for these additional valves using the constant optimized settings of the valve on Pipe 1. If the optimization is not carried out separately, only the valve on Pipe 1 controls the pressure in the network and the other valves become inactive. It can be seen from Table 5-38 that when the PRVs placed on Pipes 1 and 8 are optimized together, the leakage reduction is 3.47% for Case I, which is almost the same result obtained from using only one valve on Pipe 1 (3.43% - Table 5-28). If the optimization is handled separately, this amount increases to 5.85% (Table 5-32).
- Further leakage reduction can be obtained by placing additional PRVs to the forward parts of the branches, which are not within a loop.
- Comparing Case I and Case II formulations, it can be concluded that the leakage reduction rates are very close.

Table 5-38: Comparison of the leakage reduction results of Network-2

Valve Location	Case	Leak Reduction (%)
Pipe 1	I	3.43
	II	3.58
Pipe 31	I	5.31
	II	5.31
Pipe 22	I	0.63
	II	0.61
Pipe 8	I	2.29
	II	1.97
Pipe 6	I	1.72
	II	1.98
Pipe 1 + Pipe 31	I	3.27
	II	2.58
Pipe 1 + Pipe 8	I	3.47
	II	3.58
Pipe 31 + Pipe 8	I	7.61
	II	7.07
Pipe 1 (c) + Pipe 31	I	8.66
	II	8.66
Pipe 1 (c) + Pipe 8	I	5.85
	II	5.23
Pipe 1 + Pipe 31 + Pipe 8	I	3.70
	II	3.58
Pipe 1 (c) + Pipe 31 + Pipe 8	I	10.80
	II	10.80

5.4 Example Network-3

The third example network is North Marina Water District - Zone 1 (California) and it is a modified version of the example network in EPANET version 2.0, which is studied by (Sakarya, 1998). The WDN shown in Figure 5-14 consists of 1 river, 1 lake, 92 consumer nodes, 3 storage tanks and 117 pipes. Also, there are two pumping stations at the outlets of the reservoir and the lake.

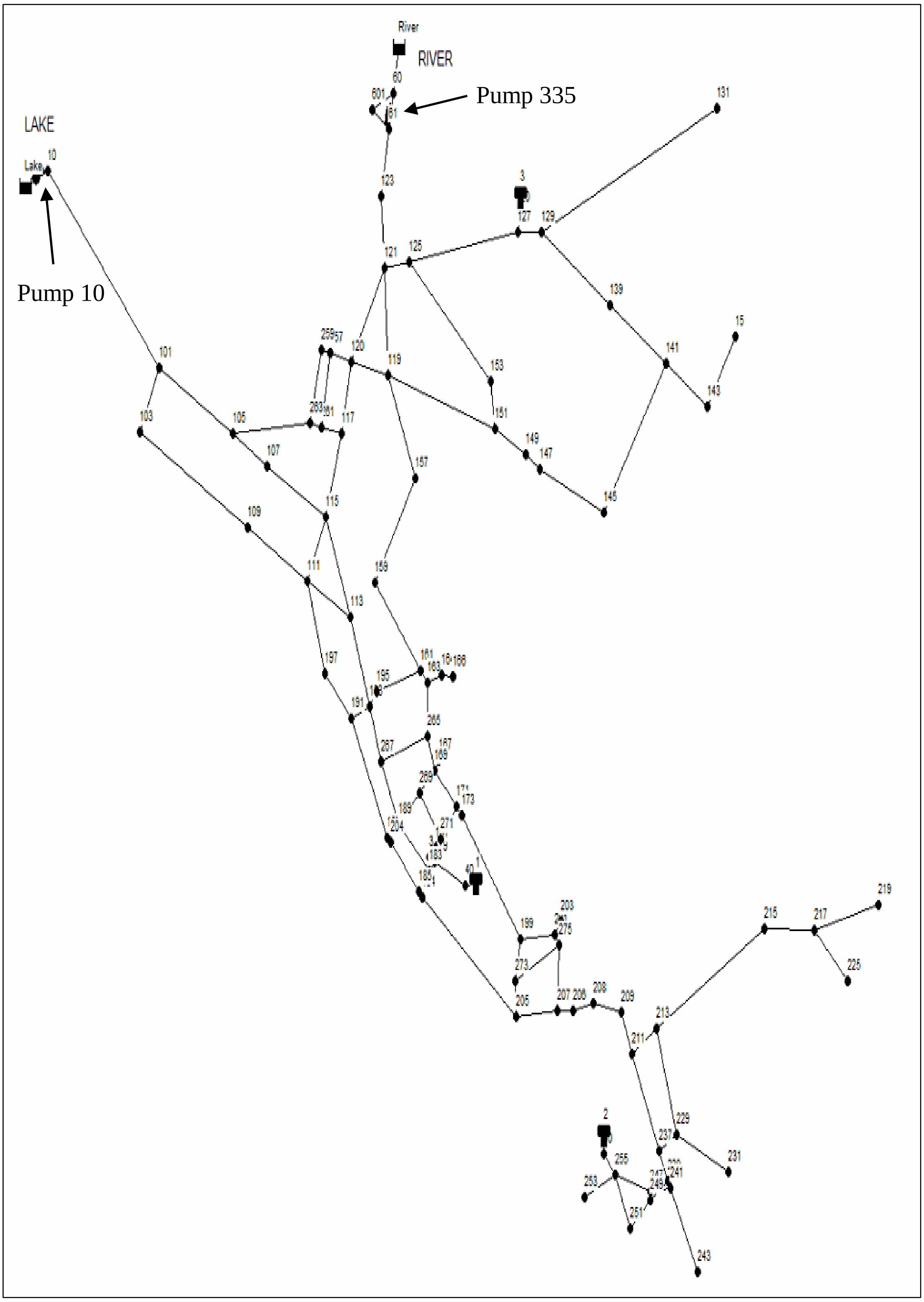

Figure 5-14: Example Network-3

As stated above, the network is supplied by 1 river, 1 lake and 3 tanks and their characteristics can be seen in Table 5-39. Likewise, the characteristics of the pump stations are represented in Table 5-40. All the terms in Table 5-40 correspond to significant points on the pumping curve. The term H_0 indicates the shutoff head of the pump; H_1 and Q_1 are the design head and design flow, respectively; and H_2 and Q_2 are the head and flow at the upper end of the normal operating flow range.

