OPTIMIZING PUMP SCHEDULE
AND VALVE CHARACTERISTICS
OF WATER DISTRIBUTION NETWORKS

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ABSTRACT

**OPTIMIZING PUMP SCHEDULE
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From design stage to operation, water distribution networks hold the vital part of the infrastructure systems. Pumps contain significant operational consumptions by pumping and maintenance costs. Wise scheduling is an important tool that may decrease these costs.

Leakage, defined as a portion of treated and pumped water; and through a typical water distribution network, it may possess a large percentage of the total water supplied. Pressure heads within the water distribution network are one of the major causes of leakage.

This study is a combination of pump scheduling and excess pressure minimization of the same network. The methodology is divided into (i) pump schedule optimization and (ii) valve locating and opening determination. For pump scheduling studies, objective is to reduce operational costs of pumps. On the other hand, for valve locating and opening determination studies, objective is minimizing excess pressures. Genetic algorithms are applied on both optimization problems, with specific objective and penalty functions.

Through pump scheduling studies, the schedules casting the energy usage, tank volume periodicity and pump switches are obtained. Real time daily demand measurements and predictions are integrated to the developed program to model unexpected cases. Kalman Filter is applied on the improved demand prediction model. The results indicate that the developed program is applicable to the network for real time scenarios.

Throughout valve location and opening determination studies, the groups of open and closed valves are found considering different simulation durations. By determining the openings of the valves; almost 60 % excess pressure decrement is obtained.

Keywords: Genetic algorithms, water distribution network, pump scheduling, valve characteristics, Ankara.

ÖZ

SU DAĞITIM ŞEBEKELERİNDE POMPA ZAMANLARININ VE VANA KARAKTERİSTİKLERİNİN OPTİMİZASYONU

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Tasarım aşamasından işletmeye, su dağıtım şebekeleri altyapı sistemlerinin hayati bir parçasını oluşturmaktadır. Pompalar, pompaj ve bakım maliyetlerinden ötürü önemli miktarda işletme maliyeti oluşturmaktadır. Pompa zamanlarının akıllı biçimde ayarlanması, işletme maliyetlerinde azalmalar meydana getirebilen önemli bir araçtır.

Su kayıpları, tipik bir su dağıtım şebekesinde arıtılmış ve pompalanmış suyun bir kısmı olarak tanımlanmakla birlikte, toplam sağlanan suyun büyük yüzdesini oluşturabilir. Kayıplara neden olan başlıca sebeplerden biri su dağıtım şebekelerindeki basınçlardır.

Bu çalışma, aynı şebeke üzerinde pompa zamanlarının ayarlanması ve aşırı basınçların azaltılmasının bir kombinasyonudur. Yöntem, (i) pompa zamanlarının optimizasyonu ve (ii) vana yeri ve açıklığı belirlenmesi olarak ikiye ayrılmıştır. Pompa zamanlarının optimizasyonunda hedef, işletme maliyetlerini azaltmaktır. vana yeri ve açıklığı belirlenmesindeki amaç ise aşırı basınçların azaltılmasıdır. Her iki optimizasyon problemi için de belirli hedef ve ceza fonksiyonlarıyla birlikte genetik algoritmalar kullanılmıştır.

Pompa zamanlarının optimizasyonu çalışmasında, enerji kullanımıyla birlikte depo hacim döngüleri ve pompa aç-kapa sayıları da dikkate alınmıştır. Beklenmedik durumların modellenebilmesi için, geliştirilen programa, gerçek zamanlı ölçüm ve tahminler eklenmiştir. Geliştirilen su tüketimi tahmin modeline Kalman Filtresi uygulanmıştır. Elde edilen sonuçlar, geliştirilen programın gerçek zamanlı olarak şebekelerde kullanılabilir olduğunu göstermiştir.

Vana yeri ve açıklığı belirlenmesi çalışmasında, farklı simülasyon süreleri dikkate alınarak açık ve kapalı vana grupları belirlenmiştir. Vanaların açıklıklarının belirlenmesi ile yaklaşık %60 oranında aşırı basınç azalması sağlanmıştır.

Anahtar Kelimeler: Genetik algoritmalar, su dağıtım şebekesi, pompa zamanlamaları, vana karakteristikleri, Ankara.

To my conscientious Parents;

my lovely wife Gülden;

my sweetie daughter Irmak

and

to people who respect to science.

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INTRODUCTION

Water is the most important resource on this planet for the continuation of life. Since ancient times, people have tried to manage fresh water to be able to survive. Today, in modern cities people use water supply systems to access potable water. A water supply system may be defined as a collection of elements such as reservoir(s), pump(s), pipes, different kinds of valves, storage tank(s), having the purpose of providing required amount of potable water at sufficient pressure to the consumers.

As a vital part of water supply systems, water distribution networks (WDNs) represent one of the largest infrastructure assets of water authorities. The realization of planning, design, construction, including operation and maintenance of water distribution networks are among the largest infrastructure projects of municipalities; the cost of water distribution networks may reach values at the order of million dollars for greater cities. Although the capital cost of networks is substantial, the operational costs hold a significant amount in the budgets of municipalities.

For a typical water distribution network, energy costs resulting from pumping, and renewal and maintenance costs of pumps hold two major components of operational costs. Optimizing pumping schedule is considered to be a key operation which may lead lower operational costs. Pump scheduling can basically be explained as, deciding on which pump shall be in operation through which duration.

Pumping systems are designed depending on the estimated demand for the target year. The target design year is generally 20 to 35 years ahead of the design year. Therefore, the characteristics of pumping systems are selected for the demand estimate for future where basically, pumps have an economic life of 10 years. However; these systems are active from the beginning of operation till the end of its economic life. Since the capacities of pumps are sufficient for the design year's, maximum demand; for the rest of their economic life, they serve for lower demands. Using optimal pump schedules, the pumps are being employed in an efficient way by considering the hydraulic conformities and varying daily demands. By optimizing pump schedules, significant reductions in operational costs are achievable without making changes to the elements of water supply systems.

By pump schedule optimization, the number of pump switches may also be decreased. Unnecessary and excessive switching of pumps, shortens their economic lives, while increasing the maintenance costs until renewal. Moreover, by causing water hammer through the pipeline, excessive switching may also cause pipe damages in the water supply systems (Bozkuş, 2008; López-Ibáñez et al. 2011). Pump switch may be defined as the change of status of pumps; being on or off. Destructive effects of excessive switching both reduce the reliability of the network and negatively affect the opportunity to access to safe drinking water services. Because, when any burst in the pipe or any problem in the pumping service occurs, the network could not be fed. This phenomenon may basically be reflected as service cut to the consumers. Till the service is back (it may take several hours); the quality standard of water may be lost that may result in health problems for the consumers. Preventing of such problems is another benefit of careful scheduling.

Pumping is a common water supply method for water distribution networks. Feeding by gravity is also frequent for water distribution networks. For both; water is transmitted to consumers within network pipes. From supply to consumer, some proportion of potable water is lost. This phenomenon may basically be defined as leakage. Leakage holds a significant portion of non revenue water which may be defined as "lost water" before reaching to consumers. In practice, house connections, pipe joints, cracks or bursts are potential leakage spots.

Leakage is a portion of treated and pumped water; however depending on the characteristics of the system, it may represent a large percentage of the total supplied water. When leakage can not be reduced to tolerable levels, it may force authorities to make additional investments to expand the capacity of the water supply system. Thus, leakages shall not be considered as only lost water; it may also increase the investments of authorities even if it is not the right solution.

In common practice, the diameters of network pipes are designed considering maximum and minimum service pressures. However, in many of the nodes, there exist excess pressures which means higher than maximum limit. Since water distribution networks are active systems for 24 hours of every day, any pipe being exposed to more pressure than its upper service limit is a potential leakage point.

Pressure heads within the water distribution network are one of remarkable, measurable and manageable causes of leakages. Leakage among the system is directly proportional to the hydraulic pressures. Thus, decreasing nodal pressures may be considered to be an appropriate method for leakage minimization.

Pressure minimization may be accomplished by employing several types of valves. Operation of isolation valves is an applicable method for pressure minimization since; these types of valves are being widely used in current water supply projects. The isolation valves may be in open, partially open or closed positions.

This study represents an operational optimization methodology that is applicable for large water distribution networks. By decomposing the network to its skeleton and district metered areas, the methodology is a combination of pump scheduling and pressure minimization study on the same network. The methodology is mainly divided into two phases. At the first phase, the pump scheduling optimization is applied to the skeleton of the main network. By utilizing the outcomes of the obtained optimal pump schedules; in the second phase, valve locating and valve opening determination studies are accomplished on the network of any district metered area.

At the first phase, the objective is to minimize the energy costs while considering the hydraulic conformities, periodicity of water tank volume and number of pump switches. In the second phase, the objective becomes excess pressure minimization. For both phases, the developed models use EPANET2 as hydraulic simulation software and Genetic Algorithms for decision making process. For both steps, N8-3 network of Ankara is studied, with its district metered areas (DMAs).

For pump schedule optimization, binary coding is used to identify pump operations during the run time duration. Initially, the run time duration is selected as 24 hour. After applying the pump scheduling optimization method for 24 hour run time duration, additional analyses are accomplished by dividing the whole duration into short periods. The chromosome length is determined by the multiplication of the number of pipes and total run time steps. The triggers for changing the status of pumps are depending on time. While setting the boundaries to the algorithm, pump switches and tank water levels are controlled. Following the application of method by predetermined demand patterns; real time daily demand measurements and predictions are introduced to the pump scheduling problem. For these predictions, first, demand multiplier factors are used to model the unexpected cases such as emergency. Then, the prediction model is improved by considering long time measurements. To judge the measurement data and make predictions for upcoming demands, Kalman Filter technique is applied on the prediction model.

At the second step of the main methodology, the objective becomes minimizing excess pressures among the network of selected DMA. After obtaining the nodal pressures of the network for the optimal pump schedule; initially, optimal valve location study is applied in Steady State (SS) conditions while the number of valves was not limited with a predefined number. Then, Extend Period Simulation (EPS) was applied to the network with the defined group of valves as a part of the valve locating study. Completion of valve locating studies is followed by valve opening determination studies. Evaluating the outcomes of previous SS and EPS studies, some valves are modeled as Throttle Control Valve (TCV) and suitable openings of these are found at the valve opening determination study. By following these steps, it is aimed to reduce excess pressures by employing as low number of valves as possible.

One of the main contributions of this study is the application of real time daily demand predictions to the pump scheduling optimization problem using partial run time intervals among the whole simulation duration. Within this application; using of Kalman Filter as a demand predictor corrector is also a novel method for pump scheduling optimization problem for WDNs.

For valve studies; determination of partial openings of valves, using the outcomes of valve locating studies shall also be considered as a contribution. Partial or completely closure of isolation valves is a known tool for pressure minimization; however this study offers an operation method by combining open, closed and partial open valves.

This thesis consists of seven chapters. Chapter 2 gives a brief information related with the hydraulics of water distribution networks and the used hydraulic simulation model; this chapter also includes a detailed explanation and operators of the Genetic Algorithms. The past studies related with the pump scheduling and pressure minimization are also summarized in Chapter 2.

In Chapter 3, the problem definition and solution methodology are presented in detail. Within the methodology, the interaction between the pump scheduling and valve characteristics studies is explained. This chapter also includes the explanation of the structure of optimization models and their components.

In Chapter 4, characteristics of the case study network which both optimization methods are applied on; are explained in detail. In this chapter, the daily demand patterns of each DMA are given as well. The applied decomposition technique to make optimization models conveniently applicable is described in this chapter. The characteristics of network DMAs which the valve locating and opening determination studies are applied on system characteristics including boundary elements are also defined and shown in this chapter.

Chapter 5 and Chapter 6 include the main works of the thesis study. In Chapter 5, initially pump scheduling optimization studies for 24 hour run time duration and then variable run time periods are presented to visualize the relationship between pump schedules and tank water level oscillations. This chapter also includes pump scheduling studies depending of real time daily demand measurements and predictions. The application of Kalman Filter to the demand prediction model is also presented in this chapter.

Chapter 6 includes all works related with valves within the thesis study. Initially application of valve locating studies on the network of selected DMA is presented. These studies include the application under both SS and EPS conditions. Then valve opening determination studies are applied combining the results of valve locating studies. This chapter also includes the sensitivity analysis of valves to the excess pressure minimization objective. Conclusions are presented in the last chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Hydraulics of Water Distribution Networks

As briefly indicated in Chapter 1, this thesis involves optimization studies which are integrated with hydraulic simulation models. Model based simulation is a technique for mathematically approximating the behavior of water distribution systems. To effectively utilize the capabilities of distribution system simulation software and interpret the produced results, the mathematical principles involved should be understood.

Water distribution networks are comprised of connected hydraulic elements. The entire system is interrelated in such a way that the condition of one element must be consistent with the condition of all other elements. Two concepts define these connections:

- Conservation of mass
- Conservation of energy (Walski et al., 2003).

2.1.1 Conservation of Mass

The law of conservation of mass, states that for any system closed to all transfers of matter, the mass of the system must remain constant over time. In fluid mechanic point of view, this rule states that, any fluid mass entering any pipe will be equal to the mass leaving the pipe (Walski et al., 2003).

$$\sum_{i=1}^{n} Q_i - U = 0 \qquad (2.1)$$

Where ;

Q_i = inflow to node from pipe i (L^3/T)

U = water extracted from node (L^3/T)

n = number of pipes adjoining to that node

2.1.2 Conservation of Energy

The law of conservation of energy, states that the difference in energy between two points must be the same regardless of the path that is taken (Bernoulli, 1738). The equation of conservation of energy is given as follows;

$$Z_1 + \frac{P_1}{\gamma} + \frac{{V_1}^2}{2g} + \sum h_p = Z_2 + \frac{P_2}{\gamma} + \frac{{V_2}^2}{2g} + \sum h_L + \sum h_m \qquad (2.2)$$

where;

Z = elevation (L)

P = pressure ($M/L/T^2$)

γ = specific weight of fluid ($M/L^2/T^2$)

V = velocity (L/T)

g = gravitational acceleration constant (L/T^2)

h_p = head added at pumps (if any) (L)

h_L = head loss in pipe (L)

h_m = head loss due to minor losses (L)

2.2 Network Simulation Model

In real case, water distribution networks consist of many nodes and pipes which makes the solution mechanism more complex. For each node, one continuity equation is developed while one energy equation is developed for each loop. In a real water distribution network, the number of these equations may reach high values. Since energy equations are nonlinear in terms of flow and head, the equations are not solved directly but iteratively.

Throughout this thesis study, EPANET is employed as hydraulic simulation software. EPANET is reliable, robust, quick, well known and widely applied (Keedwell and Khu, 2005; Neelakantan and Suribabu, 2005; Araujo et al., 2006; Zyl et al., 2004; Whittle et al.,2009; Nicolini and Zovatto, 2009; Nazif et al.,2010) hydraulic simulation software. It may perform steady state (SS) and extended period simulation (EPS) of hydraulic and water-quality behavior within pressurized pipe networks. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank and the concentration of chemical species throughout the network during a simulation period which is comprised of multiple time steps. In addition to chemical species, water age and source tracing can also be simulated.

EPANET was developed by the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory. It is public domain software that may be freely copied and distributed (U.S. Environmental Protection Agency, 2007). EPANET also has a Programmer's Toolkit that is a dynamic link library (DLL) of functions that are allowed to be modified to customize EPANET's computational engine for specific needs. The functions can be incorporated into 32-bit Windows applications written in C/C++, Delphi Pascal, Visual Basic, or any other language that can call functions within a Windows DLL (U.S. Environmental Protection Agency, 2007).

In this study, EPANET Programmer’s toolkit is employed and interconnected with the developed genetic algorithms.

2.2.1 Hydraulic Basis of EPANET

The method used in EPANET to solve the flow continuity and head loss equations that characterize the hydraulic state of the pipe network at a given point in time can be termed a hybrid node-loop approach. Todini and Pilati (1988) and later Salgado et al. (1988) chose to call it the "Gradient Method" (Rossman, 2000). The flow continuity and conservation of energy equations (headloss equations) were used, as described in section 2.1.1 and 2.1.2.

EPANET has capability of computing friction headlosses using the Hazen-Williams, Darcy-Weisbach, or Chezy-Manning formulas. In this study, Hazen-Williams formula is used since, through the network the flow velocities may reach low values. As in these cases the turbulent flow conditions may not be satisfied. Thus; Hazen-Williams equation is preferred which is one of the frequently used head loss formulas. It is based on empirical expressions and applicable to water under turbulent flow conditions (Walski et al., 2003). The Hazen-Williams formula is given as follows;

$$h_L = \frac{10.7L}{C^{1.852}D^{4.87}}Q^{1.852} \tag{2.3}$$

where;

h_L = head loss in pipe (m)

L = pipe length (m)

C = Hazen-Williams C factor

D = diameter of pipe (m)

Q = flow rate (m^3/s)

2.2.2 Pump Curves

Pump curve is the graphical representation of the amount of water that can be supplied by pump at which head under normal settings. Head is the gain by the pump, supply is the rate of pumping and these two are represented in Y and X axes respectively. EPANET supplies single point and three point curves. A sample representation for both types of curves is given in Figure 2.1.

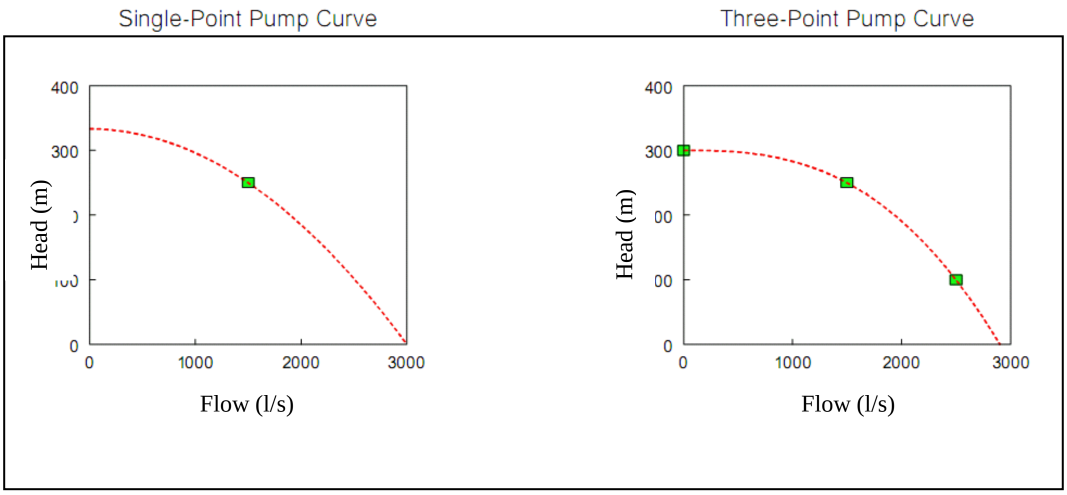


Figure 2.1. Sample Representation of Pump Curves (U.S. Environmental Protection Agency, 2007).

When, a single-point pump curve is defined by a single head-flow combination that represents a pump's desired operating point, EPANET adds two more points to the curve by assuming a shutoff head at zero flow equal to 133% of the design head and a maximum flow at zero head equal to twice the design flow. It then treats the curve as a three-point curve.

When a three-point pump curve is defined by three operating points: a Low Flow point (flow and head at low or zero flow condition), a Design Flow point (flow and head at desired operating point), and a Maximum Flow point (flow and head at maximum flow), EPANET tries to fit a continuous function through the three points to define the entire pump curve. The expression is shown below;

$$h_G = A - Bq^C \tag{2.4}$$

Where;

h_G = head gain (M)

q = flow rate (M/L^3)

A, B and C : constants (Rossman, 2000).

2.3 Genetic Algorithms

In this thesis study, Genetic Algorithms (GAs) are applied for the decision making process; which is interconnected with the network simulation model (EPANET). As shown in sections 2.1.2 and 2.2.1, the equations for solving the hydraulics of network are nonlinear. Due to nonlinear behavior of the problem; it is not preferred to apply linear integer programming. Nonlinear optimization would have been applied on the problem; however rounding up and down of the continuous solution to discrete decision variables is inevitable in this method. Besides it generates one solution where, GAs generate whole class of alternate solutions close to optimum. Due to these reasons; it is preferred to employ Genetic Algorithms on both optimization problems.

GAs are one of the search techniques that is based on the mechanism of natural evolution. The idea behind is the Darwin's evolution theory and the survival of the fittest. GAs have been developed by Holland (1975), his colleagues and his students at the University of Michigan. The goals of their research were to explain the adaptive processes of natural systems and to design artificial systems software that retains the important mechanisms of natural systems (Goldberg 1989).

When compared to traditional optimization techniques, GAs differ from these techniques in four ways:
GA works with coding of the parameters set, not the parameters themselves.
GA searches from a population of points, not a single point.
GA uses objective function, not the derivatives.
GA uses probabilistic transition rules, not deterministic rules (Goldberg 1989).

GAs act using the chromosomes of the population, in order to accomplish basic genetic operations such as selection, crossover and mutation. These genetic operators do not concern network hydraulics. Hydraulic conformities of the network are checked on the basis of a hydraulic network solver; in this study this hydraulic solver is EPANET. The parameters that help to measure the performance of the network is dependent on the objective function. At each step, the hydraulic conformity of each chromosome (candidate pump schedule or valve location etc.) is measured by means of specific penalty functions. These penalty functions are the crucial step of the whole algorithm since they are the key to differentiate the valuable, promising and hopeless candidates.

GAs initiate with randomly generated initial set of chromosomes. These chromosomes form a population. The size of the population, in other words, the number of chromosomes should be defined previously. The chromosomes are strings of binary bits and their size depends on the characteristics of the network. With predefined number of chromosomes, evolution initiates and it continues till the last iteration. Throughout iterations new chromosomes are obtained, called offspring. The iterations, which lead to obtain offspring, are called generations. In every generation the chromosomes evolve to reach the global optimum; then, the best chromosome is stored. This loop of generating offspring continues until reaching a predefined generation number. After that, the best solution found among all generations is displayed as the near optimal solution of the problem. During the evolution process, three main parameters are employed; selection, crossover and mutation.

2.3.1 Selection

Throughout the evolution process, from the beginning of each generation all chromosomes should be evaluated. This evaluation is made by converting the binary chromosomes of the population, to real networks and solving all these networks by a network solver one by one.

Solving each chromosome supplies hydraulic results (nodal pressures and flow velocities) for each network that makes the algorithm make smart decisions. To rank the chromosomes according to optimization goal, penalty functions play a significant role. These functions differentiate the chromosomes by casting the hydraulic results and/or main features of the network into single fitness value. The formulation of penalty functions shall be composed of mathematical formulas that best classify the chromosomes. The formation of penalty function strictly depends on the optimization goal. For example, for the problem of pump scheduling, the penalty functions consider the tank levels, electricity costs and optionally pump switches. While for valve locating problem the nodal pressures should be penalized. By penalizing the characteristic properties of networks, each chromosome takes its position among the population.

Then, the selection process is initiated considering the fitness values of each chromosome. During this selection process the roulette wheel method is used. The mate chromosomes are selected according to their probability values on the roulette wheel. The chromosomes have their portions on the wheel equivalent to their fitness values (see Figure 2.2). Then a random number is generated (wheel is turned) and selection is made according to this number. Consequently, more fit chromosomes are more willing to be selected with respect to its slot size on the wheel. The roulette wheel selection method is advised by Goldberg (1989). This method helps preferential selection of more fit parents with the expectation of producing more fit offspring for next generation. After mating the chromosomes according to their fitness values, the population moves to the crossover process. Basic schematic of roulette wheel selection is shown in Figure 2.2.

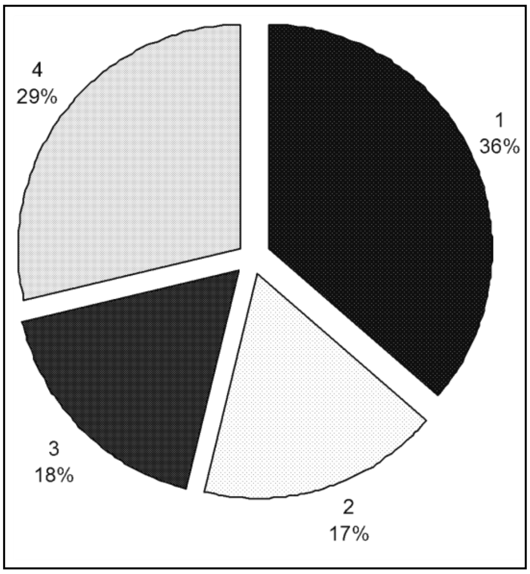


Figure 2.2. Chromosomes with Portions According to Their Fitness Values (Gençoğlu, 2007)

2.3.2 Crossover

Crossover is the parameter of reproducing new chromosomes. After the mating of selected chromosomes, the parents may crossover some of their bits with each other. The occurrence of crossover is controlled by a random number and a predefined crossover probability. Using the selection process, when the mating of chromosomes is completed, a random number is generated. If this number is less than the predefined crossover probability the crossover is applied to the selected mates, otherwise these parents are passed to next generation as offspring and the algorithm moves to the next couple. This looped process repeats for all mates throughout the population.

Crossover can be explained basically as the exchange of bits (genetic information) between the parents. The occurrence of exchange creates offspring different than both parents. The exchange of bits among the parents can be made using one point, two points or multi point crossover. The points indicate the bits that will transfer to the other parent. For example; if two point crossover is made, two random numbers (one greater than the other) are generated. The bits between these two numbers are exchanged. For more detailed explanation see Figure 2.3.

Parents before crossover	Parents after crossover points are determined	Offspring
010011001010101	010[***0110010***]10101	010[***0011001***]10101
101001100101100	101[***0011001***]01100	101[***0110010***]01100

Figure 2.3. An Example for Two Point Crossover

2.3.3 Mutation

Mutation is another operator of GAs and maybe the most effective one that affects the performance of search. Mutation is the exchange of bits from 1 to 0 or reverse (Figure 2.4). After crossing over of selected chromosomes is completed, mutation operator is applied to the population. During mutation operation, all the population is considered bit by bit. From the beginning of the population till the end, for each bit a random number with a normal PDF is generated. If this number is less than the mutation probability that is predefined, mutation occurs on this bit. If the random number is greater or equal to the predefined mutation probability, mutation operator moves to the next bit and another random number is generated for that bit. This process continues till the end of the chromosome at the same manner.

Before mutation	0100110010101010101101000110100101001001
After mutation	0100110110101010101101000110000101001001

Figure 2.4. An Example for Mutation

Each chromosome can be exposed to mutation several times depending on its own length and the predefined mutation probability. Concerning this operator, mutation rate is one of the parameters that affect the algorithm. There is not a commonly accepted value for this rate in the literature. Meanwhile, the probability of mutation is generally kept at minimum levels.

The operators described above are the general steps that are all discussed and delineated in the literature. The predefined values that manage the performance of operators are dependent on the problem to be formulated and the characteristics of the network. There may not be any common constants for each operator (Gençoğlu, 2007). Throughout this study, these values are chosen by trial-error processes and suitable ones were used within the models.

2.3.4 Elitism

Elitism is not a common component for the GAs. This operator could be mentioned as a modification to simple GAs. This operator protects some promising chromosomes from the crossover and mutation operators. As mentioned above, during crossover and mutation, the selected chromosomes are modified. Crossover and mutation are conducted to improve fitness. However, it may be possible that they can lead to less fit individuals. Therefore, elitism concept is the protection against destructive changes in the population. It is first introduced by De Jong (1975). Savic et al. (1997), Zyl et al. (2004), Araujo et al. (2006), López-Ibáñez et al. (2011) used this operator during their optimization study on the pump scheduling problem. Montesinos et al. (1999) applied some modifications that is similar to the elitism for the optimal design of water distribution networks; but did not clearly emphasize elitism parameter.

Elitism rate is the control parameter of this operator. Similar to the previously mentioned operators parameters of GAs, elitism rate is a predefined number. In this study elitism rate is kept at the minimum level not to reduce the search space.

2.3.5 Penalty Method

In this study, the objective functions of the optimization problems are unconstrained. However, there are some constraints that should be taken into account for the optimization goal. To consider these external constraints, penalty method is used. Penalty method is explained as transforming a constrained problem in optimization into an unconstrained problem by associating a cost or penalty with all constraint violations (Goldberg, 1989). This method simply penalizes the violated constraints and helps the algorithm rank the individuals. This method uses constraint based penalty functions depending on the problem. In the Chapter 3, penalty functions are shown with its integration to the related objective functions.

2.4 Overview of Past Studies

Over the past 40 years, many technical papers have been published on Water Distribution Network (WDN) optimization using variety of techniques. Though, design of WDNs is a popular optimization objective (Gençoğlu, 2007); in recent years many researchers also focused on operational optimization objectives of the WDNs. Simulation of hydraulic behavior within a pressurized, looped pipe network is a complex task, which means effectively solving a set of nonlinear equations.

Even though the capital cost of network is substantial, the operation costs of WDNs may also be comparable and needs to be minimized. Besides, with increased urbanization and consumer demands, most WDNs' pump scheduling has become increasingly complex. Recently, many researchers focused on pump scheduling optimization of WDNs due to these reasons.

The problem of pump scheduling was an early optimization objective for many researchers. A detailed review of optimization approaches to pump scheduling problem is made by Ormsbee and Lansey (1994). They classified the previous works into groups considering number of pumps and sources (single tanks or multiple tanks), hydraulic model (simplified hydraulics, mass balance), demand model and control algorithm. The reviews of algorithms contain linear, non linear, dynamic and specialized forms of these base techniques. They commented on the choice of appropriate algorithm is largely dependent on the physical characteristics and configuration of the system. Their foresight is; depending on the increase in the use of SCADA (Supervisory Control and Data Acquisition) systems, there will be widespread applications of optimal control strategies on the water supply systems.

A dynamic optimization algorithm was developed by Lansey and Awumah (1994), focusing on the pump switches constraints. They defined the pump switch as "turning on a pump that was not operating in the previous period" and they paid special attention to limit the number of pump switches while minimizing the energy consumption cost.

However, due to nonlinear behavior of WDN's and large search spaces of the optimization problem; these optimization methods had limited success. All these approaches, i.e., linear, nonlinear, and enumeration techniques require simplifications on the general problem; as a result, they do not guarantee to find the near- optimal point in the search space. Being unimodal functions their solutions are strictly dependent on the initial population and they are all prone to fall into the local optimums. This phenomenon forced researchers to utilize evolutionary algorithms for the problem of operational optimization of WDN's.

Savic et al. (1997) used multi-objective genetic algorithms (GA) into the pump scheduling problem presented by Mackle et al. (1995). The multi-objective approach considers both the energy cost and pump switching criteria in the same objective. They considered the electricity tariff for two periods; day and night. They also made some improvements in combining GA with two local search strategies based on different definitions.

Yu et al. (2005) developed a model for optimal allocation of water supplies between pump sources. The location of water supply basically means the start level of water reservoir. They introduced genetic algorithms into the problem using pump station pressure head and initial tank levels as decision variables. The objective is to minimize the total energy cost of pumping.

Zyl et al. (2004) developed a hybrid method by introducing two hillclimber search strategies into the genetic algorithms to find the optimal schedule of pumps. Throughout their study, the optimization variables were defined in terms of tank level controls due to its widespread use in practice. The primary aim is to find the optimum trigger levels to minimize the pumping costs. They also employed electricity tariff and pump switch constraint into the optimization problem. The developed model used EPANET2 (Rossman, 2000) as hydraulic solver.

Boulos et al. (2001) presented a management model for optimal control and operation of water distribution systems using genetic algorithms. They measured the system performance using the upper and lower limits of nodal pressures, maximum pipe velocities, maximum pumped volumes, maximum and minimum tank levels and initial and final tank volumes to maintain hydraulic periodicity. They also tried to limit the number of pump switches to a defined value.

Rao and Salomons (2007) combined genetic algorithm optimizer with and Artificial Neural Network (ANN) predictor to develop a real-time, near optimal control strategy. They applied their approach first on the well known anytown network. Then, Salomons et al. (2007) applied the same dynamic model to Haifa-A network serving 60,000 people and 25% energy cost saving was achieved when the results of a simulated year is compared to the cost of study year's current practice.

Wu et al. (2009) used multi-objective GA to investigate the trade-offs of minimizing pumping costs and Green House Gas (GHG) emissions. They considered the capital and operating costs of pumping systems in terms of GHG emissions while utilizing the objective of minimum electricity consumption.

López-Ibáñez et al. (2011) focused on the comparison of two most used representations in pump scheduling; binary representation and level-controlled triggers. They defined and analyzed two explicit representations based on time-controlled triggers where the maximum number of pump switches is limited. They found out that the proposed time-controlled triggers' representation gives better results when compared with the level-controlled triggers being used with evolutionary algorithms.

For operational optimization studies, forecasting the demand has significant effect on the cost minimization problem. The most of the works summarized above use previously defined demand data for a given period of time. However, in real-time cases, the demand may possibly vary from its predicted value. Though water demand predictions depend on the solid data supplied from control systems, demand estimation for real-time case shall be considered as a corrector to any model's water demand data. Shang et al. (2006), proposed a method and algorithm for real-time water demand calibration process. They proposed a predictor-corrector methodology to predict demands and correct this prediction using real-time measurements with the integration of extended Kalman filter.

Whittle et al. (2009) used M5 Model-Trees algorithm (Quinlan, 1992) to forecast future demands for 24 hr period and genetic algorithms to calibrate predicted values in real-time. Subsequently, they used the corrected outputs as inputs for prediction. EPANET was employed as hydraulic solver in their study.

Operation of a WDN does not only mean to control the pumping systems. The nodal pressures which are not inside the serviceable limits may also be a subject for operational optimization. Low pressure problem within a network may cause insufficient water at the demand nodes and the solution is generally replacing of pump with a sufficient one. High pressures, on the other hand may lead leakage of water or breaking of pipes depending its degree of exceeding the service limits.

On the other hand water leakage means the loss of treated and pumped water through possible cracks of pipes; besides it may force authorities to look for new sources which mean unnecessary investment. Even for networks that are being operated within the pressure boundaries, water leakages are inevitable. The amount of leakage may mean a large amount of water loss depending on the robustness of system.

Being one of the pioneers of the subject, Germanopulos and Jowitt (1989) listed the causes of water leakage and chose the convenient way of reducing leakage as pressure control. They proposed a methodology for determination of optimal valve settings for pressure minimization involving a function relating nodal pressures and leakage amount. They formulated the excess pressure minimization problem with linear objective function and non-linear set of constraints; linear theory was used to linearize the constraints. Jowitt and Xu (1990) used again linear theory for the problem of optimal valve setting. They improved their objective function which minimizes total volume of loss rather than total nodal pressure.

An evolution program with principles of evolutionary design and genetic algorithms were introduced into the problem of leakage minimization by Savic and Walters (1995). In their methodology, a steady state network analysis model was used that is based on linear theory. Aiming pressure regulation, they used the valve settings as decision variables and pressure bound limits as constraints. Using their algorithm various times; they concluded on finding near optimal solutions by using very different set of valves. The setting used in their algorithm is quite different in that; the valves are considered fully open or closed. So the optimal setting of valves also gives idea about its location.

Reis et al. (1997) adopted the leakage-pressure model of Germanopulos and Jowitt (1989) to their study to find the suitable location and setting of valves in a WDN using GA. Aiming to obtain maximum leakage reduction, the objective was defined as the determination of optimal valve settings for a given location of valves. By employing GA for the optimization problem, their study was differing from previous studies by determining the optimal settings of valves and the optimal location of given number of valves at the same time. First, leakage is minimized to obtain the valve settings for a given number of valve locations, and the optimal location of these valves was determined while maximizing the leakage reduction.

Vairavamoorthy and Lumbers (1998), introduced flow reduction valves into the problem of leakage minimization. They developed an optimization model to find the most effective settings of such valves which are placed on predefined places. Their solution technique involve a sequence of quadratic programming. In their objective function, to predict the amount of leakage, they used the formulation of Germanopulos and Jowitt (1989). Their approach allows minor violations in the target pressure (so called - relaxed pressure constraint) which supplies improvements for the leakage minimization problem.

Özger and Mays (2004) offered a reliability approach for optimal location of isolation valves. Though their aim is not the minimization of leakage in particular, but the network reliabilty; the optimization of valve locating problem is discussed in detail. They used the Node Flow Analysis (Bhave, 1991) to solve the network instead of standard demand driven analysis. For the problem of optimal valve locating, simulated annealing was introduced.

A pressure-driven demand and leakage simulation model is accomplished by Giustolisi et al. (2008). They used a steady-state network model to simulate the pressure-driven demand and leakages at pipes. Their study does not include any leakage minimization approach.

Araujo et al. (2006) used two phase optimization model using genetic algorithms for the problem of optimal pressure control. In the first phase, the number and location of control valves are optimized; while the valve opening adjustments were made beyond extended period simulation in the second phase. In the first phase, the pseudo valves were placed on each pipe by changing the roughness value of pipe. Additional roughnesses bring network minimization of nodal pressures. In the second phase, opening adjustments were made using head loss coefficients for selected Throttle Control Valves (TCV) or Pressure Regulating Valves (PRV). For such valves, operating dynamic conditions (Extended Period Simulation) were considered. They used EPANET 2 for hydraulic network analysis for its robustness. They also used “elitism” to conserve the best member of each generation that lets the chromosome pass through to the next generation.

For optimal pressure management, Nicolini and Zovatto (2009) introduced the regulation of pressure reducing valves (PRVs). They also introduced the concept of multi-objective genetic algorithms into the problem of leakage minimization to determine the number, location and setting of these valves. They divided the method into two; first minimize the number of valves, then minimize the total leakage. They used flow-modulated type of PRVs that can control the downstream pressure according to the demand, due to allowance of flexibility. EPANET 2 was used as hydraulic solver and coupled with the optimization model.

Recently, Nazif et al. (2010) proposed a pressure management model, considering water levels of tanks in order to minimize the nodal pressures and leakages. They considered demands of different seasons while modeling the water level variations. To simulate the hydraulics of the network, “emitter” option of EPANET is used. Emitter capability is used to model the leakage depending on the nodal pressures (like sprinklers). Actually, EPANET is used to train the Artificial Neural Network (ANN) model; and completely replaced by ANN afterwards. For the main process, the ANN model is integrated with the GA based optimization model. This coupling decreased the computation times while also decreasing the accuracy when compared with coupling a hydraulic simulation model.

CHAPTER 3

PROBLEM DEFINITION AND SOLUTION METHODOLOGY

3.1 Introduction

This chapter introduces the solution methodologies concerning the following objectives:

1) pump schedule optimization for energy cost minimization
2) valve location and valve opening determination for pressure minimization of water distribution networks.

For both objectives, there is an interconnection with network simulation model and decision making algorithms. Although these objectives are both related with water distribution networks, the optimization aims are different. This situation emerges the need of specific solution methods for each objective. Therefore, for pump scheduling and valve operation studies, different methodologies with different computer models have been developed.

The main solution methodology is stepwise; it starts with the evaluation and skeletonization of network, continues with pump scheduling optimization studies. Using the results of optimum pump schedules, methodology continues with the valve locating and opening determination step. The main flowchart of the solution methodology is shown in Figure 3.1.

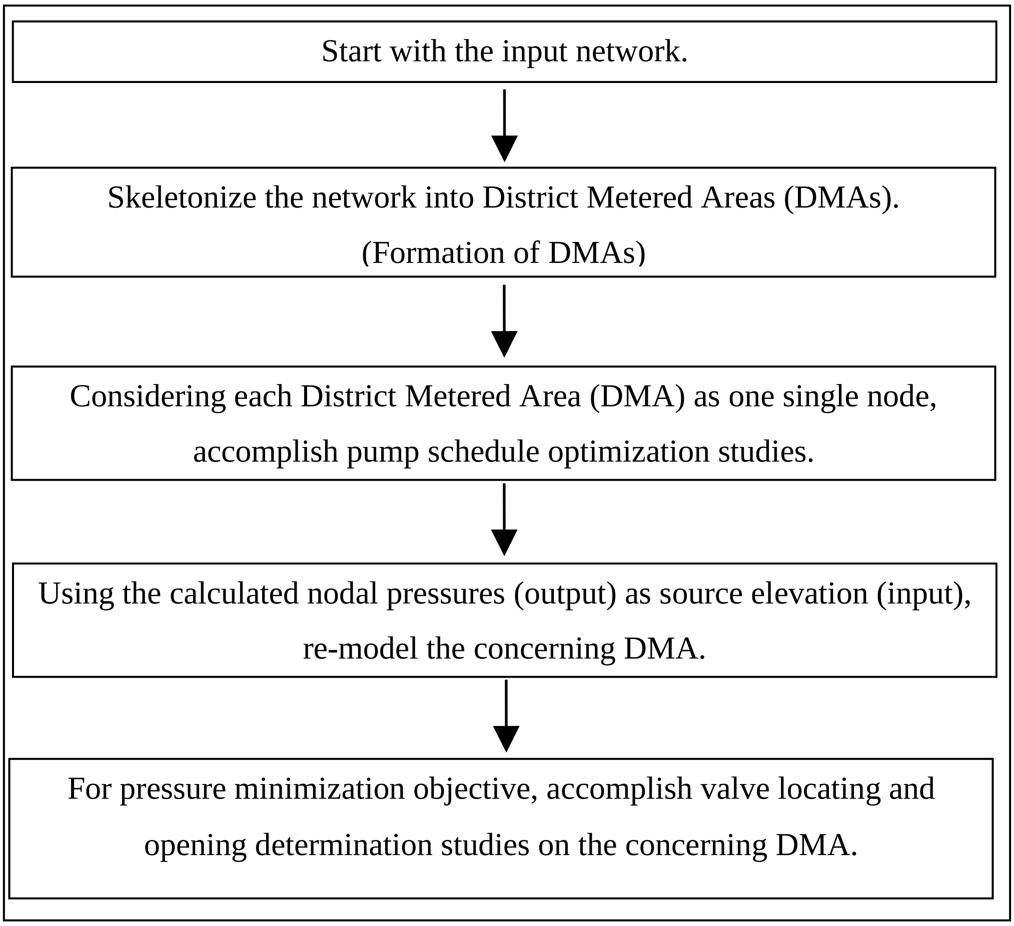


Figure 3.1. Main Flowchart of the Solution Methodology

As can be followed from the flowchart in Figure 3.1, there exists a connection between pump scheduling and valve characteristic determination studies. After obtaining suitable pump schedules, the nodal pressures for each demand node will also be found. The obtained nodal pressures are then used as source elevations for the valve subject studies. For this interaction, the network models need some modifications.

As mentioned at the second step of Figure 3.1, before beginning optimization studies, the network is skeletonized into its District Metered Areas (DMAs). This skeletonization simplifies the size of the network by eliminating the DMA's pipes while considering the whole DMA by a single node. The demand data for each DMA is summed and considered as a single demand node with the summation of all area. This method is only available for the networks which have isolated DMAs. In this study, a network consisting of isolated DMAs is studied.

Skeletonization may be defined as the process of selecting the parts of the hydraulic network that have significant impact on the behavior of the system. It is also a practical approach for modeling process since it allows the designer to produce reliable, accurate results in shorter time (Walski et al., 2003). In this study, the used method for skeletonization may be named as “pipe removal”.

