OPERATION
OF
WATER DISTRIBUTION NETWORKS

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ABSTRACT

OPERATION OF WATER DISTRIBUTION NETWORKS

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With continuously increasing urbanization, consumer demands and expansion of water supply systems, determination of efficient pump schedules became a more difficult task. Pumping energy costs constitute a significant part of the operational cost of the water distribution networks. This study aims to provide an effective daily pump schedule by minimizing the energy costs for constant and also for multi tariff of electricity (3 Kademeli Elektrik Tarifesi) in water distribution network. A case study has been performed in an area covering N8.3 and N7 pressure zones which are parts of Ankara water distribution network. Both pressure zones consists of 3 multiple pumps in pump station and one tank having 5000 m^3 storage volume each. By using genetic algorithm based software (WaterCAD Darwin Scheduler) least-cost pump scheduling and operation policy for each pump station has been determined while satisfying target hydraulic performance requirements such as minimum and maximum service pressures, final water level of storage tank and maximum velocity in pipeline. 32 different alternative scenarios have been created which include multi tariff energy prices, constant tariff energy price, insulated system condition, uninsulated system condition and different pump combinations. The existing base scenario and alternative scenarios which were prepared by using optimal pump schedules have been compared and the achievements of optimizing pump operation have been analyzed. At the end of the study, a satisfying result has been observed that by using determined optimal pump schedule, minimum % 14 of total energy cost can be saved in existing water supply system.

Keywords: Pump Schedule, Genetic Algorithm, Optimization, Pump Combinations, Multi Tariff, Constant Tariff, Insulated, Uninsulated, Water Supply System, SCADA, DMA, Ankara

ÖZ

İÇME SUYU ŞEBEKELERİNİN İŞLETİLMESİ

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Sürekli artan kentleşme, artan tüketici su talebi ve genişleyen su sağlama sistemleri, verimli bir pompa programının belirlenmesini zor bir hale getirmektedir. Pompa enerji maliyetleri, dağıtım şebekelerinin işletme maliyetlerinin büyük bir kısmını oluşturmaktadır. Bu çalışmanın amacı, sabit ve çoklu elektrik tarifeleri kullanan içme suyu dağıtım şebekelerinde, enerji maliyetlerini en aza indirecek etkili bir günlük pompa programı sağlamaktır. Bu çalışma, Ankara'nın su dağıtım şebekesinin parçaları olan N8.3 ve N7 basınç bölgelerini kapsayan sahada gerçekleştirilmiştir. Her iki basınç bölgesi üçer adet pompa içeren bir pompa istasyonundan ve bir adet 5000 m^3 hacme sahip su deposundan oluşmaktadır. Her bir pompa için hidrolik performans gerekliliklerini (minimum- maksimum servis basınçları, su deposundaki son su seviyesi ve borulardaki maksimum hız) sağlayan en ucuz pompa programı ve pompa işletme şekli genetik algoritma tabanlı bir yazılım (WaterCAD Darwin Scheduler) kullanılarak belirlenmiştir. Çoklu ve sabit elektrik fiyat tarifeleri, izole ve izole edilmemiş sistemler ve farklı pompa kombinasyonları içeren 32 farklı alternatif senaryolar oluşturulmuştur. Optimum pompa programları kullanılarak oluşturulan alternatif senaryolar ve mevcut senaryo karşılaştırılmış ve optimize edilmiş pompa işletme başarısı analiz edilmiştir. Bu çalışma sonucunda belirlenen optimum pompa programı kullanılarak mevcut su sağlama sisteminde toplam enerji maliyetinin minimum % 14'ü kadar bir enerji tasarrufunun sağlandığı gözlemlenmiştir.

Anahtar Kelimeler: Pompa Programı, Genetik Algoritma, Optimizasyon, Pompa Kombinasyonları, Çoklu Elektrik Tarifesi, Sabit Elektrik Tarifesi, İzole, İzole edilmemiş, Su Temini Sistemleri, SCADA, DMA, Ankara

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To my wife “Çağla” and my son “Rüzgar”

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Cc : Unit energy cost of constant tariff (TL/kWh)
Cd : Unit energy cost in day period (TL/kWh)
Ce : Total energy cost of pumps in 24 hours. (TL)
$Ce_{constant\ tariff}$: Total energy cost of pumps in 24 hours by using constant tariff energy price. (TL)
$Ce_{multi\ tariff}$: Total energy cost of pumps in 24 hours by using multi tariff energy price. (TL)
Cn : Unit energy cost in night period (TL/kWh)
$Cn(bp)$: Maximum demand charge for pump number n during billing period bp (TL/max.kW)
Cp : Unit energy cost in peak period (TL/kWh)
D_t : Average demand measured at DMA inlet node (m^3/hr)
D_x : Demand per meter pipe (m^3/hr)
DMA: District Metered Area
$E_n(t)$: Energy consumption of pump n during schedule time interval from t to t+1 (kW)
$Emax_n^{Bp}$: Maximum energy consumption of pump number n during billing period Bp (kW)
g : The acceleration of gravity (m/s^2)
h_L : Total friction and minor losses (m)
H_p : Pump head (m)
H_n : Head of pump n (m)
L_i: Length of pipe i (m)
N : Total number of pumps
$NBPn$: Number of billing period
P : Pump Power (Watt)
$\sum Penalty$: Total penalty due to violations of system constraints
$P_i(t)$: Pressure at node i at time t (bars)
P_{inlet} : Inlet pressure of pump station (bars)
$Pmax_i$: Maximum pressure limit at node i (bars)
$Pmin_i$: Minimum pressure limit at node i (bars)
PS_k : Number of pump switch for pump k
$PSmax_k$: Maximum allowable number of pump switched permitted for pump k
Q_n : Discharge of pump n (lt/s)
Q_p : Pump flow rate (m^3/s)
$S_k(t)$: Control setting of pump k at time period t. (1, 0)
T : Control time span
$TL_k(t)$: Water level in storage tank k at time t (m)
$TL_k^{initial}$: Initial water level of storage tank k (m)
TL_k^{final} : Final water level of storage tank k (m)
$TLmax_k$: Maximum water level limit in storage tank k (m)
$TLmin_k$: Minimum allowable water level in storage tank k (m)
$V_j(t)$: Water flow velocity in pipe j during time interval t (m/s)
$Vmax_j$: Maximum flow velocity permitted in pipe j (m/s)
Z_A : Total static head between source tank and tank A (m)
Z_B : Total static head between source tank and tank B (m)
η: Pump efficiency
ρ : Fluid density (Kg/m^3)
ΔTL_k : Allowable tolerance of the final water level for storage tank k (m)
ΔZ: total static head (m)

CHAPTER 1

INTRODUCTION

1.1. General Information

Water is essential for life on Earth; water can be accepted as one of nature's most valuable endowment to human being. Civilizations throughout centuries were settled near drinking water resources. According to Wong (2006), places such as Nile, Tigris and Euphrates became first settlement areas in which human populations established their inhabitation on Earth. In other words, the major rivers on Earth provided effective roles in the evolution of human being. Since ancient times, people have tried to be close to potable water resources and manage water resources to be able to survive. Increase of human population over time caused residential areas close to fresh water sources to be insufficient. Therefore, people started to meet the needs of potable water by using water supply systems.