Table 5-39: Characteristics of the storage nodes of Network-3

Node ID	Elevation (ft)	Initial Level (ft)	Minimum Level (ft)	Maximum Level (ft)	Diameter (ft)
River	220	-	-	-	-
Lake	167	-	-	-	-
Tank 1	131.9	13.1	0.1	32.1	85
Tank 2	116.5	23.6	6.5	40.3	50
Tank 3	129	29	4	35.5	164

Table 5-40: Characteristics of the pumping stations of Network-3

Pump ID	H_0 (ft)	H_1 (ft)	Q_1 (gpm)	H_2 (ft)	Q_2 (gpm)
10	104	92	2000	63	4000
335	200	138	8000	86	14000

In the original input file, certain controls exist on pumping operations. Pump 10, which is located at the outlet of the lake, pumps water to the network for the first 15 hours of the day and, then, it closes. The operation of Pump 335 is controlled by the level of Tank-1. If the level of Tank-1 goes below 17.1 ft, the pump starts working and when the same level goes above 19.1 ft, it stops. When the pump is not working, the by-pass line is opened and the water is delivered to the system from that line. When pump starts working, the by-pass line is closed.

A default demand pattern is defined for the consumer nodes, but for four specific nodes, different demand patterns are described. All of the pattern data of this network can be seen in Table 5-41.

Table 5-41: Demand pattern data of the Example Network-3

Time Period	Demand Multipliers				
	Default	**Node 123**	**Node 15**	**Node 35**	**Node 203**
1	1.34	0	1.72222	0.952298	0.984039
2	1.94	0	1.72222	0.992437	1.004434
3	1.46	0	1.72222	1	1
4	1.44	0	1.72222	1	1.015739
5	0.76	0	1.72222	1.041885	1.004434
6	0.92	0.67052	1	1.058173	1.015739
7	0.85	0	1	1.033741	1.013523
8	1.07	0	0	1.071553	1.022611
9	0.96	0	0	1.055846	1.029262
10	1.10	1.02640	0	1.061664	1.029262
11	1.08	1.00990	0	1.079697	1.017956
12	1.19	1	1	1.047702	1.022611
13	1.16	1	1	1.058173	1.004434
14	1.08	1.00220	1	1.008144	1.002217
15	0.96	1.00220	1	0.968005	0.986256
16	0.83	0.99945	1	0.942408	0.984039
17	0.79	1.00330	0	0.938336	0.986256
18	0.74	0.99890	0	0.942408	0.988694
19	0.64	1.00825	0	0.940081	0.984039
20	0.64	0.99945	0	0.958115	0.979605
21	0.85	1.00660	0	0.946481	0.968300
22	0.96	0.99780	0	0.946481	0.975172
23	1.24	1.01210	1	0.972077	0.990911
24	1.67	1.02255	1	0.970332	0.993128

5.4.1 Emitter Coefficient Calculations

For this network, the assumed percentage of leakage is also 40. The calculation method of the base demand is the same with Network-2 (Section 5.3.1). After making the necessary calculations, the total base demand is found as 10947.63 gpm. With the 40% leakage assumption, $Q_{Net,real}$ in Equation (2.11) becomes 4379.05 gpm.

The average system pressure is calculated by taking the pressure values of each node for each time interval for 24 hours into consideration. The average system pressure without the emitters is 59.86 psi and the pressure exponent α is taken as 1.18 (Section 5.1.3). By using these parameters, $K_{net}^{(1)}$ is estimated to be 35.024 gpm.psi$^{-1.18}$ (= 4379.05 /(59.86$^{1.18}$)). After the iterative process, which in this case is ten iterations, the final values of emitter coefficients, $K_j^{(10)}$ are calculated and presented in Table 5-42. Note that, the entire length of the pipes after the storage nodes are assigned to the consumer nodes just after them.

Table 5-42: Emitter coefficients of Network-3 for the first and the last iteration

Node ID	**Length γ_j (ft)**	$\boldsymbol{\Gamma_j}$	$\boldsymbol{K_{net}}^{(1)}$ **(gpm.psi$^{-1.18}$)**	$\boldsymbol{K_j}^{(1)}$ **(gpm.psi$^{-1.18}$)**	$\boldsymbol{K_{net}}^{(10)}$ **(gpm.psi$^{-1.18}$)**	$\boldsymbol{K_j}^{(10)}$ **(gpm.psi$^{-1.18}$)**
10	0	0.0000	35.024	0.000	31.060	0.00000
15	825	0.0038	35.024	0.134	31.060	0.11879
20	491.5	0.0023	35.024	0.080	31.060	0.07077
35	15	0.0001	35.024	0.002	31.060	0.00216
40	694	0.0032	35.024	0.113	31.060	0.09993
50	561.5	0.0026	35.024	0.091	31.060	0.08085
60	1232	0.0057	35.024	0.200	31.060	0.17739
601	0	0.0000	35.024	0.000	31.060	0.00000
61	22751	0.1055	35.024	3.694	31.060	3.27588
101	16145	0.0748	35.024	2.621	31.060	2.32469
103	2645	0.0123	35.024	0.429	31.060	0.38085
105	3367.5	0.0156	35.024	0.547	31.060	0.48488
107	1710	0.0079	35.024	0.278	31.060	0.24622
109	2970	0.0138	35.024	0.482	31.060	0.42765
111	3815	0.0177	35.024	0.619	31.060	0.54932
113	2670	0.0124	35.024	0.434	31.060	0.38445
115	3645	0.0169	35.024	0.592	31.060	0.52484
117	2347.5	0.0109	35.024	0.381	31.060	0.33801
119	4135	0.0192	35.024	0.671	31.060	0.59539
120	2647.5	0.0123	35.024	0.430	31.060	0.38121
121	3240	0.0150	35.024	0.526	31.060	0.46652
123	23500	0.1089	35.024	3.816	31.060	3.38373
125	4365	0.0202	35.024	0.709	31.060	0.62851
127	2462.5	0.0114	35.024	0.400	31.060	0.35457

(continued)

Table 5-42 (continued): Emitter coefficients of Network-3 for the first and the last iteration