Skeletonization of a network provides an excessive decrease on the number of pipes and nodes while keeping the characteristics of the network the same for the pump scheduling study. Since, time needed for each run of network directly connected to the number of nodes, this skeletonization decreased the computer evaluation times at significant levels depending on the simplification of the network.

Upon completing the pump schedule optimization studies, by using the optimal schedule of pumps, the nodal pressures are found. These nodal pressures indicate the entrance pressures for each DMA. Depending on the chosen run time duration, these nodal pressures vary. To regard these nodal pressures as the supply node pressure for each DMA; the network of each DMA is re-modeled. For this modification, the node of measurement chamber is turned into a supply reservoir with constant head. The elevation of this supply node is considered to be the average of nodal pressures resultant of the chosen optimal pump schedule. Upon the supply node modification, the methods for valve locating and opening determination studies are applied on the network of DMA. The interaction between the pump scheduling and valve locating and opening determination studies is shown in Figure 3.2 on a flowchart.

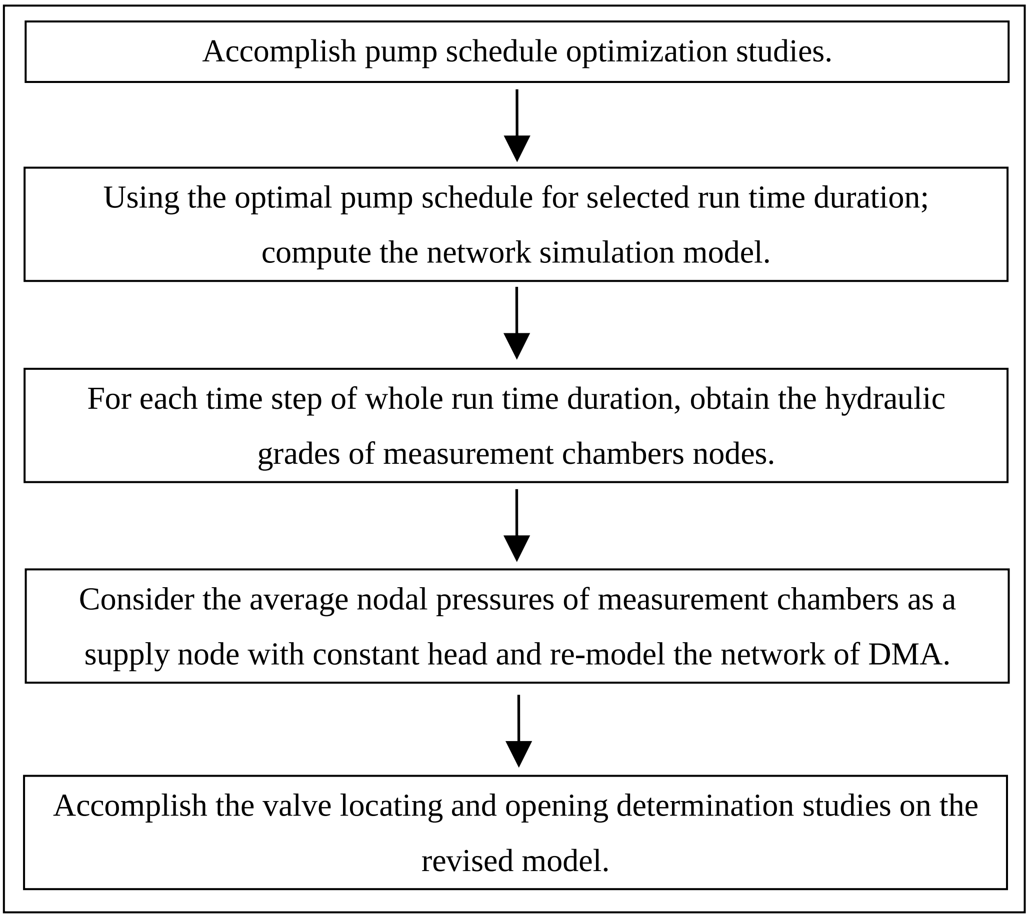


Figure 3.2. Interaction Between Pump Scheduling and Valve Locating and Opening Determination Studies

3.2 Structure of the Developed Computer Models

As mentioned before, this study involves a combination of two different optimization studies. Consequently, two different computer models are needed for pump schedule and valve locating and opening determination studies. The computer structures of the models are similar where the objectives differ.

For pump scheduling optimization study, the developed program is named as POGA (Pump Optimization using Genetic Algorithms). POGA computes the optimal pump schedule of a given run time duration, casting tank volumes and pump switches to minimize the energy costs. Pumps are taken as individuals and should be located properly including defined head-discharge curves.

For valve locating and opening determination studies, VOGA (Valve Optimization using Genetic Algorithms) is developed. VOGA is capable of computing the optimal locations and openings of valves among the network. For pressure minimization objective, VOGA may consider each valve individually or in groups.

For both pump schedule and valve characteristic determination objectives, there is an interconnection with network simulation software (EPANET) and decision making algorithms (GAs). The needed connection is supplied by developed codes which are built in the MATLAB environment. Both POGA and VOGA are the continuation of NOGA (Network Optimization using Genetic Algorithms) which was developed during the master thesis study of the author (Gençoğlu, 2007). The codes of both POGA and VOGA are developed by Gençer Gençoğlu in MATLAB language.

MATLAB code can be written using MATLAB's own editor and evaluated using MATLAB's command window. The main code consists of several **.m files** and these files can be executed calling commands from the MATLAB command window. These **.m files** work inside the kernel of MATLAB and they can be connected to each other. The main code can be divided into various .m files and this flexibility gives many advantages to the developer while debugging. After having divided the main code into **.m files**, the computer application performance of all **.m files** can be investigated individually. Besides its user interface, complicated visualization options, user friendly warnings and convenience in debugging are the major advantages of MATLAB. For these reasons it is preferred to use MATLAB language to design the programs.

The developed models need a solid interaction between the hydraulic solver and MATLAB environment. This is supplied by the EPANET Programmers Toolkit. For the connection of EPANET and MATLAB, the network should be built using EPANET. The built network shall have all data including the lengths of pipes, nodal elevations, demands etc. The GIS database may also be included in the network; in other words the network to be studied should be hydraulically solvable condition with all the data driven inside. After completing the layout of the network, it should be saved as an **.inp file**.

This can be done as follows by clicking in the menu bar: file >> export >> network. Using the popup window, the **.inp file** can be saved by giving a name into the root directory of MATLAB on the hard disk (Figure 3.3). Another way to create the **.inp file** is to write it using any text editor - for example, Microsoft Notepad - and changing the extension of saved file to **inp**. The difficulty of this way is that, all the network elements should be written in the accurate format. In Figure 3.4 an example format of an **.inp file** is given.

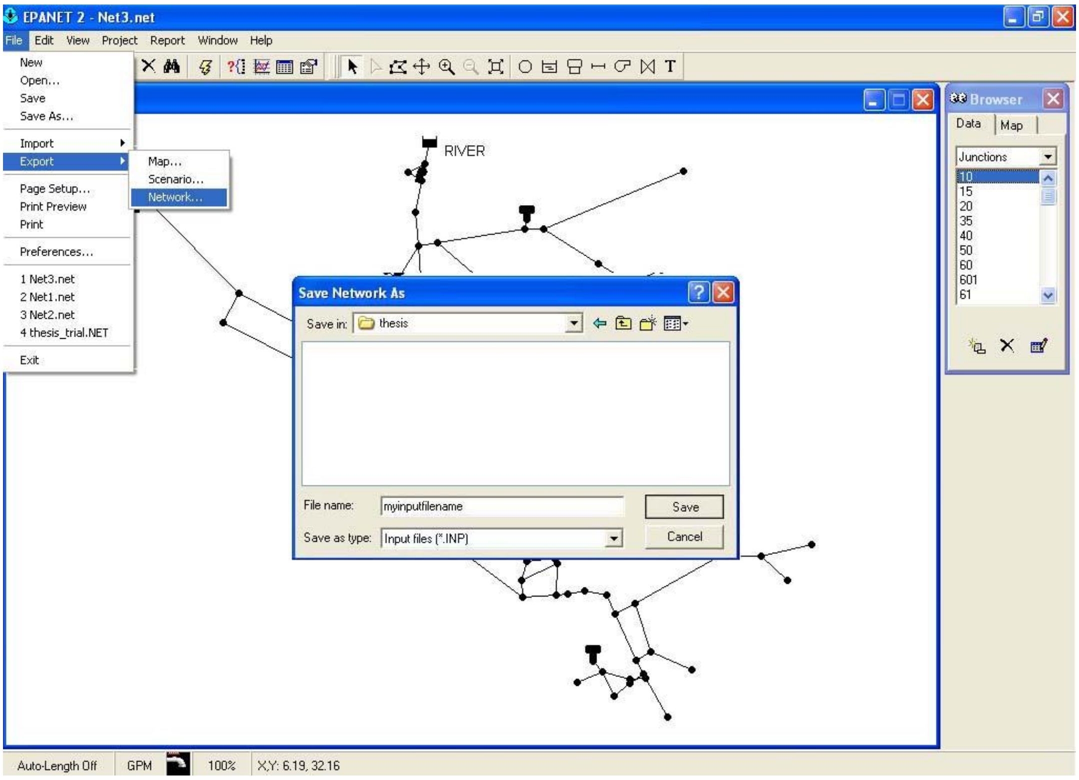
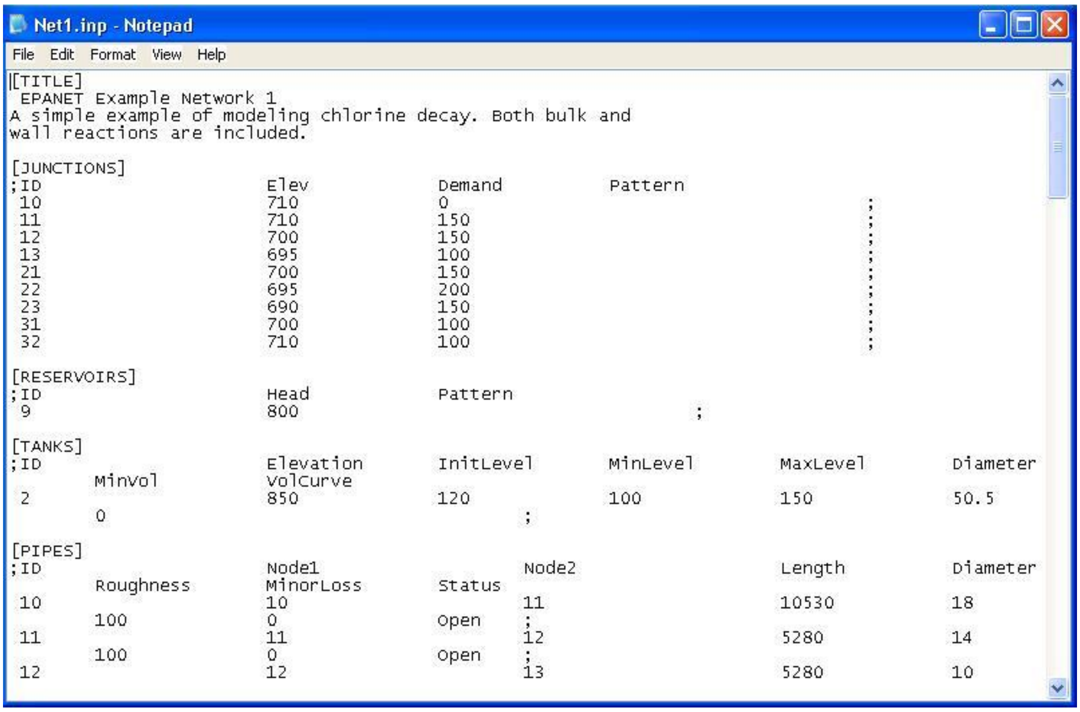


Figure 3.3. Steps to Save a Network as .inp File



```
[TITLE]
 EPANET Example Network 1
A simple example of modeling chlorine decay. Both bulk and
wall reactions are included.

[JUNCTIONS]
;ID              Elev        Demand      Pattern
 10              710         0                       ;
 11              710         150                     ;
 12              700         150                     ;
 13              695         100                     ;
 21              700         150                     ;
 22              695         200                     ;
 23              690         150                     ;
 31              700         100                     ;
 32              710         100                     ;

[RESERVOIRS]
;ID              Head        Pattern
 9               800                     ;

[TANKS]
;ID              Elevation   InitLevel   MinLevel    MaxLevel    Diameter
        MinVol   VolCurve
 2               850         120         100         150         50.5
        0                         ;

[PIPES]
;ID                                       Node2       Length      Diameter
        Roughness   MinorLoss   Status
 10              10                       11          10530       18
        100         0           Open      ;
 11              11                       12          5280        14
        100         0           Open      ;
 12              12                       13          5280        10
```

Figure 3.4. An Example .inp File

Before running POGA or VOGA, the gene size and chromosome length should also be defined by looking at the decision variables and these numbers should be entered to the programs as input. For example, while using POGA, for a network consisting of 2 pumps, for 24 hour run time interval, chromosome length should be 24 x 2 = 48 bits.

After having declared the input information, the programs could be run in MATLAB environment. They start with initial random population consisting of predefined number of chromosomes. These chromosomes denote candidate decision variable configurations. For pump scheduling problem, the chromosomes indicate the on-off status of pumps for given time. When the problem is valve locating, the chromosome indicate the status of valves; in other words which pipe is open or closed. When the opening of valve is the decision variable, the chromosomes indicate the set of statuses of predefined valves. The mentioned chromosomes are utilized separately. Related chromosome is built for corresponding optimization problem. The pump scheduling and valve optimization problems are integrated but they are separate models. The chromosomes of POGA and VOGA are represented in Sections 3.3.4 and 3.4.4, respectively.

After forming the random initial population, the chromosomes are converted to corresponding network elements using EPANET toolkit. By this modification, the network decision variables are being controlled by the MATLAB code. After solving the networks (the whole population) and obtaining the hydraulic results, the population is penalized using the penalty functions. These penalty functions act in a different way depending on the problem and briefly very explained in Section 2.3.5. The details of penalization methods for POGA and VOGA are explained in Sections 3.3.2 and 3.4.2, respectively.

By penalizing all chromosomes, the fitness values are computed for each chromosome. Then the genetic operators (selection, crossover and mutation) play their role. As explained in the previous chapter, before crossover and mutation, some of the best chromosomes are chosen as elite and they move directly to the next generation without any process. After the completion of genetic operators, children of previous generation become parents of the next generation. Again the chromosomes are converted into networks and all the population (each network) is solved using EPANET toolkit. With the same process, the best chromosome for the second generation is saved and the loop continues till the limiting generation number is reached.

As the programs reach to the limiting generation number, they find the lowest total penalty cost among the generations and display this result as the best solution for the optimization problem. By making additional runs, the code gives alternative results which are potential near optimal results. There is not a certain limit of additional runs. It depends on time and the performance of the developed model. The mechanism of the developed programs is shown through a flowchart in Figure 3.5.

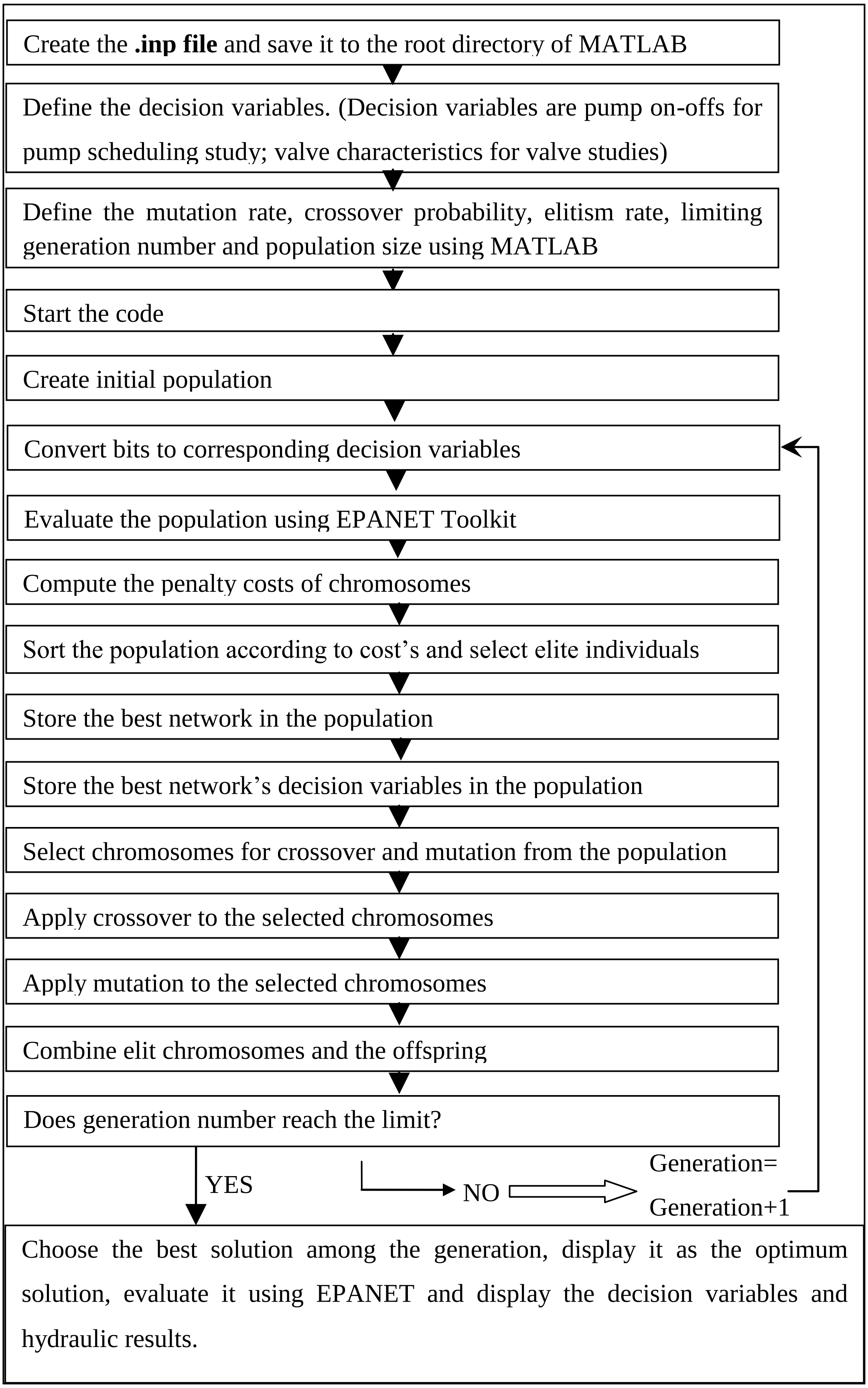


Figure 3.5. Detailed Flowchart of the Optimization Processes

3.3 Solution Methodology of Pump Scheduling

3.3.1 Objective Function and Constraints

The pump scheduling optimality process shall result in the lowest operating cost for a given set of boundary and system constraints. This optimality procedure mainly depends on the energy consumption costs resulting from pumping.

Energy consumption of a pump is dependent on the rate of pumping and the head supplied by the pump. The equation of energy consumption is given as follows;

$$E_{i,t} = \frac{Q_{i,t} \times h_{i,t} \times \gamma \times 10^{-3} \times t}{e_{i,t}} \tag{3.1}$$

Where;

$E_{i,t}$: Energy consumption of pump i during time interval t (kWh)

$Q_{i,t}$: Rate of pump i during time interval t (m^3/s)

$h_{i,t}$: Head supplied by pump i during time interval t (m)

$e_{i,t}$: Efficiency pump i during time interval t (%)

γ: Specific weight of water (N/m^3)

t: Time interval of pumping (h)

As mentioned in Section 2.2.2 there is a nonlinear relationship between the pump rate and supplied head. The pump head and rate are correlated with each other and the values of them are determined by the simulation model. The head discharge curves of big and small pump are given in Figure 4.4 and Figure 4.5, respectively.

The energy cost minimization objective function and the basic constraints are given below. The basic constraints are the hydraulic necessities of the network such as tank volume and node pressure boundaries.

$$\text{Minimize } Z = \sum_{i=1}^{N_p} \sum_{t=0}^{N_t} \left(E_{i,t} \times C_t\right) \tag{3.2}$$

Subject to;

$$\mathrm{P_{t,j}} \geq \mathrm{P_{min}} \tag{3.3}$$

$$\mathrm{P_{t,j}} \leq \mathrm{P_{max}} \tag{3.4}$$

$$\mathrm{V_t} \geq \mathrm{V_{min}} \tag{3.5}$$

$$\mathrm{V_t} \leq \mathrm{V_{max}} \tag{3.6}$$

Where;

N_p:	Number of pumps
N_t:	Number of time steps
$E_{i,t}$:	Energy consumption of pump i during time step t (kWh)
C_t:	Unit energy cost during time step t (TL/kWh)
V_t:	Volume of tank at time t (m^3)
V_{min}, V_{max}:	Minimum and maximum volumes of tank (m^3)
$P_{t,j}$:	Hydraulic pressure of node j at time t (m)
P_{min}, P_{max}:	Minimum and maximum node pressure limits (m)

The C vector contains the electricity prices per time steps through the run time duration. The electricity prices may hourly variable in the market and may also vary depending on the type of consumer. In such a case, C vector shall contain hourly prices per unit energy. However, in this thesis study, electricity price is considered to be constant during the day. For this study, run time duration is taken as maximum 24 hours. Through the upcoming studies, varying run time durations are also applied.

Besides the mentioned fundamental constraints, additional constraints are included in the optimization study such as tank volume deficit and pump switches.

3.3.1.1 Tank Volume Deficit

While trying to minimize the energy costs of pumping, the trivial solution is to switch off all the pumps. If network can be fed by tank (eg. N8-3 network) and if the capacity of tank is big enough to feed the network during run time duration, there is no need for pumps to run. In this case, it is obvious that the tank will be emptied. Since this is not an acceptable situation for water supply security of the network, periodicity of the volume at the water tanks shall be maintained. To supply this balance, the volume of the tank at the end of scheduling duration shall not be either lower or higher than the initial level. The ideal form is the equality of the final and initial volumes for the scheduling duration; however it may not be completely possible to equalize the volumes. This constraint is inserted to the objective function using penalization methods. The formulization of this constraint can be shown as follows;

$$V_0 - V_t \leq V_{tol} \qquad (3.7)$$

Where;

V_0: Initial volume of tank

V_t: Volume of tank at time t

V_{tol}: Tolerance for volume deficit

t: Run time duration.

3.3.1.2 Pump Switches

Besides the node pressure and tank volume deficit constraints, excessive number of pump switches are tried to be avoided. Lansey and Awumah (1994) defined pump switch as “turning on a pump that was not operating in the previous period”. In this thesis study, this term is redefined as “changing the operational status of pump” including the switch off for the pump. Thus, number of pump switches indicates the number of on-off changes of each pump during the run time duration. For example, for a pump making one start and one stop during 24 hours, the number of pump switches becomes 2.

Pumps are the major equipments of the pumping systems and the most vulnerable also. In pump scheduling point of view, a schedule turning pumps on and off many times may reduce energy costs. However, concerning schedule may increase the wear on the pumps which leads pump maintenance costs which is hard to be quantified (Lansey and Awumah, 1994). Moreover, frequent switching may lead pressure surges throughout the network which increases maintenance costs of pipes also (López-Ibáñez et al., 2011). Due to these reasons, pump switch constraint is implemented into the optimization problem as a constraint. This constraint can be mentioned as follows;

$$N_P \times N_{s,i} \leq \ N_P \times m_{ps} \tag{3.8}$$

Where;

$N_{s,i}$: Number of switches for pump i

N_P: Number of pumps

m_{ps}: Maximum allowed number of switch for single pump

In the formulation of this constraint, the term m_{ps} is a constant value. If a pump starts, runs for a continuous period, then stops during the run time duration, the number of switch (N_s) becomes 2. If the pump is in on or off position during the run time duration, N_s will be equal to 0. To keep the number of pump switches as low as possible, the m_{ps} could be given as 0. However, it will result in violations; since there should be some switches. The balance of this constraint is reflected to the objective function using penalization method. This constraint supplies an overall limitation to the total number of switches for pumps; there is no separate limit for each pump to switch on & off.

3.3.2 Penalty Methods

In order to weigh all constraints into the objective function, relevant penalty functions are used for each constraint. Besides the main objective of energy cost minimization, penalty functions are embedded in the optimization to cast all penalizations into one single equation. These penalty functions are discussed in the following sections.

3.3.2.1 Nodal Pressure Constraint

As briefly described in Section 3.3.1, the nodal pressures that are out of the boundary limits are penalized. For this penalization, conditional penalty functions are used. The representation of penalty functions is given below.

$$P_{np} = \sum_{i=1}^{n} \begin{bmatrix} (P_{min} - P_i)^2 \times C_{np} & \text{if } P_i \leq 0 \\ (P_{min} - P_i) \times C_{np} & \text{if } 0 < P_i < P_{min} \\ 0 & \text{if } P_{min} \leq P_i \leq P_{max} \\ (P_i - P_{max}) \times C_{np} & \text{if } P_{max} < P_i \end{bmatrix} \tag{3.9}$$

Where;

P_{np}: Node pressure penalty

P_i: Pressure of node i (m)

P_{min}: Minimum allowed pressure (m)

P_{max}: Maximum allowed pressure (m)

C_{np}: Node pressure penalty constant

n: Number of nodes

For this penalty function, minimum and maximum allowed node pressures are selected as 30 m and 80 m respectively. The penalty constant term, C_{np} is selected as 1 by trial and error.

3.3.2.2 Tank Volume Constraints

Tank volume penalizations may basically divided into two. First penalization considers the minimum and maximum volume violations while the second penalized tank volume deficit for the run time duration.

In this study, the minimum and maximum tank volumes are set to constant values while building the network simulation model. By setting these values, these constraints are removed from the penalization methods. This shall not be considered as a simplification, since the characteristics of tanks such as minimum and maximum levels have to be set while modeling the network.

The second penalization of tank volume is the deficit. The need for this penalty is discussed in Section 3.3.1.1. As mentioned in Section 4.2., water tank of N8-3 (T53) is a rectangular reservoir with constant cross section. Thus, the volume has a linear relationship with the water level in the tank. For convenience, the volume deficit constraint is formulated using the water levels of the tank.

For this constraint, through the run time duration the imbalance between initial and final tank volumes, greater than the deficit tolerance (V_{tol}) is penalized linearly proportional to the absolute value of difference. In this study, the tolerance of imbalance is set to zero. This means the perfect balance is aimed. However, perfectly equal initial and final levels are hard to achieve. Thus, when evaluating the applicability of the results of several trials, the alternatives having almost equal water levels and slight positive difference (final volume greater than initial) are considered as applicable solutions. The penalty function of tank volume deficit constraint is shown below.

$$P_{tv} = \sum_{i=1}^{n} abs(\mathrm{WL}_{\mathrm{E,i}} - \mathrm{WL}_{\mathrm{S,i}}) \times C_{tp} \quad (3.10)$$

Where,

P_{tv}: Tank volume deficit penalty

C_{tp}: Tank volume deficit penalty constant

$WL_{E,i}$: Water level of tank i at the end of run time duration (m)

$WL_{S,i}$,: Water level of tank i at the start of run time duration (m)

n: Number of tanks

The C_{tp} term is a constant value that is dependent on the penalty function. This value is chosen as 10^5 by trial and error. This number may sound huge when compared to the other penalty constant terms. As described above, the water levels are measured in meters. Thus, the difference between the final and initial levels is measured in meters too. For example, the level deficit of 1 mm (10^{-3} m) gives the penalty 100 units. While searching for zero volume deficit, the difference between water levels drops below the mm units. Consequently, while working with that much small values, multiplication factor (penalty constant term) must be large enough.

3.3.2.3 Pump Switch Constraint

As discussed in Section 3.3.1.2, every switch on-off means wearing of pumps, causing higher maintenance costs and most probably shorter economic life. For these reasons, to make the program discourage changing the status of pumps, pump switch penalization is introduced using the penalty function given below.

$$P_{ps} = C_{ps} \times \sum_{i=1}^{n} \mathrm{SC_i} \qquad (3.11)$$

Where,

P_{ps}: Pump switch penalty

C_{ps}: Pump switch penalty constant

SC_i: Number of status change for pump i

n: Number of pumps

The C_{ps} term is a constant value that is dependent on the penalty function. This value is chosen as 10^2 by trial and error. If one pump, switches on and off once (2 switches) during the run time duration, the penalty of switches becomes 200 units per pump.

3.3.3 Modified Form of Objective Function

The objective function given in Section 3.3.1 does not include the constraints inside. However, in this study, to use this objective in genetic algorithms, the main objective and the penalizations are cast into a single equation. This modified form of the objective function includes all penalty functions which are defined in Section 3.3.2. The modified form of the objective function is given below. This equation is the core of the pump scheduling optimization algorithm.

$$Min.Z = \sum_{i=1}^{N_p}\sum_{t=0}^{N_t}\left(E_{i,t} \times C_t\right) + P_{np} + P_{tv} + P_{ps} \tag{3.12}$$

Where;

N_p:	Number of pumps
N_t:	Number of time steps (run duration)
$E_{i,t}$:	Energy consumption of pump i during time interval t (kWh)
C_t:	Unit energy cost during time interval t (TL/kWh)
P_{np}:	Node pressure penalty
P_{tv}:	Tank volume deficit penalty
P_{ps}:	Pump switch penalty

3.3.4 Chromosome Representation of Pump Schedules

In this study, for the pump schedule optimization, binary representations based on time controlled triggers are used for each pump. The decision variables are the status of pumps (on/off) per time step. The schedule of each pump, compose the chromosome of the genetic algorithms. Since the representation is based on time controls; the length of the chromosome depends on the time step and run time duration. Chromosome representation of a pump schedule for varying number of pumps is shown in Figure 3.6.

t_{i0}	t_{i1}	t_{i2}	t_{i3}	t_{i4}	…	t_{if}	t_{i0}	t_{i1}	t_{i2}	t_{i3}	t_{i4}	…	t_{if}
1	1	0	0	0	…	1	0	0	1	1	0	…	0
			Pump i			i=1, 2, ...				Pump i			

Figure 3.6. Chromosome Representation of a Pump Schedule

As can be seen from Figure 3.6, status of pump in each time interval is indicated with “0” or “1”. In this string, “0” means pump is closed, where “1” means pump is in operation through corresponding time interval. The letter “i" indicates the number of pumps and the letter “f” indicates the final step of run time interval. For example, if the run time interval is selected as 24 hours; when the time step is chosen as 1 hour, the string length for each pump becomes 24. If there are 2 pumps in operation, the length of the chromosome becomes 48.

3.4 Solution Methodology of Valve Locating and Opening Determination

As mentioned in Chapter 1, pressure minimization is one of the effective methods for leakage minimization; operation of isolation valves is one of the efficient methods to reduce nodal pressures. Thus, the aim of valve operation studies can be stated as creating approximate pressure decrements at the demand nodes.

For this aim, many types of valves may be applicable. In this study, the isolation valves are considered due to their widespread use among the water distribution networks. Isolation valve may be defined as the most common type of valve in water distribution systems which can be manually closed to block off the flow (Walski, 2003). As the definition implies, these valves are supposed to be left open through normal process. However, in case of need; they could be kept closed or stay in partial open position. Therefore, pressure minimization problem should consider completely open, partially open or completely closed valve statuses.

In a water distribution network, it is obvious that some valves should be in fully open position. These valves could be considered as the ones, located on the main water transmission lines or on the branches to isolated district metered areas. These valves may be changed to closed status, in case of emergency or maintenance. However, the rest of valves may have fully open, partially open or closed status. In order not to define all valves having capability of all positions; the valve operation methodology is divided into two steps. These are (i) valve locating and (ii) valve opening determination studies. The valve location study is also divided into two sub-steps depending on the simulation times; (i_i) steady state (SS) and (i_{ii}) extended period simulation (EPS).

(i) For valve locating study, status of valves are considered to be open or closed. Thus, the decision variables of GAs are the status of valves. First, the developed program (VOGA) is applied in steady state using both minimum and maximum hour demand loadings. By evaluating the results, closure percentages of each valve is obtained, and the valves are grouped by 5% closure percentage intervals. Using these groups, VOGA is applied to network in extended period simulation. At the end of both SS and EPS studies, the group of closed valves which gives the maximum pressure decrement is found. In addition to closed ones; the valves that shall be left open are also determined.

(ii) After obtaining the valve groups with unchanged status (left open or closed) at valve locating step; valve opening determination study is applied. In this step, the closed valves of previous study (valve locating) are kept closed while partial openings are searched for the rest. Since the isolation valves do not have capability of partial opening in network simulation point of view, they are modeled as Throttle Control Valves (TCVs). In this step, the decision variables of GAs are the openings of valves.

Following these steps, the valve locating and opening determination studies are completed. The flowchart of these valve operation studies is shown in Figure 3.7.

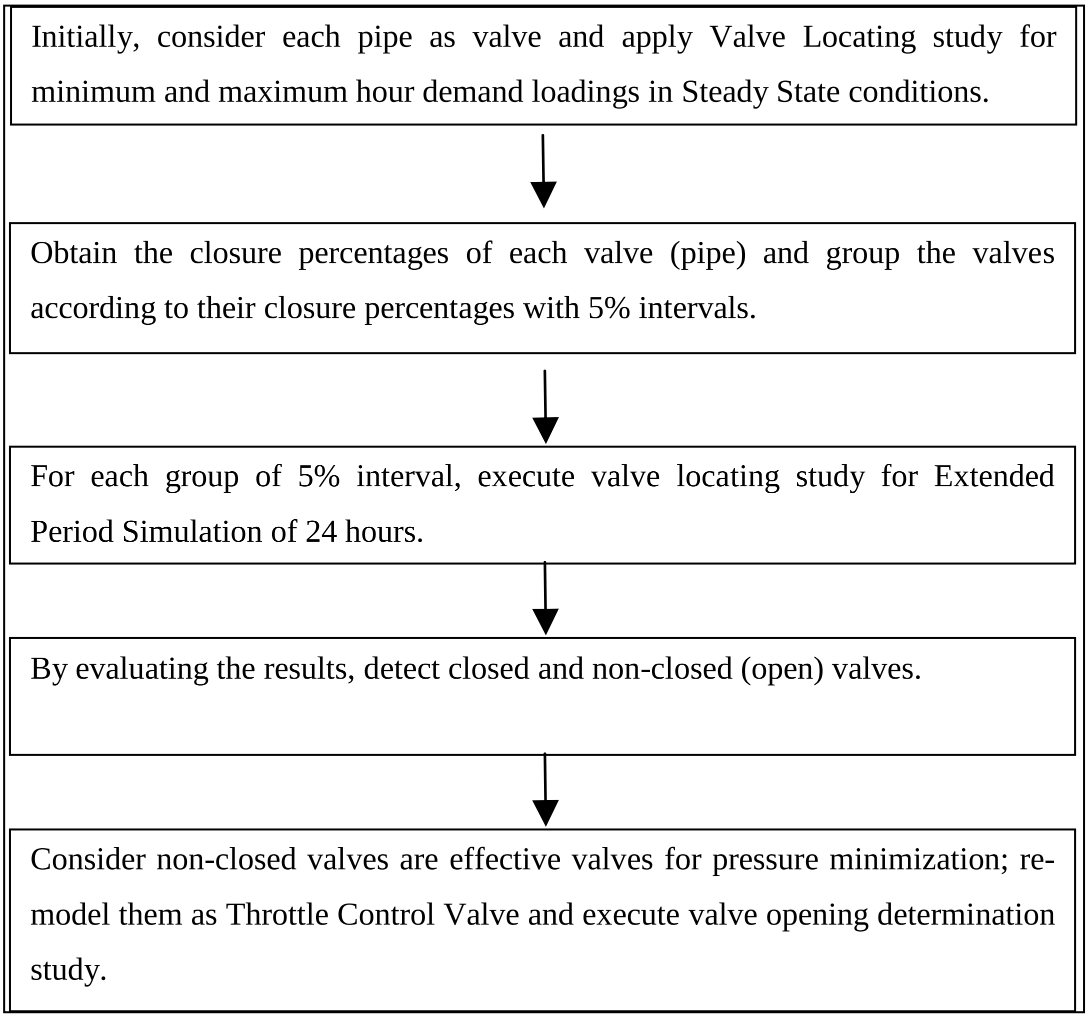


Figure 3.7. Flowchart of Valve Operation Methodology

3.4.1 Objective Function and Constraints

As previously mentioned, the objective of the problem is to minimize the excess nodal pressures in the network. The objective function can be formulated as follows;

$$Minimize\ Z = \sum_{i=1}^{N_n} Pe_i \tag{3.13}$$

Subject to;

$$P_{t,i} \geq P_{min} \quad (3.14)$$

Where;

N_n: Number of demand nodes

Pe_i: Excess pressure head at the i^{th} Node (m)

$P_{t,i}$: Hydraulic pressure head of node i at time t (m)

P_{min}: Minimum node pressure head limit (m)

Excess pressure, Pe_i is a measure taken from the results of hydraulic simulation and is calculated as follows for each node;

$$Pe_i = \begin{bmatrix} 0 & \text{if } P_i \leq P_{max} \\ (P_i - P_{max}) \times C_{ep} & \text{if } P_{max} < P_i \end{bmatrix} \quad (3.15)$$

Where;

P_i: Pressure head of node i (m)

P_{max}: Maximum node pressure head limit (m)

C_{ep}: Excess node pressure penalty constant

In this study, maximum node pressure head limit (P_{max}) is selected as 80 m. Consequently, the nodal pressures above 80 m are considered to be excessive.

Besides the mentioned fundamental constraint, an additional constraint is included in the optimization study to limit the number of operating valves.

3.4.1.1 Limit for Valve Operations

While the main objective is to minimize excess pressure, number of operative valves is also desired to be kept at low levels. Since isolation valves are manually controlled valves, each valve operation is associated with an operational cost. If this operations (on-off) are considered to be continuous during 24 hour; it becomes a non practical task for authorities as the number of valve operation reaches high levels. Consequently, minimizing the excess pressures by employing as low number of valves as possible is favorable.

For this reason, besides the main pressure minimization objective, a valve operation limiting constraint is included in the optimization problem. This constraint is introduced to the developed optimization model in valve locating step. The formulation of the constraint differs for steady state (SS) and extended period simulation (EPS) conditions of the methodology.

3.4.2 Penalization Methods

3.4.2.1 Nodal Pressure Constraint

Similar to the pump scheduling optimization problem, the nodal pressures that are out of the lower boundary limits are penalized for valve operation study. For this penalization, conditional penalty functions are used. The representation of penalty functions is given below.

$$P_{np} = \sum_{i=1}^{n} \begin{bmatrix} (P_{min} - P_i)^2 \times C_{np} & \text{if } P_i \leq 0 \\ (P_{min} - P_i) \times C_{np} & \text{if } 0 < P_i < P_{min} \\ 0 & \text{if } P_{min} \leq P_i \end{bmatrix} \quad (3.16)$$

Where;

P_{np}: Node pressure penalty

P_i: Pressure of node i (m)

P_{min}: Minimum allowed pressure (m)

C_{np}: Node pressure penalty constant

n: Number of nodes

For this penalty function, minimum allowed node pressure (P_{min}) is selected to be 30 m. The penalty constant term, C_{np} is selected as 10^0 by trial and error.

3.4.2.2 Valve Operation Limit

As discussed in Section 3.4.1.1, the formulation of this penalization differs for SS and EPS conditions. For valve locating studies in SS condition, all pipes are regarded as a potential valve location. If the pipe is selected to be closed, this means to place a valve on this pipe or operate the valve if it is already installed. If the pipe selected to be open, there is no need for valve placement or operation. Thus, to limit the number of valve operations; first, number of valve locations are penalized in SS condition. The mentioned penalty function is given below.

$$P_{vl} = C_{vl} \times N_{vl} \tag{3.17}$$

Where,

P_{vl}: Penalty for number of valve locations for SS conditions

C_{vl}: Penalty constant for number of valve locations

N_{vl}: Number of located valves

The C_{vl} term is a constant value that is dependent on the formulation of penalty function. This value is chosen as 10 by trial and error. For each valve, the network is penalized by 10 units.

In EPS conditions, the number of valves is set depending on the closure percentage intervals which are the outcomes of SS studies. Thus, locations of valves are considered to be constant. However, in EPS conditions, if a valve is set to be closed for 24 hour duration, this means that this valve is not necessary to be located, or operated. Consequently, an extra penalization to limit the number of valve operations is needed for EPS conditions. In this case, any valve which is open in any time step of simulation duration is penalized. The mentioned penalty function is shown below.

$$P_{vo} = C_{vo} \times \sum_{i=1}^{n} Vo_i \tag{3.18}$$

Where,

P_{vo}: Penalty for valve operation for EPS conditions

C_{vo}: Penalty constant for number of valve operation

Vo_i: Number of open time steps for valve i during run time duration

n: Number of Valves

The C_{vo} term is a constant value that is dependent on the penalty function. This value is chosen as 0.417 (10/24=0.417) by trial and error. For each open valve, the network is penalized by 0.417 units per time step.

3.4.3 Modified Form of Objective Function

The objective function given in Section 3.4.1 does not include the constraints. However, in this study, to use this objective in GAs, the main objective and the penalizations are cast into a single equation. This modified form of the objective function includes all penalty functions which are defined in Section 3.4.2. The modified form of the objective function is given below for SS and EPS conditions respectively.

$$Min.Z = \sum_{i=1}^{N_n} Pe_i + P_{np} + P_{vl} \quad for\ SS\ conditions \tag{3.19}$$

$$Min.Z = \sum_{i=1}^{N_n} Pe_i + P_{np} + P_{vo} \quad for\ EPS\ conditions \tag{3.20}$$

3.4.4 Chromosome Representation of Valve Locations

To mention the valve locations, binary representations based on time controlled triggers are used for each possible valve (pipe). The decision variables are the status of valves (on/off) per time step. Since the representation is based on time controls; the length of the chromosome depends on the time step and run time duration. For SS condition, chromosome indicates the whole network where any valve has binary code. Whereas for EPS condition; chromosome indicates one valve for each time interval. Chromosome representations of valve locations are shown in Figure 3.8 and Figure 3.9 for SS and EPS conditions, respectively.

v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	…	v_{n-2}	v_{n-1}	v_n
1	0	0	1	0	…	1	0	…	0	1	1

Figure 3.8. Chromosome Representation of Valve Locations (SS Condition)

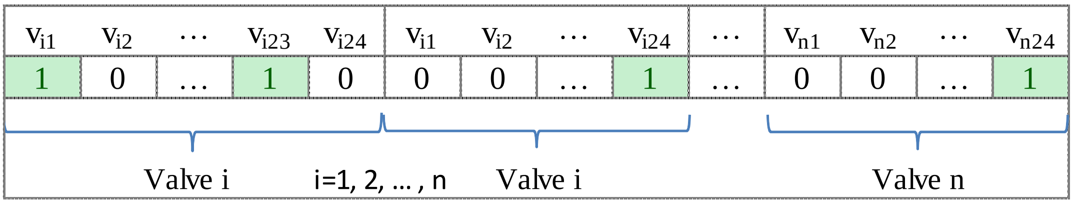


Figure 3.9. Chromosome Representation of Valve Locations (EPS Condition)

As can be seen from Figure 3.8 and Figure 3.9, location of valve is mentioned with “0” or “1”. For both SS and EPS conditions, “0” means pipe is closed (valve is located) where “1” means pipe is open (no valve needed). In the chromosome of EPS condition, letter “i" and “n” indicates the counting number of valve and total number of valves, respectively. For SS and EPS conditions, the length of chromosomes varies. In case of considering same number of valves, chromosome length of EPS study is 24 times SS study.