A water supply system is an infrastructure for the collection, storage, transmission and distribution of water to consumers. Thus, it is composed of different hydraulic elements such as pipes, reservoirs, storage tanks, pumps and valves. The main purpose of water supply system is providing adequate amount of potable water to the consumers at required pressures.

Today, water utility department of municipalities are struggling to meet the water demand of consumers. Because of rising population, water demand increases continuously. Moreover, increasing demand for drinking water boosts operation and maintenance costs of existing water supply systems and also obligate water utilities to make new investments for meeting additional demands. Similarly, increasing world population raises world energy demands. In addition, increasing world energy demands and declining energy resources lead to rapid increase in world energy prices. Providing water service to high number of consumers in a large area is a difficult mission for water utilities, especially in Greater Cities. Therefore, under the influence of increasing water demands, energy prices and requirements of new investments, water utilities face economic difficulties while providing service to customers. Such increasing expenses and needs cause budget gaps in water utilities' economy. Main purpose of water utility is providing adequate amount and quality of potable water to the consumers at required pressures. Therefore, to ensure continuity of water service to consumers, all expenses to run water supply systems should be taken into consideration by water utility. However, water utilities could find themselves offering inadequate quantity and quality of water service while trying to decrease the budget deficit. To overcome these problems, water utilities should diligently plan, design and construct new water supply systems and should improve operation and maintenance policies of existing water supply systems. Therefore, planning, design and construction periods are essential components to establish an adequate water supply system. Water utilities spend huge amounts of money to meet the cost of planning, design and construction periods. For instance, Ankara water utility is planning to spend 600 000 000 TL in 2012 to construct required water source infrastructures and incomplete water distribution network pipelines (Ankara Water and Sewerage Administration Performance Program of 2012 Budget Year, 2011). This amount is approximately 45 percent of 2012 estimated total budget of Ankara Water Utility.

Planning of water supply system can be considered in two parts: determination of basic system structure and creation of the layout system (American Water Works Association, 1989). In this manner, engineer deals with some important considerations like, selection of sources and their order of priority, locations of pump stations and main storages, type of network skeleton system and so on. Then, in design process, sizes of water supply system components are selected by engineer. Components of water supply system have different economic life periods. Although transmission lines, distribution lines, storage tanks have an economic life between 30 and 35 years, economic life of pumps in pump stations could be at most 15 years. Due to this constraint, staged design should be employed. In staged design, water supply system is devised with respect to water supply system component's economic life period. In general, pumps are the components having smallest economic lifetime period in a water supply system. Therefore, number of upgrade cycle of pumps will be higher than the other components in a water supply system. If the economic life periods of pumps are 10 years in a 30 years water supply system project, at the end of each 10 years pumps completed its life time should be changed. And also, other components having different lifetime periods should be replaced at the end of their lifetime periods. To prevent over size design and extra costs of upgrade, each period design should be prepared by considering requirements of its life time period. For instance, at every stage, size of new pump must be larger enough to provide system requirements till the end of next upgrade stage. For any water supply network system, there may have been infinite number of different designs satisfying all requirements and hydraulic conformity criteria. Traditionally, engineers may use different optimization techniques to determine least cost design. However, least cost design of water supply system can be applied while getting started to new water supply system constructions. After construction of new water supply system, operation and maintenance costs of the system come into consideration. Although the cost of additional water supply system investment due to required upgrade is high, the rate of additional new system size to existing water system size is too small in Greater Cities. Therefore, to minimize the total expense of water utilities, instead of constructing additional system, it will be more effective to concentrate on the existing part of water supply system.

Planning, design, operating and maintenance policies are complementary elements of water supply systems. Even if a water supply system is well planned and designed, the efficiency of the system will be low unless operating policy is good. Operation consists of two operating policies (American Water Works Association, 1989). First policy decides how components of water supply systems, such as pumps, storage tanks and valves are operated under design conditions. Second operating policy determines real-time control operations of components in the system. Real time operation may be carried on water supply system hour by hour for one day or may be extended for one week. For existing water supply systems, improvement of operating policy can effectively increase system efficiency and reduce system expenses such as operation and energy costs. If the energy expenditure of drinking water distribution system is examined, pump stations can be considered as the most energy consuming unit in the system. Therefore, water utilities can reduce pump energy costs by improving operation policy of pumps without making any new investment. In water supply systems, sizes of pumps are determined to meet the needs till the end of its lifetime. Throughout their economic lifetime, pumps can be considered as over designed components. For example, a pump in a water supply system can ceaselessly run (7/24) to meet the demand at the last year of its lifetime. Since, size of pump is determined with respect to projected demand at the end of its life time. On the other hand, at early years of its lifetime, same pump can run for a few hours in a day while providing system requirements. During the time period between first execution of pump and the first day of continuous operation of a pump, on-off operation of pumps will prevent excessive or inadequate pumping. Determination of on-off operation policy of pumps in a pump station can be performed by developing daily pump schedule. In undeveloped countries, pump stations are controlled manually by operators. In other words, operator of pump station switches on or off the pumps according to needs of the system without regarding any expense. However, in developing countries, operation policy of pump stations is prepared by optimal pump schedules and pumps are automatically operated with respect to these pump schedules. Optimal pump schedule allows the most economical and efficient way of operating pump stations of complex water distribution systems. In this manner, developing an optimum pump schedule in a pump station can effectively improve pump operation and provide reductions in total energy consumption of pump station.

1.2. The Aim of the Study

This study aims to provide an effective daily pump schedule of pump combinations for minimizing the energy costs regarding constant and multi tariff of electricity (3 Kademeli Elektrik Tarifesi). Therefore, a case study was performed in an area covering two pressure zones (N8 and N7) which are parts of a complex water distribution network system of Ankara (Ankara North Water Distribution Network) that consists of multiple pumps and tanks. By using simple genetic algorithm based software (WaterCAD Darwin Scheduler), least-cost pump scheduling and operation policy for each pump station were determined while satisfying target hydraulic performance requirements. Models of two pressure zones in separated form have been prepared with the help of the data gathered from AYBIS (Aski Data Bank). System characteristics of the network were obtained from Geographic İnformation System (GIS) of water utility. Operational data of pumps have been provided by SCADA (Supervisory Control and Data Acquisition) of water utility. The existing base scenario and alternative scenarios which were prepared by using optimal pump schedule will be compared and the achievement of optimizing pump operation will be analyzed.