Node ID	Length γ_j (ft)	Γ_j	$K_{net}^{(1)}$ (gpm.psi$^{-1.18}$)	$K_j^{(1)}$ (gpm.psi$^{-1.18}$)	$K_{net}^{(10)}$ (gpm.psi$^{-1.18}$)	$K_j^{(10)}$ (gpm.psi$^{-1.18}$)
129	5065	0.0235	35.024	0.822	31.060	0.72930
131	3240	0.0150	35.024	0.526	31.060	0.46652
139	2400	0.0111	35.024	0.390	31.060	0.34557
141	3480	0.0161	35.024	0.565	31.060	0.50108
143	1525	0.0071	35.024	0.248	31.060	0.21958
145	2855	0.0132	35.024	0.464	31.060	0.41109
147	1540	0.0071	35.024	0.250	31.060	0.22174
149	950	0.0044	35.024	0.154	31.060	0.13679
151	2825	0.0131	35.024	0.459	31.060	0.40677
153	2865	0.0133	35.024	0.465	31.060	0.41253
157	2495	0.0116	35.024	0.405	31.060	0.35925
159	2455	0.0114	35.024	0.399	31.060	0.35349
161	2365	0.0110	35.024	0.384	31.060	0.34053
163	890	0.0041	35.024	0.145	31.060	0.12815
164	320	0.0015	35.024	0.052	31.060	0.04608
166	245	0.0011	35.024	0.040	31.060	0.03528
167	30	0.0001	35.024	0.005	31.060	0.00432
169	1283	0.0059	35.024	0.208	31.060	0.18474
171	1040	0.0048	35.024	0.169	31.060	0.14975
173	2025	0.0094	35.024	0.329	31.060	0.29158
177	30	0.0001	35.024	0.005	31.060	0.00432
179	715	0.0033	35.024	0.116	31.060	0.10295
181	160	0.0007	35.024	0.026	31.060	0.02304
183	1035	0.0048	35.024	0.168	31.060	0.14903
184	2314.95	0.0107	35.024	0.376	31.060	0.33333
185	967.45	0.0045	35.024	0.157	31.060	0.13930
187	1579.95	0.0073	35.024	0.257	31.060	0.22749
189	1863	0.0086	35.024	0.302	31.060	0.26825
191	2115	0.0098	35.024	0.343	31.060	0.30454
193	1855	0.0086	35.024	0.301	31.060	0.26710
195	1330	0.0062	35.024	0.216	31.060	0.19150
197	1970	0.0091	35.024	0.320	31.060	0.28366
199	2677.5	0.0124	35.024	0.435	31.060	0.38553
201	525	0.0024	35.024	0.085	31.060	0.07559
203	60	0.0003	35.024	0.010	31.060	0.00864

(continued)

Table 5-42 (continued): Emitter coefficients of Network-3 for the first and the last iteration

Node ID	**Length γ_j (ft)**	Γ_j	$K_{net}^{(1)}$ **(gpm.psi$^{-1.18}$)**	$K_j^{(1)}$ **(gpm.psi$^{-1.18}$)**	$K_{net}^{(10)}$ **(gpm.psi$^{-1.18}$)**	$K_j^{(10)}$ **(gpm.psi$^{-1.18}$)**
204	712.45	0.0033	35.024	0.116	31.060	0.10258
205	3187.5	0.0148	35.024	0.518	31.060	0.45896
206	480	0.0022	35.024	0.078	31.060	0.06911
207	1540	0.0071	35.024	0.250	31.060	0.22174
208	697.5	0.0032	35.024	0.113	31.060	0.10043
209	1047.5	0.0049	35.024	0.170	31.060	0.15083
211	2140	0.0099	35.024	0.347	31.060	0.30814
213	3737.5	0.0173	35.024	0.607	31.060	0.53816
215	2972.5	0.0138	35.024	0.483	31.060	0.42801
217	2635	0.0122	35.024	0.428	31.060	0.37941
219	1025	0.0048	35.024	0.166	31.060	0.14759
225	780	0.0036	35.024	0.127	31.060	0.11231
229	2475	0.0115	35.024	0.402	31.060	0.35637
231	980	0.0045	35.024	0.159	31.060	0.14111
237	1690	0.0078	35.024	0.274	31.060	0.24334
239	487.5	0.0023	35.024	0.079	31.060	0.07019
241	1340	0.0062	35.024	0.218	31.060	0.19294
243	1100	0.0051	35.024	0.179	31.060	0.15839
247	922.5	0.0043	35.024	0.150	31.060	0.13283
249	945	0.0044	35.024	0.153	31.060	0.13607
251	1275	0.0059	35.024	0.207	31.060	0.18359
253	550	0.0025	35.024	0.089	31.060	0.07919
255	2257.5	0.0105	35.024	0.367	31.060	0.32505
257	1197.5	0.0056	35.024	0.194	31.060	0.17243
259	875	0.0041	35.024	0.142	31.060	0.12599
261	1197.5	0.0056	35.024	0.194	31.060	0.17243
263	2237.5	0.0104	35.024	0.363	31.060	0.32217
265	1685	0.0078	35.024	0.274	31.060	0.24262
267	1990	0.0092	35.024	0.323	31.060	0.28654
269	1291	0.0060	35.024	0.210	31.060	0.18589
271	1155	0.0054	35.024	0.188	31.060	0.16631
273	1800	0.0083	35.024	0.292	31.060	0.25918
275	1980	0.0092	35.024	0.321	31.060	0.28510

5.4.2 Analysis Configurations

In this network, two different one-valve applications and two different two-valve applications will be studied. Similar to Network-2, there are three common properties which will be same for all cases. The minimum pressure for the control nodes and the limitations of the pressure head settings of the PRVs are the same with Network-2 (see Section 5.3.2).

In the selection of the control nodes, the nodes with zero base demand are excluded. Among 92 consumer nodes, there are 33 nodes that does not have base demand. Thus, the remaining 59 nodes are examined according to their pressures. Nodes 15, 101, 103, 153 and 253 within these 59 nodes have pressures below 42.66 psi. Thus, initially, the rest of the 54 nodes are selected as control nodes. The list of the nodes and their control point status can be seen in Table 5-43. It must be noted that the list of the control points are modified throughout the analyses, which will be explained in the results section.

The last common property is the penalty coefficients. Initial values of both minimum pressure head and tank violation penalty coefficients, R_H and R_y, are taken as 10000 in order to adjust the order of magnitude of the penalties in the objective function. Note that, initially, the values 1, 10, 100 and 1000 were applied for the penalty coefficients but optimality condition could not be met with these values. Thus, the coefficients values were increased to 10000.

5.4.3 Results of the Applications

Mainly, three different PRV configurations are studied in this network which are a single PRV at the outlet of the reservoir (Pipe 125) before Node 121, a single PRV at the outlet of the lake (Pipe 101) before Node 101, and both of them together. Apart from these configurations, other locations were also analyzed, but they were found to be infeasible. The reasons behind these unsatisfactory results will be explained below. All of the analyzed locations for PRV placements are shown in Figure 5-15.