CHAPTER 4

CASE STUDY NETWORK

Throughout this study, N8-3 pressure zone of the Northern Supply of Ankara Water Distribution network is examined for both pump scheduling optimization and valve locating and opening determination studies. N8-3 network is located in Keçiören and Yenimahalle, Ankara. This pressure zone serves about 40,000 people living in these districts.

N8-3 network consists of one pump station (P23), one rectangular storage tank with 5000 m^3 capacity (T53) and network pipes varying from 100 to 250 mm diameter with an approximate total length of 170 km covering an area of 210 hectares. There are 390 demand nodes and 481 pipes in the network model.

One main line with 500 mm ductile iron pipe conveys water from P23 to T53 and the other line with 300 mm ductile iron pipe feeds Yayla district located at the east side. General layout of N8-3 network is shown in Figure 4.1.

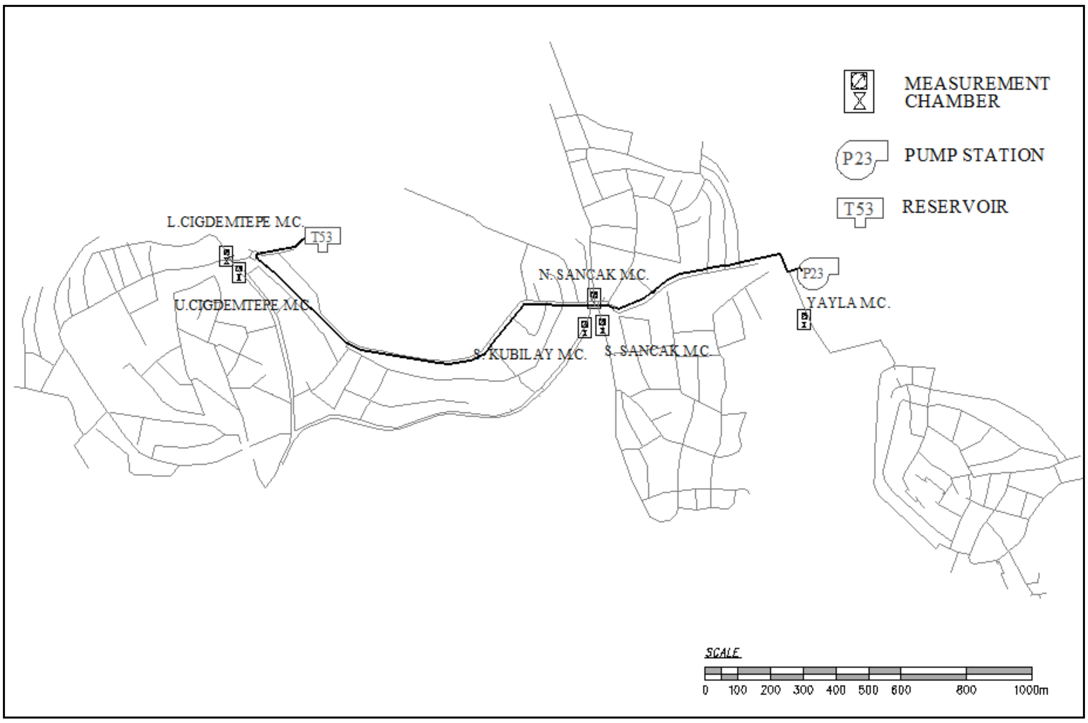


Figure 4.1. General Layout of N8-3 Network

The characteristic of topography varies among the N8-3 network. Maximum and minimum serving nodal elevations are 1152 m and 1048 m respectively. The topographical and pipe size representation of N8-3 network (Şendil, 2013) is shown in Figure 4.2 and Figure 4.3 respectively.

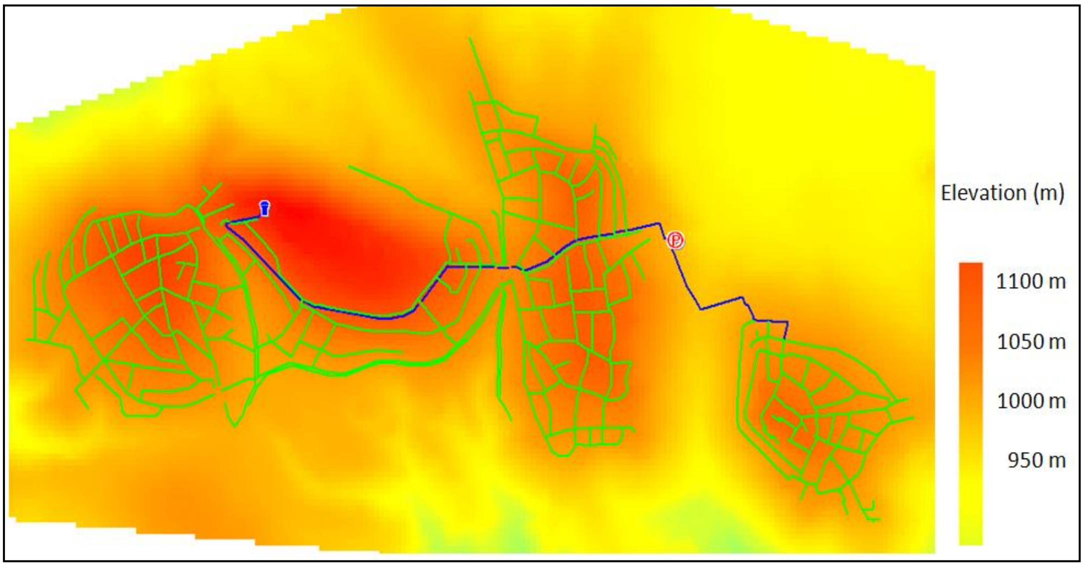


Figure 4.2. Topographical View of N8-3 Network

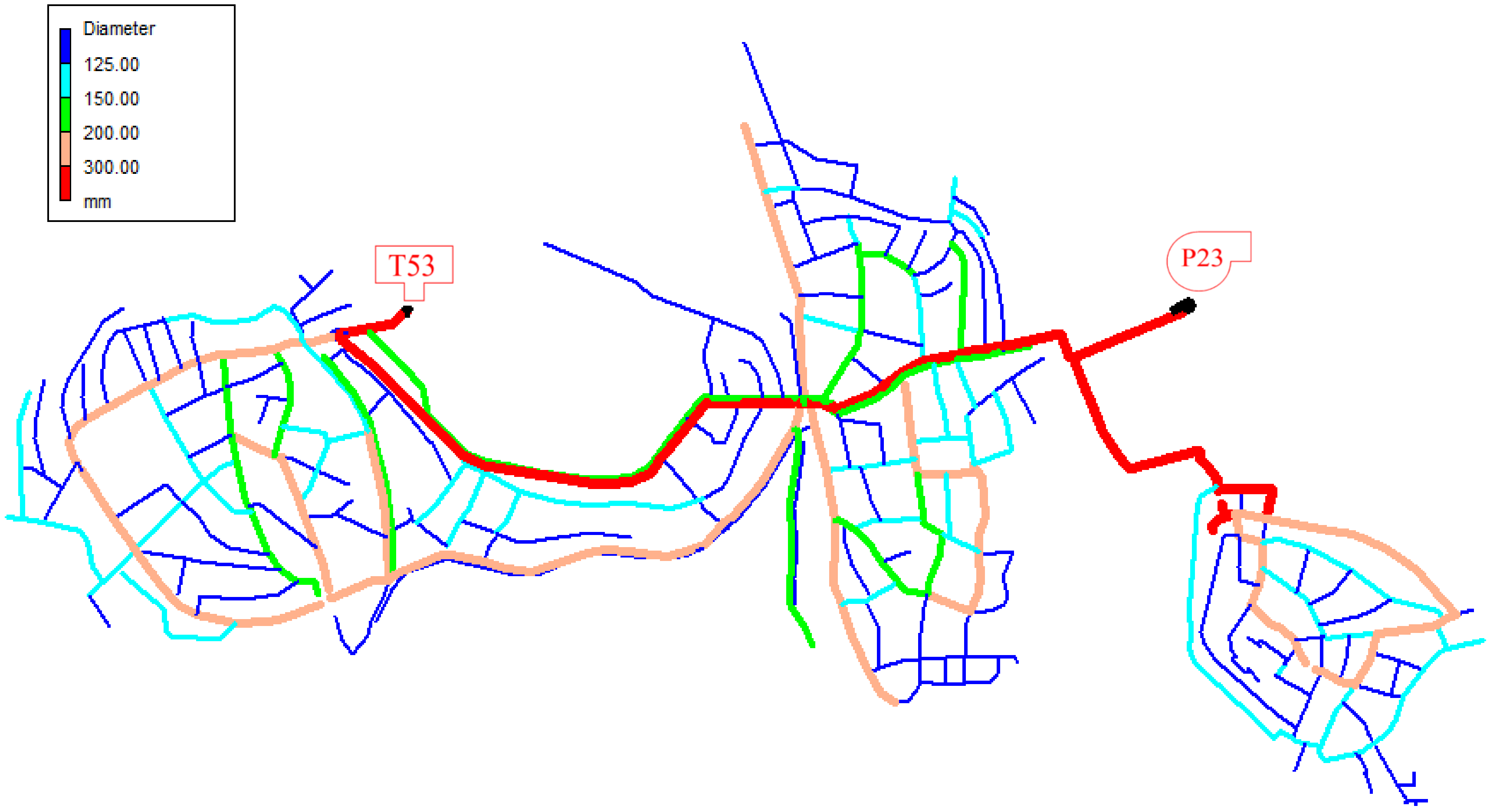


Figure 4.3. Pipe Size Representation of N8-3 Network

4.1 Pump Station (P23)

The pump station (P23) of N8-3 network includes 2 operative pumps. These pumps are mentioned as big pump and small pump in this study. The definition curves of big and small pumps of P23 are shown in Figure 4.4 and Figure 4.5 respectively.

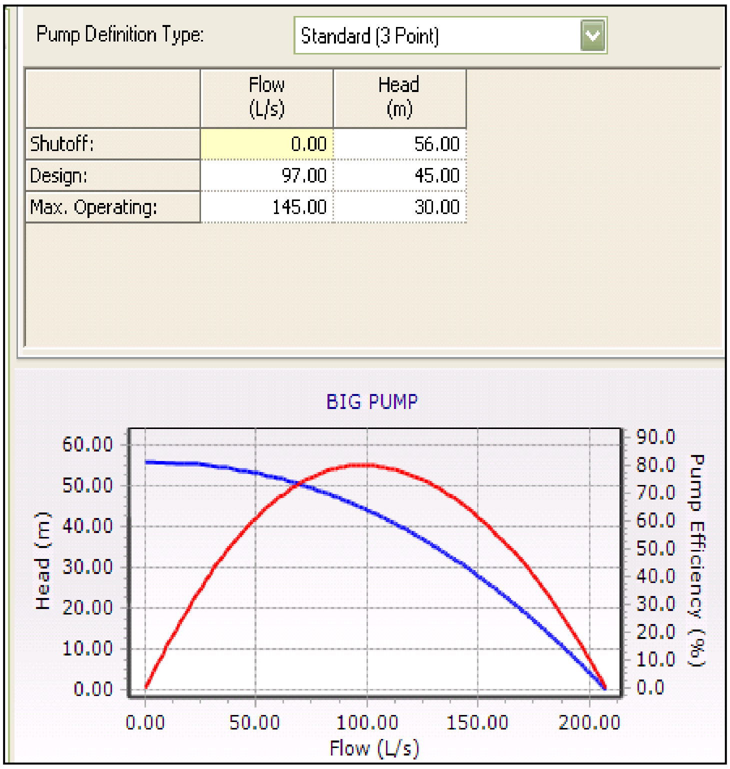


Figure 4.4. Definition Curve of Big Pump

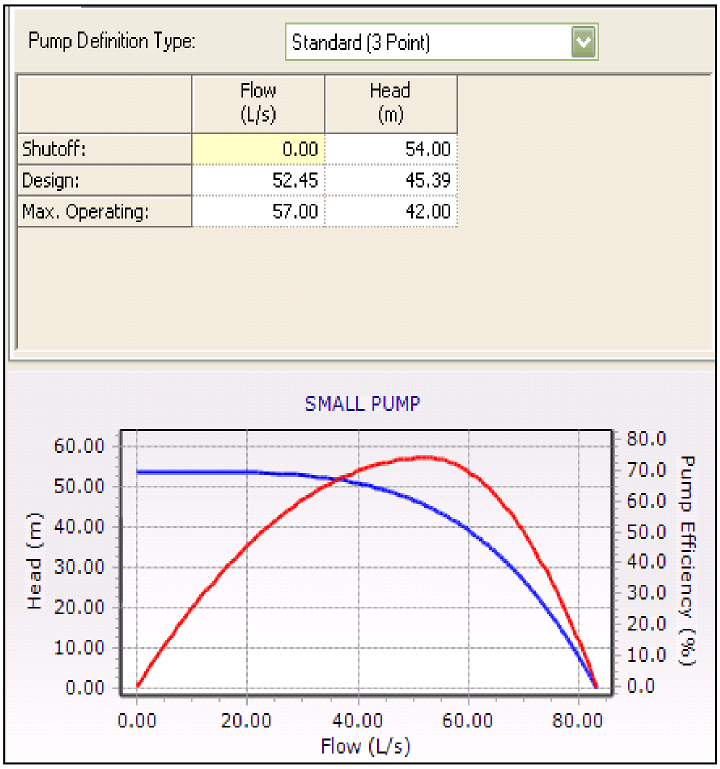


Figure 4.5. Definition Curve of Small Pump

In current situation, P23 pump station is being operated by ASKİ (Ankara Water and Sewage Authority) without considering any optimality policy for pump scheduling. While operating the pumps, only electricity tariff is being considered and pumps are run during hours of cheap electricity price and do not run for the rest of the day.

4.2 Storage Tank (T53)

N8-3 network includes one rectangular storage tank with total volume of 5000 m^3. Base elevation of T53 is 1151.58 m. The total water height in the tank is 5 meters. Out of this 5 m height; bottom 2.5 m is used for emergency purposes only. So, the remaining 2.50 m is considered to be the operative height. The initial water height in the tank is assumed to be 3.75 m which is equal to level of 1155.33 m.

4.3 District Metered Areas

N8-3 network consists of 6 District Metered Areas (DMAs) with different demand loadings. These are West Çiğdem, East Çiğdem, North Sancak, South Sancak, Şehit Kubilay and Yayla DMAs. Each DMA has an already installed measurement chamber at the connection pipe between the main supply line of N8-3. Thus, these measurement chambers may be considered as entrance nodes for each DMA. The flow rate passing from these measurement chambers has been measured. In this study, corresponding flow measurements are considered to be demand loadings for each DMA. By this simplification, the whole N8-3 network is changed to a skeleton that have single nodes for each DMA. This simplification needs remodeling of N8-3 network. For remodeling, pipes of all DMAs are removed and the flow rate measurements of DMAs are considered to be nodal daily demands for each DMA. For pump schedule optimization studies, this skeletonized form of N8-3 network is utilized. The skeletonized form and the district metered areas of the N8-3 network are shown in Figure 4.6 with its pipe size representation. The daily demands for each DMA and total demand of N8-3 network (Şendil, 2013) is given in Figure 4.7.

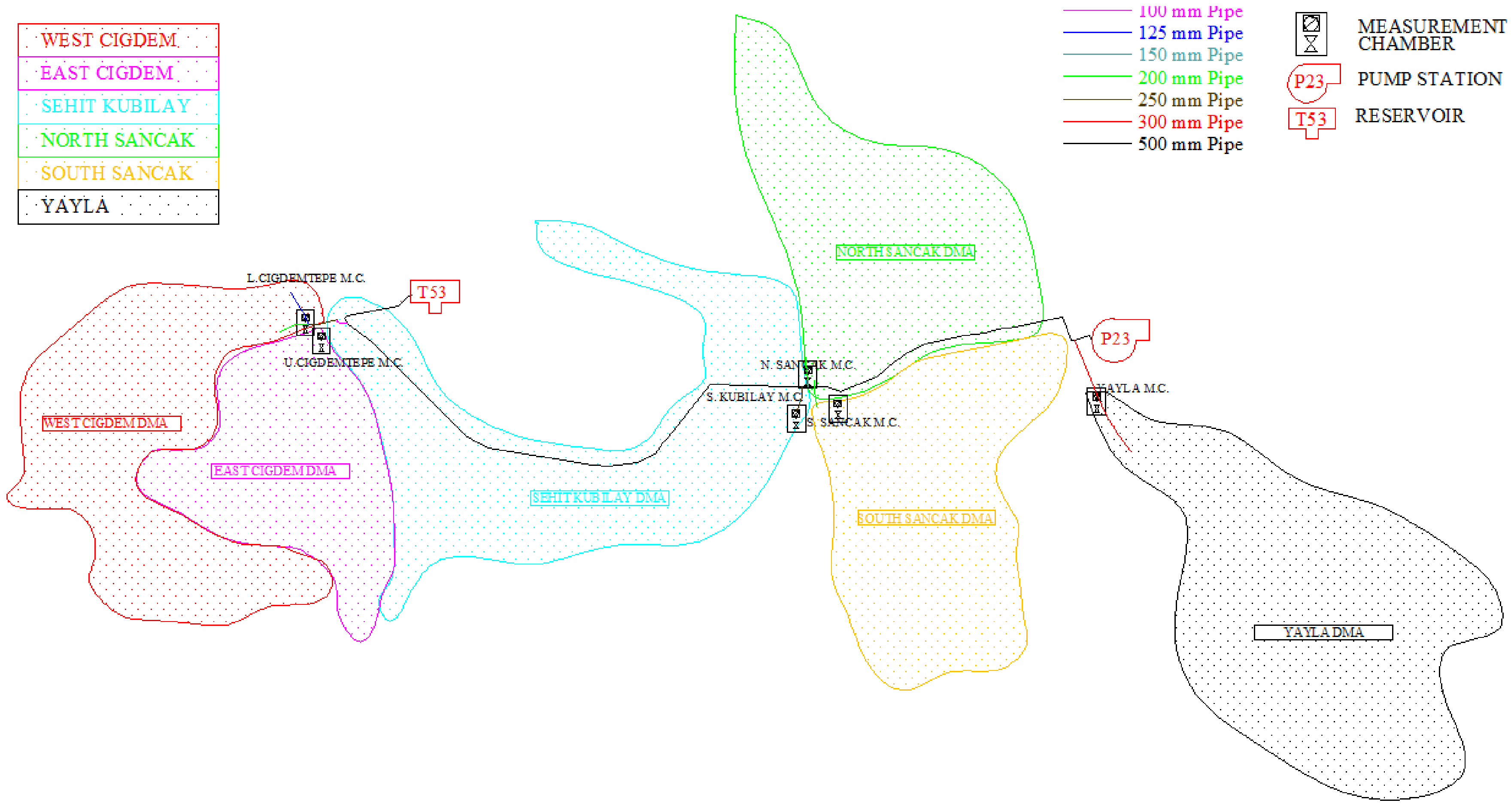


Figure 4.6. District Metered Areas and Skeletonized Form of N8-3 Network

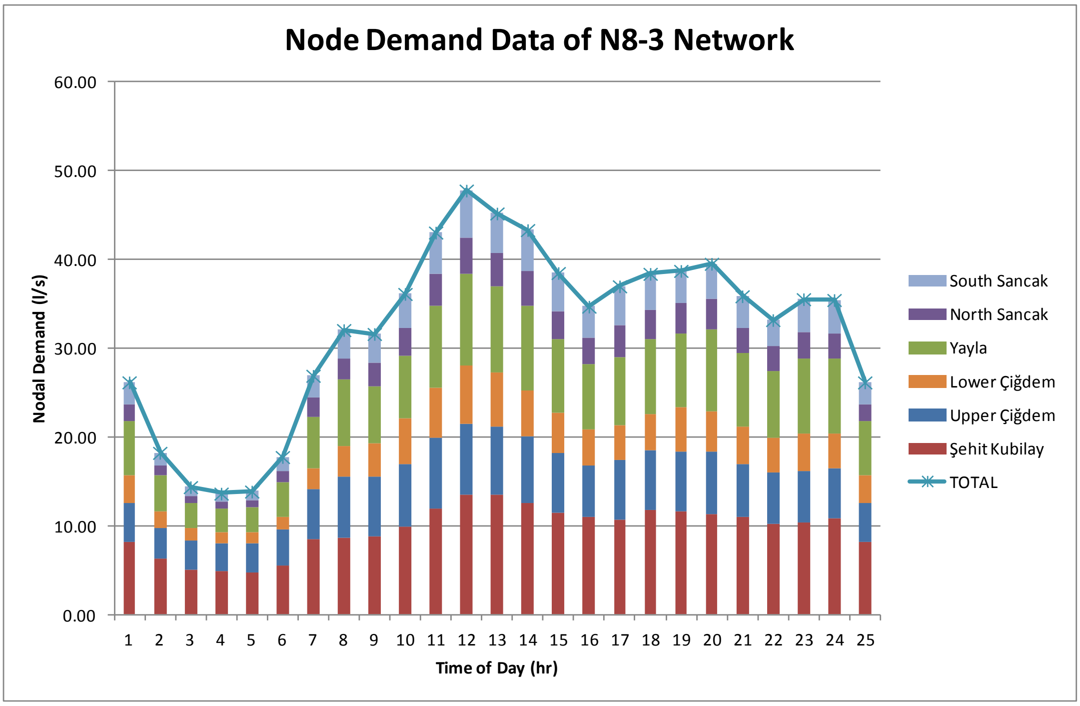


Figure 4.7. Nodal Demands of N8-3 with District Metered Areas

For valve locating and opening determination studies, networks of Yayla and East Çiğdemtepe DMAs are studied. Brief information, related with these networks is given in Sections 4.3.1 and 4.3.2, respectively.

4.3.1 Network of Yayla DMA

Yayla district is located at the east of N8-3 network. Yayla district is physically isolated from the main network. Yayla is the first DMA which the valve locating and valve opening determination studies are applied on. Yayla network consists of 107 pipes and 89 nodes, while there are no pumps installed on.

As briefly explained in Section 3.2, while separating the Yayla DMA from the main network, the measurement chamber node is converted to a supply reservoir with constant head. The source elevation is equalized to the average of the measurement chamber's node pressures which are calculated at the end of the pump scheduling study. The general layout of Yayla network is shown in Figure 4.8 with its pipe size representation.

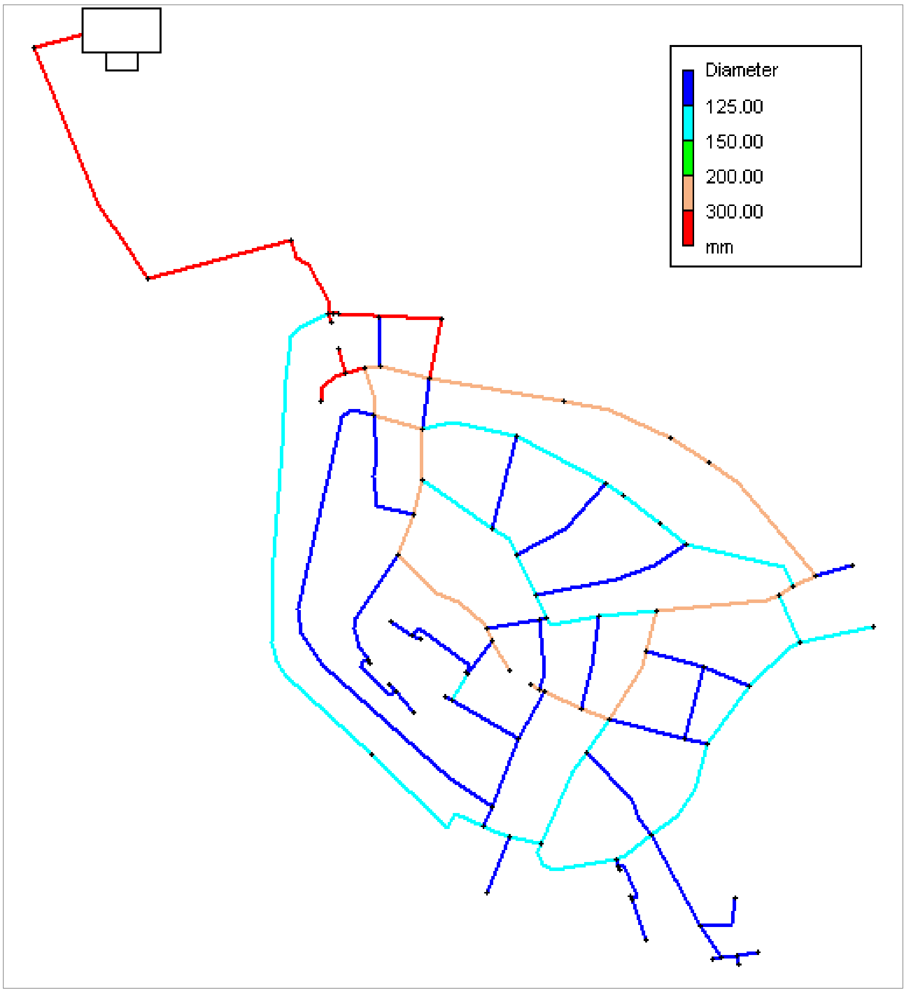


Figure 4.8 General View of Yayla Network

4.3.2 Network of East Çiğdemtepe DMA

East Çiğdemtepe district is located at the West of N8-3 network. East Çiğdemtepe network is the second DMA which is chosen to be studied on the valve subject. Similar to Yayla, while separating the DMA from the main network, the measurement chamber node is converted to a supply reservoir with constant head. The source elevation is equalized to the average of the measurement chamber's node pressures which are calculated at the end of the pump scheduling study.

East Çiğdemtepe network consists of 35 nodes and 46 pipes while there are no pumps installed. The general layout of East Çiğdemtepe network is shown in Figure 4.9 with its pipe size representation.

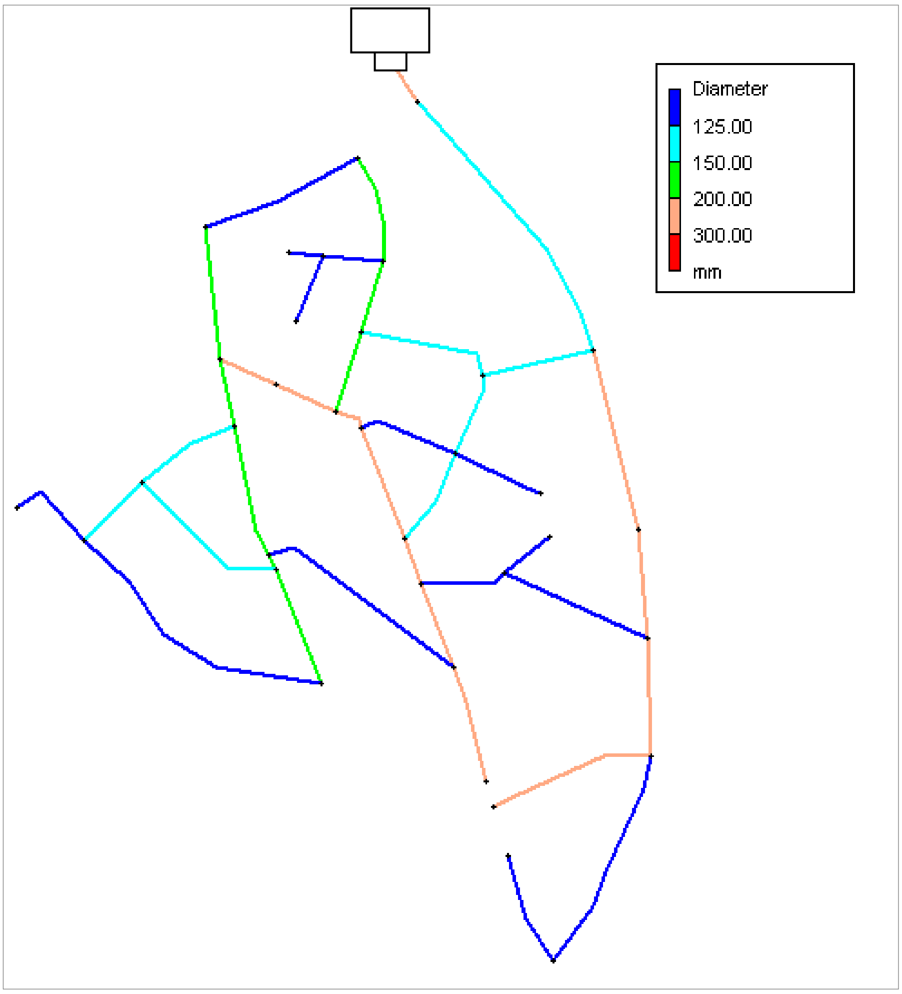


Figure 4.9. General View of East Çiğdemtepe Network

CHAPTER 5

PUMP SCHEDULING

In this chapter, pump scheduling studies on the skeletonized form of N8-3 are presented. The studies include the application of developed program POGA (Pump Optimization using Genetic Algorithms), for various scenarios of the network.

5.1 Application of the Model for 24 hr Period

As briefly explained in Section 3.2, for pump scheduling optimization, the program namely POGA is developed. The developed program is applied to the skeletonized form of N8-3 network with varying run time durations. The most common run time duration is 24 hour (1 day). Thus, the developed program is first applied on the case study network with 24 hour run time duration.

Using the defined objective function including the constraints, Genetic Algorithms (GAs) are applied to the optimization problem using constant electricity prices (C_t). Since the results of GAs depend on the initial population which is random; it is needed to run the optimization model several times. Among all results, the best 4 are kept while considering both tank volume deficit and energy usage results.

According to the results of computations, it can be seen that best schedules run each pump for single period of time through the day; in other words each pump, switches on and off once a day. For all results, depending on the running period of pumps, the tank water level oscillates but the levels at the beginning and end of the day become almost equal.

To verify if the results of GAs are reliable, partial enumeration technique is applied. Since, full enumeration means an excessive search space which is certainly inefficient, enumeration technique is limited with 4 pump switches only. In other words, for each pump to switch on and off once in 24 hr period, program is run for all circumstances and all results are obtained. Throughout the outcomes, the one having both least tank level difference and energy cost is accepted to be the best result for the problem. The summary and comparison of the results of GAs and Partial Enumeration (PE) can be seen in Table 5.1.

Table 5.1 Summary of Results of GAs and PE

	GA (1st Alternative)	GA (2nd Alternative)	GA (3rd Alternative)	GA (4th Alternative)	Partial Enumeration
Number of Pump Switches	4	4	6	8	4
Tank Level Difference (m)	<1E-03	0.0011	0.0012	0.0009	<1E-03
Energy Usage (kWh)	479.89	476.63	477.04	465.61	479.89

As can be seen from Table 5.1, the results of Partial Enumeration and the 1^{st} alternative solution of GAs are the same. This phenomenon verifies the developed GAs for the pump scheduling, gives reliable solutions and adds alternatives depending on the priorities of authorities.

Figure 5.1 shows the pump scheduling results and corresponding tank level oscillation of PE and GA (1^{st} alternative) while 2^{nd}, 3^{rd} and 4^{th} alternative solutions of GAs are shown in Figure 5.2, Figure 5.3 and Figure 5.4 respectively.

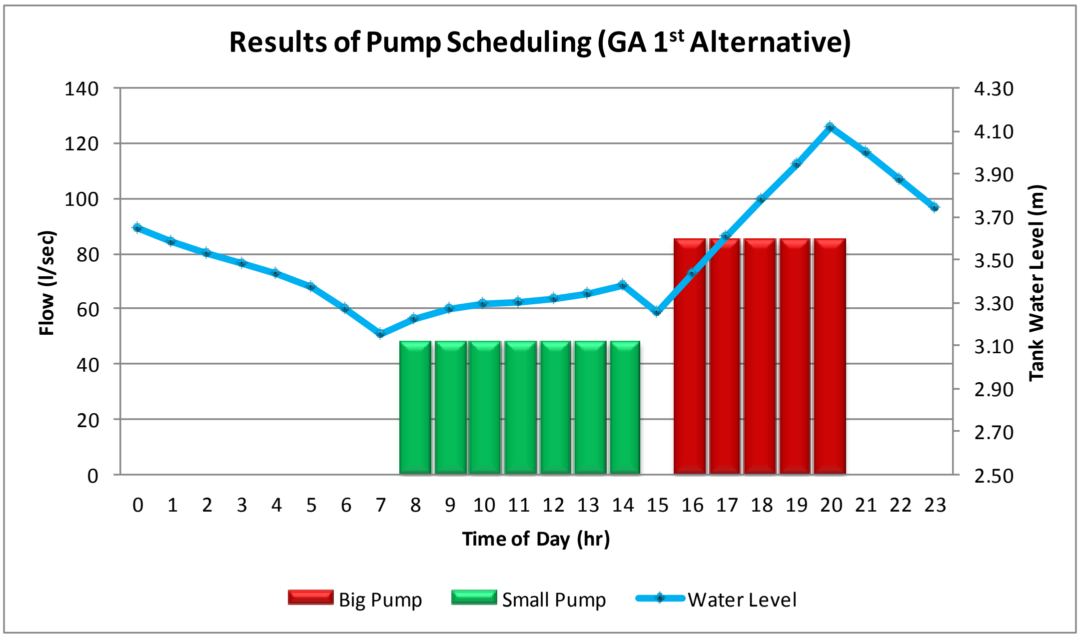


Figure 5.1. Pump Schedules and Tank Oscillations of PE and GA (1st Alt.)

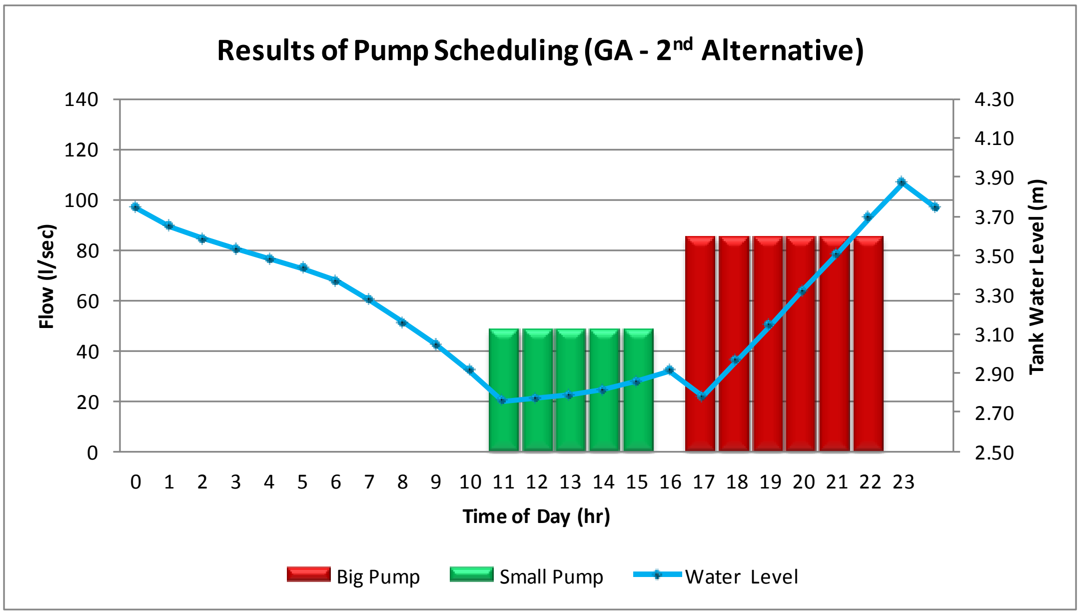


Figure 5.2. Pump Schedules and Tank Oscillations of GA (2nd Alternative)

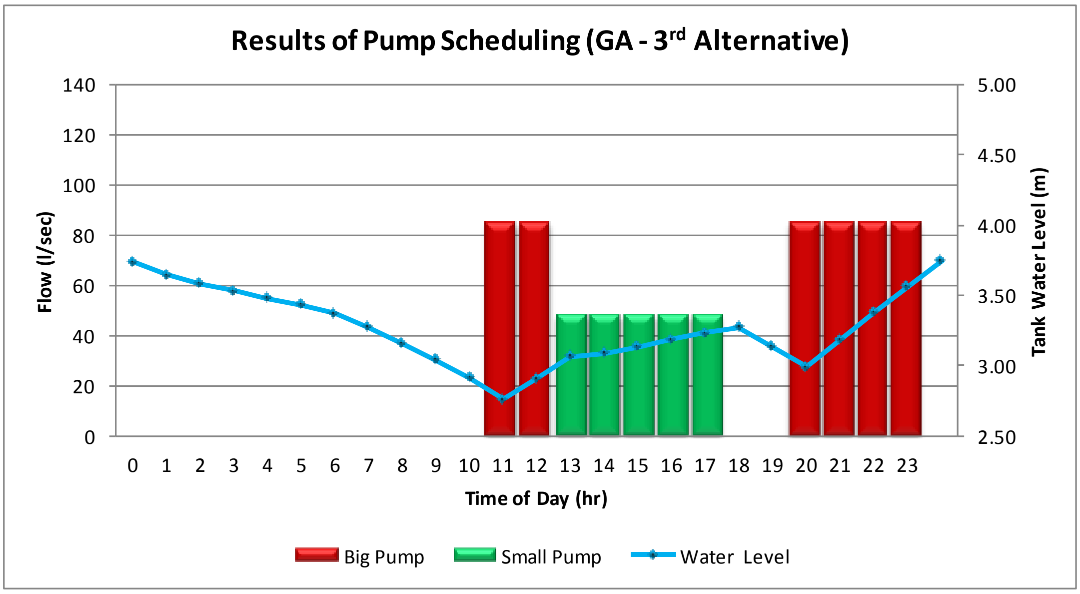


Figure 5.3. Pump Schedules and Tank Oscillations of GA (3rd Alternative)

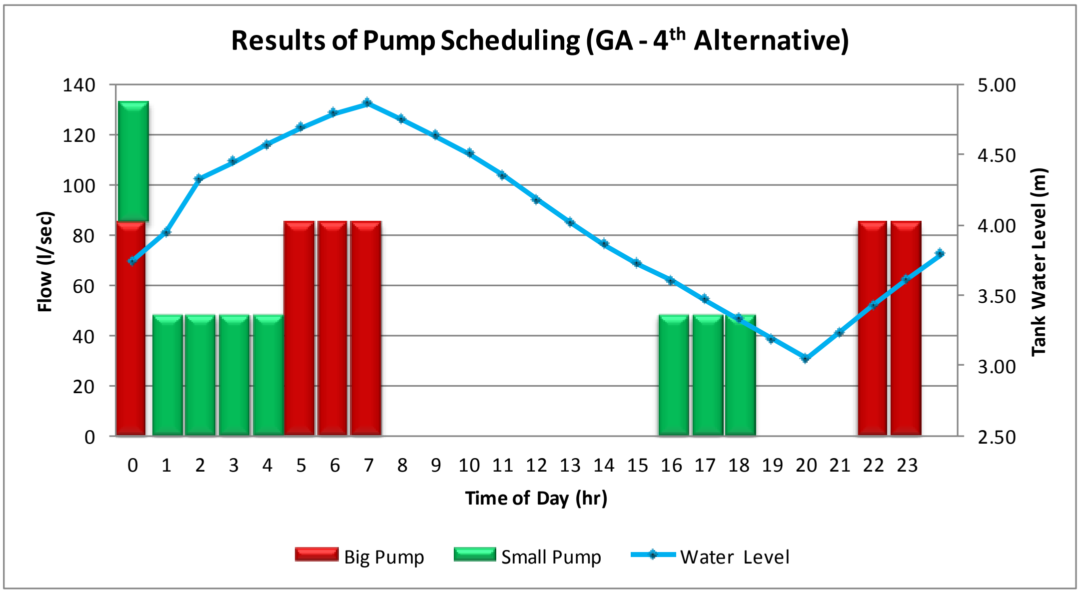


Figure 5.4. Pump Schedules and Tank Oscillations of GA (4th Alternative)

When pump schedules from Figure 5.1 to Figure 5.4 are investigated, it can be seen that all four near optimal results have very close energy consumptions but completely different pump schedules. First two schedules employ each pump once a day, while the big pump is switched on and off twice in the 3rd result. In all results, the tank volume deficit could be accepted as within the tolerable limit; that means the periodicity constraint is sustained.

5.2 Application of the Model for Varying Time Steps

After having proved that the model gives satisfactory results for 24 hour duration, the model is tested on varying time steps on the same network to see the response in terms of pump switches and tank level oscillations. For these studies the total duration is set to 24 hours, and the run time steps among the 24 hour duration are changed. These time steps (time periods) are chosen to be 2, 4, 6, 8, 12 and 24 hours. Since total duration is 24 hours, the time periods have to be divider of 24.

While running the program for these time periods, the same genetic operators are applied with the same objective function and constraints. For every time period, the tank level at the end is transferred to the next period as the initial tank level. Within the selected time period, it is aimed to minimize the energy consumption while trying to keep the initial and final tank levels close and make pump switches as low as possible.

After applying the optimization algorithms to network within, 2, 4, 6, 8, 12 and 24 hour time periods, the results giving the minimum energy consumption while keeping the tank level difference at the low rates are summarized in Table 5.2.

Table 5.2. Summary of Best Results for Each Time Period

Runtime Step	Tank Level Difference (m)	Energy Consumption (kWh)
2hr	0.0218	485.85
4hr	0.0014	483.39
6hr	0.0093	484.27
8hr	0.0085	484.09
12hr	0.0010	480.49
24hr	0.0009	479.89

As can be seen from Table 5.2, for 2 hr time durations, both tank level difference and energy consumption results are worse than other run time durations. And, as run time duration is lengthened, both the results of energy consumption and tank level difference become better. Using these outcomes of the algorithms; the tank level oscillations are drawn for each run time duration for 2 to 6 hrs, 8 to 24 hrs and to visualize all oscillations once; 2 to 24 hrs in Figure 5.5, Figure 5.6 and Figure 5.7 respectively.