This thesis contains 7 chapters. In the first chapter, a brief introduction is mentioned about the topic of thesis. Then in second chapter, the necessary theoretical considerations for the study will be explained. Operation of pump stations will be examined in Chapter 3 to understand working mechanism of pumping system more clearly. Before performing case study, required information about modeling of water supply systems will be discussed in Chapter 4. Then in Chapter 5 Genetic Algorithm search and optimization technique will be explained. After Chapter 5, conducted case study and its results will be elaborated in Chapter 6. Finally, in Chapter 7, obtained conclusions and suggestion for the study will be discussed.

CHAPTER 2

THEORETICAL CONSIDERATIONS

2.1. Components of Water Distribution Systems

2.1.1. Distribution Reservoirs

Water is collected for use in distribution reservoirs which may be natural or artificial. The primary water sources of water supply system are distribution reservoirs. Dams, water wells and water treatment plant storages are some examples to the distribution reservoirs. Distribution reservoirs store large volumes of water to let the water supply system to run continually.

2.1.2. Storage Tanks

Storage Tanks are artificial structures that store water and provide water to the system when needed. Equalizing and emergency storage are the two basic task of storage tanks (Curley 2011). In peak demand hours, required water may not be satisfied by pumps only. At this situation, extra water is taken from storage tank and water distribution network is equilibrated by storage tank. Moreover, in low demand hours when the water consumptions of consumers are almost zero, amount of pumped water is higher than system demand and extra water coming from pumps are stored at storage tank and equilibrium of water distribution system is satisfied again. This equilibrium purpose of storage tank is called as equalizing storage. In addition, storage tanks help water utility to easily manage pressure distribution by preventing pressure fluctuations.

Emergency storage ability of storage tanks provide required water to perform fire-fighting operations or maintenance operations. For instance, if the pump of distribution network is turned off due to power cut, distribution network continues to serve to the customers by using water stored in the storage tank till the end of power outages.

2.1.3. Pipes

Pipes are the essential elements of a water distribution system. All the elements of water distribution system, such as junction nodes, pumps, reservoirs, valves and tanks are linked to the each other by pipes. Earlier, only limited sizes and types of water supply pipes were available, but nowadays with the help of developing technology, pipes are produced in different materials and sizes to be used in residential and commercial water supply network applications.

Type of water supply pipes can be divided into three major categories: cement pipes, metallic pipes and plastic pipes. Cement pipes include asbestos cement pipes, concrete cement pipes and pre-stressed cement pipes. Metallic pipes include ductile iron pipes, cast iron pipes, steel pipes and galvanized iron pipes. Plastic pipes include Poly Vinyl Chloride (PVC) pipes, low-density polyethylene (LDPE) pipes and high density polyethylene (HDPE) pipes. Today, pre-stressed concrete, cast iron, ductile iron, steel, high density polyethylene (HDPE) polyvinyl chloride (PVC) are the common used pipe materials in Turkey.

Based on needed amount of water, different pipe sizes can be selected. In Turkey for the water distribution networks, pipe diameters starting from 19 mm to 2200 mm are ordinarily used. To meet more excessive water needs, pipe with large diameters may need to be produced by manufacturers.

In a water distribution network, pipes can be classified in to three categories based on distribution type.

- Main Transmission Line Pipes
- Distribution Network Pipes
- Service Connection Pipes

2.1.4.1. Main Transmission Line Pipes

Major duty of main transmission line pipes is to transport huge amount of water from source to distribution network nodes, pump stations and storage tanks. Main transmission line pipes work as a main artery vessel of the body that transports high volume of blood from heart to internal organs like lungs and capillary vessels. Therefore, they are important components of water supply system, because any failure on this component causes quick collapse of total water supply system due to shortage of water.

Diameters of main transmission line pipes are larger than other pipes in the water supply system as artery vessels having larger diameters than capillary vessels. At some important points, main transmission line pipes are connected to distribution line nodes to appropriately feed the network. Pipe material of main transmission lines are usually selected as ductile iron, steel, HDPE and pre-stressed concrete.

2.1.4.2. Distribution Network Pipes

Water coming from nodes connected to transmission lines should be distributed to overall network. At that point, distribution network pipes are used to transmit water to the streets of the water distribution network. Like a spider web, distribution network pipes are placed at every street to supply water to consumers properly.

Mostly ductile iron, steel, LDPE, HDPE and PVC pipes are used in distribution networks.

2.1.4.3. Service Connection Pipes

Consumers are directly connected to distribution network pipes at their street with the help of service connection pipes. Generally, HDPE and LDPE pipes are preferred for service connections because this type of pipes can be placed easily and quickly. In a city, everyday hundreds of service connections of new consumers can be needed to be placed. Therefore, it is important to select type of pipe to place.

After establishing the connection between building and distribution network with the service connection pipes, water comes from service connection lines is distributed on interior pipeline of building to deliver water to each consumer in the building.

2.1.4. Valves

In a water supply system, valves are the major component to control the flow of water. By operating the valve the flow can be controlled in different ways. Completely preventing water flow, adjusting the amount of water flow, directing flow to different paths and reducing flowing water pressure are some of capabilities of valves in water supply system.

Valves may be operated manually, either by a handle, lever or wheel. Valves may also be operated automatically by electronic devices and may be operated remotely.

There are many types of valves for use in water supply system pipelines. Selection of valves depends on the duty. For different flow control applications, different type of valves may be selected.

2.1.4.1. Check Valves

Check valves are the type of valves which normally allows water to flow through it in only one direction. The flow in the opposite direction is prevented. Under normal flow conditions the gate in the valve body is kept open by the flow, and when the flow stops, the horizontally hinged gate in valve body closes by gravity or with the aid of springs. So, this type of valve does not need any operator. It is installed to the system according to desired water flow direction. Mainly, it is used at storage tank inlet-outlet and pump outlets to prevent flow in opposite direction.

2.1.4.2. Isolation Valves

Isolation valves are type of valves that isolate a part of the network area from the entire distribution network. In a water supply system isolation valves can be used for different purposes. For example, if a break occurs on pipeline, water starts to leak from pipes. Then to perform maintenance operation, flow in the pipeline to the damaged area direction should be blocked by closing the isolation valve. By isolating the damaged area, maintenance area is dried and pipe can be repaired.

Isolation valves also are used to control the flow direction in the distribution network. The flow direction of water in a street may be changed by using a couple of isolation valves with different positions (closed-open). Another application area of isolation valves is to separate water distribution system to isolated sub networks to simplify the management of large water distribution networks.