Table 5-43: Control node check for Network-3

Node ID	Control Node Check	Node ID	Control Node Check	Node ID	Control Node Check
10	No	153	No	213	Yes
15	No	157	Yes	215	Yes
20	No	159	Yes	217	Yes
35	Yes	161	Yes	219	Yes
40	No	163	Yes	225	Yes
50	No	164	No	229	Yes
60	No	166	Yes	231	Yes
601	No	167	Yes	237	Yes
61	No	169	No	239	Yes
101	No	171	Yes	241	No
103	No	173	No	243	Yes
105	Yes	177	Yes	247	Yes
107	Yes	179	No	249	No
109	Yes	181	No	251	Yes
111	Yes	183	No	253	No
113	Yes	184	No	255	Yes
115	Yes	185	Yes	257	No
117	Yes	187	No	259	No
119	Yes	189	Yes	261	No
120	No	191	Yes	263	No
121	Yes	193	Yes	265	No
123	Yes	195	No	267	No
125	Yes	197	Yes	269	No
127	Yes	199	Yes	271	No
129	No	201	Yes	273	No
131	Yes	203	Yes	275	No
139	Yes	204	No	River	-
141	Yes	205	Yes	Lake	-
143	Yes	206	No	Tank 1	-
145	Yes	207	Yes	Tank 2	-
147	Yes	208	No	Tank 3	-
149	Yes	209	Yes	-	
151	Yes	211	Yes		

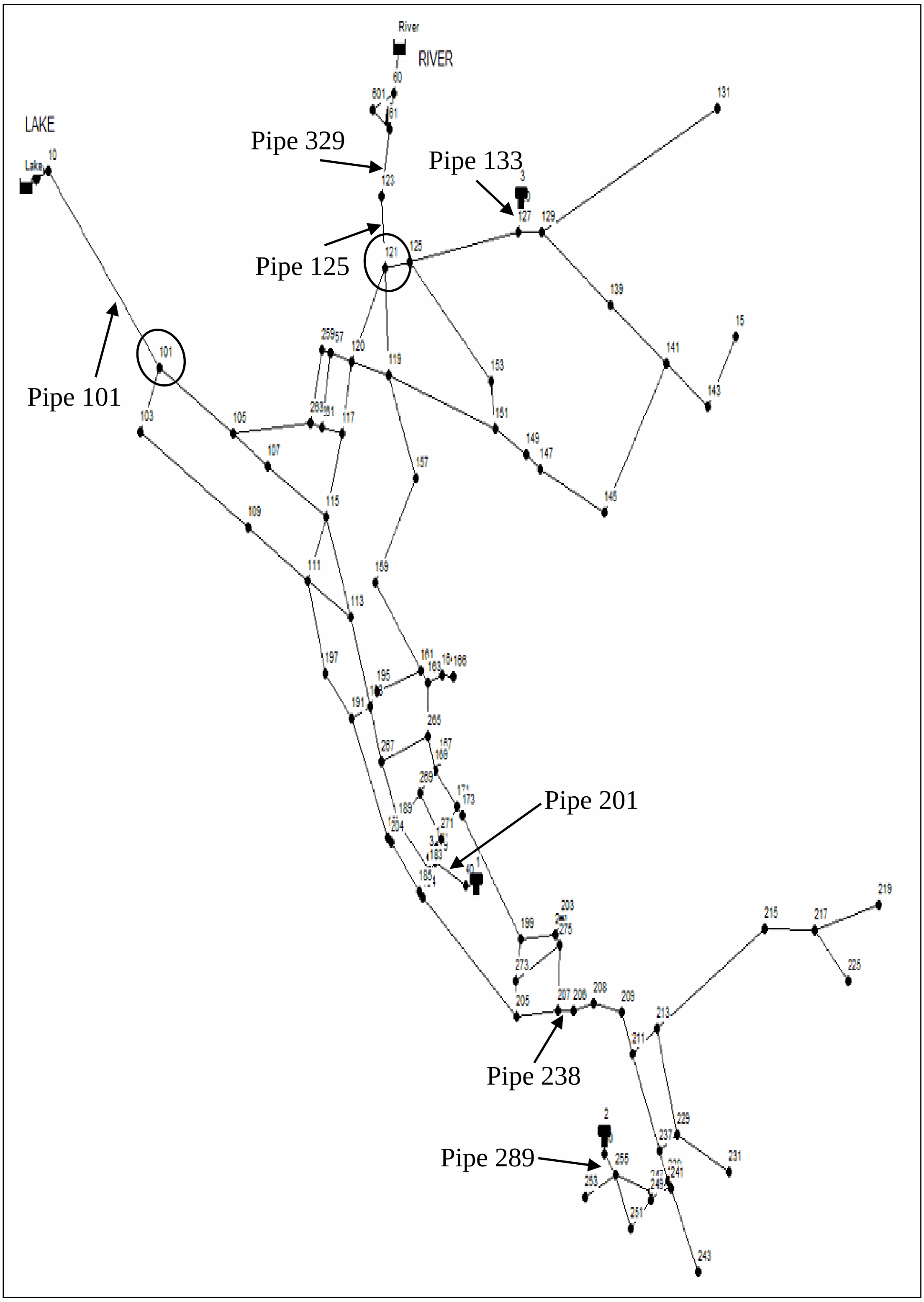

Figure 5-15: Analyzed PRV locations of Network-3

As a first case, placing a single PRV to Pipe 329 before Node 123 is tested. The results show that when PRV starts to be active, the system closes Pipe 329 and stops using the river as a source. Nodes 60, 601 and 61 are no-demand points; thus, there is no flow between the river and Node 123. All of the demands of the consumer nodes in the network including the Node 123 is supplied from the lake and the 3 tanks. This causes Tanks 1 and 2 to deplete. Hence, it can be concluded that adjusting the pressure heads with this configuration is not possible. It should also be noted that when the tank is completely depleted, the tank level at the end of the 24 hour daily period is not lower than the tank level at the beginning of the period; thus, no tank penalty occurs according to the definition of the tank variation limit (Equation 2.4).

For the next three cases, the outlets of the tanks are checked by individually placing the PRV after Tanks 1 (on Pipe 201 before Node 179), 2 (on Pipe 289 before Node 255) and 3, (on Pipe 133 before Node 127). For all these three cases, a by-pass line is added to enable flow to the tank during filling periods. When PRV becomes active at the outlets of both Tanks 1 and 2, the system stops using them as a source and the demands are supplied from other sources. Especially for the Tank 1 outlet case, other resources become inadequate and negative pressures start to occur. For the Tank 3 outlet case, when the PRV becomes active, the system becomes unstable and the 24 hour periodicity of Tank 3 is disrupted as can be seen from Figure 5-16. In light of these results, it is concluded that placing the PRV directly at the outlet of the tanks are not feasible.