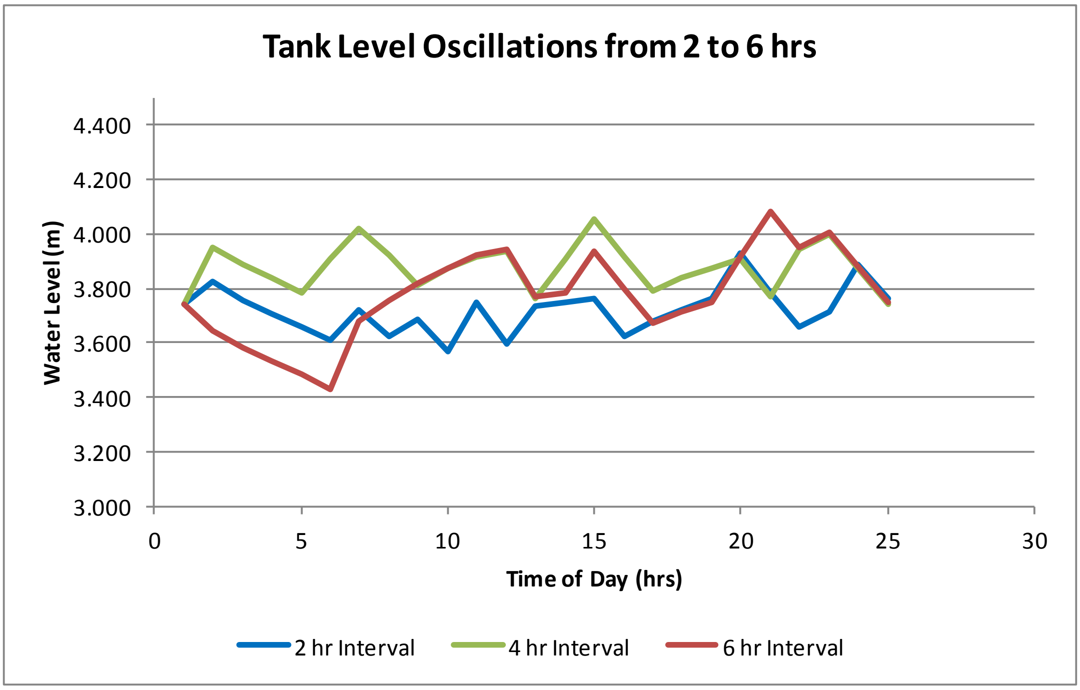


Figure 5.5. Tank Level Oscillations from 2 to 6 hrs

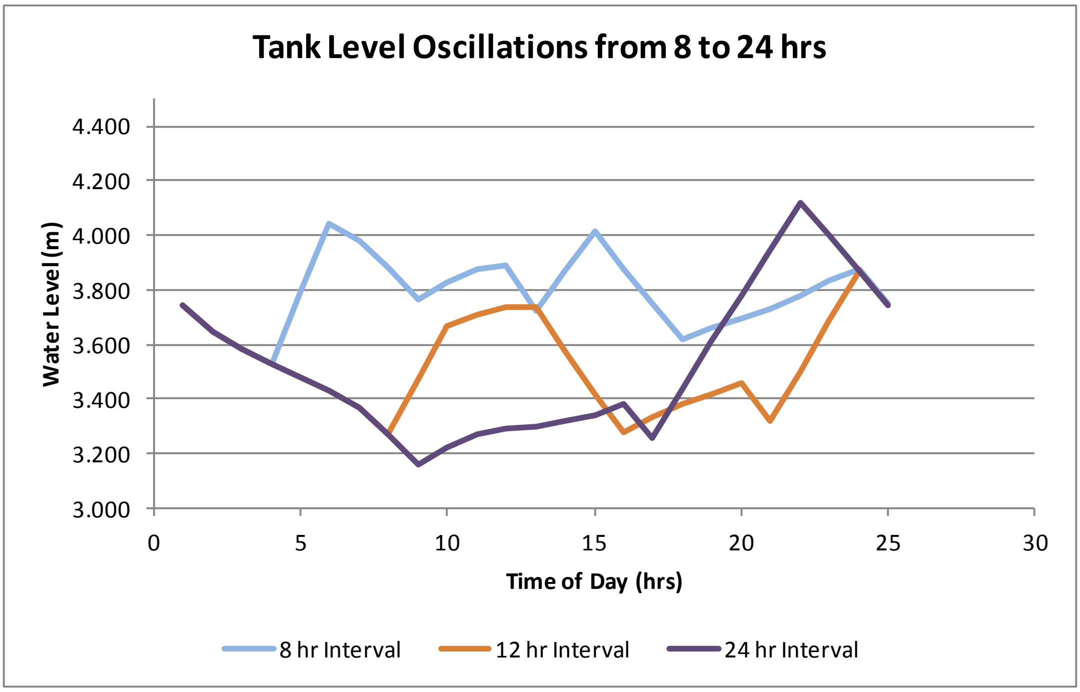


Figure 5.6. Tank Level Oscillations from 8 to 24 hrs

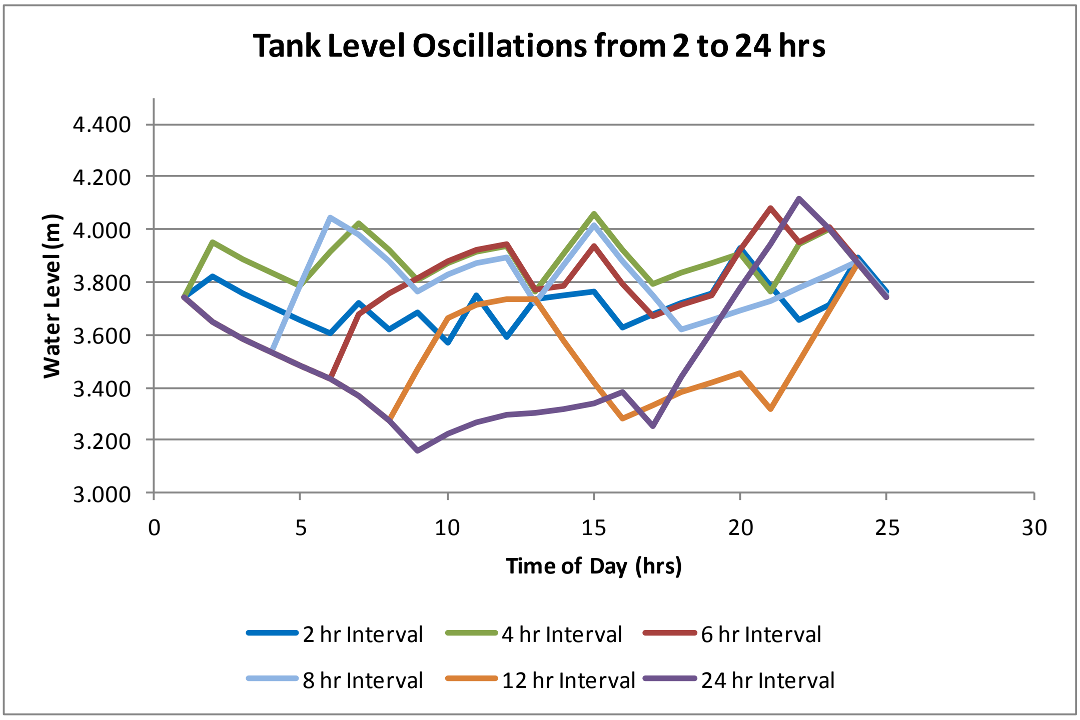


Figure 5.7. Tank Level Oscillations from 2 to 24 hrs

As can be seen from Figure 5.7, as the run time period lengthens, the magnitude of oscillations becomes larger. For each time period, the algorithm decides on the pump switches to equalize the tank volumes at initial and final stages. Consequently, during short period of simulation, algorithm tends to supply the needs of the network by pumping; it does not empty the tank to feed the system. This phenomenon results in lower magnitude oscillations for short run time periods. On the other hand, as the simulation period lengthens, the algorithm lets the tank feed the network during the pumps are not working. In addition, the algorithm tends to group the pump operations to avoid large number of switches. Corresponding grouping of pump operations can be seen in Figure 5.8.

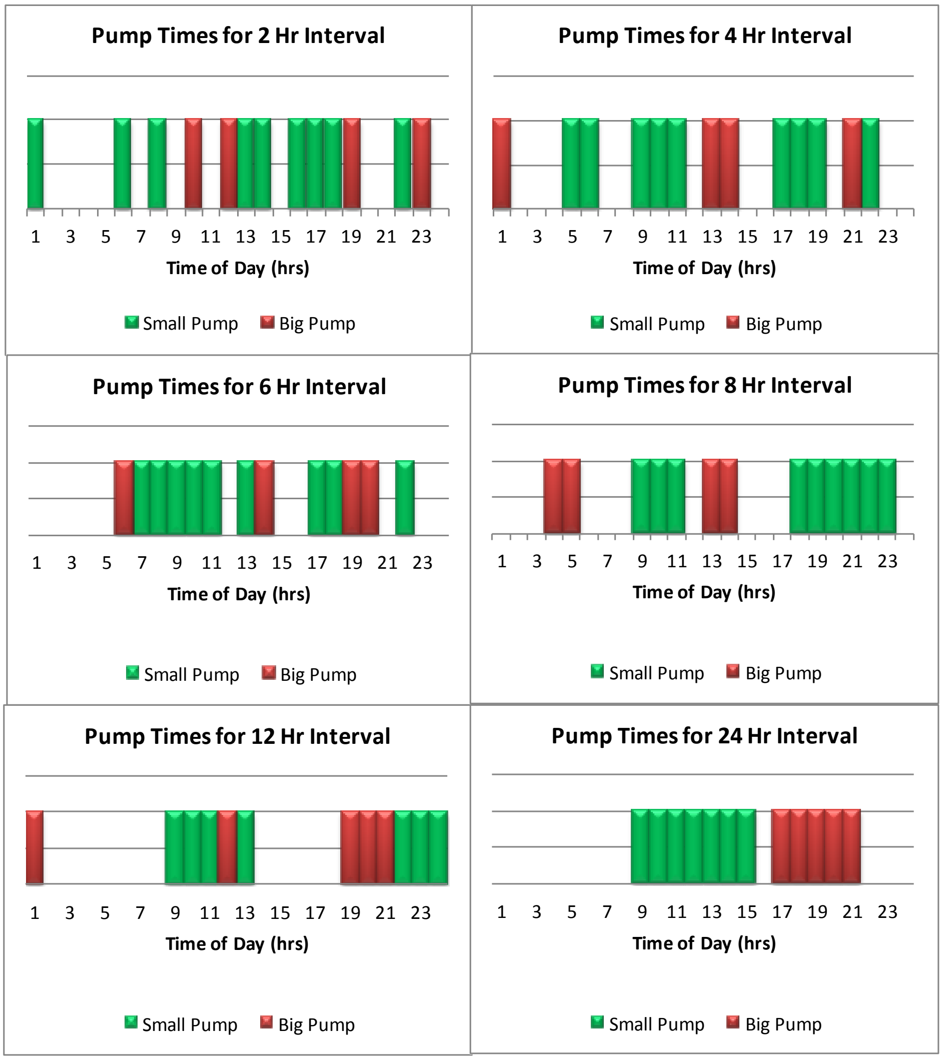


Figure 5.8. Pump Switches for 2 to 24 hrs Time Durations

As can be seen from Figure 5.8, pump operations are grouped as the run time period increases. Since POGA considers minimizing the number of switches in the defined run time period, when short time periods are repeated for 24 hours, it is expected more pump switches to occur. These results indicate the decisions of POGA are strictly dependent on the run time period.

To sum up the pump scheduling studies for varying run time periods; it can be stated that the program does produce applicable pump schedules with minimum number of pump switches and sustainable periodicity regardless of the chosen run time duration. However, the magnitude of tank level oscillations and the grouping of pump switches vary by run time duration.

For authorities which have water reservoirs having enough size, scheduling problem may consider 24 hour duration or more. Otherwise, if scheduling is made for shorter duration, the system will be mainly fed by pumping and the water in the tank may not be circulated.

5.3 Application of the Model with Real Time Demand Prediction

After performing pump scheduling optimization using predefined demand and run time durations; POGA is applied on the same network including the real time demand measurements and predictions. Including real time demand measurements helps to predict the upcoming hour's demand data. While optimizing the pump schedule for any predefined time duration; the nodal demands are previously set and there is no way to recalculate or update them. However, in real time application of POGA, the predicted and measured node demands are analyzed and upcoming hour's model demands are predicted.

For this basic prediction technique, initially the upcoming hour's node demand is assumed to be equal to its value measured 24 hours ago.

$$\hat{d}_t = \tilde{d}_{t-24} \tag{5.1}$$

Where,

$\hat{d}_t$ = Predicted demand at time t

$\tilde{d}_{t-24}$= Measured demand at time t-24

Tilde sign (˜) and cap sign (^) indicates measurement and prediction respectively.

After initiating the basic prediction; the demand is corrected by a factor after analyzing the measurement and prediction of previous hour's demand.

$$k_c = \frac{\tilde{d}_{t-1}}{\hat{d}_{t-1}} \tag{5.2}$$

Where,

k_c = Demand correction factor

Then the upcoming demand of next hour is corrected using the demand correction factor.

$$\hat{d}_t = \hat{d}_{t-24} \times k_c \tag{5.3}$$

Where;

$\hat{d}_t$ = Updated demand at time t

By predicting the nodal demands at each time step (1 hour), POGA is applied to pump scheduling program for 4 hours run time periods continuously, for the total duration of 24 hours. The objective function, constraints and applied genetic operators remain the same.

Since there existing demand data for only one day period, some measurement data is needed to be produced for real time demand prediction studies. While producing the measurement data, constant multiply factors are used. These multiply factors are defined as the ratio between the predicted and measured demand for each time step.

$$\tilde{d}_t = \hat{d}_t \times k_{mf} \tag{5.4}$$

Where;

$\tilde{d}_t$ = Measured demand at time t

k_{mf} = Multiply factor

The application of real time simulation is divided into three which depend on the time pattern of multiply factors. First, multiply factors are kept constant for 24 hour period; second multiply factors become variable for each time step and third, emergency case is simulated by sudden increase at the measurement (multiply factor) at the middle of the day.

5.3.1 Real Time Simulation with Constant Multiply Factors

N8-3 network model consists of 2 pumps with different capacities. (see Figure 4.4 and Figure 4.5). For convenience they are mentioned as big and small pumps. To apply real time demand prediction study with constant multiply factors, the combination of pumps and the multiply factor changed and the results are investigated.

The multiply factor values are changed from 0 to 6 with steps of 0.25 and for every factor, the pump scheduling optimization is applied in real time demand prediction mode. While increasing the factor value step by step, the network is highly demanded and the algorithm is forced to respond these unexpected high demands with increasing pumping times. For each multiply factor, program is run 25 times and the results of them are summarized. Table 5.3 summarizes the outcomes of the runs indicating the Energy Consumptions and Tank Level differences corresponding to increasing multiply factors are shown in Figure 5.9.

Table 5.3. Summary of Real Time Study for Big + Small Pump

	REAL TIME 24hr RUNS - MULTIPLY FACTORS vs ENERGY USAGE & TANK LEVELS (N8-3) Big Pump + Small Pump								
		Energy Usage (kWh)				Tank Level Diff. (m)			
No	Multiply Factor	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
1	0.00	79.39	37.15	52.52	178.66	0.00	0.00	0.00	0.00
2	0.25	131.58	12.15	120.61	150.25	0.01	0.01	-0.01	0.01
3	0.50	249.06	13.20	218.93	262.98	0.00	0.01	-0.01	0.01
4	0.75	371.18	29.25	336.11	443.66	0.00	0.01	-0.02	0.01
5	1.00	505.35	65.69	438.42	672.72	0.00	0.01	0.00	0.01
6	1.25	672.98	99.70	590.94	868.49	0.00	0.01	-0.02	0.01
7	1.50	794.48	126.41	709.61	1088.76	0.02	0.03	-0.02	0.08
8	1.75	854.07	56.92	794.33	989.73	0.00	0.03	-0.05	0.03
9	2.00	1076.60	180.77	914.29	1376.43	0.02	0.06	-0.06	0.15
10	2.25	1314.83	254.58	1052.67	1767.37	0.06	0.09	-0.04	0.21
11	2.50	1382.07	159.36	1177.49	1675.02	0.03	0.06	-0.03	0.16
12	2.75	1523.21	386.01	1257.02	2290.29	-0.05	0.11	-0.17	0.22
13	3.00	1577.09	219.04	1413.96	2035.57	-0.06	0.06	-0.17	0.05
14	3.25	1621.62	200.45	1462.88	2148.10	-0.28	0.31	-0.74	0.27
15	3.50	1716.65	102.40	1599.90	1943.30	-0.40	0.37	-1.08	-0.05
16	3.75	1902.30	376.56	1695.01	2921.46	-0.68	0.34	-1.17	-0.10
17	4.00	2727.59	1453.50	1753.77	6132.15	-1.07	0.21	-1.25	-0.67
18	4.25	3274.72	2505.29	1687.57	9138.49	-1.17	0.16	-1.25	-0.75
19	4.50	2887.51	1486.04	1740.75	5559.25	-1.25	0.00	-1.25	-1.24
20	4.75	2594.45	2346.13	1747.21	9266.49	-1.25	0.00	-1.25	-1.25
21	5.00	7607.93	4620.36	1813.23	12955.47	-1.25	0.00	-1.25	-1.25

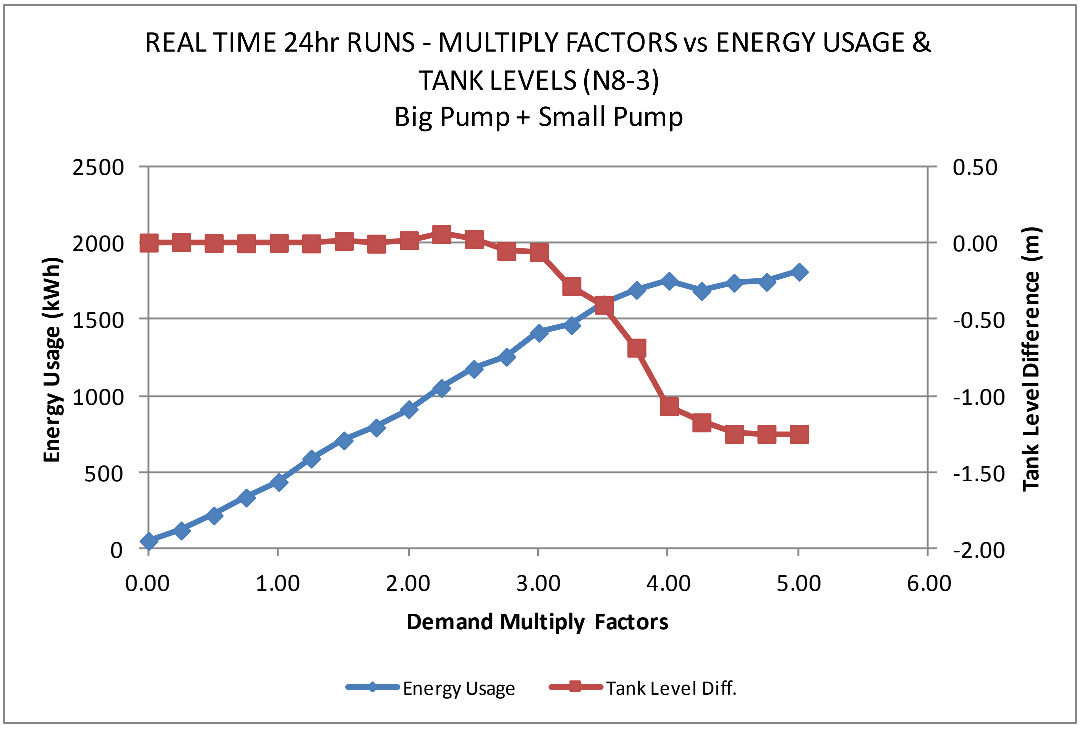


Figure 5.9. Energy Usage and Tank Level Differences for Big + Small Pump

As can be seen from Table 5.3 and Figure 5.9, until multiply factors have reached to the value of 3.5, the tank level differences are within acceptable limits. When multiply factors exceed 3.5, the pumps become insufficient for that much demand loading and increasing pumping costs could not equalize the tank levels at initial and final stages.

After applying varying factors to N8-3 network's big and small pumps, the capacities of pumps are changed and the method is re-applied considering the same demand loadings. First, small pump is replaced with big pump and model is run with big + big pump combination. Table 5.4 and Figure 5.10 show the results of these runs. Then, two big pumps are replaced with two small pumps and model is run with small + small pump combination. Table 5.5 and Figure 5.11 show the results of small + small pump runs.

When all these results are investigated, it can be seen that, increasing multiply factors helps visualizing the ability of pumps to equalize the tank levels of initial and final stages. While small + big pump combination can respond the demand till the multiply factor reaches to 3.5; for big + big pump combination this limit is increased to 4.5. On the other hand, small + small pump combination can make the model retain the demand multiplier of 2.5.

Table 5.4. Summary of Real Time Study for Big + Big Pump

	REAL TIME 24hr RUNS - MULTIPLY FACTORS vs ENERGY USAGE & TANK LEVELS (N8-3) Big Pump + Big Pump								
		Energy Usage (kWh)				Tank Level Diff. (m)			
No	Multiply Factor	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
1	0.00	79.62	41.97	0.00	99.53	0.46	0.24	0.00	0.57
2	0.25	151.93	0.01	151.92	151.94	0.17	0.00	0.17	0.17
3	0.50	253.47	1.94	252.86	258.98	0.05	0.00	0.05	0.06
4	0.75	352.85	1.41	350.07	353.54	-0.04	0.08	-0.07	0.10
5	1.00	503.12	4.82	500.00	512.83	-0.04	0.05	-0.08	0.06
6	1.25	605.40	13.60	588.08	624.43	-0.06	0.04	-0.13	-0.01
7	1.50	745.16	27.69	704.26	778.61	-0.02	0.09	-0.16	0.08
8	1.75	851.66	17.70	819.98	879.99	-0.03	0.04	-0.08	0.03
9	2.00	991.84	47.97	952.09	1075.35	-0.07	0.13	-0.20	0.08
10	2.25	1087.51	6.31	1077.45	1096.96	-0.06	0.01	-0.08	-0.04
11	2.50	1209.37	11.96	1187.92	1225.24	-0.11	0.06	-0.22	-0.03
12	2.75	1326.22	15.77	1302.59	1339.77	-0.09	0.06	-0.20	-0.04
13	3.00	1443.31	9.51	1429.52	1457.79	-0.12	0.04	-0.19	-0.09
14	3.25	1565.12	10.72	1551.59	1586.25	-0.14	0.03	-0.19	-0.09
15	3.50	1697.30	21.07	1670.57	1714.64	-0.11	0.09	-0.24	-0.03
16	3.75	1822.10	18.12	1791.87	1837.71	-0.12	0.09	-0.27	-0.04
17	4.00	1943.95	1.65	1942.17	1946.33	-0.10	0.03	-0.13	-0.06
18	4.25	2041.19	19.28	2029.72	2076.15	-0.22	0.10	-0.28	-0.03
19	4.50	2170.07	12.27	2146.81	2176.44	-0.24	0.08	-0.39	-0.20
20	4.75	2186.94	74.25	2073.96	2245.99	-0.76	0.18	-1.03	-0.57
21	5.00	2277.66	54.61	2192.50	2318.86	-1.09	0.10	-1.22	-0.89
22	5.25	2262.58	51.16	2127.50	2296.47	-1.25	0.00	-1.25	-1.25
23	5.50	2332.33	22.32	2307.95	2359.51	-1.25	0.00	-1.25	-1.25
24	5.75	2315.48	73.87	2161.45	2414.84	-1.25	0.00	-1.25	-1.25
25	6.00	2395.89	37.78	2329.03	2470.23	-1.25	0.00	-1.25	-1.25

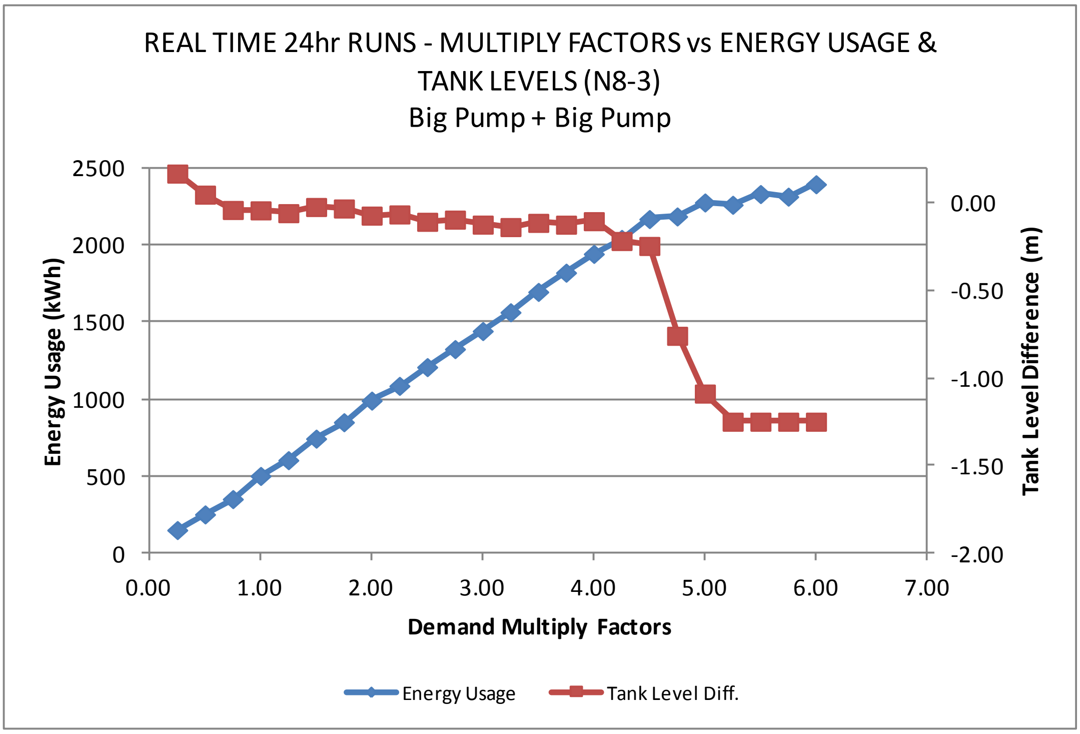


Figure 5.10. Energy Usage and Tank Level Differences for Big + Big Pump

Table 5.5. Summary of Real Time Study for Small + Small Pump

	REAL TIME 24hr RUNS - MULTIPLY FACTORS vs ENERGY USAGE & TANK LEVELS (N8-3) Small Pump + Small Pump								
		Energy Usage (kWh)				Tank Level Diff. (m)			
No	Multiply Factor	Mean	Std Dev	Min	Max	Mean	Std Dev	Min	Max
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.25	120.63	0.01	120.63	120.65	0.00	0.00	0.00	0.00
3	0.50	240.72	0.58	240.43	242.29	0.00	0.00	0.00	0.01
4	0.75	364.79	0.75	363.36	366.21	0.02	0.00	0.01	0.03
5	1.00	485.41	1.28	482.54	486.77	0.01	0.01	0.01	0.03
6	1.25	606.53	1.44	604.79	608.68	0.04	0.01	0.03	0.05
7	1.50	727.29	2.07	724.16	730.22	0.03	0.01	0.01	0.04
8	1.75	823.70	11.67	816.81	845.70	-0.08	0.10	-0.14	0.14
9	2.00	948.21	12.06	938.07	966.60	-0.09	0.07	-0.15	0.01
10	2.25	1065.38	2.25	1060.25	1067.17	-0.11	0.01	-0.13	-0.10
11	2.50	1185.50	0.72	1184.53	1186.76	-0.11	0.01	-0.13	-0.09
12	2.75	1235.98	13.40	1225.44	1251.69	-0.50	0.07	-0.56	-0.42
13	3.00	1293.53	24.38	1252.59	1315.92	-0.87	0.11	-1.03	-0.76
14	3.25	1348.04	31.61	1302.10	1367.77	-1.25	0.00	-1.25	-1.25
15	3.50	1460.26	9.94	1431.97	1463.49	-1.25	0.00	-1.25	-1.25
16	3.75	995.43	15.16	1433.69	1013.29	-1.25	0.00	-1.25	-1.25
17	4.00	6490.51	1461.49	1497.12	9263.50	-1.25	0.00	-1.25	-1.25

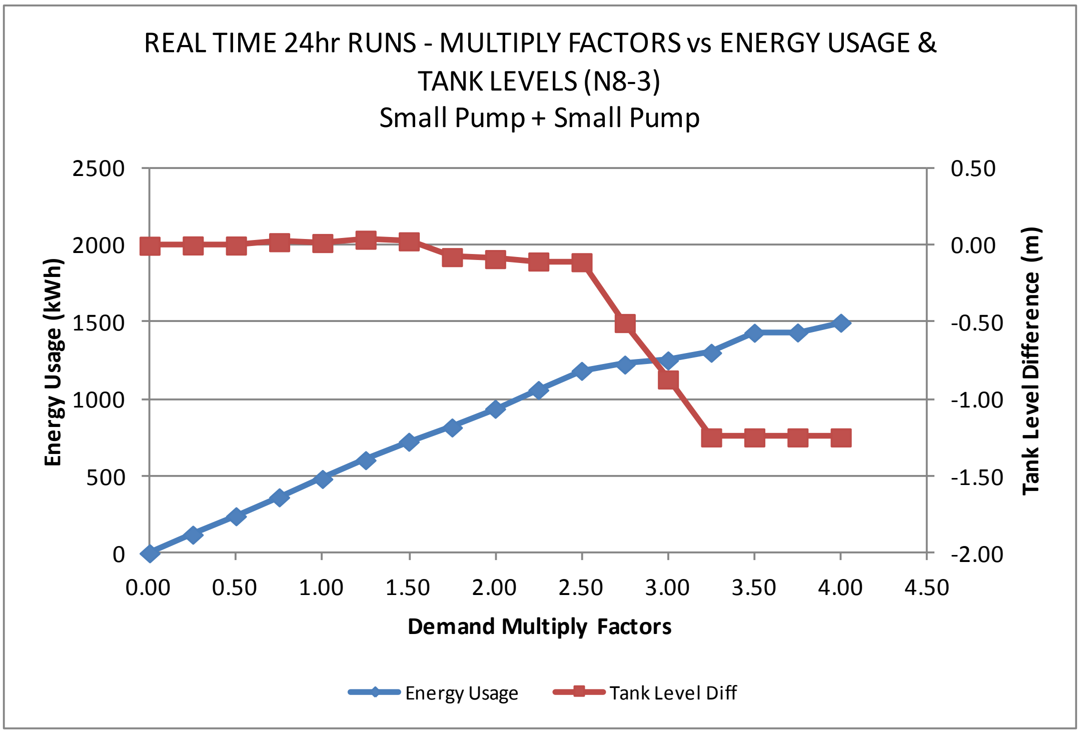


Figure 5.11. Energy Usage and Tank Level Differences for Small + Small Pump

5.3.2 Real Time Simulation with Varying Multiply Factors

After applying constant multiply factors to N8-3, the real time simulation methodology is re-applied with varying multiply factors. For real time simulation with varying multiply factors, the multiply factor values are changed for each time step (1 hour). For this study, small + big pump combination (the actual case) is employed. The multiply factors are changed from 0 to 3; first in predefined manner, and second randomly.

Two predefined multiply factors series are selected for the model. One is starting high, decreasing and increasing at the finish. The other is its symmetry; starting low, increasing and decreasing at the finish. By choosing that much different multiply factor series, it is tried to visualize the response of POGA by determining the pumping schedules.

Figure 5.12 and Figure 5.13 show the initially predicted demands, measured demands and corresponding POGA's pump schedule and tank water levels for multiply factor series 1 and 2 respectively. When both figures are investigated, it can be seen that during periods of measured demands increase, POGA employs the pumps; especially big pump or two pumps in parallel. In which periods the measured demands decrease, POGA shuts off the pumps for these periods and let the network is fed by the tank. Also, for both types of multiply factors, it can be seen that the initial and final level of tank is close to each other.

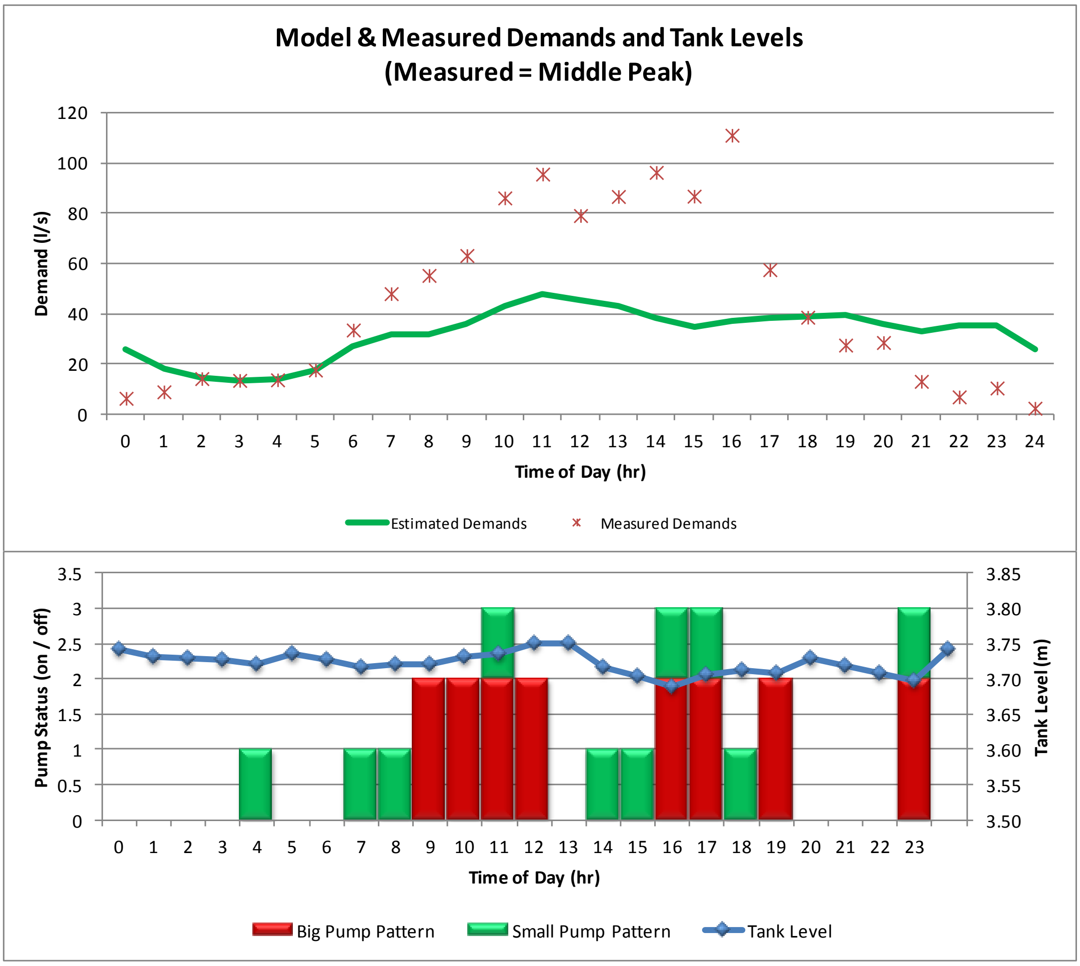


Figure 5.12. Tank Levels and Pump Schedules for Predefined Multiply Factors - 1

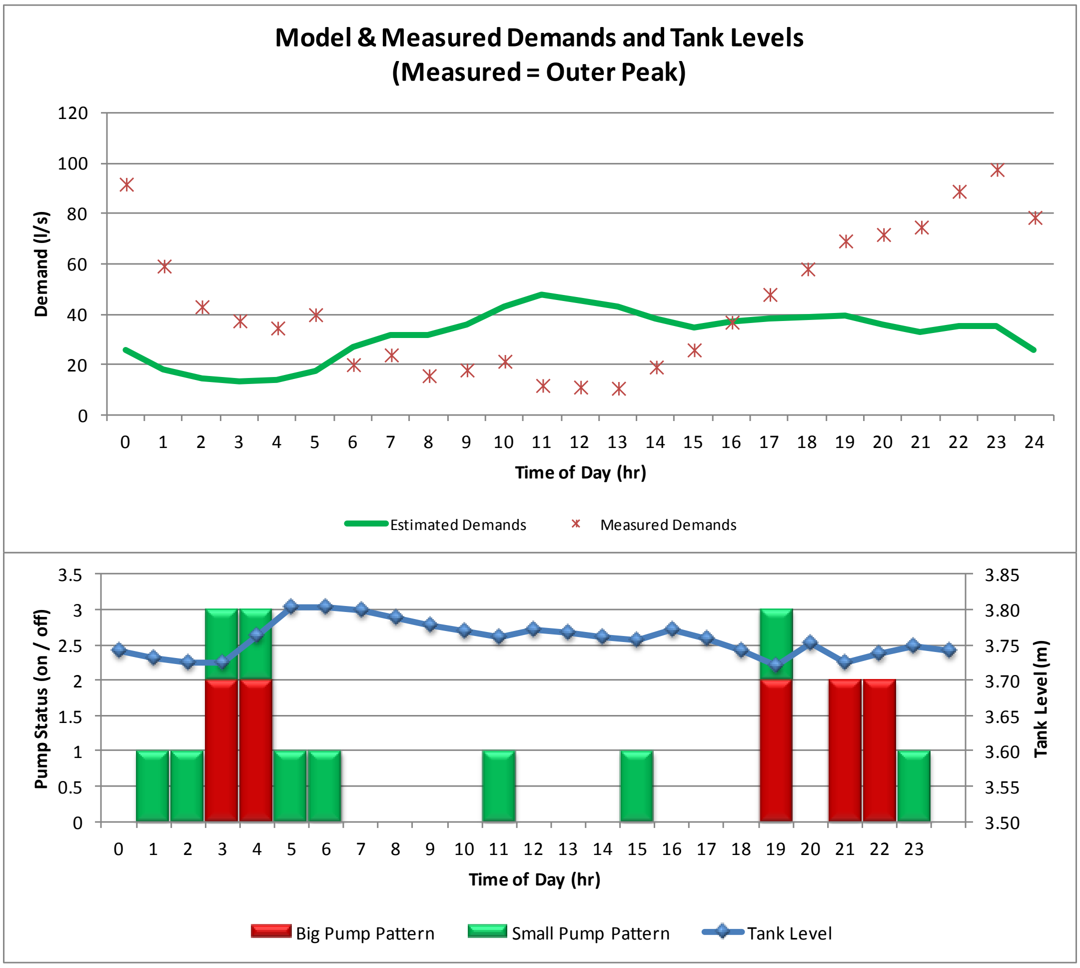


Figure 5.13. Tank Levels and Pump Schedules for Predefined Multiply Factors - 2

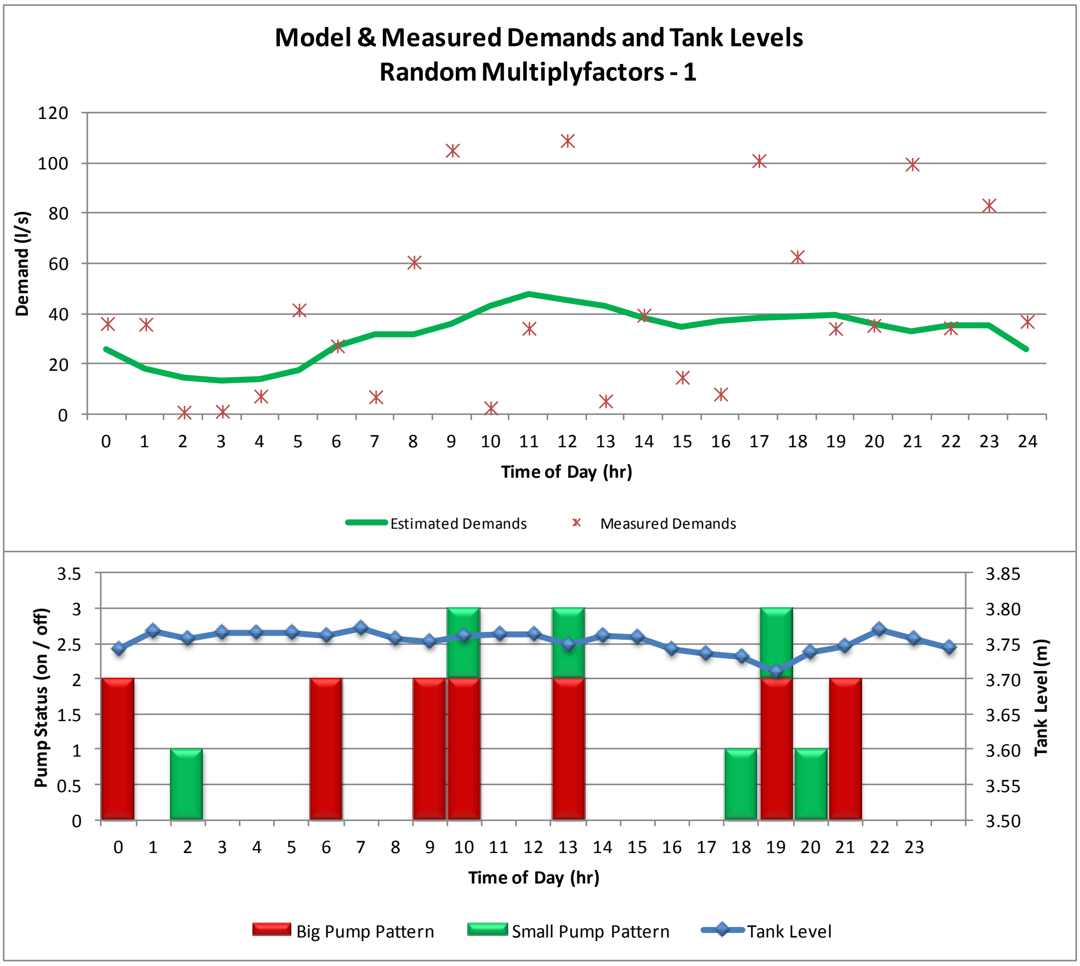


Figure 5.14. Tank Levels and Pump Schedules for Random Multiply Factors - 1

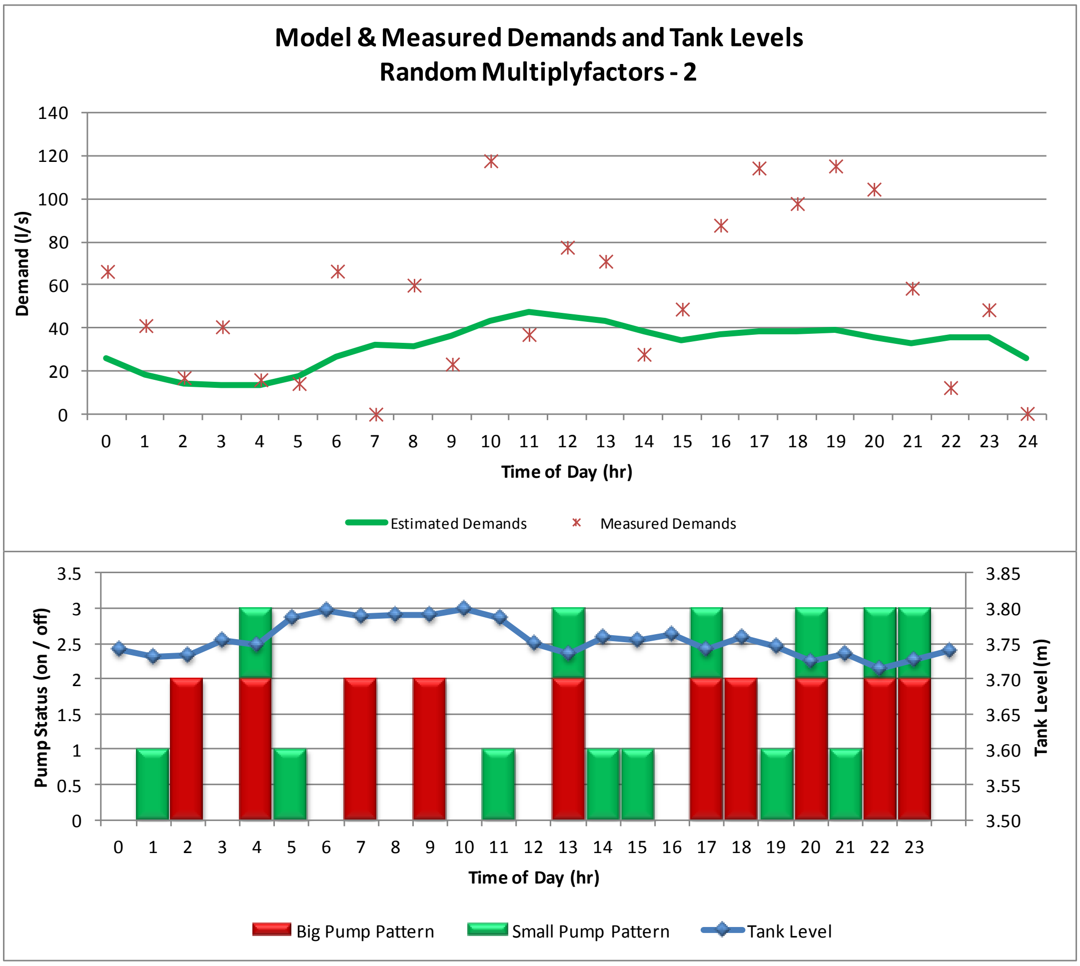


Figure 5.15. Tank Levels and Pump Schedules for Random Multiply Factors - 2

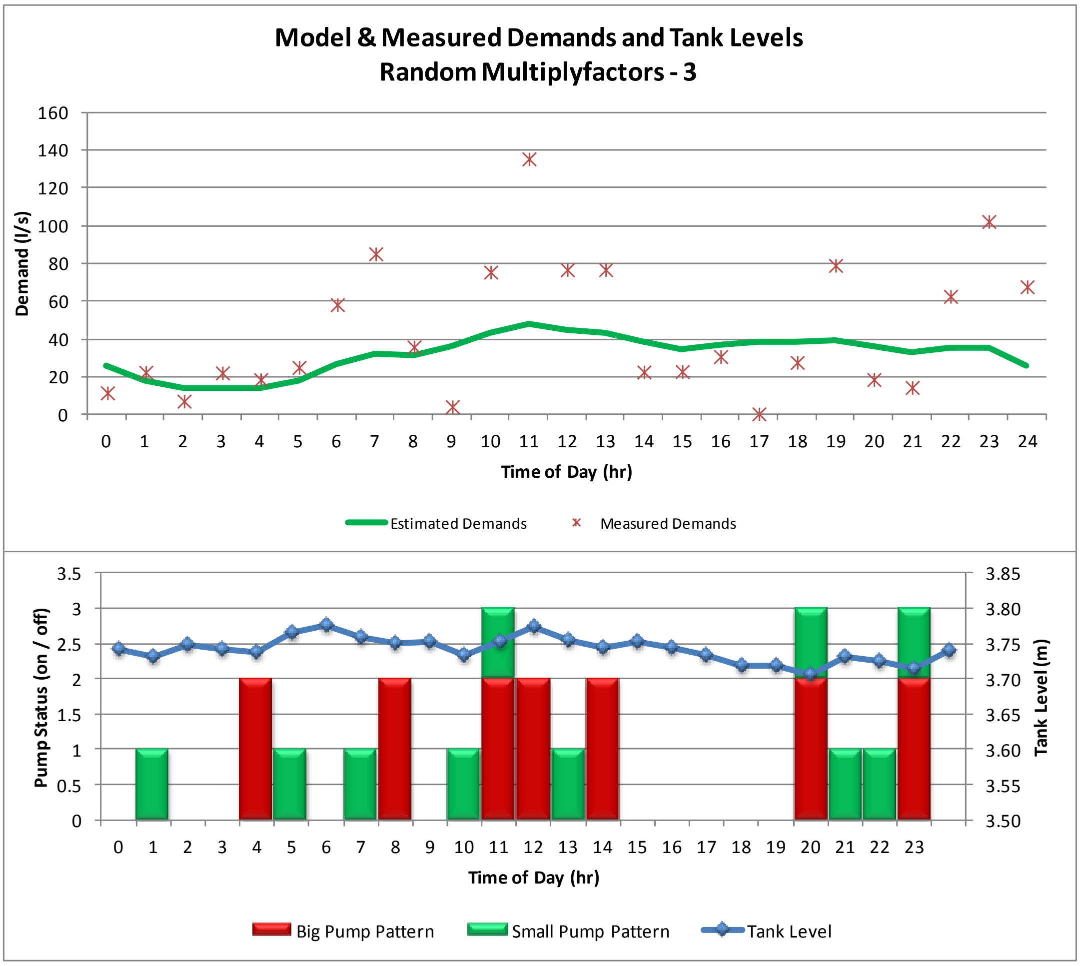


Figure 5.16. Tank Levels and Pump Schedules for Random Multiply Factors – 3

Figure 5.14, Figure 5.15 and Figure 5.16 show initially predicted demands, measured demands and corresponding POGA's pump schedule and tank water levels for random multiply factor series 1, 2 and 3 respectively. Similar to previous application of predefined multiply factors, in these figures it can be seen that, POGA employs the pumps when the demands increase and shuts off the pumps when demands decrease. Also, for all types of multiply factors, it can be seen that the initial and final level of tank is close to each other.