Gate valves are the most common types of isolation valves. They are designed to work in two positions which are fully opened or closed valve openings. Using gate valve to control the amount of water flow by closing partially is not recommended.

2.1.4.3. Flow Control Valves

Flow control valves are used to adjust the flow in the pipelines of water distribution network. The amount of flow can be increased or decreased between zero and maximum flow (with fully opened valve section) by operating flow control valves. Butterfly type valves are most widely used flow control valves. In Butterfly valves, valve opening is controlled by the disc placed in valve body. Operator turns the valve shaft to change the disc position in the butterfly valve. So that, valve opening change causes to decrease or increase flow section in the valve body. Amount of water flow in the pipeline is adjusted by the different valve openings.

2.1.4.4. Air Valves

In water supply systems, air may be found in freely dissolved form. This air may be present in the system due to different cases (Web1);

- In the first run of water distribution system, distribution network may not be fully filled by water and air may be remained in higher places.
- While performing maintenance and repair operations air enters to the distribution system.
- When the pressure decreases too or suction occurs in the system, dissolved air in water comes out.
- Air may be occurred in the water distribution system due to consisted vortexes in the pump.
- Air may enter to the system directly through openings or system components.

Present air in a water supply system can result in many different damages;

- Due to air presented in the system, water flow may be restrained or completely stopped by water column separation.
- At air trapped points, due to reduction of net cross section area, water flow capacity is decreased, energy losses are increased and high vibrations occur in the system.
- More severe water hammer occurs.
- Corrosion rate of metal components in the system is increased.
- Efficiency reduction occurs in pumps.
- Flows can’t be measured accurately.
- Cavitation damage occurs in the system.

To prevent such damages, air is to be avoided in water supply system. Air release valves are the components that installed at local high points to allow air to come into the system during periods when the head drops below the pipe elevation and expels air from the system when water columns begin to rejoin. Air release valves works automatically without need of any operator and discharge or intake large volumes of air when filling or emptying a system.

2.1.4.5. Pressure Reducing Valves

Water utilities use pumps and pumping stations to boost water supply pressures in supply mains to be able to supply water for fire-fighting, high rise buildings to overcome loss of pressure as the elevation increases, and to maintain water supply in water towers and supply tanks. Higher pressures could rupture pipes, damage other water supply system components, causes increase in water leaks and also injure the people using them.

Pressure reducing valves are used to decrease high pressures in the water supply systems where it is necessary. High pressure water entering the valve is constricted within the valve body and directed through the inner chamber controlled by an adjustable spring loaded diaphragm and disc. Therefore, the force created by the help of the spring meets with incoming water and decrease the pressure of entered water. Even if the supply water pressure fluctuates, the pressure reducing valve ensures a constant flow of water at a functional pressure, as long as the supply pressure does not drop below the valve's pre-set pressure. Earlier pressure reducing valves are adjusted by mechanically one time and it reduces pressure at constant amount set before. Today, inlet pressure can be adjusted dynamically depending on time, flow in the pipeline or both by using program controlled pressure reducing valves. In addition, this program control operation can be done remotely with advanced communication technologies.

2.1.4.6. Drain Valves

Drain valves are valves connected to system to emptying water in the pipeline. Upstream side of the valve is connected to the network and downstream side of the valve is open to the atmosphere. Generally, discharge valves are placed at lower elevation points of the system to discharge all the water in the pipeline. Downstream ends of the discharge valves are usually connected to stormwater collection system or sewerage system to prevent water flood while making discharge operation. However, discharged water from this valve should not drain into sewerage system, because water discharged from water distribution network is unused and not need to be treated as sewerage. Therefore, discharge valves are essential components for water supply system for maintenance operations.

2.1.5. Fire Hydrants

A fire hydrant is an essential element of water distribution network to provide required water for fire-fighting. In fire-fighting operation, pressure and flow of water are important factors while extinguishing a fire. Fire hydrants are designed to provide required high water pressure and flow. Therefore, fire hydrants are connected to the distribution network with pipe having larger diameters to provide excessive water flow required for fire-fighting. The fire hydrants are distributed over entire water network to provide sufficient connection points for fire-fighting. Mostly, 80 and 110 mm diameter fire hydrant are used in Turkey. This large diameter fire hydrants enable municipality units to use fire hydrants for different purposes such as network flushing, sewage cleaning and maintenance operation.

2.1.6. Pumps

A pump is a device used to move water by mechanical action. An electrical motor is used to convert electrical energy to mechanical energy and this mechanical energy is transferred to the pump with the help of driveshaft. The transferred mechanical energy is used to overcome friction losses of pipes, minor losses of system components and also to provide pressurized flow at needed points.

As mentioned in introduction part energy cost of water supply system is directly related to pumps. Therefore, in the design process of water supply network, pumps are carefully selected depending on design requirements. In addition, operation process of pump station should be diligently maintained during the lifetime of pump with respect to dynamically changing water supply systems.

Pumps are divided into three type categories; centrifugal pumps, rotary pumps and reciprocating pumps. In this study, types of all pumps used in case study are centrifugal pumps.

CHAPTER 3

PUMP STATION OPERATIONS

3.1. General Characteristic of Pumping Systems and System Head Curve

Pumps are used in water supply systems to provide total head necessary to overcome resistance against flow and to meet the pressure requirements of the system components. Thus, water flow from lower places to higher places is maintained.

In water supply systems, pumps may be used indirectly as supply pumps to provide water flow between water source and water distribution network or may be used directly within the system to provide required pressure over entire system as a booster pump. Layout of system structure and system components such as pipes, fittings, valves and measurement equipments (flow meter, chlorine meters, etc) are the factors that determine behavior of pump operation.

The flow provided by running pumps is directly related to its head capacity given by manufacturer and also system head which is the total system resistance due to flow (Doruk, 2001). Therefore, flow provided by running pump varies with the total system head. Head versus discharge curve of pump and system head curve are superimposed to determine total head losses which are friction and minor losses of the system and operating point of pump (Figure 3.1). As shown in the figure, operating point is the intersection point of pump curve and system head curve. At operation point, equilibrium between pump head and total system head due to head losses is achieved.