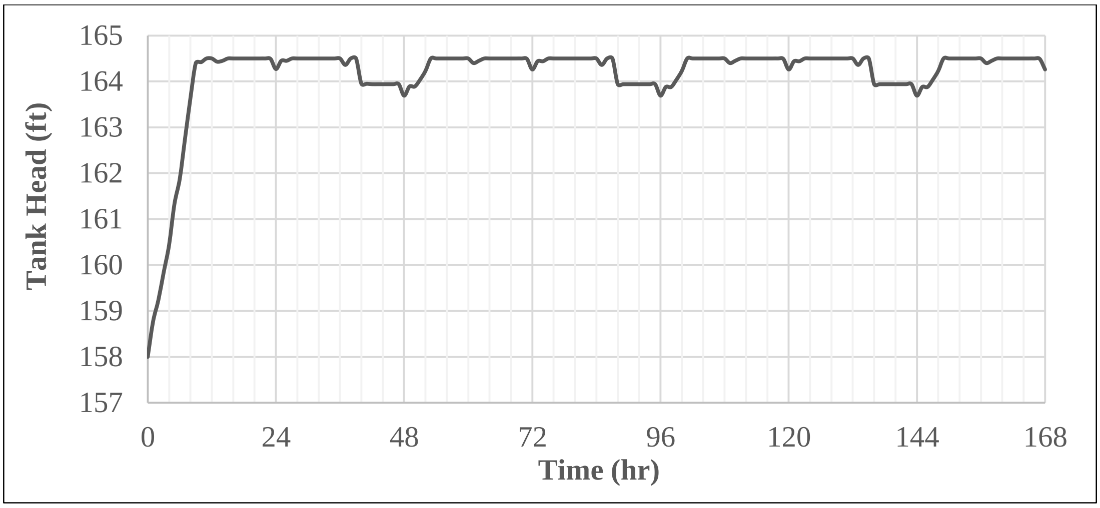

Figure 5-16: Total head variation of Tank 3

For the next case, placing a single PRV to Pipe 238 before Node 206 is examined. With all 54 control points, no leakage reduction can be obtained. This results from the low pressures of the Nodes 251 and 255 located below Tank 2. Both of the nodes have pressures around 43 psi without any valve installation. In order to see these nodes' effects, the control point list is modified. Only the nodes after the Node 206 are taken as control points and Nodes 251 and 255 are excluded from the list. It should be noted that the flow is always in the direction of Node 206 to Node 208 and as there is no backflow, no by-pass line is necessary. With this 13 control point configuration, the leakage reduction is increased to 1.06%.

For the following cases, placing a single PRV to Pipe 125 before Node 121 and to Pipe 101 before Node 101 are analyzed. With all 54 control points, again, no leakage reduction can be obtained for both of the applications. Similarly, this is due to the nodes with low pressures in the network such as Nodes 127, 251 and 255. Thus, for a solution methodology, the control point list is refined. Selected 54 nodes are sorted with respect to their average daily pressures and 7 nodes are selected due to their high pressures which are Nodes 119, 121, 123, 125, 131, 143 and 145. The pressures of the corresponding nodes without any valve installation can be seen in Table 5-44. It should be noted that the maximum pressure observed in the network among 54 control points is 73.15 psi.

With the modified control point list, the results of Pipe 125 and Pipe 101 applications for both Case I and Case II formulation can be seen in Table 5-45. It can be seen from the results that placing PRV after the lake exit have a very minor effect on the leak reduction. The reason for this is the location of the control points. All of the control points are mainly supplied by the river and Tank 1. Thus, controlling the pressure from the outlet of the lake does not have a significant effect on the pressures of the control nodes. Placing the PRV at the river exit results in highest feasible reduction as no tanks are depleted or become unstable and no negative pressures occur at the consumer nodes.

Table 5-44: The initial pressures of 7 control points

Time Interval	**Nodal Pressures (psi)**						
	119	**121**	**123**	**125**	**131**	**143**	**145**
1	68.07	71.20	67.27	65.38	67.04	59.79	63.24
2	67.67	70.98	67.05	65.25	67.15	58.83	62.25
3	68.18	71.36	67.42	65.57	67.32	59.80	63.25
4	68.37	71.55	67.61	65.76	67.51	60.01	63.45
5	69.44	72.40	68.44	66.50	67.89	61.56	65.05
6	69.06	71.98	67.74	66.23	68.05	66.83	66.82
7	69.98	72.94	68.97	67.04	68.44	67.57	67.59
8	70.15	**73.15**	69.17	67.28	68.77	72.09	69.75
9	68.96	71.68	66.67	66.08	68.39	71.22	68.88
10	67.77	70.42	65.18	64.94	67.75	70.11	67.76
11	67.43	70.06	64.84	64.57	67.31	69.76	67.41
12	68.51	71.39	67.03	65.67	67.60	66.08	66.06
13	68.59	71.48	67.12	65.77	67.72	66.20	66.18
14	68.75	71.62	67.25	65.90	67.84	66.42	66.39
15	69.01	71.84	67.46	66.10	67.98	66.73	66.72
16	68.32	71.54	67.18	65.91	68.04	66.50	66.45
17	68.28	71.46	67.09	65.82	67.96	70.73	68.39
18	68.21	71.40	67.04	65.76	67.90	70.69	68.35
19	68.18	71.35	66.98	65.71	67.84	70.70	68.35
20	68.12	71.30	66.94	65.66	67.79	70.64	68.30
21	67.99	71.22	66.86	65.59	67.72	70.43	68.09
22	67.83	71.10	66.75	65.47	67.61	70.23	67.89
23	67.33	70.77	66.41	65.15	67.37	65.29	65.22
24	66.55	70.17	65.82	64.58	66.96	64.24	64.16
Average:	68.36	71.43	67.09	65.74	67.75	66.77	66.50

Table 5-45: The results of Network-3 for: one-valve applications, 7 control points