5.3.3 Real Time Simulation In Emergency Cases

Following varying multiply factors, the real time simulation methodology is re-applied to N8-3 for emergency cases. In this case, again the big + small pump combination is used. To model the emergency case, the measurement data is produced by multiplying the initial prediction by a constant factor starting from the middle of the day. By changing the multiply factor, it is tried to visualize the response of POGA to determine the pumping schedules.

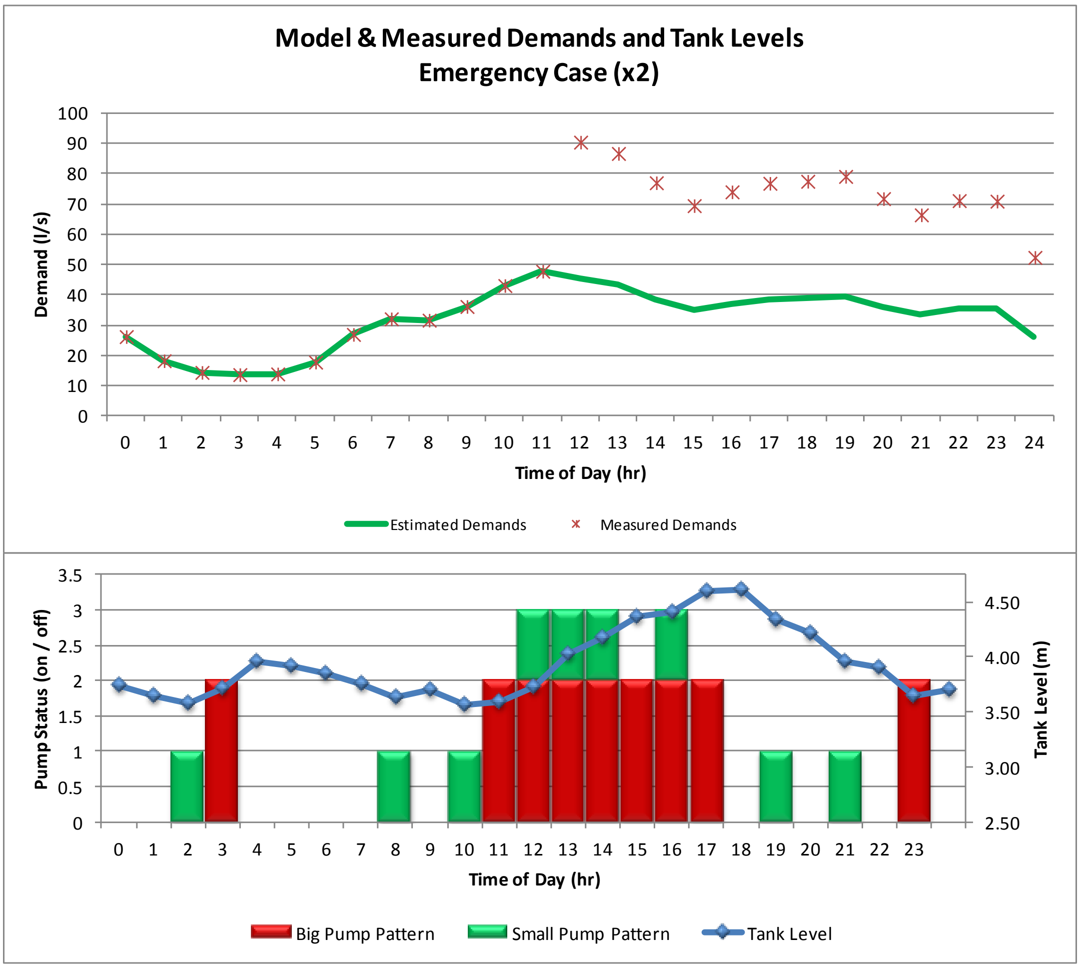


Figure 5.17. Tank Levels and Pump Schedules for Emergency Case (x2 loading)

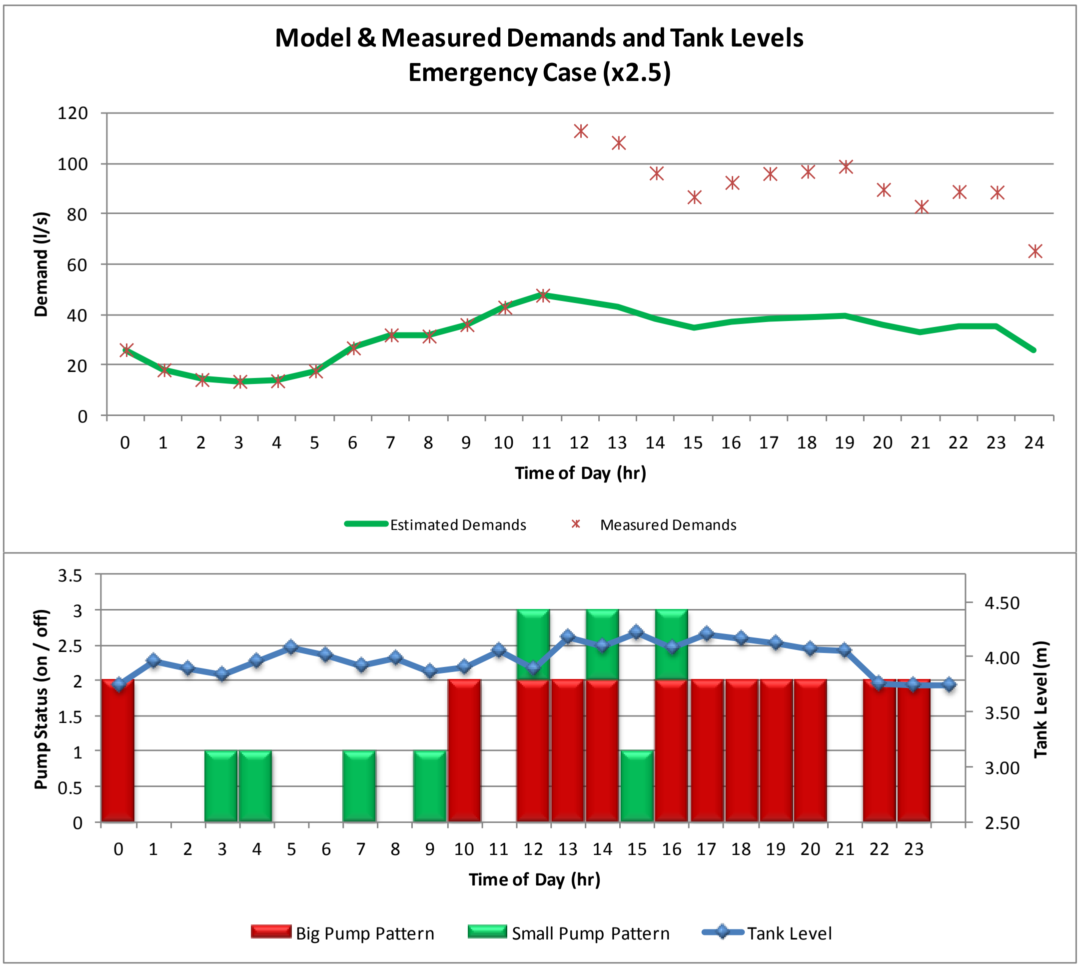


Figure 5.18. Tank Levels and Pump Schedules for Emergency Case (x2.5 loading)

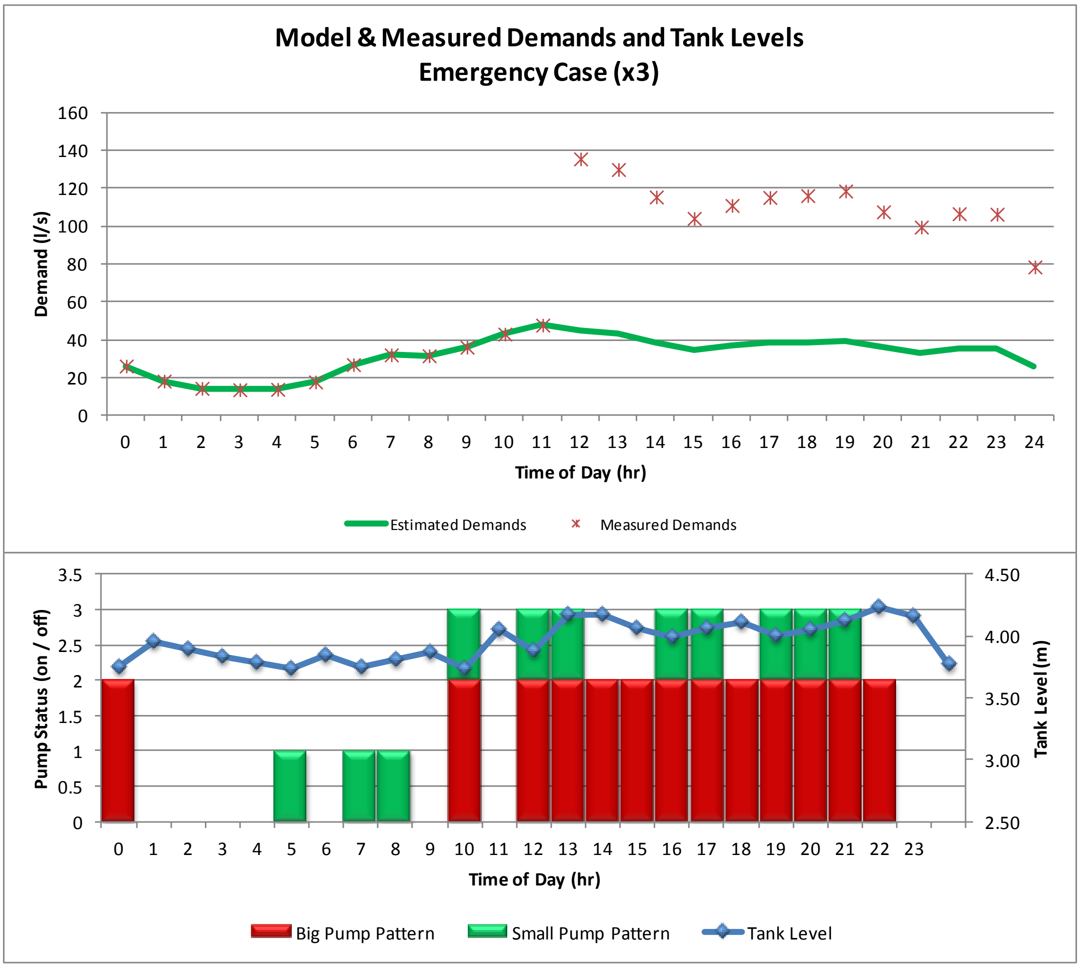


Figure 5.19. Tank Levels and Pump Schedules for Emergency Case (x3 loading)

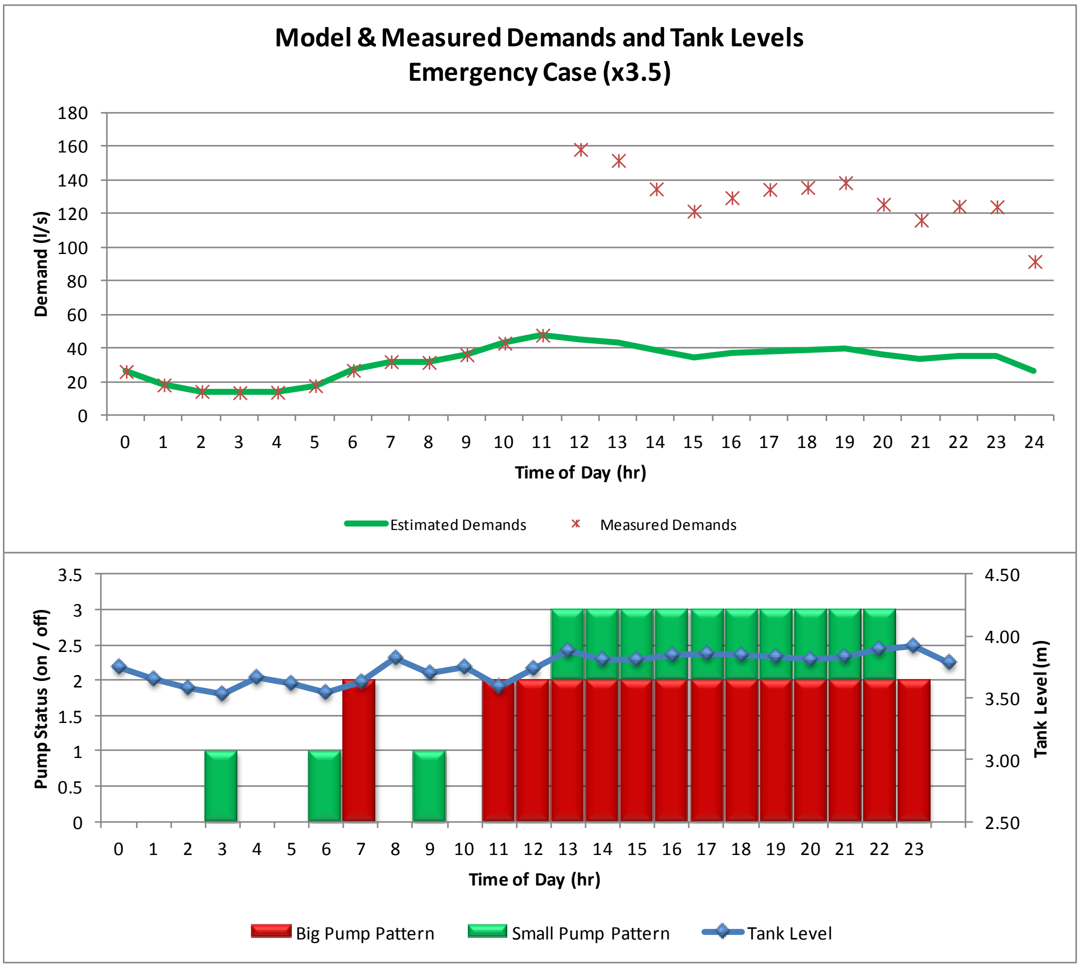


Figure 5.20. Tank Levels and Pump Schedules for Emergency Case (x3.5 loading)

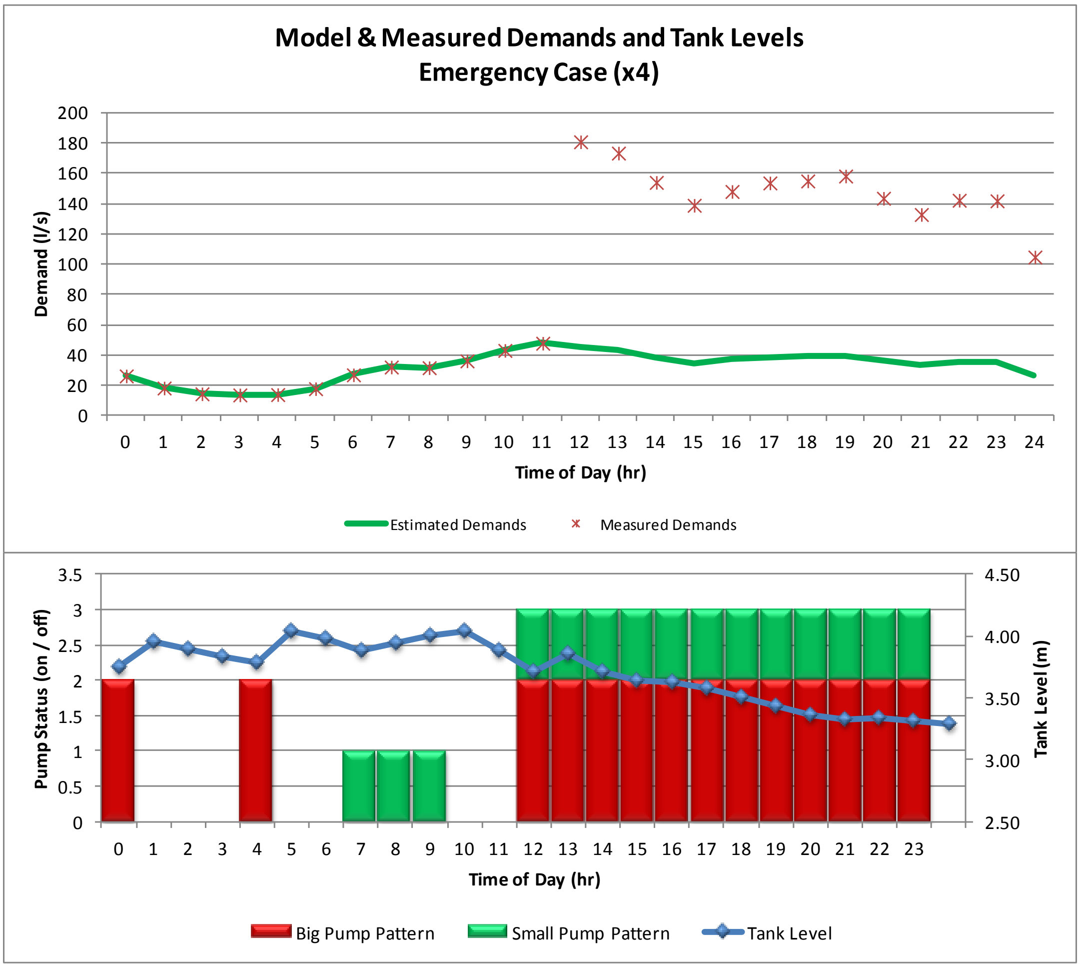


Figure 5.21. Tank Levels and Pump Schedules for Emergency Case (x4 loading)

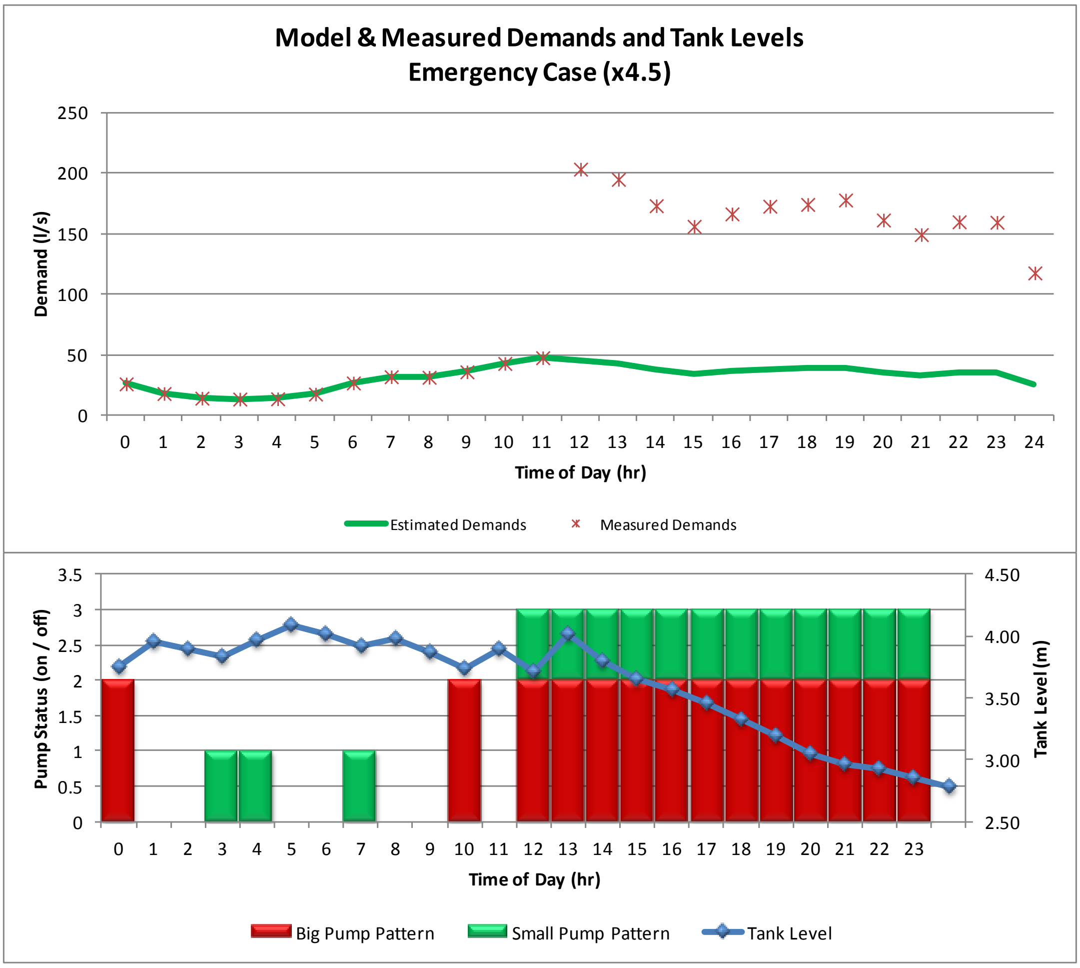


Figure 5.22. Tank Levels and Pump Schedules for Emergency Case (x4.5 loading)

As can be seen from Figure 5.17 to Figure 5.22, POGA employed the pumps as the emergency flow drawn from the network. The combination of big + small pump supplied the extra flow for emergency case of multiply factor 2 and 3. However, this combination could not supply enough water to maintain the periodicity of tank for cases of multiply factor 4 and 5. Though the periodicity of tank is supplied or not, POGA is capable of employing the pumps in emergency cases.

5.4 Application of the Model to Real Time Simulation Using Kalman Filter

In previous works, the measurement data were used for prediction without any filtering. In real case, the measurement data and/or prediction method may contain some noise (random variations). This noise could be considered as error in particular. While applying pump scheduling model into real time demand prediction cases; in order to estimate the hourly demands considering these noise, Kalman Filter (Kalman,1960) is applied to the prediction method.

The Kalman Filter is a set of mathematical equations that provide efficient computational means to estimate the state of a process, in a way that minimizes the mean of the squared error (Welch and Bishop, 2006). More formally, the Kalman filter operates recursively on streams of noisy input data to produce a statistically optimal estimate of the underlying system state. The filter is named after Rudolf (Rudy) E. Kalman, one of the primary developers of its theory (Web 1).

The Kalman Filter estimates the process state at some time and then obtains feedback to measurements. As such, the equations for the Kalman filter fall into two groups: time update equations and measurement update equations. The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain a priori estimates for the next time step. The measurement update equations are responsible for the feedback, i.e. for incorporating a new measurement into a priori estimate to obtain an improved a posteriori estimate.

The schema of time and measurement updates including the equations are given in Figure 5.23.

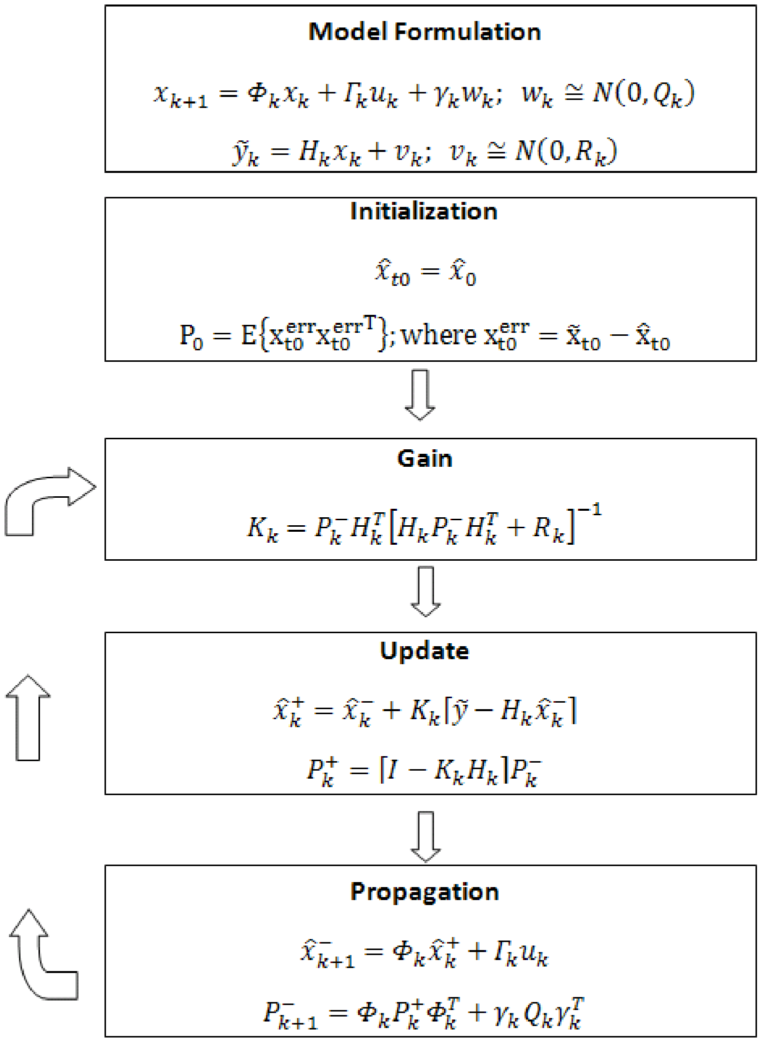


Figure 5.23. The Schematic of Operation of Kalman Filter (Crassidis and Junkins, 2011)

Where;

x: State vector

Φ: State transition matrix

Γ:Input matrix

u: Input control vector

P: Covariance matrix of state estimation uncertainty

Q: Covariance matrix of process noise

R: Covariance matrix of measurement uncertainty

y: Measurement vector

H: Measurement sensitivity matrix

To estimate the nodal demand using Kalman Filter, a blind demand estimation model is needed.

The demand estimation model is formulated as;

$$\hat{d}_k = \alpha\tilde{d}_{k-24} + \beta\tilde{d}_{k-1} \tag{5.5}$$

To find α and β, 6 days of demand data is produced using;

$$\tilde{d}_k = \tilde{d}_{k-24} + e;\ where\ e \cong N(0,\sigma) \tag{5.6}$$

σ = 1 (white noise)

Then, α and β is found using;

$$Min \sum_{k=25}^{168} \left(\tilde{d}_k - \hat{d}_k\right)^2$$

$$Subject\ to;\ \alpha + \beta = 1 \tag{5.7}$$

This simple optimization problem is solved using MS-Excel solver (Fylstra et al., 1998) and α and β are found 0.981and 0.019 respectively. For this α and β, sum of square error becomes;

$$\sum_{k=25}^{168} \left(\tilde{d}_k - \hat{d}_k\right)^2 = 196.08 \tag{5.8}$$

The produced 1 week long measured demand data, the results of blind prediction and squared errors are shown in Appendix 1.

After handling α and β, demand data of day 2 is estimated using Kalman Filter equations. The estimated demands, measurements and blind estimation results are shown for comparison in Table 5.6 and in Figure 5.24

Table 5.6. Estimated Demands, Measurements and Blind Estimation results

Time (hr)	Measurements (LPS)	Kalman Filter Estimation (LPS)	Blind Estimate (LPS) α - β method
24	35.48		
25	26.35	26.40	24.17
26	17.50	19.41	18.09
27	14.86	15.08	12.99
28	14.76	13.86	14.42
29	12.89	13.91	10.94
30	18.10	17.22	16.65
31	25.88	25.59	28.29
32	32.36	31.17	32.61
33	31.60	31.59	32.32
34	36.22	35.52	35.80
35	42.38	42.03	44.03
36	50.46	46.99	49.29
37	46.41	45.52	44.24
38	44.50	43.68	45.71
39	38.25	39.26	38.63
40	33.19	35.36	33.77
41	36.53	36.76	35.61
42	37.00	38.19	37.42
43	38.94	38.66	39.53
44	39.16	39.43	40.69
45	36.94	36.39	36.29
46	34.21	33.68	31.63
47	34.61	35.32	36.08
48	36.24	35.44	34.88

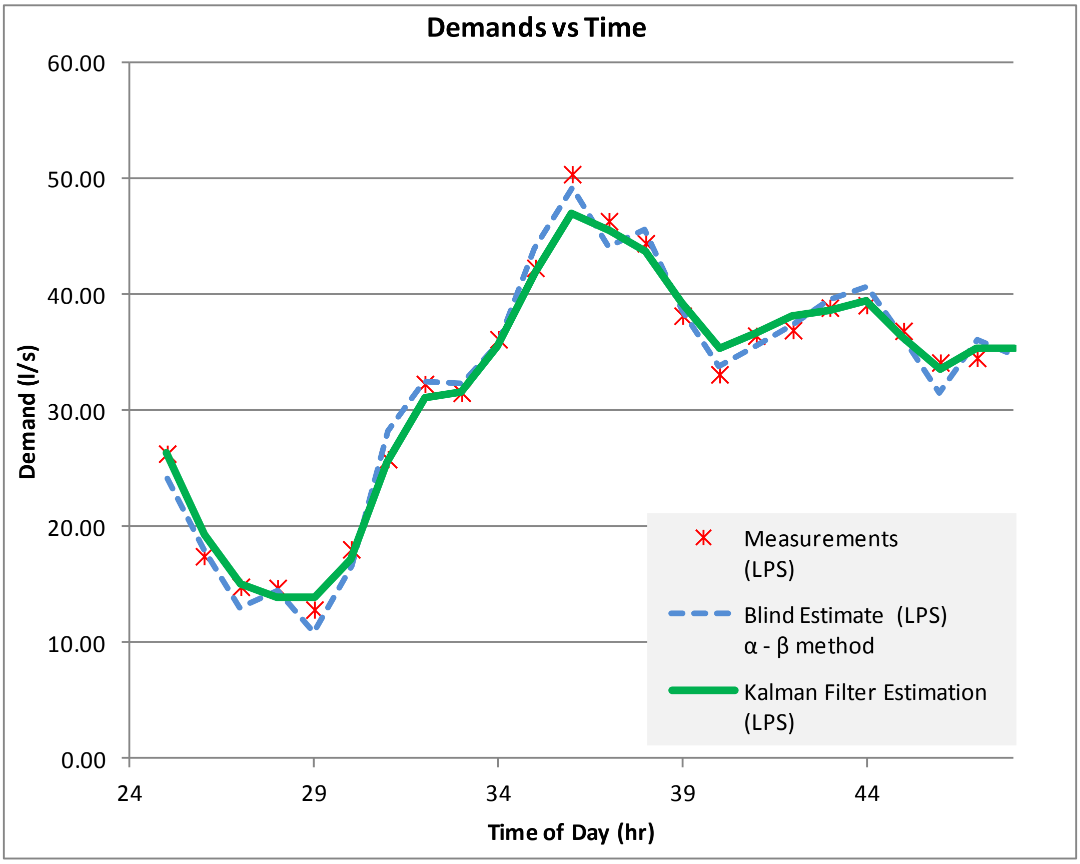


Figure 5.24. Estimated Demands, Measurements and Blind Estimation results

After the prediction steps, the errors of each prediction is calculated as follows;

$$\sum_{k=1}^{24} \left(\tilde{d}_k - \hat{d}_k\right)^2 \tag{5.9}$$

Where;

$\tilde{d}_k$ is the measured hourly demand and $\hat{d}_k$ is the filtered and unfiltered prediction of Blind Prediction method. The hourly errors and their summation are shown in Table 5.7.

Table 5.7. Hourly Errors for Each Prediction Method

Time (hr)	Measurements (LPS)	Kalman Filter Estimation Errors	Blnd Estimation Errors
24	35.48		
25	26.35	0.00	4.77
26	17.50	3.66	0.35
27	14.86	0.05	3.49
28	14.76	0.81	0.11
29	12.89	1.02	3.80
30	18.10	0.76	2.10
31	25.88	0.09	5.82
32	32.36	1.42	0.06
33	31.60	0.00	0.52
34	36.22	0.49	0.18
35	42.38	0.13	2.73
36	50.46	12.05	1.38
37	46.41	0.78	4.70
38	44.50	0.67	1.46
39	38.25	1.02	0.15
40	33.19	4.71	0.34
41	36.53	0.05	0.84
42	37.00	1.40	0.17
43	38.94	0.08	0.34
44	39.16	0.08	2.35
45	36.94	0.31	0.43
46	34.21	0.29	6.69
47	34.61	0.51	2.17
48	36.24	0.64	1.86
	Sum of Errors	**31.02**	**46.81**

As can be seen from Table 5.7, for Kalman Filter prediction, the sum of errors between the prediction method and measurements are lower than the blind prediction.

Using the estimated demand, program is run in real-time conditions. Results of Pump Schedules and Tank Levels are shown in Figure 5.25.

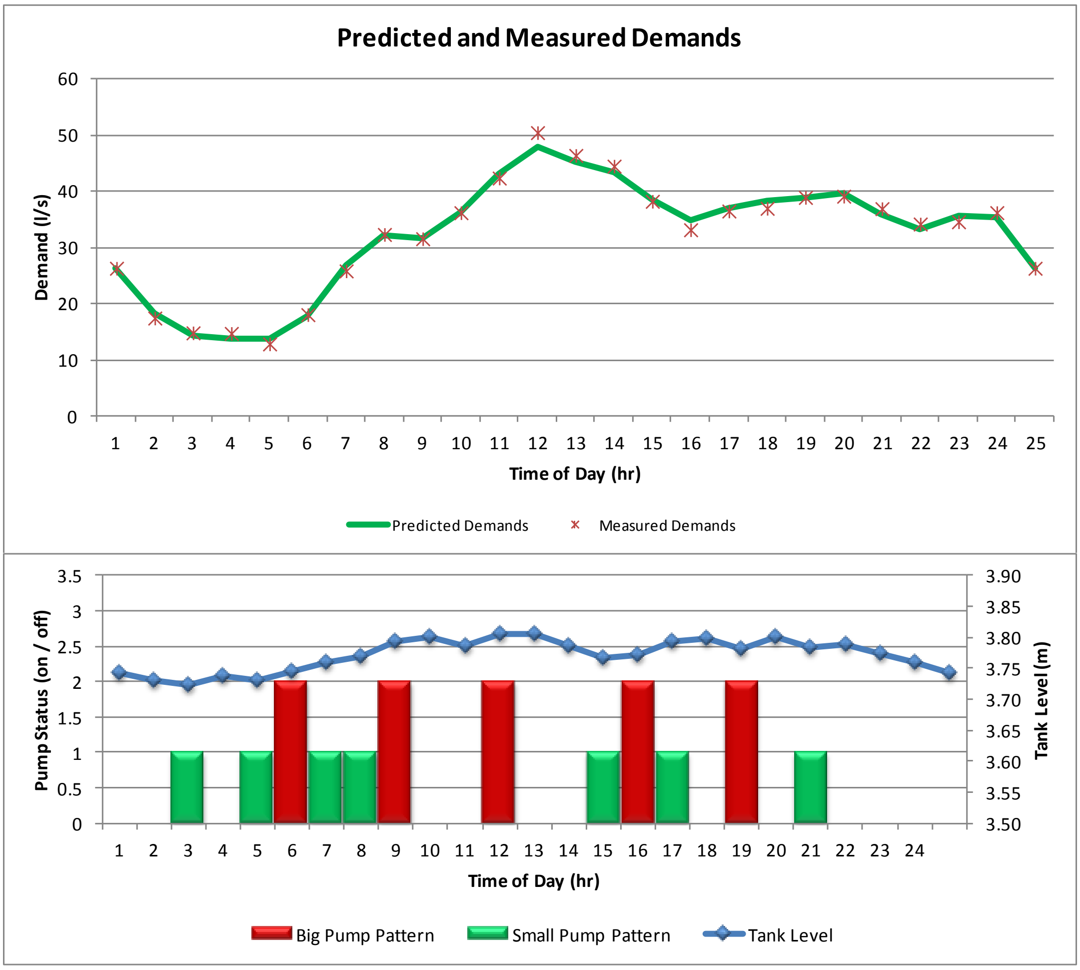


Figure 5.25. Pump Schedule Results of Kalman Filter Estimation

CHAPTER 6

VALVE LOCATING AND OPENING DETERMINATION

In this chapter, valve locating and opening determination studies on two District Metered Areas (DMAs) of N8-3 are presented. The studies include the application of developed program VOGA (Valve Optimization using Genetic Algorithms), for various steady state (SS) and extended period simulation (EPS) aiming excess pressure minimization through the networks.

6.1 Application of VOGA to Yayla Network

As briefly explained in Section 3.2, for pump scheduling optimization, the program namely VOGA is developed. The developed program is applied to two DMAs of N8-3 network. Initially, for valve operation studies, network of Yayla DMA is selected. This network is located at the east side of the main N8-3 network (see Figure 4.1 and Figure 4.6). Furthermore, this district is located at lower elevations than the other ones. Therefore, higher pressures are prominent. The mean entrance total head is 1155.82 m. The elevation of nodes and static heads with respect to DMA entrance are given in Table 6.1.