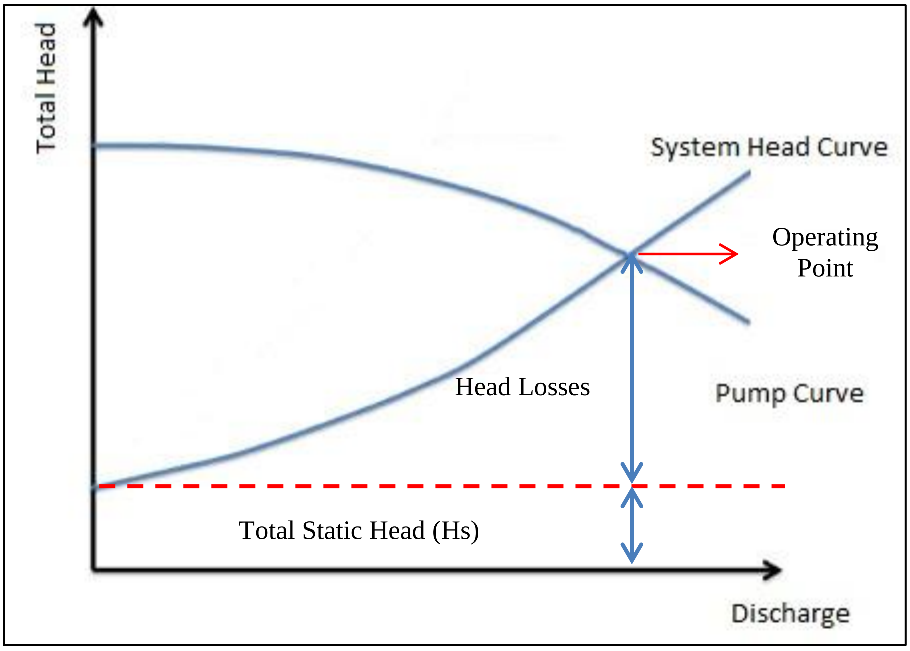


Figure 3.1. Pump and System Head Curve

In other words, operating point is a balancing point between running pump and total system resistance. Thus, total friction and minor losses of the system caused by flow defines the running behavior of pump in the system and exact flow and head values of pump are determined.

Pumping system will be discussed in more details in the following section to effectively observe their working mechanism in water supply system.

3.1.1. Pumping Systems

Pump provides water flow from source point to discharge point. Pumping System is composed of piping and all other equipment between these source and discharge points. Flow of water in a particular length of pipe is controlled by operated pump. This length of piping indicates pumping system limits. Length limit of the system and pump are represented in Figure 3.2 (Karassik et al., 2008).

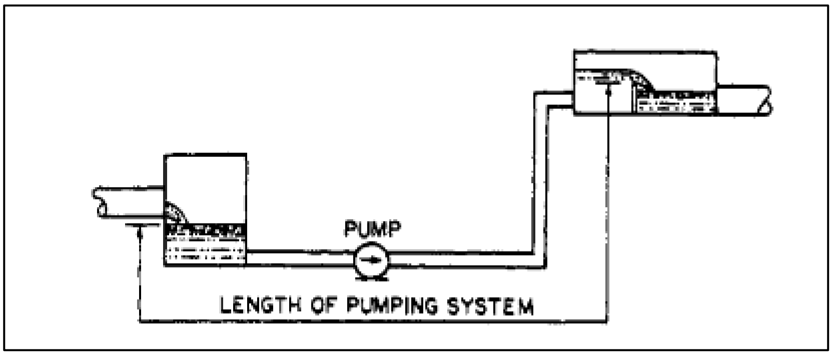


Figure 3.2. Length of the system controlled by pump (Karassik et al., 2008)

A group of branch lines can be connected to pump inlet and outlet separately. This type of system is called branch line pumping system (Figure 3.3). In this example, two source tanks shown on the left and three discharge tanks on the right are working together in branch form.

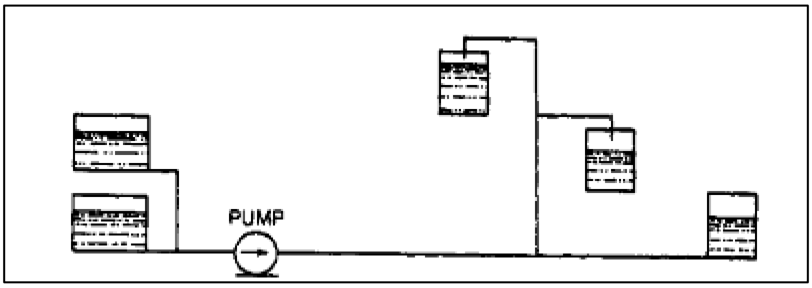


Figure 3.3. A pumping system constructed in branch-line form (Karassik et al., 2008)

In a pumping system, a couple of same or different type of pumps can be operated together in series or in parallel or both as shown in Figure 3.4. When there are multiple pumps used in the pumping system, total behavior of pumps should be determined (combined pump curve). Then, system head and flow values can be determined by superimposing total system curve and combined pump curve.

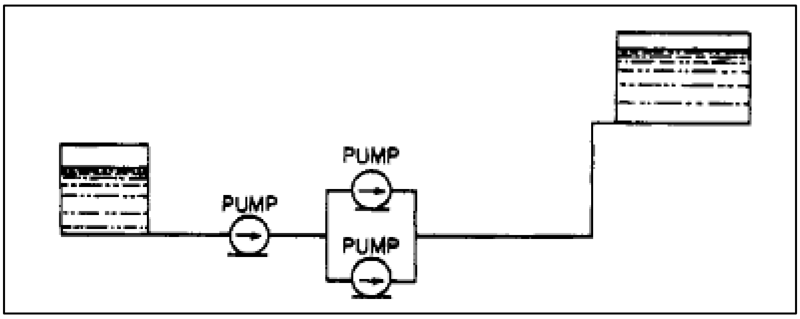


Figure 3.4. Multi pumps running in series and in parallel (Karassik et al., 2008)

As mentioned at the previous part, the system through which the water is pumped causes resistance to flow. This resistance is mainly produced by friction due to flow through pipes and fittings. Moreover, if the water is desired to be lifted to higher elevations or desired to have higher pressure because of service requirement, additional resistance is encountered. Therefore, pumps must overcome the total system resistance due to friction and, as required, produce an increase in elevation or pressure at the desired rate of flow. Moreover, system requirements may be such that the pump discharges to a lower elevation or pressure but additional pump head is still required to overcome pipe friction and obtain the desired rate of flow.

3.1.1.1. Hydraulic Head Parameters in Pumping Systems

In pumping system, pumps have four different head parameters which are static suction lift, static discharge head, total discharge head and total dynamic head. These head parameter values allow engineer to have an idea about inlet, outlet condition of pump and performance of pump.

Static suction lift is the elevation difference between water level in source tank and centerline axis level of the pump. If the elevation of water level in source tank is higher than pump, the static suction lift is positive. In addition, if the elevation of water level in source tank is lower than pump, then water in source tank flow by the pump vacuum effect and static suction lift is negative.

The elevation difference between water level in discharge tank and centerline axis level of the pump is static discharge head. Summation of both static suction lift and static discharge head is total static head which is the elevation difference of source and discharge tanks directly.