Time Interval	River Exit Pipe 125: $\overline{HP}_v$ (ft)	River Exit Pipe 125: x_v (ft) Case I	River Exit Pipe 125: x_v (ft) Case II	Lake Exit Pipe 101: $\overline{HP}_v$ (ft)	Lake Exit Pipe 101: x_v (ft) Case I	Lake Exit Pipe 101: x_v (ft) Case II
1	71.20	71.20	71.20	55.60	55.60	55.60
2	70.98	70.98	70.98	53.65	53.65	53.65
3	71.36	71.36	71.36	55.34	55.34	55.34
4	71.55	71.55	71.55	55.55	55.55	55.55
5	72.40	72.40	72.40	58.15	58.15	58.15
6	71.98	71.98	71.98	57.47	57.47	57.47
7	72.94	72.94	72.94	58.33	58.33	58.33
8	73.15	73.15	73.15	57.89	57.89	57.89
9	71.68	42.66	71.03	57.45	57.45	57.45
10	70.42	42.66	68.82	56.26	56.26	56.26
11	70.06	42.66	70.06	56.05	56.05	56.05
12	71.39	42.66	42.83	56.47	56.12	56.11
13	71.48	42.66	43.46	56.59	56.26	56.25
14	71.62	42.66	43.91	56.91	56.59	56.58
15	71.84	42.66	44.38	57.42	57.11	57.11
16	71.54	71.54	71.54	45.67	45.67	45.67
17	71.46	67.35	71.46	45.63	45.63	45.63
18	71.40	65.78	71.40	45.60	45.60	45.60
19	71.35	60.38	71.35	45.72	45.72	45.72
20	71.30	71.30	71.30	45.65	45.65	45.65
21	71.22	71.22	71.22	45.12	45.12	45.12
22	71.10	71.10	71.10	44.68	44.68	44.68
23	70.77	70.77	70.77	43.46	43.46	43.46
24	70.17	63.15	70.17	42.66	42.66	42.66
Leak Reduction (%)		3.35	3.09	-	0.05	0.05
Runtime (min)		83.85	32.07	-	23.45	19.55

For the next case, placing a valve each on Pipe 125 (river) and Pipe 101 (lake) together is tested. At first, both valves optimized together and the results are represented in Table 5-46. It can be seen from the results that using the Case I formulation results in a 6.13% leakage reduction and the PRV on the lake line decreases to the minimum level. However, by doing this, the system changes its supply balance and tanks are depleted (Figure 5-17).

Table 5-46: The results of Network-3 for: two-valve application optimized together, 7 control nodes

	Case I				**Case II**			
	Pipe 125 + Pipe 101				**Pipe 125 + Pipe 101**			
	PRV-1		**PRV-2**		**PRV-1**		**PRV-2**	
Time Interval	$\overline{HP}_1$ **(ft)**	x_1 **(ft)**	$\overline{HP}_2$ **(ft)**	x_2 **(ft)**	$\overline{HP}_1$ **(ft)**	x_1 **(ft)**	$\overline{HP}_2$ **(ft)**	x_2 **(ft)**
1	71.20	71.20	55.60	42.66	71.20	71.20	55.60	55.60
2	70.98	70.98	53.65	42.66	70.98	70.98	53.65	53.65
3	71.36	71.36	55.34	42.66	71.36	70.53	55.34	55.34
4	71.55	71.55	55.55	42.66	71.55	70.67	55.55	55.55
5	72.40	72.40	58.15	42.66	72.40	72.40	58.15	58.15
6	71.98	71.98	57.47	42.66	71.98	71.02	57.47	57.47
7	72.94	72.94	58.33	42.66	72.94	72.18	58.33	58.33
8	73.15	73.15	57.89	42.66	73.15	72.18	57.89	57.89
9	71.68	71.68	57.45	42.66	71.68	69.94	57.45	57.45
10	70.42	50.43	56.26	42.66	70.42	42.66	56.26	56.26
11	70.06	42.66	56.05	42.66	70.06	68.31	56.05	42.66
12	71.39	42.66	56.47	42.66	71.39	42.66	56.47	56.47
13	71.48	42.66	56.59	42.66	71.48	42.66	56.59	56.59
14	71.62	42.66	56.91	42.66	71.62	42.66	56.91	56.91
15	71.84	42.66	57.43	42.66	71.84	42.66	57.43	57.43
16	71.54	71.54	45.67	45.67	71.54	71.54	45.67	45.67
17	71.46	71.46	45.63	45.63	71.46	71.46	45.63	45.63
18	71.40	71.40	45.60	45.60	71.40	71.40	45.60	45.60
19	71.35	71.35	45.72	45.72	71.35	71.35	45.72	45.72
20	71.30	71.30	45.65	45.65	71.30	71.30	45.65	45.65
21	71.22	71.22	45.12	45.12	71.22	70.47	45.12	45.12
22	71.10	71.10	44.68	44.68	71.10	71.10	44.68	44.68
23	70.77	70.77	43.46	43.46	70.77	70.77	43.46	43.46
24	70.17	70.17	42.66	42.66	70.17	70.17	42.66	42.66
Leak Reduc. (%)	6.13				3.50			
Runtime (min)	88.2				59.3			

It can be seen from Figure 5-17 that, Tank 2 is completely depleted, Tank 1 is nearly depleted and Tank 3 is actively working.

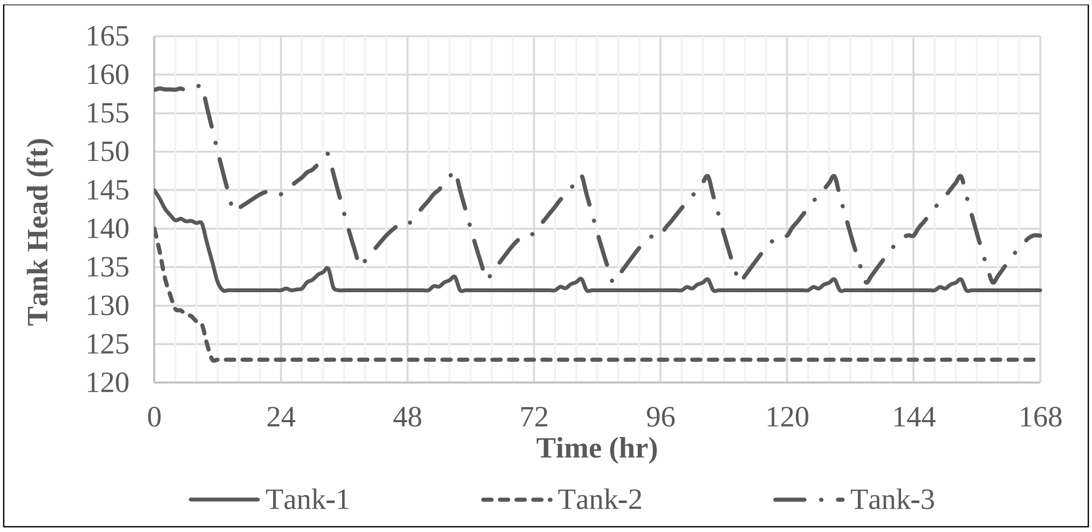

Figure 5-17: Total tank head variations of Network-3 for two valve optimization with Case I formulation

For Case II, the leakage reduction rate is 3.5% and only PRV-1 is actively working. In this way, although Tank 2 is close to depletion, all of the tanks are working properly (Figure 5-18).