Table 6.1. Topographic Elevations and Static Head Differences of Nodes

Node ID	Elevation (m)	Static Head (m)	Node ID	Elevation (m)	Static Head (m)	Node ID	Elevation (m)	Static Head (m)
J- 26	1112.86	42.96	J- 174	1090.10	65.72	J- 332	1080.48	75.34
J- 27	1112.98	42.84	J- 175	1091.10	64.72	J- 333	1078.70	77.12
J- 29	1077.36	78.46	J- 177	1061.87	**93.95**	J- 354	1086.09	69.73
J- 30	1077.26	78.56	J- 191	1100.73	55.09	J- 355	1078.05	77.77
J- 32	1076.91	78.91	J- 192	1104.75	51.07	J- 357	1112.08	43.74
J- 43	1078.48	77.34	J- 196	1114.34	41.48	J- 358	1111.88	43.94
J- 45	1062.39	**93.43**	J- 197	1114.46	41.36	J- 364	1093.20	62.62
J- 46	1062.33	**93.49**	J- 205	1104.70	51.12	J- 376	1081.83	73.99
J- 48	1109.58	46.24	J- 206	1103.26	52.56	J- 377	1088.76	67.06
J- 49	1109.91	45.91	J- 217	1079.18	76.64	J- 387	1094.24	61.58
J- 51	1085.89	69.93	J- 218	1075.26	**80.56**	J- 392	1087.16	68.66
J- 52	1083.94	71.88	J- 223	1084.69	71.13	J- 404	1103.10	52.72
J- 74	1086.48	69.34	J- 224	1078.31	77.51	J- 422	1108.32	47.50
J- 75	1087.16	68.66	J- 226	1085.59	70.23	J- 423	1108.79	47.03
J- 77	1062.16	**93.66**	J- 228	1100.72	55.10	J- 425	1080.16	75.66
J- 78	1060.35	**95.47**	J- 229	1097.96	57.86	J- 440	1058.38	**97.44**
J- 95	1090.93	64.89	J- 239	1095.89	59.93	J- 467	1076.93	78.89
J- 96	1093.97	61.85	J- 240	1097.46	58.36	J- 481	1077.60	78.22
J- 104	1093.96	61.86	J- 245	1112.32	43.50	J- 528	1114.09	41.73
J- 105	1095.23	60.59	J- 247	1102.10	53.72	J- 530	1107.38	48.44
J- 123	1106.72	49.10	J- 261	1086.63	69.19	J- 552	1073.04	**82.78**
J- 124	1106.07	49.75	J- 273	1103.44	52.38	J- 591	1060.97	**94.85**
J- 126	1084.53	71.29	J- 274	1099.80	56.02	J- 599	1109.16	46.66
J- 127	1090.16	65.66	J- 276	1084.18	71.64	J- 632	1094.62	61.20
J- 129	1082.87	72.95	J- 289	1110.07	45.75	J- 685	1102.70	53.12
J- 137	1090.46	65.36	J- 317	1069.98	**85.84**	J- 688	1088.34	67.48
J- 150	1101.44	54.38	J- 318	1067.44	**88.38**	J- 698	1082.29	73.53
J- 151	1104.68	51.14	J- 320	1079.18	76.64	J- 730	1076.59	79.23
J- 156	1109.30	46.52	J- 321	1068.43	**87.39**	J- 744	1051.74	**104.08**
J- 172	1090.32	65.50						

In Table 6.1, the static heads higher than 80 m are shown in bold characters. These nodes are potential excess pressure points for Yayla network. When the sum of the static head differences above 80 m is calculated using formula below, the potential excess pressures are found to be 151.32 m.

$$Upper\ Limit\ of\ Excess\ Pressures = \sum_{\mathrm{i=1}}^{\mathrm{Nn}} \{P_i - 80 \quad if \quad P_i > 80\} = 151.32 \text{ m}$$

This value is theoretically unreachable under operation of network. Since, the flows produce head losses; the excess pressure sum will be lower than 151.32 m. In the the following sections, the summation of excess pressures will be calculated to indicate the effectiveness of the pressure minimization studies.

Yayla network consists of 107 pipes and 89 nodes. There are no pumps or tanks in the network. The general layout of Yayla District is shown in Figure 4.8. Topographically, the center of the network has the higher elevations, which is the low pressure region. The outer sides, especially the south region has lower elevations which is a potential high pressure area. The general layout of Yayla network with the nodal elevations color map is shown in Figure 6.1.

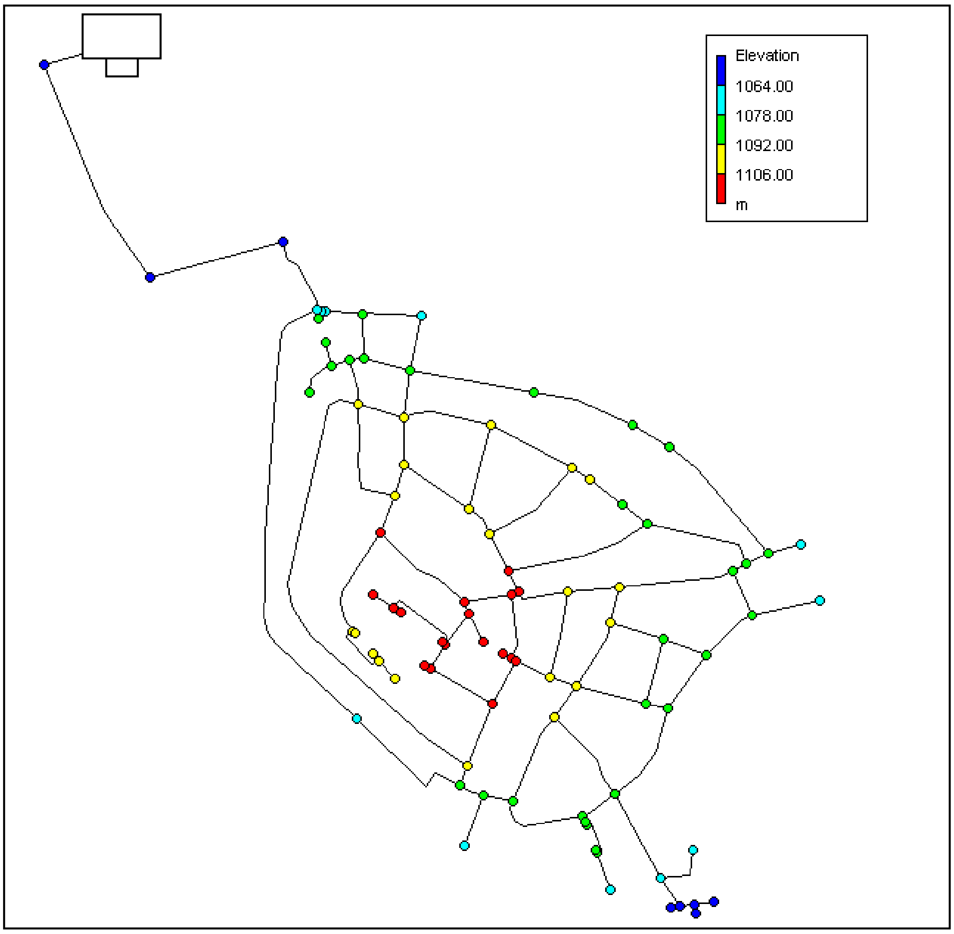


Figure 6.1. Nodal Elevations View of Yayla Network

6.1.1 Determination of Valve Locations

6.1.1.1 Steady State Studies

In the first step of valve locating studies (i_i), network is run under SS conditions. For studies in SS condition, beginning of all pipes are considered to be potential valve locations. At this step, it is only aimed to select which valves are effective for pressure minimization. While applying the optimization method in SS, the demand loadings are chosen for instant time. The daily demands of Yayla network are shown in Table 6.2 and in Figure 6.2. To reflect the characteristics of the whole daily demands into steady state in an efficient way, the minimum and maximum hour demands are taken into consideration.

Table 6.2. Total Daily Demands of Yayla District Metered Area

Total Daily Demands of Yayla District				
Time of Day (hr)	Hourly Total Demand (l/s)		Time of Day (hr)	Hourly Total Demand (l/s)
0	6.15		12	9.73
1	3.97		13	9.53
2	2.81		14	8.3
3	**2.72**		15	7.22
4	2.88		16	7.72
5	3.92		17	8.34
6	5.85		18	8.26
7	7.64		19	9.28
8	6.44		20	8.3
9	7.06		21	7.47
10	9.15		22	8.47
11	**10.25**		23	8.43

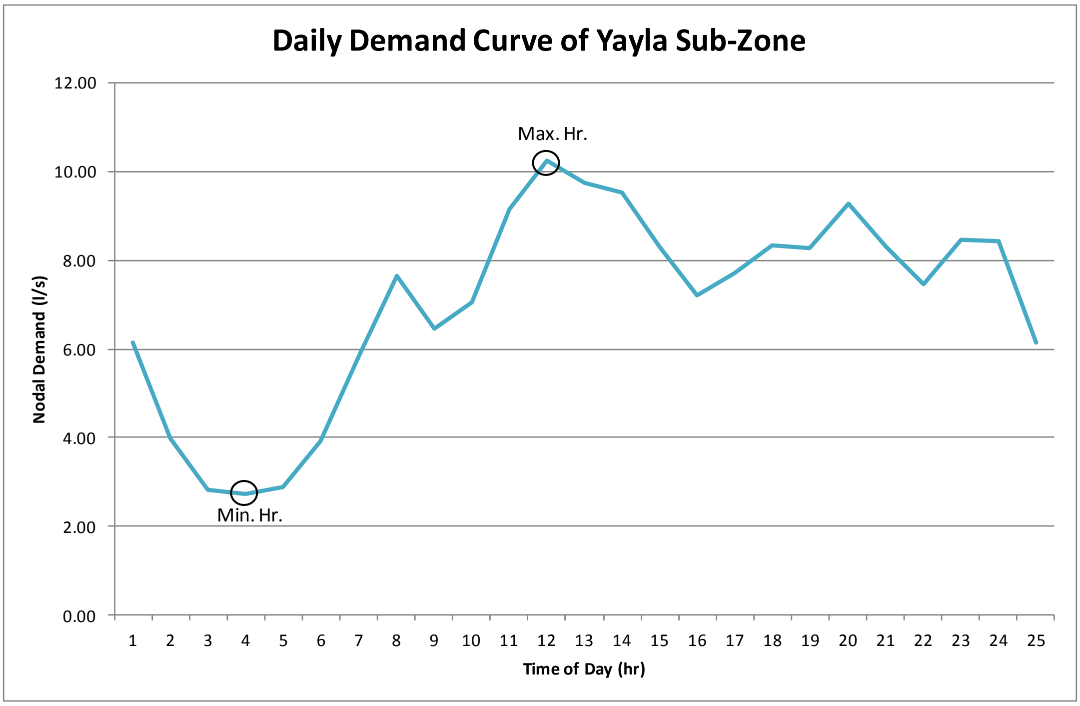
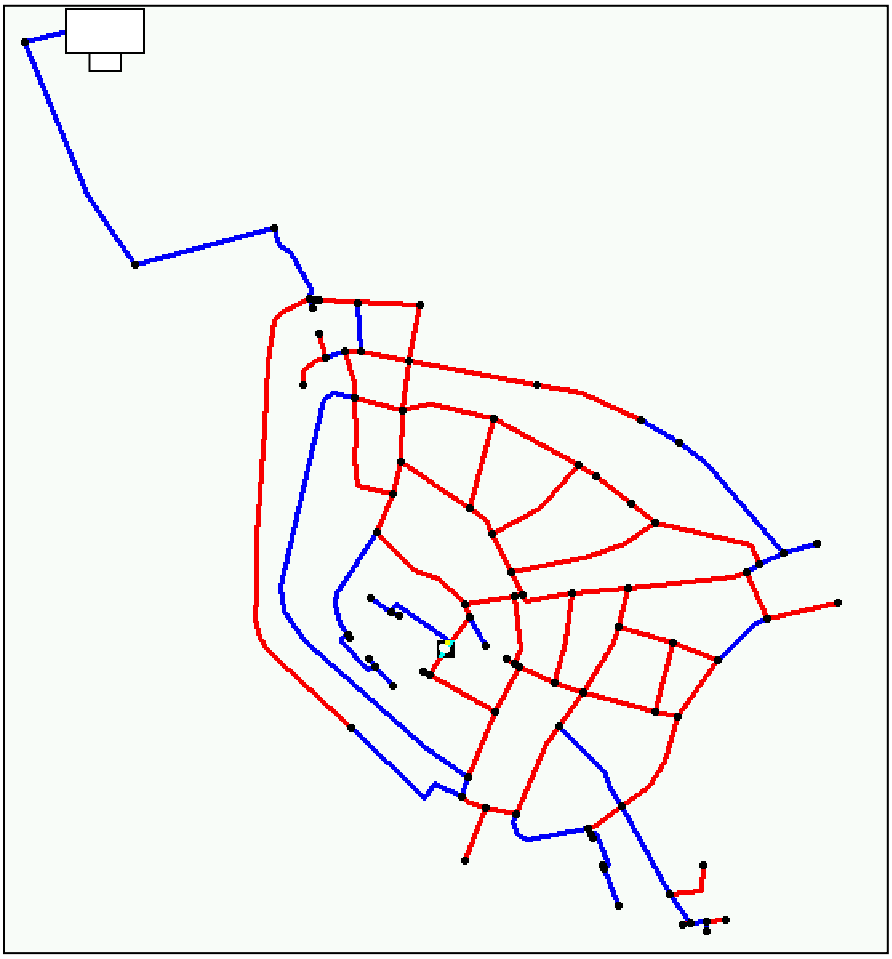


Figure 6.2. Daily Demand Curve of Yayla District Metered Area

VOGA is applied to Yayla network 25 times for each minimum and maximum hour demand loadings. Then, results of 50 runs are examined. These results indicate, which valves are selected to be open or closed for each demand loading. To investigate the results conveniently, the closure percentages of valves are grouped using 5% intervals. These intervals indicate the selected "closed" frequency of each valve (pipe). For example, if Pipe 11 is decided to be closed 20 times out of 50 runs; its closure percentage becomes (20/50) 40%. As stated in example, closure percentage for all pipes are found and shown in Table 6.3. It can also be seen from Table 6.3 that, there are 43 pipes which are kept open in all of the runs. The remaining (64 pipes) are selected to be potential locations for operation of isolation valves. The valves which are kept open and closed at least once are shown in Figure 6.3. The importance of Figure 6.3 lies on the fact that; blue colored pipes (valve) indicate the needless to operate valves. For all trials, these valves are left in open status. Thus, closure of these valves result in unrecoverable situations for the network.

Table 6.3. Closure Percentages of Pipes

ID of Pipe	Closure Number (out of 50 runs)	Closure Percentage	ID of Pipe	Closure Number (out of 50 runs)	Closure Percentage	ID of Pipe	Closure Number (out of 50 runs)	Closure Percentage
Pipe 1	0	0%	Pipe 37	10	20%	Pipe 73	2	4%
Pipe 2	0	0%	Pipe 38	46	92%	Pipe 74	27	54%
Pipe 3	11	22%	Pipe 39	8	16%	Pipe 75	0	0%
Pipe 4	34	68%	Pipe 40	33	66%	Pipe 76	4	8%
Pipe 5	0	0%	Pipe 41	21	42%	Pipe 77	0	0%
Pipe 6	0	0%	Pipe 42	21	42%	Pipe 78	0	0%
Pipe 7	0	0%	Pipe 43	3	6%	Pipe 79	2	4%
Pipe 8	0	0%	Pipe 44	13	26%	Pipe 80	0	0%
Pipe 9	1	2%	Pipe 45	0	0%	Pipe 81	0	0%
Pipe 10	0	0%	Pipe 46	12	24%	Pipe 82	0	0%
Pipe 11	20	40%	Pipe 47	3	6%	Pipe 83	8	16%
Pipe 12	19	38%	Pipe 48	0	0%	Pipe 84	1	2%
Pipe 13	15	30%	Pipe 49	0	0%	Pipe 85	2	4%
Pipe 14	1	2%	Pipe 50	11	22%	Pipe 86	0	0%
Pipe 15	40	80%	Pipe 51	14	28%	Pipe 87	0	0%
Pipe 16	16	32%	Pipe 52	5	10%	Pipe 88	0	0%
Pipe 17	2	4%	Pipe 53	26	52%	Pipe 89	0	0%
Pipe 18	10	20%	Pipe 54	0	0%	Pipe 90	0	0%
Pipe 19	5	10%	Pipe 55	0	0%	Pipe 91	0	0%
Pipe 20	13	26%	Pipe 56	3	6%	Pipe 92	0	0%
Pipe 21	21	42%	Pipe 57	14	28%	Pipe 93	0	0%
Pipe 22	0	0%	Pipe 58	0	0%	Pipe 94	0	0%
Pipe 23	0	0%	Pipe 59	14	28%	Pipe 95	0	0%
Pipe 24	0	0%	Pipe 60	2	4%	Pipe 96	0	0%
Pipe 25	6	12%	Pipe 61	24	48%	Pipe 97	0	0%
Pipe 26	13	26%	Pipe 62	12	24%	Pipe 98	0	0%
Pipe 27	6	12%	Pipe 63	14	28%	Pipe 99	1	2%
Pipe 28	1	2%	Pipe 64	1	2%	Pipe 100	0	0%
Pipe 29	0	0%	Pipe 65	0	0%	Pipe 101	0	0%
Pipe 30	16	32%	Pipe 66	1	2%	Pipe 102	0	0%
Pipe 31	23	46%	Pipe 67	0	0%	Pipe 103	10	20%
Pipe 32	1	2%	Pipe 68	3	6%	Pipe 104	11	22%
Pipe 33	1	2%	Pipe 69	6	12%	Pipe 105	5	10%
Pipe 34	0	0%	Pipe 70	5	10%	Pipe 106	21	42%
Pipe 35	0	0%	Pipe 71	6	12%	Pipe 107	7	14%
Pipe 36	35	70%	Pipe 72	23	46%			



: Closed At Least Once : Open Through All Runs

Figure 6.3. Valves (Pipes) Closed At Least Once

The data shown in Table 6.3 is transformed into percentage intervals and given in Table 6.4. This table shows the list of valves with their corresponding closure percentage groups. The "X" sign indicate the valve is included in the indicated closure percentage group. For example pipe 4 lies in the closure percentage groups of ≤65%. If this pipe is checked from Table 6.3; its closure percentage could be seen as 68%.

Table 6.4. The List of Closed Pipes with Percentage Groups

	CLOSURE PERCENTAGES																			
ID of Pipe	CP>0 %	CP> 5 %	CP> 10 %	CP> 15 %	CP> 20 %	CP> 25 %	CP> 30 %	CP> 35 %	CP> 40 %	CP> 45 %	CP> 50 %	CP> 55 %	CP> 60 %	CP> 65 %	CP> 70 %	CP> 75 %	CP> 80 %	CP> 85 %	CP> 90 %	CP> 95 %
Pipe 1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 3	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-
Pipe 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 9	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 11	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 12	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 13	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 14	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 15	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-
Pipe 16	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 17	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 18	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 19	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 20	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 21	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-
Pipe 22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 25	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 26	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 27	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 28	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 30	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 31	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
Pipe 32	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 33	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 36	X	X	X	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-
Pipe 37	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 38	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	-
Pipe 39	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 40	X	X	X	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-
Pipe 41	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-
Pipe 42	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-
Pipe 43	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 44	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 46	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 47	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 48	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 49	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 50	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 51	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 52	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 53	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-
Pipe 54	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 6.4. (Cont'd)

ID of Pipe	CLOSURE PERCENTAGES																			
	CP>0 %	CP> 5 %	CP> 10 %	CP> 15 %	CP> 20 %	CP> 25 %	CP> 30 %	CP> 35 %	CP> 40 %	CP> 45 %	CP> 50 %	CP> 55 %	CP> 60 %	CP> 65 %	CP> 70 %	CP> 75 %	CP> 80 %	CP> 85 %	CP> 90 %	CP> 95 %
Pipe 55	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 56	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 57	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 58	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 59	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 60	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 61	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
Pipe 62	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 63	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 64	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 65	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 66	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 67	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 68	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 69	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 70	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 71	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 72	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-
Pipe 73	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 74	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-
Pipe 75	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 76	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 77	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 78	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 79	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 80	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 81	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 82	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 83	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 84	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 85	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 86	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 87	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 88	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 89	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 91	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 92	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 93	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 94	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 97	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 98	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 99	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 100	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 101	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 102	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 103	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 104	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 105	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 106	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-
Pipe 107	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	64	50	41	36	31	26	18	16	14	10	7	5	5	5	2	2	1	1	1	0
X: Selected -: Not Selected																				

6.1.1.2 Extended Period Simulation Studies

After gathering the closure percentage of each pipe, the second step (i_{ii}) of the valve locating methodology is applied under EPS conditions. At this step, the objective is the same; excess pressure minimization. However, the variables are not the locations of valves, but the status of valves. In SS studies, the locations of valves with corresponding closure percentages were found. In EPS studies, the groups of valves with closure percentages are used with 5% increment steps and the status of previously located valves becomes variable.

To explain the method; the valves located with corresponding closure percentages are defined as decision variables for EPS runs. For example, for closure percentage of 20 %, the pipes given in Table 6.4 are considered to have valves on them and the status of these valves for 24 hour run time duration becomes decision variable. The GAs, try to minimize the excess nodal pressures by changing the statuses of these valves.

The program is run using the given objective function and constraints using the list of pipes defined and results are obtained The tables (Table 6.5 to Table 6.13) indicating which valves are closed in which period of day is given in the following pages by 5% increment steps. The cells with “0” means, the valve is closed during that time step, while “1” means it is open.

Table 6.5. Status of Valves for the Closure of >0 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	1	1	1	1	1	1	0	1	0	1	1	1	1	0	1	0	1	0	1	0	1	1	1	0
Pipe 4	1	1	1	1	1	0	0	1	1	0	1	0	1	0	0	1	1	0	1	1	1	1	1	1
Pipe 9	1	1	0	0	0	0	0	1	1	0	1	1	1	1	0	0	1	0	1	1	1	0	1	1
Pipe 11	1	1	1	1	1	0	1	0	0	1	1	1	0	0	1	1	0	1	0	1	0	0	1	1
Pipe 12	0	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
Pipe 13	1	1	0	0	1	1	1	1	0	1	1	1	0	1	1	1	1	0	1	0	1	1	0	1
Pipe 14	1	0	0	1	1	0	0	1	1	1	0	1	0	1	0	1	0	0	1	1	1	1	1	0
Pipe 15	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1
Pipe 16	1	1	1	1	0	0	1	0	1	0	1	1	1	1	0	1	1	1	1	1	1	1	0	1
Pipe 17	0	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Pipe 18	0	1	1	1	0	0	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
Pipe 19	0	1	1	0	0	1	1	1	1	0	0	1	1	0	1	1	1	1	1	0	1	0	1	0
Pipe 20	0	0	1	1	1	0	1	1	1	0	1	1	0	1	1	1	0	0	1	0	0	1	1	1
Pipe 21	1	1	0	1	0	1	1	1	0	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1
Pipe 25	1	0	1	0	0	1	1	1	0	1	1	0	1	1	0	1	1	1	0	0	0	1	1	1
Pipe 26	1	1	1	1	1	1	1	1	0	1	0	1	1	0	1	1	1	1	1	0	1	0	1	1
Pipe 27	0	1	1	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	0	1	1
Pipe 28	1	0	0	1	1	0	0	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0
Pipe 30	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	1	0	1	1	1
Pipe 31	1	0	0	1	0	1	0	0	0	0	1	0	1	1	1	1	1	1	1	1	0	1	1	0
Pipe 32	0	1	1	0	1	0	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	0	1
Pipe 33	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0
Pipe 36	1	0	1	1	0	1	0	1	1	0	0	0	1	1	0	1	1	1	1	1	1	1	1	0
Pipe 37	0	0	0	1	1	1	1	0	1	1	1	0	1	1	1	1	0	1	0	1	0	0	1	0
Pipe 38	1	1	1	1	0	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
Pipe 39	1	0	0	0	1	1	0	1	0	1	0	1	1	1	0	0	0	0	1	1	1	1	1	1
Pipe 40	0	1	0	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1
Pipe 41	1	1	1	1	1	1	1	0	1	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1
Pipe 42	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	0	1	1	0	1	1
Pipe 43	0	1	0	1	1	0	1	1	0	1	0	0	1	1	1	1	0	0	0	1	1	1	1	0
Pipe 44	1	1	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1	0	1	1	1	1
Pipe 46	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0
Pipe 47	1	0	0	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1
Pipe 50	1	1	1	1	1	1	0	0	0	1	0	1	1	1	1	1	0	1	1	1	1	0	0	1
Pipe 51	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	0	1	1	0	1	1	1
Pipe 52	1	1	0	1	1	0	0	1	0	0	1	0	0	0	0	0	1	1	1	0	1	0	1	1
Pipe 53	1	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0
Pipe 56	1	0	1	1	1	1	0	0	0	0	1	1	1	1	1	0	1	0	1	0	0	0	0	0
Pipe 57	0	1	1	0	0	1	1	0	1	1	1	1	0	0	0	0	0	1	1	0	1	1	1	1
Pipe 59	0	0	0	0	1	1	1	1	1	1	0	1	0	1	1	1	0	0	0	0	1	1	1	0
Pipe 60	1	0	0	1	1	0	1	1	1	0	0	1	1	1	0	1	1	1	0	1	1	0	0	1
Pipe 61	1	0	1	0	0	1	0	1	0	1	0	0	1	1	1	0	1	0	1	1	1	0	0	1
Pipe 62	1	1	1	1	0	1	1	0	1	0	0	1	1	0	1	0	0	1	1	0	1	1	1	1
Pipe 63	1	0	1	0	0	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	0	1	0
Pipe 64	0	0	1	0	1	1	1	0	1	1	0	1	1	1	1	0	1	0	1	0	1	1	1	1
Pipe 66	0	0	1	0	1	0	1	0	0	1	1	1	1	1	1	0	1	0	1	0	0	1	1	0
Pipe 68	1	1	1	0	1	0	1	0	0	0	1	1	0	0	1	0	1	0	1	1	1	0	0	0
Pipe 69	1	0	1	1	0	0	0	1	1	0	1	1	1	0	0	1	1	1	1	1	1	0	0	1
Pipe 70	1	1	1	0	1	0	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1	0	0
Pipe 71	1	1	1	1	0	1	0	0	1	0	1	1	0	0	1	1	1	0	1	0	1	0	0	1
Pipe 72	0	1	1	1	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0
Pipe 73	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	0	0
Pipe 74	1	1	0	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	1	0	1	1	1
Pipe 76	1	1	0	0	1	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	0	1
Pipe 79	1	0	0	1	1	0	0	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	1
Pipe 83	1	1	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1
Pipe 84	1	1	1	0	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	1	0	1	0	1
Pipe 85	1	1	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1
Pipe 99	1	1	1	1	1	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
Pipe 103	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	0
Pipe 104	1	1	1	0	1	0	0	1	1	1	1	0	1	0	1	0	0	1	1	1	0	0	1	1
Pipe 105	0	1	0	1	1	1	0	1	1	1	1	0	0	1	1	1	0	0	1	1	1	0	1	1
Pipe 106	1	0	0	1	1	1	0	1	1	0	0	1	1	1	1	0	1	1	1	0	1	1	0	0
Pipe 107	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1

Table 6.6. Status of Valves for the Closure of >5 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	1	1	0	0	1	1
Pipe 4	1	0	1	1	0	1	0	1	0	0	1	1	1	1	1	0	1	1	1	0	1	1	1	0
Pipe 11	1	1	0	1	0	0	1	1	1	0	1	0	0	1	1	1	1	1	0	1	1	0	0	1
Pipe 12	0	1	0	1	1	0	1	1	0	1	1	1	1	1	0	0	1	1	1	0	0	0	0	1
Pipe 13	1	1	0	0	0	0	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1	1	1	1
Pipe 15	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1
Pipe 16	1	0	0	1	1	1	1	1	0	0	0	1	1	0	0	1	0	0	0	0	0	1	1	1
Pipe 18	1	1	0	1	1	1	1	1	1	1	0	0	1	0	1	0	1	1	1	1	1	1	0	0
Pipe 19	1	1	1	0	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	0	0	1	1	0
Pipe 20	1	1	1	0	1	0	0	1	0	0	0	1	0	1	1	1	0	1	0	1	1	0	1	1
Pipe 21	1	1	0	1	0	1	1	1	1	0	1	0	0	1	0	1	1	0	0	1	1	0	1	1
Pipe 25	0	1	0	1	1	0	0	1	0	1	1	1	0	0	0	1	0	0	1	0	0	1	0	0
Pipe 26	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	0	0
Pipe 27	1	1	1	0	0	0	1	1	0	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0
Pipe 30	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	0	1
Pipe 31	1	1	1	1	1	1	0	1	1	1	1	0	1	1	0	0	0	1	1	1	0	1	1	1
Pipe 36	0	1	1	1	1	0	1	0	1	1	0	1	0	0	1	1	1	1	1	1	1	1	1	0
Pipe 37	1	1	1	1	1	0	1	0	1	0	0	1	1	0	1	0	0	0	0	1	1	1	0	1
Pipe 38	1	1	0	0	0	1	0	0	1	0	1	0	1	1	1	0	0	1	1	0	0	0	1	0
Pipe 39	1	1	1	0	1	0	1	1	0	0	1	1	1	1	0	1	1	0	1	1	0	1	1	1
Pipe 40	0	0	1	1	1	1	1	0	1	0	1	1	1	0	1	1	1	0	1	0	1	1	0	0
Pipe 41	1	1	1	0	0	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0
Pipe 42	1	1	1	1	1	1	1	1	0	0	0	1	0	1	1	1	1	1	1	0	1	1	0	1
Pipe 43	1	0	0	0	0	1	1	0	0	1	1	0	1	1	0	0	0	1	1	0	1	1	1	1
Pipe 44	0	1	1	0	0	0	0	0	1	0	1	0	0	1	1	1	0	0	0	1	1	0	0	0
Pipe 46	0	0	1	0	1	1	0	0	1	0	0	0	0	1	0	1	0	0	1	0	0	1	0	0
Pipe 47	0	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1
Pipe 50	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
Pipe 51	1	0	0	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	0	0	1	0	1	0
Pipe 52	0	0	0	0	0	1	0	0	0	0	1	0	1	1	1	1	0	1	1	0	0	0	0	1
Pipe 53	0	0	1	0	0	0	1	0	1	1	1	1	1	0	0	0	0	0	1	1	1	0	1	1
Pipe 56	0	0	0	1	1	1	1	1	1	0	0	1	0	1	1	0	1	0	0	1	0	0	1	0
Pipe 57	1	0	1	1	0	1	1	0	1	1	1	1	1	0	1	0	1	1	1	1	1	1	0	0
Pipe 59	1	0	0	1	1	1	1	1	0	1	1	1	0	0	1	0	0	1	1	1	1	1	1	0
Pipe 61	0	1	1	0	0	1	1	0	1	1	0	1	1	1	0	1	1	0	0	1	0	0	1	1
Pipe 62	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	0
Pipe 63	0	0	0	1	1	0	1	1	0	1	0	1	1	1	1	0	1	1	0	0	1	1	0	1
Pipe 68	1	0	0	1	0	1	1	0	0	1	0	1	0	1	0	0	1	1	1	0	1	1	0	1
Pipe 69	0	1	1	1	1	1	1	1	1	0	1	0	0	1	1	0	1	1	0	0	0	1	0	1
Pipe 70	0	0	0	1	1	1	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0	1	0
Pipe 71	0	0	0	1	1	1	0	0	0	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1
Pipe 72	1	0	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1
Pipe 74	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	0	1	1	1	1	1	1
Pipe 76	1	1	1	0	0	1	0	1	0	0	0	0	1	0	0	1	0	0	0	0	1	1	0	0
Pipe 83	1	0	0	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	0	1
Pipe 103	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Pipe 104	1	1	0	1	1	1	1	1	0	1	1	0	0	0	1	0	1	1	0	0	0	1	1	1
Pipe 105	1	0	0	0	1	1	0	0	1	1	0	0	1	1	1	0	1	1	1	1	0	1	1	1
Pipe 106	1	1	1	0	1	1	1	0	0	1	1	1	1	0	1	1	0	1	0	0	1	1	1	1
Pipe 107	0	1	1	1	0	1	0	1	1	0	1	1	1	1	0	1	0	1	1	1	1	0	0	1

Table 6.7. Status of Valves for the Closure of >10 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	1	0	1	1	1	1	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	0	0	1
Pipe 4	0	1	1	0	1	0	1	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1	1	0
Pipe 11	1	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	0	1	1	1
Pipe 12	0	1	0	0	0	0	1	1	0	1	1	1	1	0	0	1	0	1	1	1	0	1	1	1
Pipe 13	0	1	1	0	0	1	1	0	0	0	0	1	0	0	1	0	0	1	0	1	1	1	0	0
Pipe 15	0	0	1	0	1	0	0	1	1	1	1	0	1	1	1	0	1	0	0	1	0	0	1	1
Pipe 16	1	1	1	0	0	1	0	0	0	1	0	0	1	0	1	0	1	0	1	0	0	1	1	0
Pipe 18	1	1	1	1	0	1	1	1	0	0	0	1	0	1	0	1	0	1	1	0	1	1	1	0
Pipe 20	0	0	1	1	1	0	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	1	0	0
Pipe 21	0	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	0	1	1
Pipe 25	1	0	0	0	0	1	1	0	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	1
Pipe 26	1	1	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
Pipe 27	1	0	0	1	1	0	1	0	1	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1
Pipe 30	1	1	1	0	1	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	0
Pipe 31	1	0	0	1	0	1	0	0	1	0	0	1	1	1	1	0	0	0	0	0	0	1	0	1
Pipe 36	1	1	0	1	0	1	1	1	0	1	0	1	0	1	1	0	0	1	0	1	1	1	0	1
Pipe 37	0	0	0	1	1	1	0	1	1	1	1	1	1	0	1	0	0	0	1	1	1	0	0	1
Pipe 38	0	1	1	1	1	1	0	0	0	1	1	0	1	1	1	0	1	0	0	1	0	0	1	1
Pipe 39	1	1	1	1	0	1	1	1	0	1	1	1	1	0	0	0	1	0	1	1	1	1	0	1
Pipe 40	0	0	0	0	1	1	0	0	1	1	1	1	0	1	1	1	0	0	1	1	0	1	1	0
Pipe 41	1	0	1	1	1	0	0	1	1	1	1	0	0	0	0	0	1	0	0	1	1	0	0	1
Pipe 42	0	1	1	1	1	0	1	1	1	0	0	1	0	1	1	0	1	1	1	1	1	0	1	0
Pipe 44	1	0	0	1	1	1	1	1	1	0	1	0	0	1	0	1	1	1	0	1	1	1	1	0
Pipe 47	1	1	0	1	0	1	0	1	1	0	0	1	1	1	1	0	0	1	1	0	0	1	1	1
Pipe 50	0	0	1	1	1	0	1	1	0	0	1	0	1	0	1	1	0	1	0	0	1	1	0	0
Pipe 51	1	0	1	1	0	0	1	0	1	1	1	0	1	1	0	0	1	1	1	0	0	1	1	0
Pipe 53	1	1	0	1	0	1	0	1	0	0	0	0	0	1	0	1	1	1	0	0	0	1	1	1
Pipe 57	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0
Pipe 59	1	1	0	0	0	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	1	1	1	1
Pipe 61	1	1	1	1	0	1	1	1	1	0	1	1	0	0	0	1	1	1	0	0	1	0	0	0
Pipe 62	1	1	1	0	1	1	1	0	1	1	1	1	0	0	1	1	0	1	1	0	1	0	0	0
Pipe 63	1	1	0	0	1	0	0	1	0	1	1	0	1	1	0	0	1	0	0	1	0	1	1	1
Pipe 69	0	1	0	0	1	1	0	1	0	0	1	0	1	1	1	1	0	0	0	0	1	0	0	1
Pipe 71	0	0	1	0	1	0	0	1	0	1	1	0	0	0	0	1	1	1	1	0	0	0	0	0
Pipe 72	0	0	0	1	1	0	0	1	1	1	0	1	0	0	1	1	1	1	1	0	1	1	1	1
Pipe 74	1	1	1	1	1	0	0	0	1	1	0	1	0	0	1	1	0	0	1	0	1	0	0	0
Pipe 83	1	0	1	0	1	0	1	0	1	1	1	0	1	0	0	1	1	1	1	0	0	0	1	0
Pipe 103	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	0	1	1
Pipe 104	1	1	0	0	0	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	0	1	1
Pipe 106	0	0	0	1	0	1	0	0	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	0
Pipe 107	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	0	0	0	1	0	0	1	1

Table 6.8. Status of Valves for the Closure of >15 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	1	1	0	1	0	1	1	0	0	1	1	0	1	1	0	1	1	0	1	1	1	0	1	1
Pipe 4	1	1	1	0	1	0	0	1	1	1	0	1	1	0	1	0	0	1	0	0	0	1	0	0
Pipe 11	0	0	1	0	0	1	0	0	1	0	1	1	0	1	1	0	0	0	1	1	1	0	0	0
Pipe 12	1	1	1	1	0	0	0	1	1	1	0	1	1	1	1	0	0	1	0	1	1	1	1	1
Pipe 13	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	1	0
Pipe 15	0	1	0	1	1	1	0	1	0	0	0	1	0	0	1	0	1	0	1	0	0	0	0	1
Pipe 16	1	1	1	1	1	0	1	1	1	1	1	0	0	0	1	1	1	0	1	1	0	1	0	0
Pipe 18	1	0	1	0	0	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	0
Pipe 20	0	1	0	1	0	1	0	1	1	0	1	0	0	1	0	0	1	1	1	1	0	1	1	1
Pipe 21	0	0	1	0	0	0	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	1	0	1
Pipe 26	1	0	0	1	0	1	1	0	1	1	1	1	0	0	1	1	0	1	0	0	0	0	0	1
Pipe 30	0	0	1	0	1	1	0	0	1	1	0	1	1	0	0	1	1	1	0	0	1	1	1	1
Pipe 31	1	1	1	1	1	0	1	1	0	1	1	0	1	0	0	0	0	0	0	0	0	1	1	0
Pipe 36	1	0	0	0	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1
Pipe 37	1	0	0	0	1	0	1	1	1	0	0	0	0	1	1	0	0	0	0	1	1	0	1	1
Pipe 38	1	0	0	0	0	0	1	0	1	0	1	1	0	0	1	0	0	0	1	1	1	1	1	1
Pipe 39	1	1	0	1	1	1	0	0	0	0	0	0	1	1	0	1	0	0	0	0	1	0	1	0
Pipe 40	1	0	1	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0	0	0	0	0
Pipe 41	1	0	0	0	0	1	1	1	0	1	1	1	1	1	0	1	0	1	1	1	0	0	0	0
Pipe 42	1	0	0	1	0	0	1	1	1	0	0	1	1	0	1	1	1	1	1	0	0	0	1	1
Pipe 44	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	1	0
Pipe 46	1	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	0	0	0	1	1
Pipe 50	1	0	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	0	1	0	1	1	0	0
Pipe 51	0	1	0	0	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0
Pipe 53	0	1	1	0	1	1	0	0	0	0	1	0	1	1	0	0	0	0	1	1	1	1	1	1
Pipe 57	0	0	0	1	0	0	0	1	0	1	1	0	1	1	1	0	0	0	0	1	0	1	0	1
Pipe 59	0	1	0	0	1	1	1	0	1	0	0	1	1	0	0	0	0	1	1	0	1	1	0	1
Pipe 61	1	0	1	0	1	0	1	1	0	1	0	0	0	1	1	1	1	0	0	1	1	0	0	1
Pipe 62	1	0	1	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0	1	1	0	0	1	0
Pipe 63	0	1	0	1	0	0	0	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	0
Pipe 72	0	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	1	1	0	0	0	1	0	1
Pipe 74	0	0	0	1	0	1	0	0	0	1	0	1	0	1	0	1	1	1	1	0	0	1	0	0
Pipe 83	0	1	1	1	0	1	1	0	0	0	1	0	1	0	1	0	0	1	1	0	0	0	0	1
Pipe 103	0	1	1	1	1	0	1	1	0	1	0	0	1	1	0	0	1	1	1	1	1	1	1	0
Pipe 104	0	1	1	0	1	0	0	0	1	0	1	1	1	0	0	0	1	1	0	1	1	0	1	1
Pipe 106	1	1	1	1	1	1	0	1	0	0	1	1	0	1	1	1	1	0	1	1	0	1	1	0

Table 6.9. Status of Valves for the Closure of >20 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	1	1	0	1	0	0	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	0	0
Pipe 4	0	0	1	0	1	1	1	0	0	0	1	0	0	0	0	1	0	1	0	0	0	0	1	1
Pipe 11	0	0	1	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	1	1	1	0	1	1
Pipe 12	1	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1
Pipe 13	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0
Pipe 15	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 16	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	1	0	0	1
Pipe 20	1	1	1	0	1	0	1	1	0	1	0	0	0	0	0	0	1	1	1	0	0	0	1	0
Pipe 21	1	1	0	1	1	1	1	1	0	1	1	1	1	0	1	1	0	0	1	0	0	1	0	1
Pipe 26	1	0	1	1	1	1	0	1	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	1
Pipe 30	0	1	0	1	0	1	1	1	0	1	0	1	1	1	0	1	1	0	1	0	1	0	1	1
Pipe 31	0	0	0	1	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	0	1	1
Pipe 36	0	0	1	1	0	0	0	1	0	0	0	0	0	1	1	0	0	1	0	0	0	1	1	0
Pipe 38	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0	1	0	0	1	1	0	0	0	0
Pipe 40	0	0	0	0	0	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	1	0	0	1
Pipe 41	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Pipe 42	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1	0	1	1	1
Pipe 44	1	0	0	1	1	0	0	0	0	0	1	1	1	0	0	0	1	1	1	0	1	1	1	0
Pipe 46	0	0	1	0	1	0	1	1	1	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0
Pipe 50	0	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
Pipe 51	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	1
Pipe 53	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0	0
Pipe 57	0	0	0	0	0	1	0	0	1	0	0	1	0	1	0	1	1	0	0	1	0	1	1	0
Pipe 59	1	1	1	1	1	1	0	0	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	0
Pipe 61	1	1	0	0	0	1	1	1	1	1	0	1	0	0	1	0	1	1	1	0	0	1	0	1
Pipe 62	0	0	0	0	1	0	0	0	0	1	0	0	1	1	0	1	1	0	0	0	1	1	0	0
Pipe 63	1	1	1	1	0	0	1	0	0	0	1	1	0	0	0	0	1	1	0	1	0	0	1	0
Pipe 72	1	0	1	0	0	1	1	1	1	1	0	1	0	1	1	0	0	0	0	1	1	1	0	0
Pipe 74	1	1	0	1	1	0	0	0	0	1	0	0	1	0	1	0	1	0	0	0	0	0	1	1
Pipe 104	1	0	1	1	0	1	1	1	1	1	0	0	0	0	0	1	1	1	0	1	1	0	0	0
Pipe 106	0	0	1	1	1	1	0	1	1	1	1	0	1	0	1	0	1	1	1	1	1	0	0	1

Table 6.10. Status of Valves for the Closure of >25 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Pipe 11	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0	1	0	0	1
Pipe 12	1	0	0	0	1	0	1	0	1	0	0	0	0	1	0	0	1	1	0	0	0	1	1	1
Pipe 13	0	0	1	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1
Pipe 15	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0
Pipe 16	0	1	1	1	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	1	0	1	0
Pipe 20	1	1	0	0	1	1	0	1	1	1	0	0	1	1	1	1	0	0	1	1	1	0	0	0
Pipe 21	0	1	1	0	0	0	1	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	1	0
Pipe 26	1	1	1	0	0	0	1	1	0	1	1	0	0	1	1	0	0	0	1	1	0	1	1	1
Pipe 30	0	0	1	0	1	1	1	1	0	0	0	0	1	0	0	1	1	0	1	0	1	1	0	1
Pipe 31	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	1	0
Pipe 36	0	0	1	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	1	1	0
Pipe 38	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
Pipe 40	0	0	1	0	0	0	1	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	1	0
Pipe 41	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Pipe 42	1	0	0	1	1	1	0	0	0	0	0	1	1	0	0	1	1	0	1	0	0	0	1	0
Pipe 44	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	1	1	0	1	0	1	0	1
Pipe 51	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	1	0	0	0	0	0	0	0
Pipe 53	0	0	0	0	1	1	0	0	1	0	0	1	0	1	1	1	0	1	0	1	1	0	0	0
Pipe 57	1	0	0	1	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0
Pipe 59	1	1	1	1	0	1	0	1	1	1	1	0	1	1	0	0	0	0	1	1	1	1	0	1
Pipe 61	0	0	1	1	0	1	1	0	0	1	1	0	1	0	1	1	1	0	0	0	0	1	0	0
Pipe 63	0	0	0	0	1	1	0	1	1	0	0	0	0	0	1	0	0	1	1	1	1	0	0	1
Pipe 72	0	1	1	1	0	0	0	0	0	1	1	1	0	0	1	0	1	0	1	1	0	0	0	0
Pipe 74	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 106	1	1	0	1	0	0	1	1	1	1	1	1	0	0	1	0	1	1	0	0	0	0	0	1

Table 6.11. Status of Valves for the Closure of >30 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 11	0	0	1	0	1	1	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	1
Pipe 12	1	0	0	0	0	0	0	0	1	1	0	1	1	1	0	1	0	0	1	0	0	1	0	1
Pipe 15	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Pipe 21	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	0	1	0	0	0	0	0	0
Pipe 30	1	0	1	1	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	1	0	1	0	0
Pipe 31	1	1	1	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0
Pipe 36	0	1	0	1	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0	1	0	1	0	0
Pipe 38	0	0	0	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
Pipe 40	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0
Pipe 41	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
Pipe 42	0	1	0	1	1	1	1	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	1
Pipe 53	0	1	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1	1	1	0	1	0	1	0
Pipe 61	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0
Pipe 74	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Pipe 106	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Table 6.12. Status of Valves for the Closure of >35 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 11	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0	0	0	0	1	1	1	1	1
Pipe 12	1	1	0	1	0	1	0	0	1	1	0	1	1	0	0	1	0	1	0	1	0	0	0	0
Pipe 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Pipe 21	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 31	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
Pipe 36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 38	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0
Pipe 40	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0
Pipe 41	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 42	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Pipe 53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 61	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
Pipe 72	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Pipe 74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 106	0	0	1	0	1	0	0	1	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0

Table 6.13. Status of Valves for the Closure of >40 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

When results of runs from Table 6.5 to Table 6.13 are examined, it could be seen that, valves with closure percentage >40% are needless to operate (see Table 6.13). In other words, all valves with closure percentage >40%, could be kept closed through the 24 hour run time duration without disturbing the hydraulic conformities of the network.