If the friction losses and minor losses are added to total static head, then total dynamic head or total head is achieved. The equation to determine total head is given below:

$$H_p = \Delta Z + h_L \tag{3.1}$$

H_p: total pump head,

ΔZ: total static head,

h_L:total friction and minor losses.

The head parameters of different pumping systems are represented in Figure 3.5.

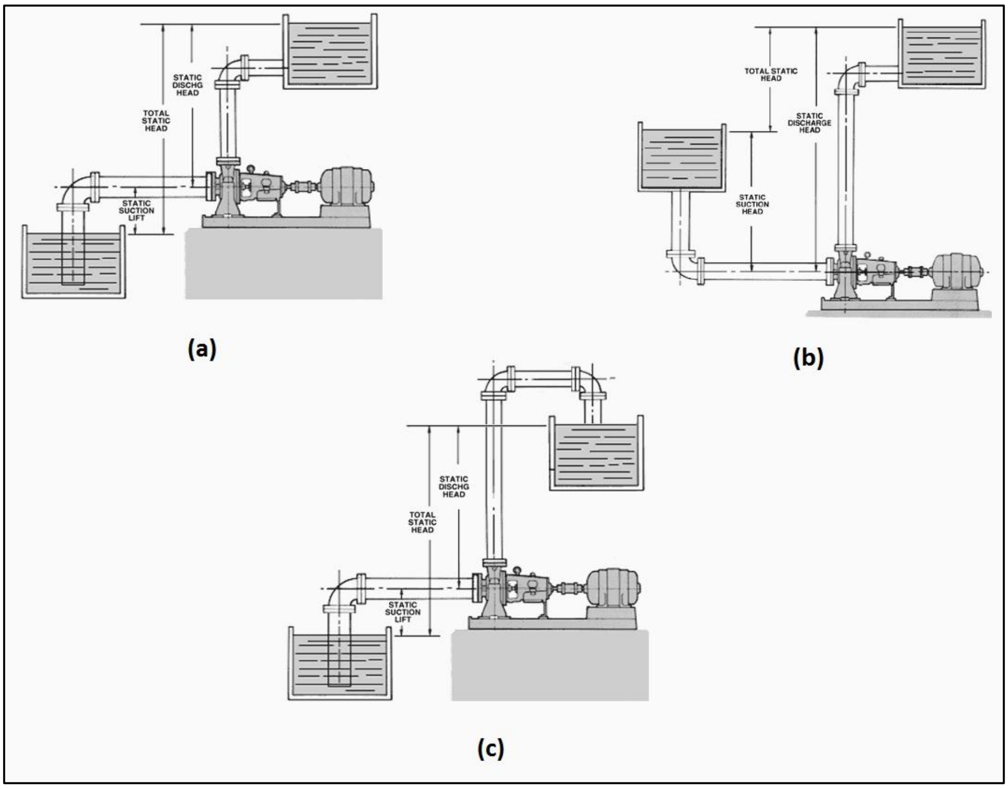


Figure 3.5. Head terms in different pumping systems

3.1.2. System Curves

As mentioned before pumping system is composed of elements which are pipes, valves, fittings, meters, process equipment through which flow is performed to provide water requirement.

Resistance to flow due to above elements in the system must be calculated to select pump or pumps properly. In some systems, overcoming of flow resistance may not be enough; there may be needed extra head to lift the water higher discharge level. Moreover, in some extreme cases, pressure at water surface in the discharge tank may be higher than the pressure at water surface in source tank (Closed to the air- Pressurized Tanks). In this situation, more pumping head is needed to overcome pressure difference.

A system head curve is a plotted from summation of total system resistance which may be variable or fixed, for various flow rates. In other words, it is a graphical representation of total dynamic head which is the summation of static head and head losses containing friction and minor losses in the system versus water flow rate. System head curve is an essential tool for pump applications.

By using system head curve, system heads for different system flow rates or operation point of pump can be easily and quickly determined. To determine system-head curve, following operations are performed. First, system is clearly analyzed and pumping part of the system is determined. Then, acting area of pump which is length of pumping system is established. After that, elevation difference between source and discharge tank which is the static head is calculated. Finally, total head losses of the system due to friction and minor losses of system components are calculated for several flows rates. This shows that total system losses varying with flow through pipeline.

As an illustration, in Figure 3.6 a pumping system is created by using source tank A and discharge tank at B. Water is taken from source tank A and pumped to discharge tank B. It is indicated that net change in total energy due to elevation difference of water level in tanks shown as Z is the fixed system head. The variable system head is the head losses due friction in pipes and other minor losses of the components in the system. By using the summation of calculated fixed head and variable heads for several flow rates system head curve is constructed and plotted as in Figure 3.6.

In equilibrium state of the system, system head and head of pump should be same. Thus, as the system head is changed flow provided by pump will be changed. Exact flow value of pump is determined by superimposing the head flow characteristic curve of pump taken from pump manufacturer on a system-head curve, as shown in Figure 3.6. Intersection of both curves gives the operating point where pump head and required system head are equal to each other.

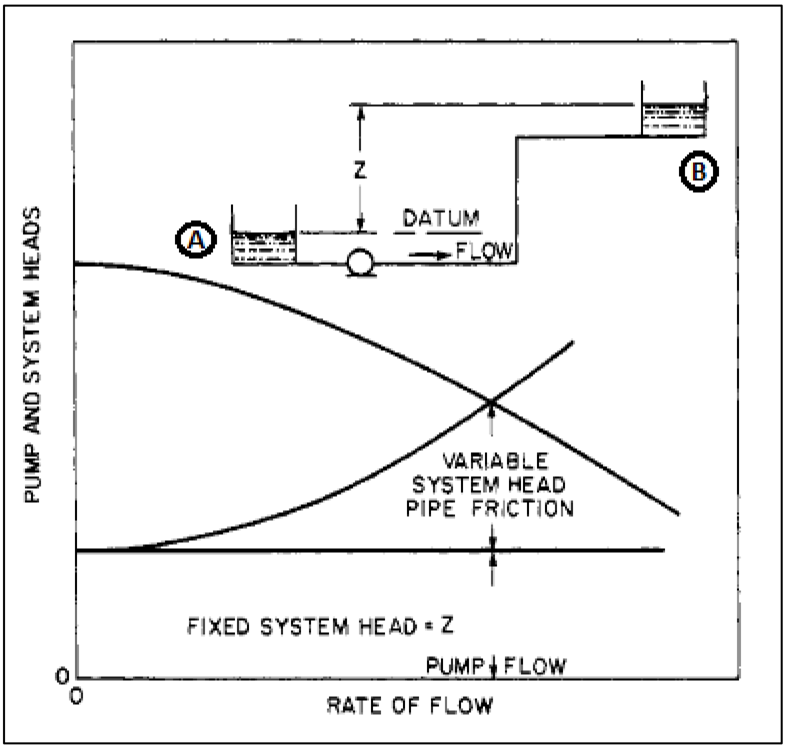


Figure 3.6. Pump and system head curves of basic pumping system (Karassik et al., 2008)