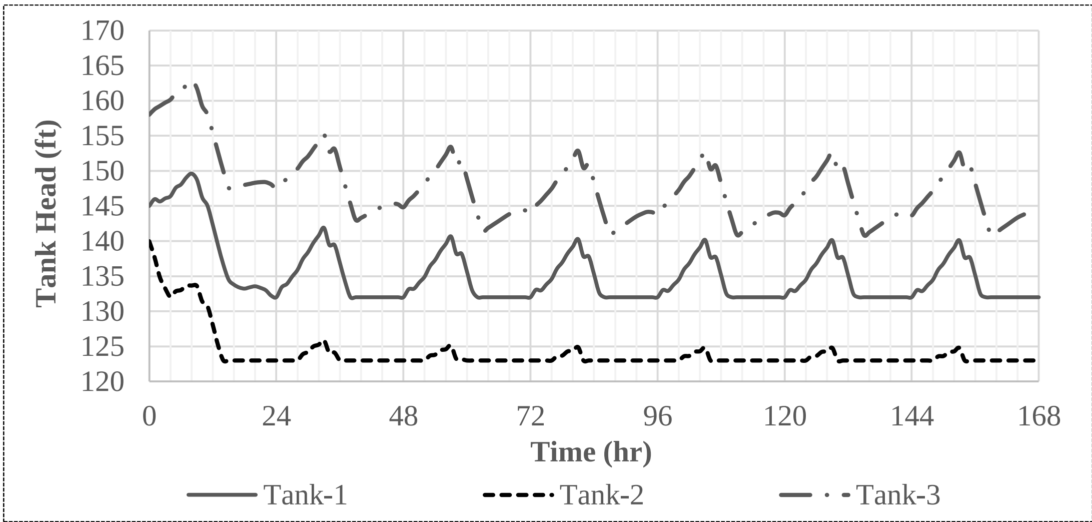

Figure 5-18: Total tank head variations of Network-3 for two valve optimization with Case II formulation

Although tanks are depleted, no tank variation penalty occurs as the final level of the tanks are equal to their initial levels. In order to overcome this problem, just for this case, the tank variation constraint (Equation 2.4) is converted into,

$$y_{s,ft} \geq y_{s,newmin} \quad \text{for } s = 1, \dots, S \tag{5.1}$$

where $y_{s,newmin}$ is the modified minimum tank level for the tank s. The penalty term of the modified constraint is replaced with the tank variation penalty in the objective function. The original minimum levels of the Tanks 1, 2 and 3 were 132, 123 and 133 ft, respectively. To avoid depletion, the modified minimum tank levels are selected as 140, 131 and 141 ft for three of the tanks respectively. When the two valve optimized together with seven control points depletion problem is solved; however, no leakage reduction can be obtained. With the new penalty, system increases the usage of the pump at the outlet of the river in order not to deplete tanks. Thus, the setting of the PRV located at the outlet of the river could not further be reduced which leads to the zero leakage reduction.

For one last comparison, the control of the pump located at the outlet of the lake is modified. In the original input file, the pump was active from 00:00 to 15:00 and closed for the rest of the day. The status of the pump is converted to active for the whole day. With the modified penalty term and controls, analyses results show that depletion problem is solved but again, no leakage reduction can be obtained. The change in the pump control could not affect the outcomes as all seven control nodes are mainly in the region which is supplied by other sources than lake.

For the final application, valves are again placed together on Pipe 125 (river) and Pipe 101 (lake), but, this time, they are optimized separately. The case I results of PRV-1 on Pipe 125 from the previous two-valve application (Table 5-46) is used as constant and the second PRV on Pipe 101 is optimized. The results can be seen in Table 5-47. For both Case I and Case II formulations, PRV-2 reduces to the minimum pressure setting and the system changes its supply balance and the tanks are depleted.

Table 5-47: The results of Network-3 for: two-valve application optimized separately, 7 control nodes

Time Interval	Pipe 125 (c) x_1 (ft)	Pipe 101 $\overline{HP}_2$ (ft)	Pipe 101 Case I x_2 (ft)	Pipe 101 Case II x_2 (ft)
1	71.20	55.60	42.66	42.66
2	70.98	53.65	42.66	42.66
3	71.36	55.34	42.66	42.66
4	71.55	55.55	42.66	42.66
5	72.40	58.15	42.66	42.66
6	71.98	57.47	42.66	42.66
7	72.94	58.33	42.66	42.66
8	73.15	57.89	42.66	42.66
9	71.68	57.45	42.66	42.66
10	50.43	56.26	42.66	42.66
11	42.66	56.05	42.66	42.66
12	42.66	56.47	42.66	42.66
13	42.66	56.59	42.66	42.66
14	42.66	56.91	42.66	42.66
15	42.66	57.43	42.66	42.66
16	71.54	45.67	42.66	42.66
17	71.46	45.63	42.66	42.66
18	71.40	45.60	42.66	42.66
19	71.35	45.72	42.66	42.66
20	71.30	45.65	42.66	42.66
21	71.22	45.12	42.66	42.66
22	71.10	44.68	42.66	42.66
23	70.77	43.46	42.66	42.66
24	70.17	42.66	42.66	42.66
	Leak Reduc. (%)		6.13	6.13
	Runtime (min)		7.2	7.1

5.4.4 Discussion of Network-3

In light of the analyses conducted on Network-3, the following conclusions can be made:

- As network complexity increases with more number of nodes and supply points, the variety of pressures at the consumer nodes increases. The pressure control from the main supply line becomes impossible as there exist nodes with very low pressures. In order to overcome this problem, either low pressure nodes must be excluded from the control points or PRV locations must be modified.
- When there exists multiple supply nodes, their schedules and balances can change rapidly during the optimization procedure. So, for the complex networks with multiple sources, additional constraints may be added to strain the depletion of the tanks or the usage of the sources.
- If there were higher number of individual branches with higher pressures in the network, the leakage reduction would have been higher.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study is to develop a computer program to optimize pressures in a water distribution network with the aim of reducing leakage. There are limitations for the pressures of the consumer nodes in a water distribution system. A maximum limit is set to protect the infrastructure from bursts in the pipes and prevent high amount of leakages. Likewise, a minimum limit is set to ensure the delivery of the required demands in the network. Concerning leakage, it is desirable to have the network pressures as low as possible without violating the minimum limit.