When the results of >35% closure percentage group are inspected (see Table 6.12), it can be seen that some valves are set to open position for some interval(s) during the entire run time duration. The difference between 35% and 40% closure percentages is the statuses of Pipe 11 and Pipe 12. As can be seen from Table 6.12 the GAs, let Pipe 11 and Pipe 12 be more open through the run duration when compared to other pipes. The GAs might have been selected Pipe 11 and 12 open while the rest completely closed; however it did not converge on that type of solution within the generation limit, for >35% closure percentage.

The summary of results of these runs with valve operation penalty including the excess nodal pressures is shown in Table 6.14, Figure 6.4 and Figure 6.5.

Table 6.14. Summary of Results for Valve Locating Study

Valve Closure Selection Interval	Excess Nodal Pressures (m)	Number of Valve Switches	Number of Valves to be Controlled	Average Valve Switch
CP > 0%	4.40E+11	654	64	10.22
CP > 5%	112.47	514	50	10.28
CP > 10%	102.64	466	41	11.37
CP > 15%	103.96	414	36	11.50
CP > 20%	92.39	324	31	10.45
CP > 25%	100.92	268	26	10.31
CP > 30%	94.92	136	18	7.56
CP > 35%	97.87	80	16	5.00
CP > 40%	77.44	0	14	0.00
CP > 45%	89.49	0	10	0.00
CP > 50%	94.06	0	7	0.00
CP > 55%	122.95	0	5	0.00

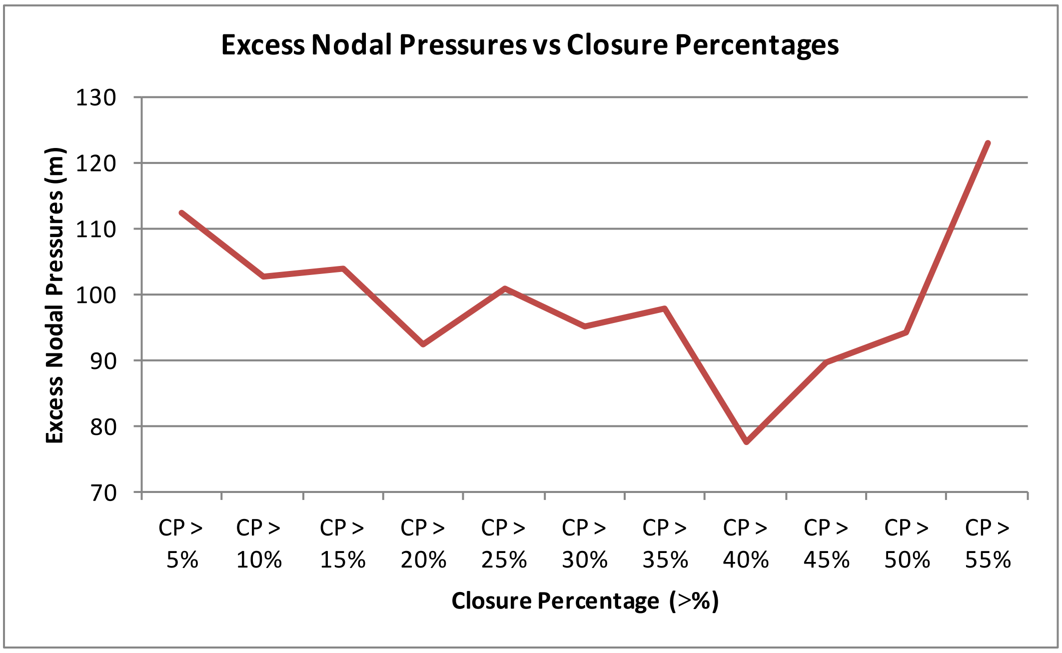


Figure 6.4. Excess Nodal Pressures vs. Closure Percentages

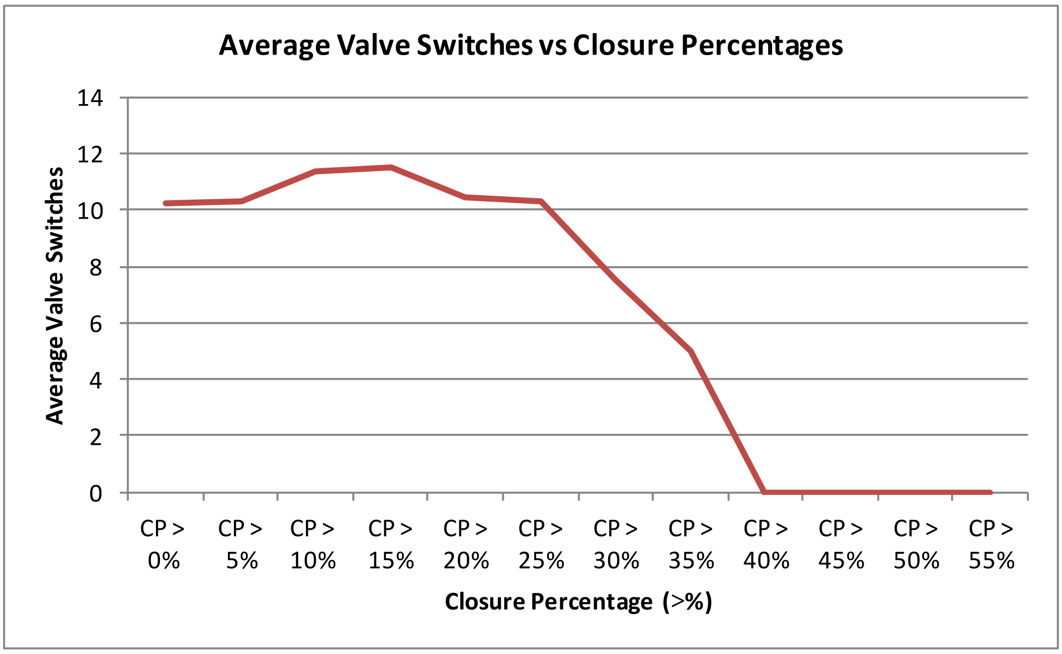


Figure 6.5. Average Valve Switches vs. Closure Percentages

When Table 6.14, Figure 6.4 and Figure 6.5 are investigated; it can be seen that, as the number of valves decreases, the excess nodal pressures also decrease till valve closure of 40%. However, the excess nodal pressures are increased for the valves with closure percentage of 45% and higher as a result of decreased number of valves.

This situation indicate the valves with closure percentage of 40% and higher are needless for operation; to keep the excess pressures at lower levels they should be kept closed through the run period. Additionally, the >40% closure percentage group is considered to be an optimal pressure decrement point.

To visualize the effectiveness of valve locating study, nodal pressures of Yayla are shown for two cases in Table 6.15; all valves open case, and valves with closure percentage >40% are closed case. As can be seen from the results, by closing of those valves, the nodal pressures of almost all nodes have been decreased. When the excess pressures are compared, it can also be seen that, summation of them is decreased at the level of 50%. When direct effect of pressure minimization to leakage reduction is considered; it could be concluded that, closing of valves is a supportive method for leakage reduction.

Table 6.15. Comparison of Nodal Pressures after Valve Locating Study

	No Valves Closed		Valves CP>40% Closed			No Valves Closed		Valves CP>40% Closed	
Node ID	**Nodal Pressure (m)**	**Excess Pressure (m)**	**Nodal Pressure (m)**	**Excess Pressure (m)**	**Node ID**	**Nodal Pressure (m)**	**Excess Pressure (m)**	**Nodal Pressure (m)**	**Excess Pressure (m)**
J - 26	42.82	-	35.05	-	**J - 228**	54.94	-	47.17	-
J - 27	42.70	-	34.93	-	**J - 229**	57.70	-	49.92	-
J - 29	78.28	-	68.81	-	**J - 239**	59.76	-	50.35	-
J - 30	78.38	-	68.91	-	**J - 240**	58.19	-	48.78	-
J - 32	78.73	-	78.73	-	**J - 245**	43.36	-	35.59	-
J - 43	77.16	-	77.16	-	**J - 247**	53.56	-	44.15	-
J - 45	**93.19**	13.19	**83.77**	3.77	**J - 261**	69.00	-	59.58	-
J - 46	**93.25**	13.25	**83.83**	3.83	**J - 273**	52.23	-	44.45	-
J - 48	46.09	-	36.70	-	**J - 274**	55.86	-	48.09	-
J - 49	45.76	-	36.37	-	**J - 276**	71.44	-	62.00	-
J - 51	69.73	-	60.32	-	**J - 289**	45.61	-	37.84	-
J - 52	71.68	-	62.26	-	**J - 317**	**85.61**	5.61	76.19	-
J - 74	69.16	-	59.71	-	**J - 318**	**88.15**	8.15	78.73	-
J - 75	68.48	-	59.03	-	**J - 320**	76.43	-	67.02	-
J - 77	**93.42**	13.42	**84.00**	4.00	**J - 321**	**87.16**	7.16	77.74	-
J - 78	**95.22**	15.22	**85.81**	5.80	**J - 332**	75.15	-	65.69	-
J - 95	64.70	-	62.38	-	**J - 333**	76.92	-	67.47	-
J - 96	61.67	-	59.15	-	**J - 354**	69.55	-	60.09	-
J - 104	61.69	-	53.18	-	**J - 355**	77.58	-	68.12	-
J - 105	60.42	-	51.94	-	**J - 357**	43.60	-	35.83	-
J - 123	48.95	-	39.78	-	**J - 358**	43.80	-	36.03	-
J - 124	49.60	-	40.45	-	**J - 364**	62.45	-	55.60	-
J - 126	71.09	-	61.67	-	**J - 376**	73.79	-	64.36	-
J - 127	65.47	-	56.06	-	**J - 377**	66.87	-	57.46	-
J - 129	72.76	-	63.31	-	**J - 387**	61.41	-	51.96	-
J - 137	65.17	-	55.76	-	**J - 392**	68.49	-	59.03	-
J - 150	54.22	-	44.81	-	**J - 404**	52.56	-	43.16	-
J - 151	50.98	-	41.58	-	**J - 422**	47.35	-	39.58	-
J - 156	46.37	-	38.60	-	**J - 423**	46.88	-	37.49	-
J - 172	65.31	-	55.90	-	**J - 425**	75.45	-	66.02	-
J - 174	65.54	-	56.93	-	**J - 440**	**97.19**	17.19	**87.77**	7.77
J - 175	64.54	-	55.98	-	**J - 467**	78.68	-	69.26	-
J - 177	**93.76**	13.76	**93.76**	13.76	**J - 481**	78.03	-	68.57	-
J - 191	54.93	-	47.15	-	**J - 528**	41.59	-	33.82	-
J - 192	50.92	-	43.15	-	**J - 530**	48.29	-	39.10	-
J - 196	41.34	-	33.57	-	**J - 552**	**82.56**	2.56	73.13	-
J - 197	41.22	-	33.45	-	**J - 591**	**94.64**	14.64	**94.64**	14.64
J - 205	50.97	-	42.49	-	**J - 599**	46.51	-	38.74	-
J - 206	52.41	-	44.49	-	**J - 632**	61.03	-	52.69	-
J - 217	76.44	-	66.99	-	**J - 685**	52.97	-	45.19	-
J - 218	**80.35**	0.35	70.91	-	**J - 688**	67.31	-	57.85	-
J - 223	70.93	-	61.52	-	**J - 698**	73.33	-	63.89	-
J - 224	77.30	-	67.88	-	**J - 730**	79.02	-	77.20	-
J - 226	70.05	-	60.59	-	**J - 744**	**103.86**	23.86	**103.86**	23.86
						TOTAL	**148.35**	**TOTAL**	**77.44**

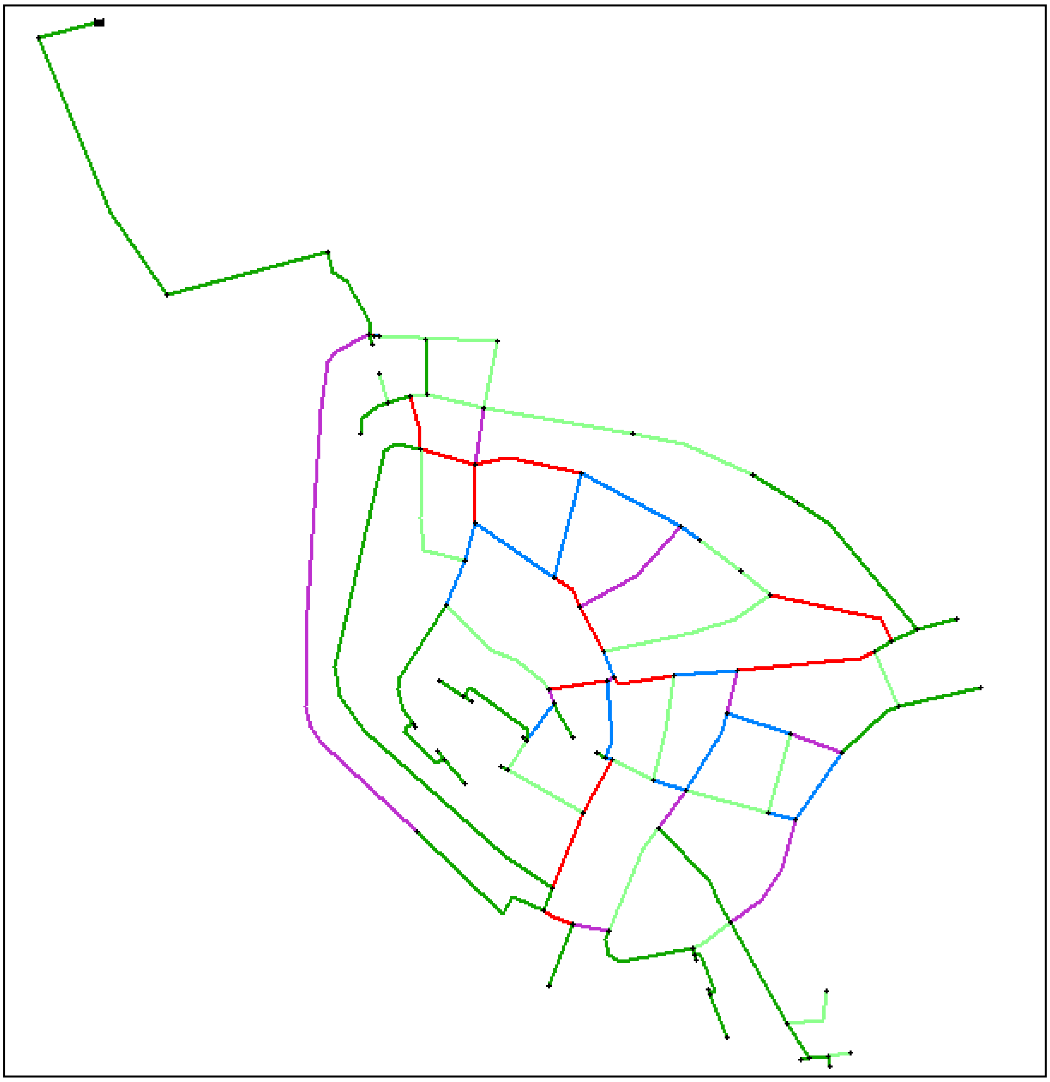
To integrate the outcomes of valve locating studies to the valve opening determination study (2nd step) the valves of Yayla network is divided into groups. While dividing, the valves never been selected to be closed and the valves with closure percentage higher than 40% are kept in fixed status and both types of valves are removed from valve opening determination search space. The rest of the pipes are divided into 3 groups. While grouping these valves, closure percentages are taken into consideration. Including the pipes left in open or closed statuses; all valves are divided totally in 5 groups. These groups are defined below.

Type I:	Closure Percentage = 0 %
Type II:	10 % ≥ Closure percentage > 0%
Type III:	20 % ≥ Closure percentage > 10%
Type IV:	40 % ≥ Closure percentage > 20%
Type V:	Closure Percentage ≥ 40%

The list of pipes including these types is given in Table 6.16 in tabular form and in Figure 6.6 on network with different colors.

Table 6.16. Types of Valves

Type I Closure Percentage = 0 %	Type II 10 % ≥ Closure percentage > 0%	Type III 20 % ≥ Closure percentage > 10%	Type IV 40 % ≥ Closure percentage > 20%	Type V Closure Percentage ≥ 40%	Type I Closure Percentage = 0 %	Type II 10 % ≥ Closure percentage > 0%	Type III 20 % ≥ Closure percentage > 10%	Type IV 40 % ≥ Closure percentage > 20%	Type V Closure Percentage ≥ 40%
1					55				
2						56			
			3					57	
				4	58				
5								59	
6						60			
7									61
8								62	
	9							63	
10						64			
			11		65				
			12			66			
			13		67				
	14					68			
				15			69		
			16			70			
	17						71		
		18							72
	19					73			
			20						74
				21	75				
22						76			
23					77				
24					78				
		25				79			
			26		80				
		27			81				
	28				82				
29							83		
			30			84			
				31		85			
	32				86				
	33				87				
34					88				
35					89				
				36	90				
		37			91				
				38	92				
		39			93				
				40	94				
				41	95				
				42	96				
	43				97				
			44		98				
45						99			
			46		100				
	47				101				
48					102				
49							103		
			50					104	
			51			105			
	52								106
				53			107		
54									



: Type I : Type II : Type III

: Type IV Type V

Figure 6.6. Types of Valves on Network View

6.1.2 Sensitivity Analysis of Valves

To verify the foundings of valve locating studies, sensitivity analysis for valve closing is accomplished. For this measure, each pipe is closed while the rest is open, and the network is run in steady state without introducing GAs. For each closing action of valve, the node pressures are calculated and the difference of node pressures between no closed valve case is calculated. The sum of pressure drops indicates how sensitive the network is to that valve. For representation, the absolute sum of differences and the average of nodal pressure drops for each valve action is shown in Table 6.17. To visualize the result conveniently, this table is sorted for absolute sum of nodal pressure differences in ascending order and shown in Table 6.18.

Table 6.17. Summary of Pipes Sensitivities

Pipe ID	Absolute Sum of Difference of Nodal Pressures (m)	Average of Differencs of Nodal Pressures (m)	Pipe ID	Absolute Sum of Difference of Nodal Pressures (m)	Average of Differencs of Nodal Pressures (m)
1	291,064,575.52	3,307,551.99	55	0.0480	0.0005
2	0.0000	0.0000	56	0.0180	0.0002
3	364.67	4.14	57	0.1270	0.0014
4	369.77	4.20	58	467,054,983.34	5,307,442.99
5	0.0000	0.0000	59	0.2090	0.0024
6	0.0010	0.0000	60	0.0150	0.0002
7	0.0010	0.0000	61	0.2520	0.0029
8	246,953.87	2,806.29	62	0.0060	0.0001
9	0.0010	0.0000	63	0.1000	0.0011
10	0.0180	0.0002	64	0.0280	0.0003
11	0.0880	0.0010	65	1,350,365.81	15,345.07
12	0.0950	0.0011	66	353.5300	4.0174
13	0.0110	0.0001	67	0.0190	0.0002
14	0.0000	0.0000	68	0.0750	0.0009
15	0.0770	0.0009	69	0.0910	0.0010
16	0.0190	0.0002	70	2.9670	0.0337
17	0.1870	0.0021	71	0.0020	0.0000
18	0.0570	0.0006	72	0.0000	0.0000
19	0.0660	0.0008	73	0.8620	0.0098
20	0.7780	0.0088	74	0.3790	0.0043
21	0.1780	0.0020	75	0.3940	0.0045
22	0.0000	0.0000	76	3.0300	0.0344
23	270,132.75	3,069.69	77	305,580,777.93	3,472,508.84
24	0.0000	0.0000	78	2.7020	0.0307
25	0.2610	0.0030	79	0.0060	0.0001
26	0.3250	0.0037	80	0.0010	0.0000
27	0.1580	0.0018	81	471,371,681.76	5,356,496.38
28	0.0040	0.0000	82	0.1590	0.0018
29	300,498.38	3,414.75	83	0.9550	0.0109
30	1.3960	0.0159	84	5.1870	0.0589
31	0.1380	0.0016	85	5.5050	0.0626
32	0.0790	0.0009	86	1.5650	0.0178
33	0.0000	0.0000	87	2.4320	0.0276
34	2.7440	0.0312	88	450,881.04	5,123.65
35	0.0000	0.0000	89	127,673.68	1,450.84
36	4.6700	0.0531	90	3,804.99	43.24
37	0.0040	0.0000	91	0.0010	0.0000
38	1.6770	0.0191	92	570,943.32	6,487.99
39	0.3520	0.0040	93	0.0000	0.0000
40	1.5910	0.0181	94	9,812.50	111.51
41	0.0770	0.0009	95	0.0000	0.0000
42	0.0170	0.0002	96	1,218,623.52	13,847.99
43	0.1470	0.0017	97	0.0000	0.0000
44	0.0110	0.0001	98	7,267.27	82.58
45	0.0010	0.0000	99	0.1360	0.0015
46	0.0170	0.0002	100	8,064.20	91.64
47	339.34	3.86	101	0.0000	0.0000
48	0.0960	0.0011	102	31,836.57	361.78
49	355,564.04	4,040.50	103	0.4330	0.0049
50	0.0490	0.0006	104	0.0480	0.0005
51	0.0410	0.0005	105	0.0160	0.0002
52	0.0070	0.0001	106	0.1680	0.0019
53	0.0390	0.0004	107	0.0070	0.0001
54	0.0000	0.0000			

Type I: Closure Percentage = 0 %
Type II: 10 % ≥ Closure percentage > 0%
Type III: 20 % ≥ Closure percentage > 10%
Type IV: 40 % ≥ Closure percentage > 20%
Type V: Closure Percentage ≥ 40%

Table 6.18. Summary of Pipes Sensitivities (Sorted)

Pipe ID	Absolute Sum of Difference of Nodal Pressures (m)	Average of Differencs of Nodal Pressures (m)
2	0.0000	0.0000
5	0.0000	0.0000
14	0.0000	0.0000
22	0.0000	0.0000
24	0.0000	0.0000
33	0.0000	0.0000
35	0.0000	0.0000
54	0.0000	0.0000
72	0.0000	0.0000
93	0.0000	0.0000
95	0.0000	0.0000
97	0.0000	0.0000
101	0.0000	0.0000
6	0.0010	0.0000
7	0.0010	0.0000
9	0.0010	0.0000
45	0.0010	0.0000
80	0.0010	0.0000
91	0.0010	0.0000
71	0.0020	0.0000
28	0.0040	0.0000
37	0.0040	0.0000
62	0.0060	0.0001
79	0.0060	0.0001
52	0.0070	0.0001
107	0.0070	0.0001
13	0.0110	0.0001
44	0.0110	0.0001
60	0.0150	0.0002
105	0.0160	0.0002
46	0.0170	0.0002
42	0.0170	0.0002
56	0.0180	0.0002
10	0.0180	0.0002
67	0.0190	0.0002
16	0.0190	0.0002
64	0.0280	0.0003
53	0.0390	0.0004
51	0.0410	0.0005
55	0.0480	0.0005
104	0.0480	0.0005
50	0.0490	0.0006
18	0.0570	0.0006
19	0.0660	0.0008
68	0.0750	0.0009
41	0.0770	0.0009
15	0.0770	0.0009
32	0.0790	0.0009
11	0.0880	0.0010
69	0.0910	0.0010
12	0.0950	0.0011
48	0.0960	0.0011
63	0.1000	0.0011
57	0.1270	0.0014
99	0.1360	0.0015
31	0.1380	0.0016
43	0.1470	0.0017
27	0.1580	0.0018
82	0.1590	0.0018
106	0.1680	0.0019
21	0.1780	0.0020
17	0.1870	0.0021
59	0.2090	0.0024
61	0.2520	0.0029
25	0.2610	0.0030
26	0.3250	0.0037
39	0.3520	0.0040
74	0.3790	0.0043
75	0.3940	0.0045
103	0.4330	0.0049
20	0.7780	0.0088
73	0.8620	0.0098
83	0.9550	0.0109
30	1.3960	0.0159
86	1.5650	0.0178
40	1.5910	0.0181
38	1.6770	0.0191
87	2.4320	0.0276
78	2.7020	0.0307
34	2.7440	0.0312
70	2.9670	0.0337
76	3.0300	0.0344
36	4.6700	0.0531
84	5.1870	0.0589
85	5.5050	0.0626
47	339.34	3.86
66	353.53	4.02
3	364.67	4.14
4	369.77	4.20
90	3,804.99	43.24
98	7,267.27	82.58
100	8,064.20	91.64
94	9,812.50	111.51
102	31,836.57	361.78
89	127,673.68	1,450.84
8	246,953.87	2,806.29
23	270,132.75	3,069.69
29	300,498.38	3,414.75
49	355,564.04	4,040.50
88	450,881.04	5,123.65
92	570,943.32	6,487.99
96	1,218,623.52	13,847.99
65	1,350,365.81	15,345.07
1	291,064,575.52	3,307,551.99
77	305,580,777.93	3,472,508.84
58	467,054,983.34	5,307,442.99
81	471,371,681.76	5,356,496.38

Type I: Closure Percentage = 0 %

Type II: 10 % ≥ Closure percentage > 0%

Type III: 20 % ≥ Closure percentage > 10%

Type IV: 40 % ≥ Closure percentage > 20%

Type V: Closure Percentage ≥ 40%

As can be seen from Table 6.18 valves of Type I (green cells), are flocked mainly on the top and bottom of the table. The top of table with zero nodal pressure changes indicate the valves which has no effect on pressure minimization. On the other hand, the bottom of the table contains essential valves, since closing of those strictly violates the hydraulic conformity of network. Also, the cells with red font indicate the closing of that valve resulted in negative pressures through the network. As can be seen, these types of valves selected to be open (Type I).

The valves with closure percentage >40% are shown with red colored cells. Except no 72, valves of Type V consist of effective valves in terms of pressure reduction. Valve 72 seems to have no effect of pressure reducing, but it isolates a region with valve 74, both of which selected to be closed.

Valves of Type III and IV are mainly located at the middle of table with spread distribution. Type II valves have more spread distribution. Also, some valves from this type are placed at the bottom of the table. However, when the topological distribution of these valves (pipes) are considered, pipes 3, 4, 66 and 47 are connected serially. The GAs selected valve 4 to be closed and let the others open. Similarly, pipes 36, 70, 76, 84 and 85 are considered to be serial. Again, GAs selected valve 36 to be closed and let the rest open. If any valves addition to valve 36 is closed, there occur negative pressures. That is the reason why pipes 70, 76, 84 and 85 are left open.

Sensitivity analysis reveal supportive results for the developed GAs. The GAs are capable of locating suitable valve combinations for pressure reducing target.

6.1.3 Determination of Valve Openings

At the second and the final step (ii) of the pressure minimization methodology, Yayla network is re-modeled using the types of valves that are defined in Table 6.16. The valves that are open or closed through the day (Types I and V) are kept with unchanged status, while the others (Types II, III and IV) are changed into Throttle Control Valve, instead of being an isolation valve.

Throttle control valve (TCV) is a type of valve that may produce resistance to flow by throttling itself. The produced resistance (minor loss) is a function of minor loss coefficient and the flow velocity. Often the throttling effect of a particular valve position is known, but the minor loss coefficients as a function of position are unknown.

The formulation of minor loss is given below.

$$h_m = K_L \frac{V^2}{2g} \quad (6.1)$$

Where;

h_m : head loss due to minor loss (m)

K_L : minor loss coefficient

V : flow velocity (m/s)

g : gravitational acceleration constant (9.81 m/s^2)

The K_L values of each valve with respect to opening position could be taken from the manufacturer. For this study, the assumed K_L values are taken from literature and given in Table 6.19.

Table 6.19. Valve Opening Positions and K_L Values (Walski, 2003)

Opening Position	K_L
Valve - open	0.39
3/4 open	1.1
2/4 open	4.8
1/4 open	27

These K_L values are available for 4 different positions of valves. To use for 8 different positions, a polynomial regression is accomplished.

Polynomial regression fits a nonlinear relationship between the value of x and the corresponding conditional mean of y and it is denoted by E(y | x). Here, the dependent variables are valve openings and loss coefficients (K_L). To complete the regression, the valve opening values are turned into opening percentages (see Table 6.20).

Table 6.20. Numerical Valve Opening Values and K_L Coefficients

Opening Position	K_L
100%	0.39
75%	1.1
50%	4.8
25%	27

Using the values given in Table 6.20, polynomial regression is made using Microsoft Excel. As a result of this study, a 3rd order polynomial is handled as shown below.

$y = -165.44x^3 + 396.16x^2 - 313.54x + 83.21$

Where, x and y denotes Valve opening and K_L respectively.

Using this formulation additional K_L values for additional valve openings are calculated. For closed valve (0% opening), polynomial fit value is changed with a very high number. Since, closed valve means there is no flow permitted; the K_L value shall be such a number that produce infinitely high minor loss. That is the reason why K_L value is chosen to be 10^9 for closed valve.

For the coefficient corresponding to 87.5 % opening (7/8 opening), the result of regression is both higher than 75 % opening. Since this is not applicable, loss coefficient corresponding to 87.5 % opening is assumed to be average of 75 % and 100 % opening. Including the calculated loss coefficients, all K_L values with respect to valve openings are shown in Table 6.21. Figure 6.7 shows the used K_L values for each opening.

Table 6.21. Valve Opening Values and K_L Coefficients

Valve Position	Valve Opening (%)	Calculated Loss Coefficient	Used Loss Coefficient
Closed	0.00%	83.21	1.00E+09
1/8 open	12.50%	49.88	49.88
2/8 open	25.00%	27.00	27.00
3/8 open	37.50%	12.62	12.62
4/8 open	50.00%	4.80	4.80
5/8 open	62.50%	1.61	1.61
6/8 open	75.00%	1.10	1.10
7/8 open	87.50%	1.34	0.74
Open	100.00%	0.39	0.39

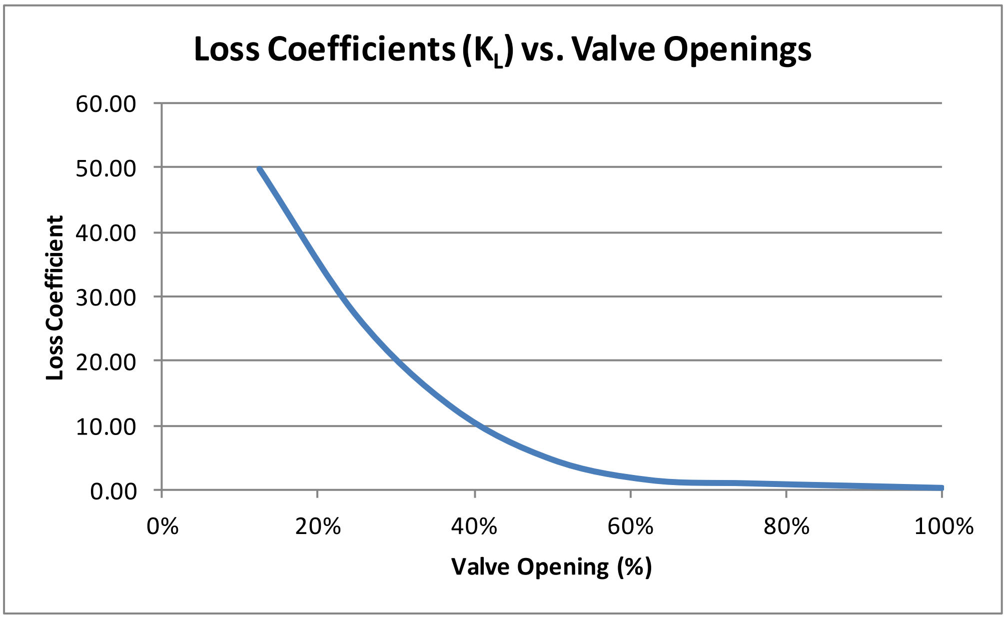


Figure 6.7. Valve Opening Values and K_L Coefficients

As mentioned before, TCVs are grouped into three, according to their closure percentages. At this step, valves with 0% closure percentage are considered to be open while the valves with closure percentages higher than 40% are considered to be closed. The TCV groups are shown in Table 6.22.

Table 6.22. Closed Valves and Groups of TCVs

Closed Valves Closure percentage = 0%	TCV Group I 40 % ≥ Closure percentage > 20%	TCV Group II 40 % ≥ Closure percentage > 10%	TCV Group III 40 % ≥ Closure percentage > 0%	Closed Valves Closure percentage = 0%	TCV Group I 40 % ≥ Closure percentage > 20%	TCV Group II 40 % ≥ Closure percentage > 10%	TCV Group III 40 % ≥ Closure percentage > 0%
	3	3	3				47
4					50	50	50
			9		51	51	51
	11	11	11				52
	12	12	12	53			
	13	13	13				56
			14		57	57	57
15					59	59	59
	16	16	16				60
			17	61			
		18	18		62	62	62
			19		63	63	63
	20	20	20				64
21							66
		25	25				68
	26	26	26			69	69
		27	27				70
			28			71	71
	30	30	30	72			
31							73
			32	74			
			33				76
36							79
		37	37			83	83
38							84
		39	39				85
40							99
41						103	103
42					104	104	104
			43				105
	44	44	44	106			
	46	46	46			107	107

Using the K_L values shown above and the objective function defined in Section 3.4.1 without valve operation penalty, the program is run in steady state using three groups of TCVs separately. The determined valve openings for both three TCV groups are shown in Table 6.23, Table 6.24 and Table 6.25.

Table 6.23. Valve Opening Results for TCV Group I

TCV Group I 40 % ≥ Closure percentage > 20%	Valve Opening	TCV Group I 40 % ≥ Closure percentage > 20%	Valve Opening
3	5/8 open	46	1/8 open
11	1/8 open	50	1/8 open
12	1/8 open	51	3/8 open
13	Closed	57	Closed
16	Closed	59	1/8 open
20	2/8 open	62	1/8 open
26	5/8 open	63	1/8 open
30	Open	104	1/8 open
44	4/8 open		

Table 6.24 Valve Opening Results for TCV Group II

TCV Group II 40 % ≥ Closure percentage > 10%	Valve Opening	TCV Group II 40 % ≥ Closure percentage > 10%	Valve Opening
3	1/8 open	62	1/8 open
11	1/8 open	63	1/8 open
12	1/8 open	104	2/8 open
13	Closed	18	3/8 open
16	Closed	25	1/8 open
20	2/8 open	27	1/8 open
26	4/8 open	37	Closed
30	5/8 open	39	6/8 open
44	2/8 open	69	1/8 open
46	1/8 open	71	5/8 open
50	1/8 open	83	1/8 open
51	1/8 open	103	3/8 open
57	Closed	107	1/8 open
59	1/8 open		

Table 6.25. Valve Opening Results for TCV Group III

TCV Group III 40 % ≥ Closure percentage > 0%	Valve Opening		TCV Group III 40 % ≥ Closure percentage > 0%	Valve Opening
3	Open		103	5/8 open
11	3/8 open		107	2/8 open
12	3/8 open		9	Closed
13	Closed		14	3/8 open
16	Closed		17	5/8 open
20	4/8 open		19	1/8 open
26	6/8 open		28	Closed
30	Open		32	1/8 open
44	2/8 open		33	6/8 open
46	1/8 open		43	5/8 open
50	2/8 open		47	5/8 open
51	3/8 open		52	1/8 open
57	Closed		56	1/8 open
59	1/8 open		60	1/8 open
62	2/8 open		64	Open
63	1/8 open		66	3/8 open
104	5/8 open		68	1/8 open
18	1/8 open		70	Open
25	5/8 open		73	Open
27	1/8 open		76	3/8 open
37	Closed		79	1/8 open
39	Open		84	6/8 open
69	6/8 open		85	Open
71	6/8 open		99	Open
83	1/8 open		105	2/8 open

The results of TCV studies indicating the percentage of excess pressure decrement and evaluation times is shown in Table 6.26 and Figure 6.8.

Table 6.26. Results of TCV Studies

	TCV Group I	TCV Group II	TCV Group III
Number of Valves in Operation	17	27	50
Percentage of Excess Pressure Decrement	20.72%	21.38%	15.50%
Evaluation Times (sec)	279	335	459

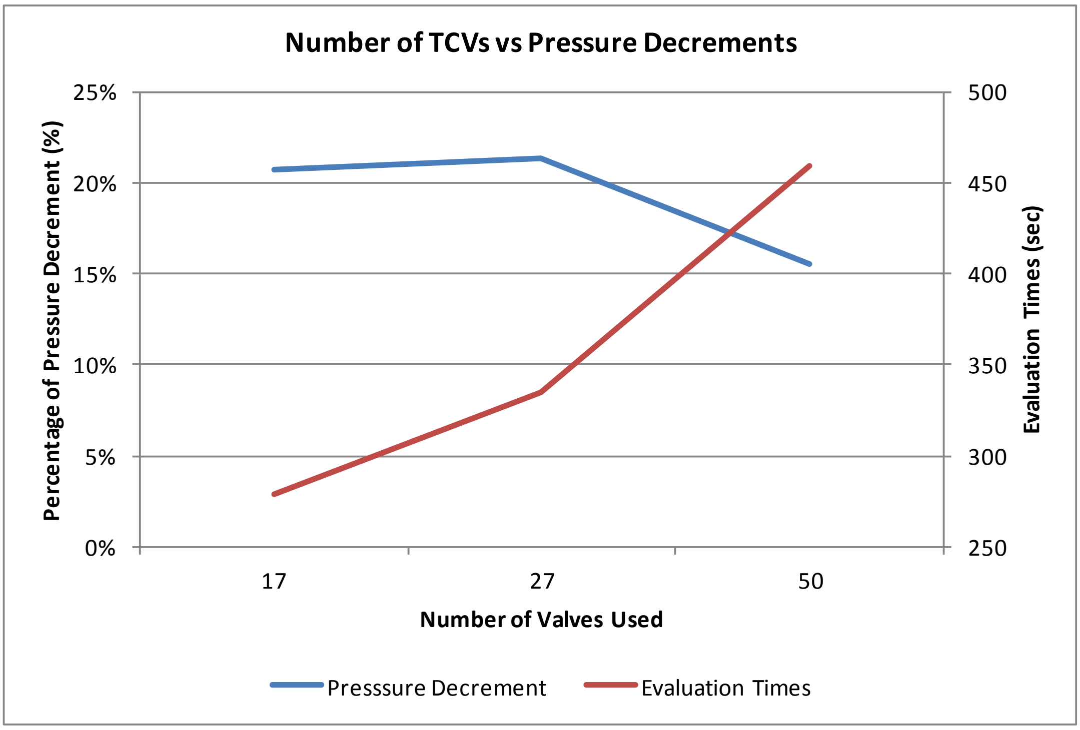


Figure 6.8. Results of TCV Studies

As can be seen from Table 6.26 and Figure 6.8, by using group II of valves (40% ≥ Closure Percentage >10%) the pressure decrement reaches at the level of % 21.4. As the number of TCVs increase, the effectiveness of algorithm decreases in terms of both pressure decrement and evaluation times. Therefore, 2nd group of TCVs could be considered to be applicable for valve opening determination study to reduce excess pressures.

When compared to “all valves open” case, at the end of TCV methodology, the pressures are reduced at the level of almost 60%. When, direct relationship between leakages and excess pressures are considered, this methodology is considered to be helpful for preventing water leakages resulting from high pressures.

6.2 Application of VOGA to East Çiğdem Network

Besides Yayla network, valve operation methodology is applied on East Çiğdem DMA of N8-3. This network is located at the west side of the main N8-3 network (see Figure 4.1 and Figure 4.6). The mean entrance total head is about 1153.96 m. The elevation of nodes and static heads with respect to district metered area entrance are given in Table 6.27.

Table 6.27. Topographic Elevations and Static Head Differences of East Çiğdem

Node ID	Elevation (m)	Static Head (m)	Node ID	Elevation (m)	Static Head (m)	Node ID	Elevation (m)	Static Head (m)
J- 54	1116.67	37.29	J- 299	1089.44	**64.52**	J- 488	1107.43	46.53
J- 55	1119.06	34.90	J- 310	1123.05	30.91	J- 523	1096.96	57.00
J- 61	1117.58	36.38	J- 328	1127.49	26.47	J- 535	1093.69	**60.27**
J- 109	1121.33	32.63	J- 329	1130.50	23.46	J- 582	1080.19	**73.77**
J- 110	1118.17	35.79	J- 345	1133.50	20.46	J- 583	1074.36	**79.60**
J- 131	1128.75	25.21	J- 394	1127.74	26.22	J- 602	1092.25	**61.71**
J- 132	1130.78	23.18	J- 432	1127.53	26.43	J- 605	1068.12	**85.84**
J- 164	1123.31	30.65	J- 443	1122.08	31.88	J- 606	1079.23	**74.73**
J- 208	1102.41	51.55	J- 448	1109.90	44.06	J- 610	1071.74	**82.22**
J- 209	1105.90	48.06	J- 449	1113.00	40.96	J- 614	1086.70	**67.26**
J- 242	1104.64	49.32	J- 451	1120.76	33.20	J- 711	1083.61	**70.35**
J- 298	1093.07	**60.89**	J- 487	1107.68	46.28	Resvr 1	1153.96	0.00

In Table 6.27, the static heads higher than 60 m are shown in bold characters. These nodes are potential excess pressure points for Yayla network. When the sum of the static head differences above 60 m is calculated using formula below, the potential excess pressures are found to be 121.16 m.

$$Upper\ Limit\ of\ Excess\ Pressures = \sum_{\mathrm{i=1}}^{\mathrm{Nn}} \{P_i - 60 \quad if \quad P_i > 60\} = 121.16\ \mathrm{m}$$

This value is theoretically unreachable under operation of network. Since, the flows produce head losses; the excess pressure sum will be lower than 121.16 m. In the following sections, the summation of excess pressures will be calculated to indicate the effectiveness of the pressure minimization studies.