3.1.2.1. Variants in Pumping Systems

If the initial condition of pumping system is not changing over time, there will be only one operation point where pump curve and system curve intersect each other. However, in real life, pumping systems do not remain constant and many changes are occurred throughout the day. These changes may be done by system operator which are named as controllable changes or may be done due to different reactions of the system beyond the control of operator which are named as uncontrollable changes. In section 3.1.2, it is mentioned that system curve is determined by plotting total system resistance for various flow rates. In addition, system resistance is composed of friction and minor losses due to flow through the system components such as pipes, fitting, valves and etc. Thus, any change on the components cause system resistance to be modified. For this reason, pump curve coincide with modified system curve at new operation point. Therefore, operation flow and operation head of pump vary. Valve operation (changing valve cross section), changes of water levels or pressures in source and storage tank, aging of pipes, replacement of pipe with different one (having different diameter, length, material and etc) are the some of the system changes with or without operator control. These changes in system conditions cause the system head curve to be modified and new operation point of pump to be generated. In the following part pump behaviors will be expressed under variable static head and variable resistance.

3.1.2.1.1. Variable Static Head

Static head which is defined before is the elevation difference of water levels in suction and discharge tanks. Static head remains unchanged as long as water levels or pressures of source and discharge tanks are constant. However, if any change occurs in the water level of tanks (emptying of tank during peak demand flow) in system while system is running, static head of the system will be changed due to new water level and new system curve will be constructed. For example, in a system where a pump is transferring water from one tank to another, the flow capacity of pump will decrease with an increase in static head. The system-head curve is constructed by plotting the variable system friction. Static head of the system is the point where the system curve intersects head axis which is zero flow axis on. In other words, static head is the starting point of the system curve. If an increase or decrease in the static head occurs due to water elevation changes in the tank, starting point of system curve will be modified and shifted vertically. The vertical movement of system curve causes new operating point of pump to be produced as shown Figure 3.7 (intersection point of pump head curve and system head curve B). As a result of this, pump run according to new operation point with different head and flow rate.

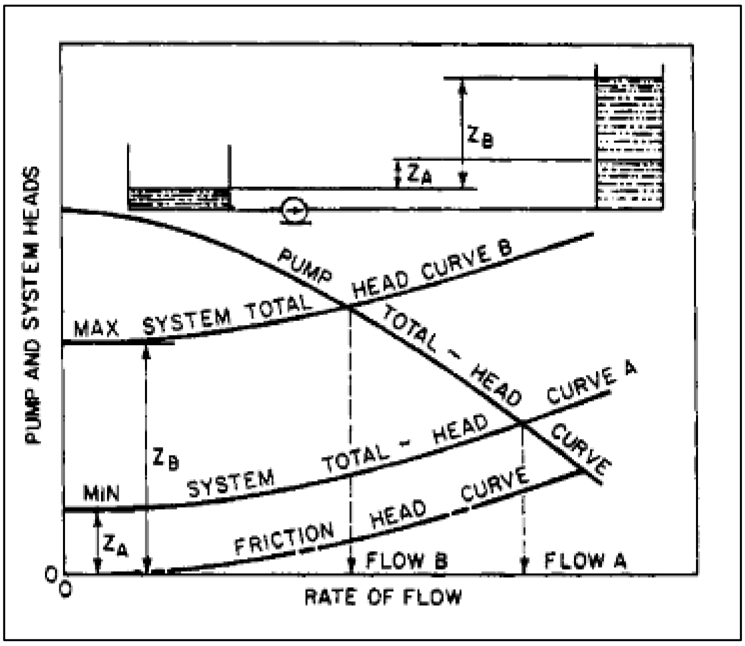


Figure 3.7. Construction of modified system head curves depending on changing static head (Karassik et al., 2008)

3.1.2.1.2. Variable System Resistance

System resistance is the combination of all head losses which are friction and minor losses of the system due to flow through system components. Thus, any change on system equipments that affects head losses will cause system resistance to be changed. For instance, aging of pumps occurs as times goes on. Aging of pipes causes reduction of the actual diameter of pipes, alteration of the original smoothness of the interior of the pipe. Thus, these effects increase friction losses occurred in pipes. In addition, operating valves by changing flow cross-section causes system resistance to be changed. Moreover, increase or decrease of demands varies the head losses and also changes the flow in the pipeline. Due to these variations, modified system curve is established and change in pump operating point is seen depending on new system curve.

If the valve opening is decreased, the resistance of the system will be increased. Vice versa, opening valve results decrease in system resistance. Thus, maximum flow is obtained when the valve is fully opened, and only resistance of flow is the friction in the pipes, fitting and other equipment in the system. In addition, fully closed valve results pump's operating at shutoff condition and produces maximum head of the pump. Therefore, by adjusting the valve position, flow can be controlled between maximum and shutoff position. System curve for various valve positions is shown in Figure 3.8.

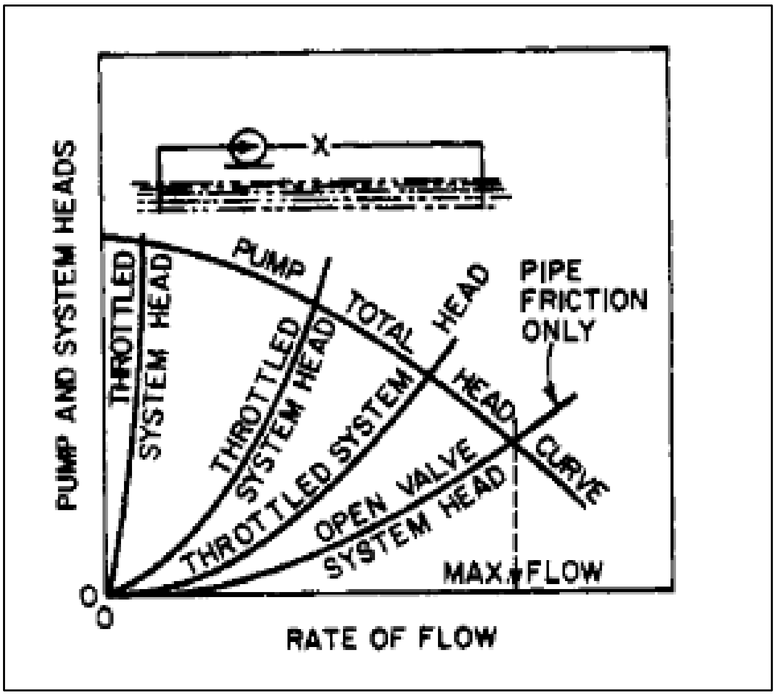


Figure 3.8. Effects of valve operations on system head curve (Karassik et al., 2008)

3.1.3. Pump Performance Curves

Pump performance curves are the graphical representation of head capacity, power capacity and efficiency curves. Pump Manufacturers test each produced pump and plot their performance curves depending on test results. These curves are the identity of pump. While selecting suitable pump for the system, pump performance curve is the most important element for the engineer to make decision. Most basic and helpful performance curve is the head capacity curve which explains relation between pump head and pump discharge. For a selected head value, only one discharge value should be obtained from performance curve. If there is more than one discharge value for a specific head, then pump shows unstable running performance by providing different flows at that head. Thus, pump head curve can give information to engineer that selected pump is stable or not.