For the regulation of the pressures, PRVs are placed in the networks. The number and the location of the valves are decided considering the analyzed network. For local pressure reductions, PRVs are placed at the entrances of the individual branches. Moreover, for the pressure reduction of the whole network, PRVs are mounted at the main supply lines. In a real network, the demands and the pressures of the consumer nodes are time dependent. Thus, in order to be compatible with demands and pressures, the pressure head settings of the PRVs are also taken as dynamic.

Two different non-linear optimization problems are formulated with the aim of reducing leakage by pressure control. The first one is the minimization of the pressure head values at the selected control points as leakage is highly dependent on pressure. The second one is the minimization of the total system leakage. In both of the cases, the decision variable of the optimization problem is the hourly PRV settings. The constraints are the conservation of mass and energy, minimum and maximum pressure head limitations at the control points, the tank level variation limit, and the bound constraint for PRV settings.

With the existing objective functions and constraints, the formulation becomes a large scale non-linear optimization problem. In order to overcome this complexity, a computer program is developed, which combines a hydraulic solver and an optimization solver. The hydraulic solver, EPANET, satisfies the conservation of mass and energy equations within its solution procedure. In addition to that, constraints of the pressure head limitations at the control points and the tank level variation limit are embedded into the objective function as penalty terms. Thus, only one constraint remains, which is the boundaries of PRV settings. The new simplified problem is solved with the non-linear optimization solver, LSGRG2. The developed computer program, LEAK_PROB, handles all data acquisitions and calls the solvers. The optimum result is found by an iterative procedure that stops when overall optimality checks are satisfied.

As nothing is as certain as it is modeled, probabilistic approach is taken into consideration for more realistic and reliable results. For the minimization of leakage in a water distribution network, the component that has random characteristics is considered to be the pressure head at the consumer nodes. This randomness results from the inaccuracy of modelling various factors that affect leakage. The only way to consider uncertainties is to obtain the probability distribution of this random variable. Normal and log-normal probability distributions are selected for the reliability analyses as they are the most frequently used ones for continuous random variables.

The main contribution of this study to the field was to perform a leakage optimization by pressure control in a WDN by the usage of PRVs, which have dynamic settings. To this end, a unique program has been developed which combines the non-linear optimization solver, LSGRG2 and hydraulic solver, EPANET while considering the uncertainties in the analysis by chance constraint application. As far as known, this is the first study that has performed the combination of these two solvers to estimate the leakage reduction in complex WDNs.

6.1 Conclusions

Through analyses conducted on three networks, the most important conclusions are as follows:

1. Pressure reduction with the usage of PRVs in a WDN is an efficient method for reducing leakage. For small networks with a single source, it is more effective to control whole system pressure with a PRV on the main supply line. As the network gets more complex with higher number of components and multiple sources, it becomes harder to control the pressure from a single supply line. This is due to two main reasons. As the number of elements in the WDN increases, the variety of pressures at the consumer nodes increases and there exists nodes with low pressures. Thus, in order to not violate the minimum pressure requirement at these low pressure points, the setting of the PRV cannot be further reduced. The second reason is, when there is multiple sources, the network changes its source usage pattern rather than forcing further pressure reduction with the PRV. Due to these reasons, it is better to control the pressure from individual branches for complex networks.

2. Setting lower minimum pressure requirements results in higher leakage reduction rates as it causes higher pressure drops in the network. However, the value of the limit must be decided carefully to not lead to any disruptions in delivering the necessary demands.

3. Likewise, setting control points with high initial pressures create higher leakage reduction rates as it causes higher pressure drops. Nonetheless, it is better to set all consumer nodes with demands as control points, as it is required to provide the necessary demands.

4. Deciding the number of PRVs is an economical concern. Thus, if there is a limited budget for a complex network, it is better to place a PRV at the entrance of the branch in which the pressure heads of the consumer nodes are higher

compared to the other branches of the network. If the network is small, placing the PRV at the main supply line can solve the problem.

5. While optimizing multiple valves in which the PRV on the supply line is coupled with other PRVs, it is better to optimize separately. Higher reduction rates are obtained when the PRV on the main line is individually optimized first and the final settings are taken as constant for the optimization of the other PRVs. This occurs due to the effect the PRV has on all consumer nodes when it is placed on the main line.

6. The analyses results for Case I and Case II formulations are almost the same, if all consumer nodes with demands are taken as control points. If only certain nodes are selected as control points, the results may differ for certain cases. In these applications, it is better to use Case II formulation as it checks not only the control points but the entire network leakage.

7. Concerning the chance constraint application, a more reliable network indicates a lower probability of not satisfying the minimum pressure requirement. Increasing both reliability level and standard deviation results in an increase in the required minimum pressure. This leads to an increase in the total system leakage. However, this does not necessarily represent a disadvantageous outcome. The user must decide which level of reliability is required for the network by examining the rate of the corresponding leakages.

8. Due to the formulations of the distribution types, leakage reduction rates differ for the normal and log-normal distributions. Between 60% and 90% reliability levels, higher leakage reductions are obtained from the log-normal distribution. On the other hand, for the reliability levels of 90% and above, the normal distribution results in higher reductions than the log-normal distribution.

9. Emitter coefficients are calculated for the non-PRV network and taken as constant throughout the optimization procedure, although the pressures of the nodes are changing. Optimized PRV settings of an example case is tested to see the difference at the end of the solution. Results show that the difference between the initial and final values is significantly small; thus, it does not affect the accuracy of the proposed solution method.

6.2 Recommendations

In this study, the emitter coefficients are updated on the non-PRV version of the analyzed network before starting the optimization procedure. The calculated emitter coefficient values are taken constant throughout the optimization. For an improvement, an additional loop can be added at the end of the program, which will update the emitter coefficients for the network with optimum PRV settings. Moreover, different emitter coefficient calibration methods, as well as the same method with additional factors, can be investigated.

Most importantly, the methodology proposed in this study can be applied to a real network. In that way, the real leakage amount will be known and the calibration of the emitter coefficients and pressure exponent can be done with actual values. Additionally, it will be more effective if the PRVs can be placed in the real network. This will allow the comparison of the actual results with the calculated ones.

As one last recommendation, an economic analysis can be carried on the PRV placement. Thus, it will enable the user to decide the number and locations of the PRVs.

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Awards

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