Yayla network consists of 42 pipes and 35 nodes. There are no pumps or tanks in the network. The general layout of East Çiğdem District is shown in Figure 4.2. Topographically, the north of the network has the higher elevations, which is the low pressure region. On the other hand, the south side of the region has lower elevations which is a potential high pressure area. The general layout of East Çiğdem network with the nodal elevations color map is shown in Figure 6.9.

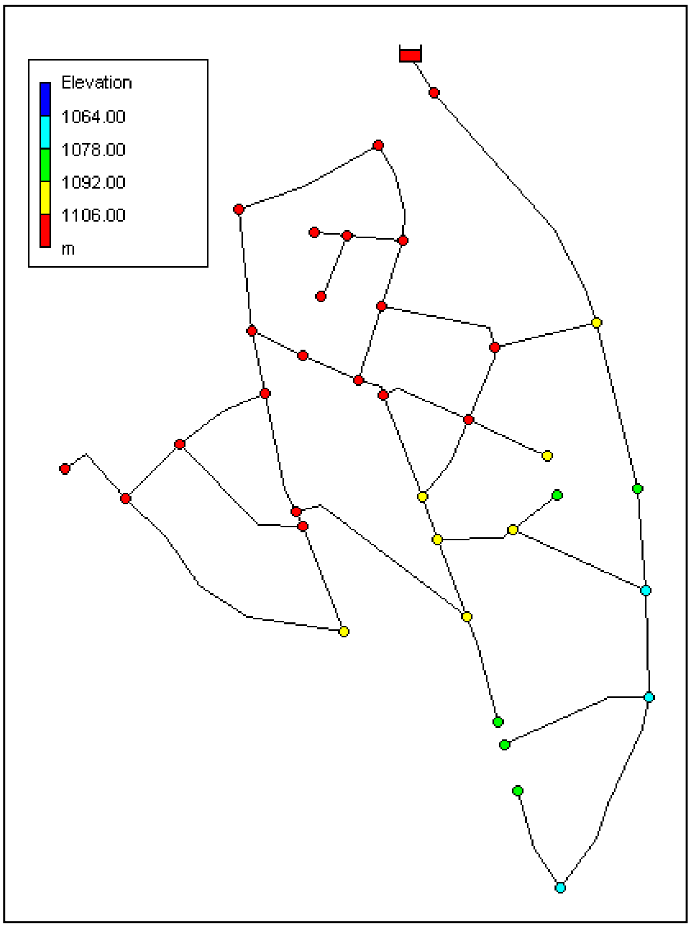


Figure 6.9. Nodal Elevations View of East Çiğdem Network

6.2.1 Determination of Valve Locations

6.2.1.1 Steady State Studies

Same as Yayla studies, in the first step of valve locating studies (i_i), network is run under SS conditions and is aimed to select which valves are effective for pressure minimization under minimum and maximum demand loadings. The daily demands of East Çiğdem network are shown in Table 6.28 and drawn in Figure 6.10.

Table 6.28. Total Daily Demands of East Çiğdem District Metered Area

Total Daily Demands of East Çiğdem DMA			
Time of Day (hr)	Hourly Total Demand (l/s)	Time of Day (hr)	Hourly Total Demand (l/s)
0	4.43	12	7.68
1	3.47	13	7.43
2	3.25	14	6.62
3	**3.20**	15	5.85
4	3.24	16	6.79
5	4.12	17	6.75
6	5.52	18	6.72
7	6.92	19	6.95
8	6.71	20	5.90
9	7.18	21	5.76
10	**8.12**	22	5.74
11	7.99	23	5.64

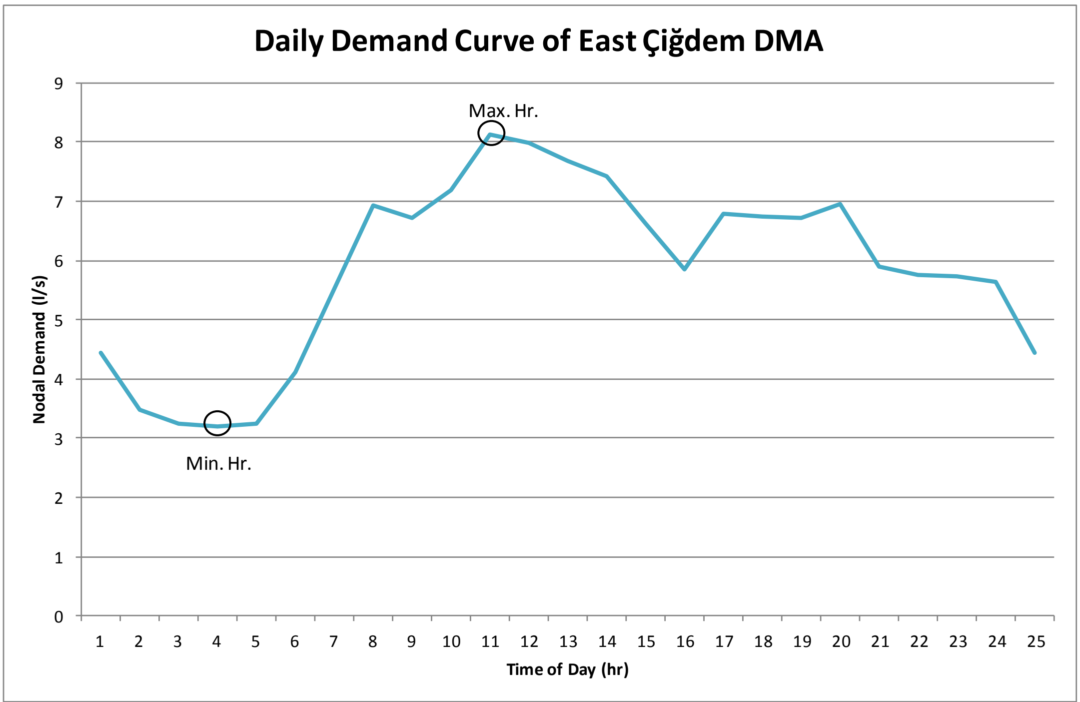


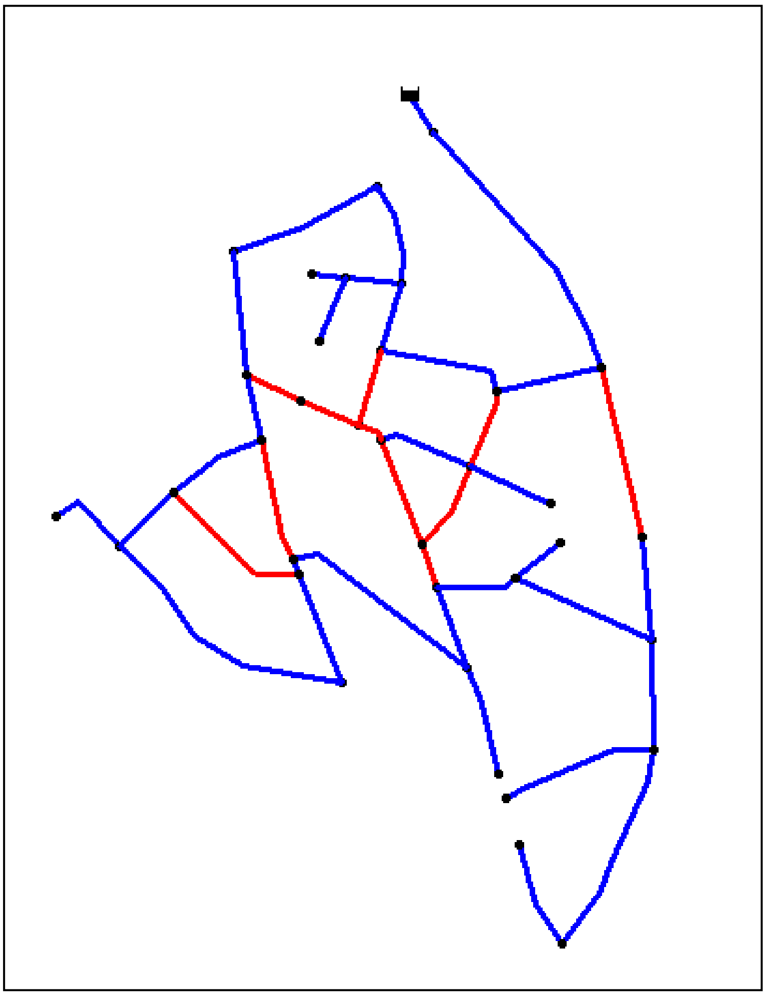
Figure 6.10. Daily Demand Curve of East Çiğdem District Metered Area

Similar to Yayla studies, VOGA is applied to East Çiğdem network 25 times for each minimum and maximum hour demand loadings. Then, results of 50 runs are examined. Closure percentage for all pipes are found and shown in Table 6.29.

It can be seen from Table 6.29 that, there are 31 pipes kept open and 3 pipes kept closed in all of the runs. The rest, 8 pipes are selected to be potential locations for operation of isolation valves. The valves which are kept open and closed at least once are shown in Figure 6.11. The importance of Figure 6.11 indicates that; blue colored pipes (valve) are the valves which are needless to operate. For all trials, these valves are left in open status. Thus, closure of these valves result in unrecoverable situations for the network.

Table 6.29. Closure Percentages of Pipes

ID of Pipe	Closure Number (out of 50 runs)	Closure Percentage	ID of Pipe	Closure Number (out of 50 runs)	Closure Percentage
Pipe 1	0	0%	Pipe 22	0	0%
Pipe 2	0	0%	Pipe 23	0	0%
Pipe 3	27	54%	Pipe 24	0	0%
Pipe 4	0	0%	Pipe 25	0	0%
Pipe 5	1	2%	Pipe 26	0	0%
Pipe 6	0	0%	Pipe 27	0	0%
Pipe 7	0	0%	Pipe 28	0	0%
Pipe 8	31	62%	Pipe 29	3	6%
Pipe 9	19	38%	Pipe 30	0	0%
Pipe 10	0	0%	Pipe 31	0	0%
Pipe 11	0	0%	Pipe 32	0	0%
Pipe 12	0	0%	Pipe 33	50	100%
Pipe 13	0	0%	Pipe 34	0	0%
Pipe 14	0	0%	Pipe 35	50	100%
Pipe 15	46	92%	Pipe 36	0	0%
Pipe 16	22	44%	Pipe 37	0	0%
Pipe 17	0	0%	Pipe 38	50	100%
Pipe 18	0	0%	Pipe 39	0	0%
Pipe 19	0	0%	Pipe 40	0	0%
Pipe 20	0	0%	Pipe 41	0	0%
Pipe 21	3	6%	Pipe 42	0	0%



: Closed At Least Once : Open Through All Runs

Figure 6.11. Valves (Pipes) Closed At Least Once

The data shown in Table 6.29 is transformed into percentage intervals and given in Table 6.30. This table shows the list of valves with their corresponding closure percentage groups. The “X” sign indicate the valve is included in the indicated closure percentage group.

Table 6.30. The List of Closed Pipes with Percentage Groups

ID of Pipe	CLOSURE PERCENTAGES																			
	CP>0 %	CP> 5 %	CP> 10 %	CP> 15 %	CP> 20 %	CP> 25 %	CP> 30 %	CP> 35 %	CP> 40 %	CP> 45 %	CP> 50 %	CP> 55 %	CP> 60 %	CP> 65 %	CP> 70 %	CP> 75 %	CP> 80 %	CP> 85 %	CP> 90 %	CP> 95 %
Pipe 1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 3	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-
Pipe 4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 5	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 8	X	X	X	X	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-
Pipe 9	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 15	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	-
Pipe 16	X	X	X	X	X	X	X	X	X	-	-	-	-	-	-	-	-	-	-	-
Pipe 17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 21	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 29	X	X	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 30	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 33	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pipe 34	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 35	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pipe 36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 37	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 38	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pipe 39	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 40	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 41	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pipe 42	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
X: Selected -: Not Selected																				

6.2.1.2 Extended Period Simulation Studies

After gathering the closure percentage of each pipe, the second step (i_{ii}) of the valve locating methodology is applied under EPS conditions for 24 hours. In EPS studies, the groups of valves with closure percentages are used with 25% increment steps and the status of previously located valves becomes variable. The blue colored pipes in Figure 6.11 are left open, while the valves 33, 35 and 38 are kept closed.

The program is run using the given objective function and constraints using the list of pipes defined and results are obtained The tables indicating which valves are closed in which period of day is given in the following pages by 25% increment steps. The cells with “0” means, the valve is closed during that time step, while “1” means it is open.

Table 6.31. Status of Valves for the Closure of >0 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	1	0	1	0	0	1	1	1	1	0	0	0	1	0	0	0	0	1	1	1	0	0	1	1
Pipe 5	1	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1	0	1	1	1	0	0	1	1
Pipe 8	1	1	0	1	1	1	1	0	1	0	0	1	0	1	1	1	1	0	0	0	1	1	0	1
Pipe 9	0	1	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	0
Pipe 15	0	1	0	1	1	0	1	1	0	1	1	1	0	1	1	1	1	0	0	1	1	1	0	0
Pipe 16	0	1	1	0	1	0	0	1	0	1	1	1	1	0	0	1	1	1	0	0	0	0	0	1
Pipe 21	1	1	1	1	0	1	0	0	0	0	0	1	1	0	1	1	0	0	1	0	1	0	1	0
Pipe 29	0	0	1	0	1	0	0	1	1	1	0	0	1	0	1	0	1	0	1	0	0	1	0	0
Pipe 33	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
Pipe 35	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 38	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0

Table 6.32. Status of Valves for the Closure of >25 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	1	0	1	1	0	1	1	1	0	1	0	0	0	0	1	0	1	0	0	0	0	0	1	1
Pipe 8	0	1	1	0	1	0	1	1	0	1	0	1	1	0	0	0	0	1	0	0	0	0	1	1
Pipe 9	1	1	0	1	0	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
Pipe 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 16	0	0	0	0	1	0	0	0	1	0	1	0	0	1	0	1	0	0	1	1	1	1	0	0
Pipe 33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 6.33. Status of Valves for the Closure of >50 %

	HOURS OF DAY																							
Pipe	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Pipe 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pipe 38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

When results of runs from Table 6.31 to Table 6.33 are examined, it could be seen that, valves with closure percentage >50% are needless to operate (see Table 6.33). It can be concluded on that, all valves with closure percentage >50%, could be kept closed through the 24 hour run time duration without disturbing the hydraulic conformities of the network.

Table 6.34. Summary of Results for Valve Locating Study

Valve Closure Selection Interval	Excess Nodal Pressures (m)	Number of Valve Switches	Number of Valves to be Controlled	Average Valve Switch
CP > 0%	157.82	113	11	10.27
CP > 25%	153.53	48	8	6.00
CP > 50%	152.82	0	6	0.00

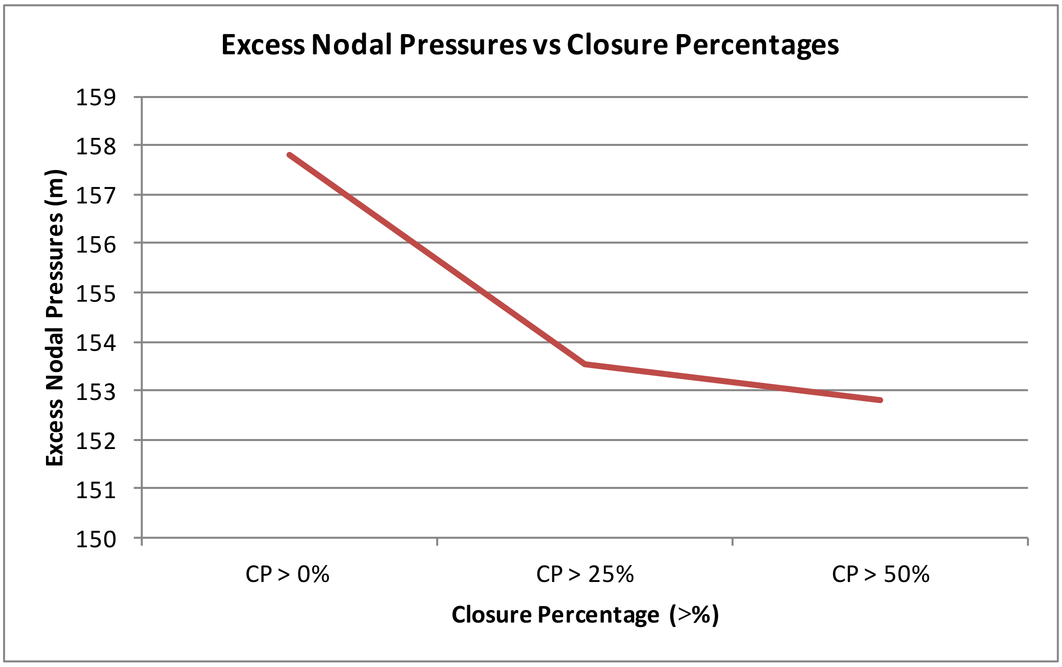


Figure 6.12. Excess Nodal Pressures vs. Closure Percentages

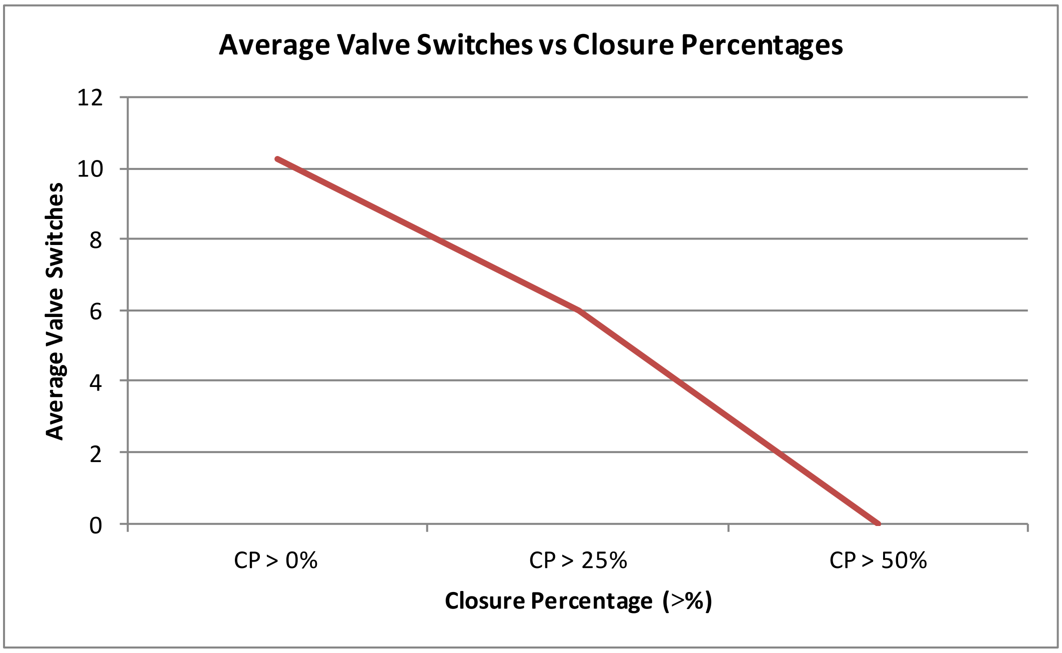


Figure 6.13. Average Valve Switches vs. Closure Percentages

When Table 6.34, Figure 6.12 and Figure 6.13 are investigated; it can be seen that, as the number of valves decreases. When the closure percentage reaches to 50%; all valves get closed and maximum pressure deficit is achieved.

This situation indicate the valves with closure percentage of 50% and higher are needless for operation; to keep the excess pressures at lower levels they should be kept closed through the run period. Also, the >50% closure percentage group is considered to be an optimal pressure decrement point.

To visualize the effectiveness of valve locating study, nodal pressures of East Çiğdem network are shown for two cases in Table 6.35; all valves open case, and valves with closure percentage >50% are closed case. As can be seen from the table, by closing of those valves, the excess nodal pressures are decreased at the level of 30%. When direct effect of pressure minimization to leakage reduction is considered; it could be concluded on a supportive method for leakage reduction.

Table 6.35. Comparison of Nodal Pressures after Valve Locating Study

	No Valves Closed		Valves CP>50% Closed			No Valves Closed		Valves CP>50% Closed	
Node ID	Nodal Pressure (m)	Excess Pressure (m)	Nodal Pressure (m)	Excess Pressure (m)	Node ID	Nodal Pressure (m)	Excess Pressure (m)	Nodal Pressure (m)	Excess Pressure (m)
J-54	35.98	-	32.85	-	**J-432**	25.15	-	24.47	-
J-55	33.59	-	30.46	-	**J-443**	30.59	-	29.98	-
J-61	36.31	-	36.31	-	**J-448**	42.73	-	40.61	-
J-109	31.34	-	30.73	-	**J-449**	39.64	-	37.51	-
J-110	34.49	-	30.81	-	**J-451**	31.90	-	29.88	-
J-131	23.93	-	23.25	-	**J-487**	44.97	-	41.28	-
J-132	21.90	-	21.23	-	**J-488**	45.24	-	45.00	-
J-164	29.36	-	28.59	-	**J-523**	55.66	-	51.99	-
J-208	50.22	-	46.54	-	**J-535**	58.93	-	55.25	-
J-209	46.74	-	43.06	-	**J-582**	**72.53**	12.53	**68.56**	8.56
J-242	47.98	-	44.91	-	**J-583**	**78.35**	18.35	**74.37**	14.37
J-298	59.58	-	55.80	-	**J-602**	**60.50**	0.50	**60.50**	0.50
J-299	**63.20**	3.20	59.42	-	**J-605**	**84.57**	24.57	**80.60**	20.60
J-310	29.62	-	28.94	-	**J-606**	**73.48**	13.48	**69.51**	9.51
J-328	25.19	-	24.58	-	**J-610**	**80.96**	20.96	**76.99**	16.99
J-329	22.18	-	20.36	-	**J-614**	**65.90**	5.90	**62.23**	2.23
J-345	19.19	-	17.46	-	**J-711**	**69.11**	9.11	**65.14**	5.14
J-394	24.93	-	23.07	-	**Resvr 1**	0.00	-	0.00	-
						TOTAL	**108.60**	**TOTAL**	**77.90**

To integrate the outcomes of valve locating studies to the valve opening determination study (2nd step) the valves of East Çiğdem network is divided into groups. While dividing, the valves never been selected to be closed and the valves with closure percentage higher than 50% are kept in fixed status and both types of valves are removed and from valve opening determination search space while the rest of the pipes are taken into consideration. These groups are defined below.

Type I: Closure Percentage = 0 % (Left open)

Type II: 50 % ≥ Closure percentage > 0%

Type III: Closure Percentage ≥ 50% (Kept closed)

The list of pipes including these types is given in Table 6.36 in tabular form and in Figure 6.14 on network with different colors.

Table 6.36. Types of Valves

Type I Closure Percentage = 0 %	Type II 50 % ≥ Closure percentage > 0%	Type III Closure Percentage >50%	Type I Closure Percentage = 0 %	Type II 50 % ≥ Closure percentage > 0%	Type III Closure Percentage >50%
1			22		
2			23		
		3	24		
4			25		
	5		26		
6			27		
7			28		
		8		29	
	9		30		
10			31		
11			32		
12					33
13			34		
14					35
		15	36		
	16		37		
17					38
18			39		
19			40		
20			41		
	21		42		

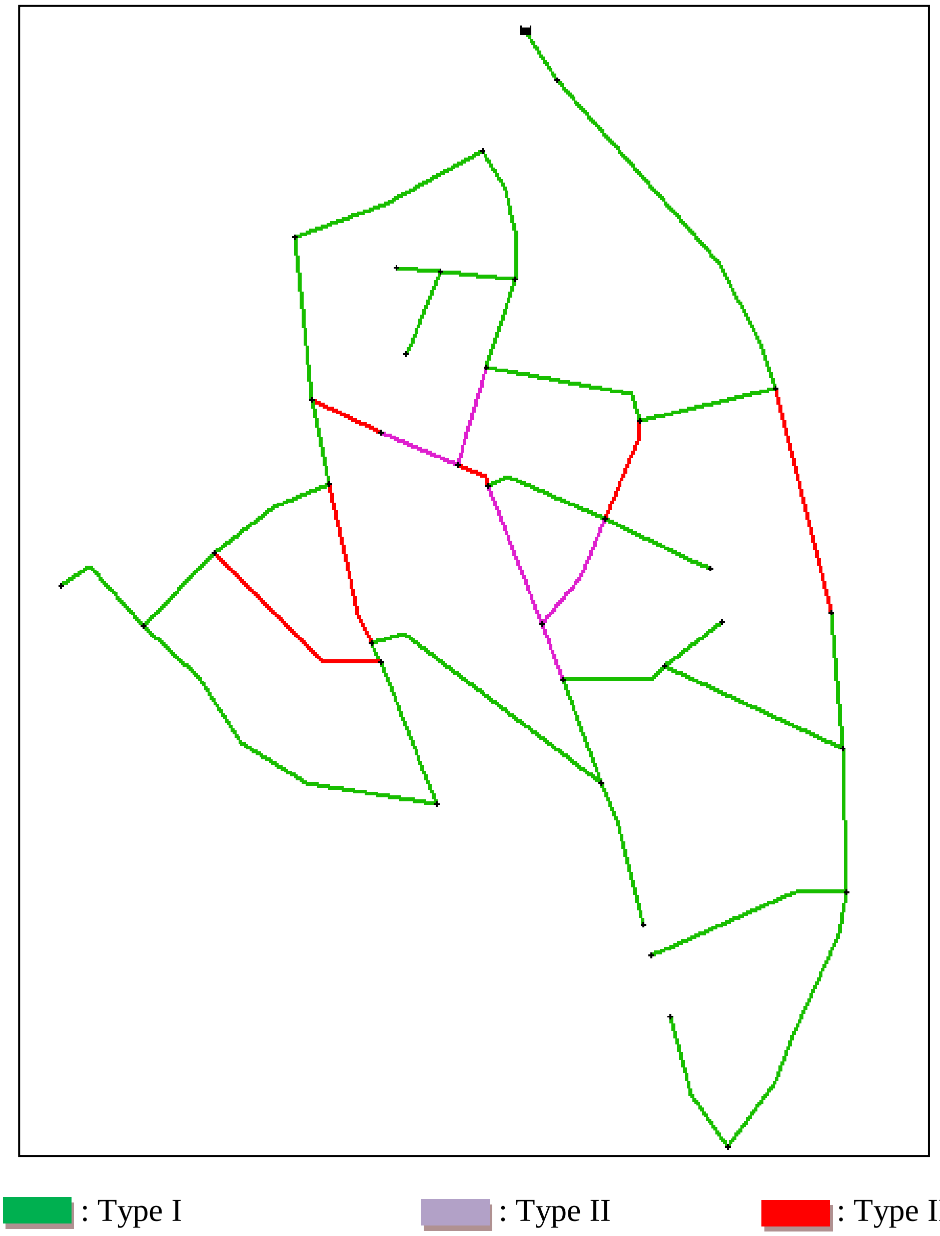


Figure 6.14. Types of Valves on East Çiğdem Network View

6.2.2 Determination of Valve Openings

At the second and the final step (ii) of the pressure minimization methodology, similar to Yayla, network of East Çiğdem is re-modeled using the types of valves that are defined in Table 6.16. The valves that are open or closed through the day (Types I and III) are kept with unchanged status, while the others (Types II) are changed into Throttle Control Valve, instead of being an isolation valve.

Since there are only 5 valves in Type II; there is no need divide the TCVs into sub groups. All these 5 valves are modeled as TCV and the methodology is applied using the K_L values shown in Table 6.21 and the objective function defined in Section 3.4.1. The determined valve openings for defined TCVs are shown in Table 6.37.

Table 6.37. Valve Opening Results for TCVs

TCV Group 50 % ≥ Closure percentage > 0%	Valve Opening
3	3/8 open
11	Open
12	Open
13	3/8 open
16	Closed
20	1/8 open

The results of TCV studies indicating the percentage of excess pressure decrement and evaluation times is shown in Table 6.38.

Table 6.38. Results of TCV Studies

	TCV Group
Number of Valves in Operation	5
Percentage of Excess Pressure Decrement	10.59%
Evaluation Times (sec)	40

As can be seen from Table 6.38, by partially closing TCVs, (50% ≥ Closure Percentage >00%) the pressure decrement reaches at the level of % 10 when compared to all TCVs are open case.

When compared to “all valves open” case, at the end of TCV methodology, the pressures are reduced at the level of almost 35%.

CHAPTER 7

SUMMARY AND CONCLUSIONS

In this research, a methodology comprised of the application of pump scheduling and valve locating and opening determination studies on the same network is developed, using EPANET Toolkit functions and MATLAB programming language. The methodology is utilized by decomposing the network into its skeleton and district metered areas; and applying optimization studies on the skeleton of the main network and district metered areas individually without disturbing the preciseness. By this technique, this thesis study represents an operational optimization methodology on large scaled water distribution networks.

The main objective of this research was to develop an operational optimization methodology by combining a hydraulic simulation model and genetic algorithms. By developing such model, both operational costs and the leakages among the network are aimed to be minimized in two phases. To minimize the operational costs, pump scheduling optimization; to minimize the leakages, valve locating and opening determination studies are applied on the components of the large scaled network. Due to non linear behavior of both problems, genetic algorithms are preferred for implementation of optimization objectives.

The studied network is N8-3 pressure zone of Ankara. Main network is comprised of 6 district metered areas (DMAs) that have measurement chambers installed at the connection nodes to the main supply pipe. These chambers are also the isolation points for DMAs from the main network. During first phase; the pump scheduling optimization phase; the main N8-3 network is skeletonized by simplifying the network of each DMA to a single node. Thus, whole N8-3 network is changed to a skeleton with 6 nodal demands. By this simplification, size of network is decreased considerably while the hydraulic characteristics are protected for pump scheduling optimization.

For the pump schedule optimization process, a program namely POGA (Pump Optimization using Genetic Algorithms) is developed. POGA is designed to be capable of considering both tank volume deficit and pump switch constraints while searching for the pumping energy cost minimization objective. Initially POGA is applied on the skeleton of the network for 24 hour run time duration. In addition, the results of POGA are inspected using partial enumeration technique.

The obtained results indicate that POGA can find reliable scheduling alternatives in terms of both least energy consumption and hydraulic conformities for water distribution networks. Moreover, the alternative solutions serve some tradeoffs between tank volume deficits and pump switches. The results indicate that, with higher number of pump switches, the program have the capability to find results with low energy consumptions. However; higher number of pump switches increase maintenance costs while reducing the economic life of pumps.

After testing the consistency of developed program, the pump scheduling optimization is applied by 2, 4, 6, 8 and 12 hour run periods for total 24 hour duration. After the application for various run time periods, it is visualized that, as the run time period gets longer, the magnitude of tank water level oscillations become greater and the total number of pump switches becomes lower. For long run time periods, water in the tank circulates more, compared to short run time periods. In addition, the program achieved on hydraulic periodicity almost for every run time period within tolerable tank volume deficits.

After the application of POGA with predefined demand patterns; real time demand measurements and predictions are introduced to the problem. Initially a basic method is used for real time predictions. At this step, demand multiplier factors are used to produce the measurement data for unexpected cases such as emergency.

The application of POGA to the network with basic real time prediction technique with these multiplier factor patterns reveals that, the developed program is capable of responding the need of network by employing pumps, in case of need. However, since the capacity of pumps is limited, as the amount of predicted demand gets higher, the water volume periodicity in the tank cannot be sustained even though the performance of pumps reaches to their maximum.

After the application with basic demand predictions, the prediction model is improved by considering 6 days long measurements. To improve the prediction of daily demands, Kalman Filter technique is integrated to POGA. Finally, POGA is applied to the network with its filtered demand prediction module. The comparison of filtered and unfiltered predictions reveal that, the predictions using Kalman Filter, give better results when compared to blind prediction technique. The application of real time daily demand predictions using partial run time intervals among the whole simulation duration, and applying Kalman Filter as a demand predictor corrector brings novelty to this study.

At the second phase for the aim of pressure minimization, pump scheduling optimization study is followed by valve locating and opening determination studies. Using the obtained, optimal schedule for the skeleton network; the entrance pressures for each DMA are calculated. Then, valve locating (i) and opening determination studies (ii) are applied on the networks of Yayla and East Çiğdemtepe DMAs.

For valve locating studies, it is aimed to select effective valves for pressure minimization. The method is applied to network first in steady state conditions. At this step, the closure percentage of each valve is found and the valves are grouped using these percentages. At this step, the valves that are never selected to be closed are also found. Then valve locating study is applied to the network under extended period simulation conditions. In this step, the groups of closed valves which give highest excess pressure decrease are found. At the end of valve locating studies, the valves which must be kept open and closed are determined.

For Yayla network, the valves with higher than 40% closure percentage are selected to be closed. On the other hand, valves with 0% closure percentage are left open. The rest of the valves are regrouped using their corresponding closure percentages. By closing of several valves, some of the loops within the network become broken. This situation may considered to be a negative point for water quality point of view. In order to eliminate such negative effect, an alternatively valve closing method could be applied to the selected valves. In other words, among selected closed valves, some of them may be left open for a while; after some time, these valves change their statuses to closed again, while some others are left open and it continues like that.

To measure the correctness of located valves; sensitivity analysis is made for each valve. The results of sensitivity analysis revealed confirming results for developed algorithm. Then finally, valve opening determination study is applied.

At this step, network is re-modeled using the types of valves that were found in step i. The valves that are found to be open or closed in the valve locating study are kept with unchanged status, while the others were changed into Throttle Control Valve (TCV), instead of being isolation valve. By this conversion; all valves gained flexibility of having partial openings. At the end of valve opening determination studies, when the excess pressures are compared with the initial “all valves open” case, it is visualized that almost 60% and 35% decrement is achieved within the Yayla and East Çiğdem networks respectively.

Determination of partial openings of valves, using the outcomes of valve locating studies also brings novelty to this study. Partial or completely closure of isolation valves is a known tool for pressure minimization; however this study offers an operation method by combining open, closed and partial open valves. When, direct relationship between leakages and excess pressures is measured, this methodology is considered to be offering a beneficial operation strategy in order to prevent water leakages through the water distribution systems.

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APPENDIX A

PRODUCED DEMAND DATA FOR KALMAN FILTER STUDIES

Table A.1 Produced Demand Data and Results of Blind Prediction

	Time of Week	Measured Demand (LPS)	Estimated Demand (LPS)	Err^2		Time of Week	Measured Demand (LPS)	Estimated Demand (LPS)	Err^2
DAY 1	Hr 1	26.20	-	-	DAY 2	Hr 25	26.35	26.38	0.0007
	Hr 2	18.25	-	-		Hr 26	17.50	18.40	0.8216
	Hr 3	14.39	-	-		Hr 27	14.86	14.45	0.1704
	Hr 4	13.66	-	-		Hr 28	14.76	13.68	1.1644
	Hr 5	13.89	-	-		Hr 29	12.89	13.91	1.0254
	Hr 6	17.78	-	-		Hr 30	18.10	17.69	0.1682
	Hr 7	26.94	-	-		Hr 31	25.88	26.77	0.7982
	Hr 8	32.09	-	-		Hr 32	32.36	31.97	0.1493
	Hr 9	31.65	-	-		Hr 33	31.60	31.66	0.0039
	Hr 10	36.16	-	-		Hr 34	36.22	36.07	0.0219
	Hr 11	43.08	-	-		Hr 35	42.38	42.95	0.3195
	Hr 12	47.81	-	-		Hr 36	50.46	47.71	7.5979
	Hr 13	45.23	-	-		Hr 37	46.41	45.33	1.1626
	Hr 14	43.36	-	-		Hr 38	44.50	43.42	1.1770
	Hr 15	38.52	-	-		Hr 39	38.25	38.63	0.1460
	Hr 16	34.73	-	-		Hr 40	33.19	34.80	2.5829
	Hr 17	37.02	-	-		Hr 41	36.53	36.95	0.1756
	Hr 18	38.43	-	-		Hr 42	37.00	38.39	1.9342
	Hr 19	38.76	-	-		Hr 43	38.94	38.73	0.0473
	Hr 20	39.56	-	-		Hr 44	39.16	39.55	0.1531
	Hr 21	35.90	-	-		Hr 45	36.94	35.96	0.9622
	Hr 22	33.22	-	-		Hr 46	34.21	33.29	0.8520
	Hr 23	35.57	-	-		Hr 47	34.61	35.54	0.8745
	Hr 24	35.48	-	-		Hr 48	36.24	35.46	0.6031

Table A.1 (continued)

	Time of Week	Measured Demand (LPS)	Estimated Demand (LPS)	Err^2		Time of Week	Measured Demand (LPS)	Estimated Demand (LPS)	Err^2
DAY 3	Hr 49	27.05	26.54	0.2626	DAY 5	Hr 97	25.99	27.38	1.9419
	Hr 50	17.87	17.68	0.0346		Hr 98	19.00	17.34	2.7359
	Hr 51	14.01	14.92	0.8322		Hr 99	15.11	15.42	0.0952
	Hr 52	13.41	14.75	1.7812		Hr 100	14.03	14.14	0.0119
	Hr 53	14.25	12.90	1.8013		Hr 101	15.01	14.53	0.2282
	Hr 54	18.38	18.02	0.1242		Hr 102	16.77	16.88	0.0141
	Hr 55	26.38	25.73	0.4160		Hr 103	27.81	25.46	5.5272
	Hr 56	31.89	32.24	0.1225		Hr 104	31.82	31.81	0.0000
	Hr 57	32.69	31.61	1.1760		Hr 105	31.20	31.72	0.2692
	Hr 58	36.88	36.15	0.5333		Hr 106	36.03	36.76	0.5430
	Hr 59	43.00	42.28	0.5182		Hr 107	43.55	41.50	4.2160
	Hr 60	48.56	50.32	3.1107		Hr 108	47.61	46.86	0.5585
	Hr 61	45.90	46.45	0.3047		Hr 109	44.51	44.31	0.0396
	Hr 62	43.18	44.53	1.8349		Hr 110	43.09	42.80	0.0811
	Hr 63	40.36	38.35	4.0488		Hr 111	39.63	39.64	0.0001
	Hr 64	33.63	33.33	0.0945		Hr 112	34.98	33.48	2.2571
	Hr 65	37.22	36.47	0.5508		Hr 113	35.53	37.11	2.5075
	Hr 66	38.13	37.01	1.2543		Hr 114	38.63	37.13	2.2412
	Hr 67	37.75	38.93	1.3981		Hr 115	38.02	39.06	1.0663
	Hr 68	38.48	39.13	0.4239		Hr 116	38.85	39.21	0.1346
	Hr 69	36.62	36.97	0.1220		Hr 117	35.04	35.13	0.0085
	Hr 70	31.81	34.26	6.0217		Hr 118	33.18	33.60	0.1780
	Hr 71	36.65	34.56	4.3950		Hr 119	35.34	35.65	0.0999
	Hr 72	34.22	36.25	4.0960		Hr 120	36.42	36.24	0.0305
DAY 4	Hr 73	27.21	27.19	0.0005	DAY 6	Hr 121	28.32	26.19	4.5464
	Hr 74	17.18	18.04	0.7519		Hr 122	19.42	19.18	0.0587
	Hr 75	15.35	14.07	1.6527		Hr 123	16.08	15.20	0.7796
	Hr 76	14.12	13.45	0.4489		Hr 124	13.25	14.07	0.6643
	Hr 77	14.54	14.24	0.0884		Hr 125	13.12	14.98	3.4393
	Hr 78	16.92	18.30	1.9124		Hr 126	19.26	16.70	6.5919
	Hr 79	25.63	26.20	0.3234		Hr 127	25.72	27.65	3.7211
	Hr 80	31.89	31.77	0.0131		Hr 128	33.23	31.70	2.3507
	Hr 81	31.72	32.68	0.9172		Hr 129	32.11	31.24	0.7643
	Hr 82	36.87	36.79	0.0075		Hr 130	36.55	35.95	0.3559
	Hr 83	41.60	42.88	1.6364		Hr 131	42.07	43.42	1.8051
	Hr 84	46.93	48.42	2.2453		Hr 132	48.33	47.50	0.6749
	Hr 85	44.25	45.92	2.7876		Hr 133	45.87	44.58	1.6648
	Hr 86	42.77	43.20	0.1827		Hr 134	43.26	43.14	0.0134
	Hr 87	39.57	40.40	0.6888		Hr 135	39.58	39.70	0.0147
	Hr 88	33.36	33.75	0.1523		Hr 136	34.66	35.07	0.1646
	Hr 89	37.16	37.14	0.0002		Hr 137	38.50	35.51	8.9435
	Hr 90	37.16	38.11	0.8996		Hr 138	39.47	38.62	0.7214
	Hr 91	39.07	37.73	1.7694		Hr 139	38.28	38.05	0.0503
	Hr 92	39.24	38.49	0.5592		Hr 140	39.19	38.84	0.1224
	Hr 93	35.06	36.67	2.6110		Hr 141	35.02	35.12	0.0085
	Hr 94	33.58	31.87	2.9139		Hr 142	33.44	33.22	0.0501
	Hr 95	35.70	36.59	0.7999		Hr 143	34.85	35.30	0.2051
	Hr 96	36.26	34.25	4.0276		Hr 144	35.96	36.39	0.1807

Table A.1 (continued)

	Time of Week	Measured Demand (LPS)	Estimated Demand (LPS)	Err^2
DAY 7	**Hr 145**	25.01	28.46	11.9486
	Hr 146	18.36	19.53	1.3538
	Hr 147	15.14	16.12	0.9673
	Hr 148	12.72	13.29	0.3248
	Hr 149	13.48	13.11	0.1352
	Hr 150	18.88	19.15	0.0739
	Hr 151	28.33	25.59	7.4988
	Hr 152	31.44	33.14	2.8951
	Hr 153	30.05	32.10	4.2236
	Hr 154	35.56	36.43	0.7431
	Hr 155	43.77	41.95	3.3273
	Hr 156	48.55	48.24	0.0997
	Hr 157	45.66	45.92	0.0682
	Hr 158	42.40	43.30	0.8134
	Hr 159	40.07	39.63	0.1895
	Hr 160	36.11	34.76	1.8141
	Hr 161	35.88	38.46	6.6584
	Hr 162	38.93	39.40	0.2270
	Hr 163	37.37	38.29	0.8453
	Hr 164	39.99	39.15	0.6950
	Hr 165	34.92	35.12	0.0414
	Hr 166	32.43	33.47	1.0756
	Hr 167	36.07	34.80	1.6232
	Hr 168	36.42	35.96	0.2042

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