Another important point in pumping system is operating pumps with maximum efficiency. Efficiency of pump shows the exact performance of pump regarding to energy consumption of pump. Efficiency curves are constructed to observe pump performance for various flow rates or heads. Thus, efficiency curves indicate the relationship between the developed head and pump efficiency. To construct pump efficiency curve, power transferred to water by pump is divided by power transferred to the pump by motor and the ratio (efficiency) is plotted for various flow rates occurred by pump.

Construction of pump power curve could be performed by using power delivered to the pump in order to provide related flow rates. This curve shows the power consumptions of pump for different flow rates. Power consumption of pump is calculated by using following equation.

$$P = \frac{\rho.g.Q_p.H_p}{\eta} \tag{3.2}$$

where:

P: Pump Power (Watt)

ρ: Fluid density (Kg/m^3)

g: The acceleration due to gravity (9.80665 m/s^2)

Q_p: Pump flow rate (m^3/s)

H_p: Pump head (m)

η: efficiency

Q_p and H_p values are directly taken from pump head curved which gives the relationship between head and discharge. Efficiency (η) values are determined from introduced pump efficiency curves. A common view of all pump performance curves are illustrated in Figure 3.9.

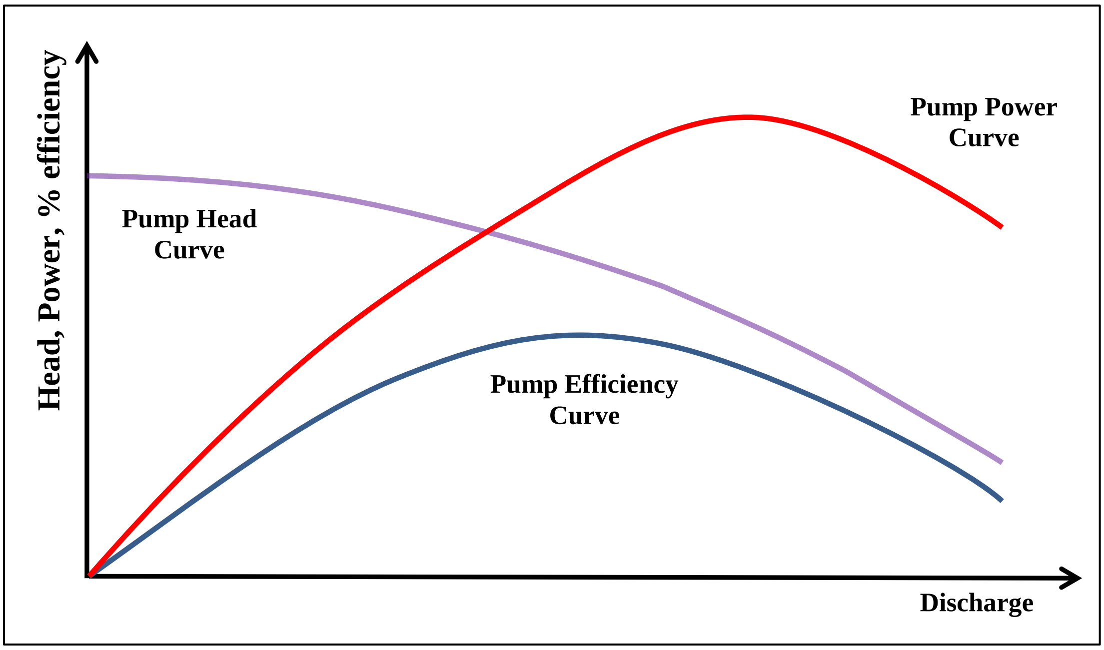


Figure 3.9. Pump Performance Curves

3.1.4. Multi Pump Systems

In a pumping system, a couple of pumps can be worked together in series or in parallel or both. When there are multiple pumps in the pumping system, the flow through the system and resultant pressure is determined by the combined performance of all the pumps.

3.1.4.1. Pumps in Series

If extra pressure is required, two or more pump can be connected in series and worked together to reach higher pressure values. Final head of serial connected pumps is calculated by adding each pump head. On the other hand, same amount of water flows thorough each pump. Therefore, combined pump curve of serial pumps is determined by adding head of each pump with respect to corresponding discharge. Then, final pump curve can be plotted with combined head for various flow rates. If the head capacity of pump is not sufficient for a distribution network having wide elevation interval, two or more pump can be used in series with staggered design. In staggered design, pump one is placed to distribution network inlet to provide water to area falling between minimum and mid elevation. Then, second pump is placed at mid elevation to provide water to area falling between mid-elevation and maximum elevation. By adding more pumps, distribution network system can be supplied by creation more pumping steps. Instead of using serial connected pumps at the system inlet point, staggered design allows head at lower elevations not to be above critical values. This application provides pressure at lower elevation to be taken into control and prevents water leaks or burst of pipes caused by high pressure. High buildings are the most commonly used fields of serial connected pumps with staggered operation. Combined head (H), flow (Q), efficiency (η) and power (P) values of serial connected pumps are mathematically calculated by the following relations.

$$H = H_1 + H_2 + H_n \tag{3.3}$$

$$Q = Q_1 = Q_2 = Q_n \tag{3.4}$$

$$\eta = \left[\frac{H_1 + H_2 + H_n}{\frac{H_1}{\eta_1} + \frac{H_2}{\eta_2} + \frac{H_n}{\eta_n}} \right] \tag{3.5}$$

$$P = \frac{\gamma \times Q \times (H_1 + H_2 + H_n)}{\eta} \tag{3.6}$$

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

The combined characteristic head curves of pumps in series can be prepared by equations above. Flow values of each pump are equal to each other as shown in equation 3.4 and also equal to combined pump flow. Thus, combined system curve can be determined by adding head values of each pump for the same flow values (Figure 3.10). Operation point of combined pumping system is determined by superimposing system head curve and combined head curve.

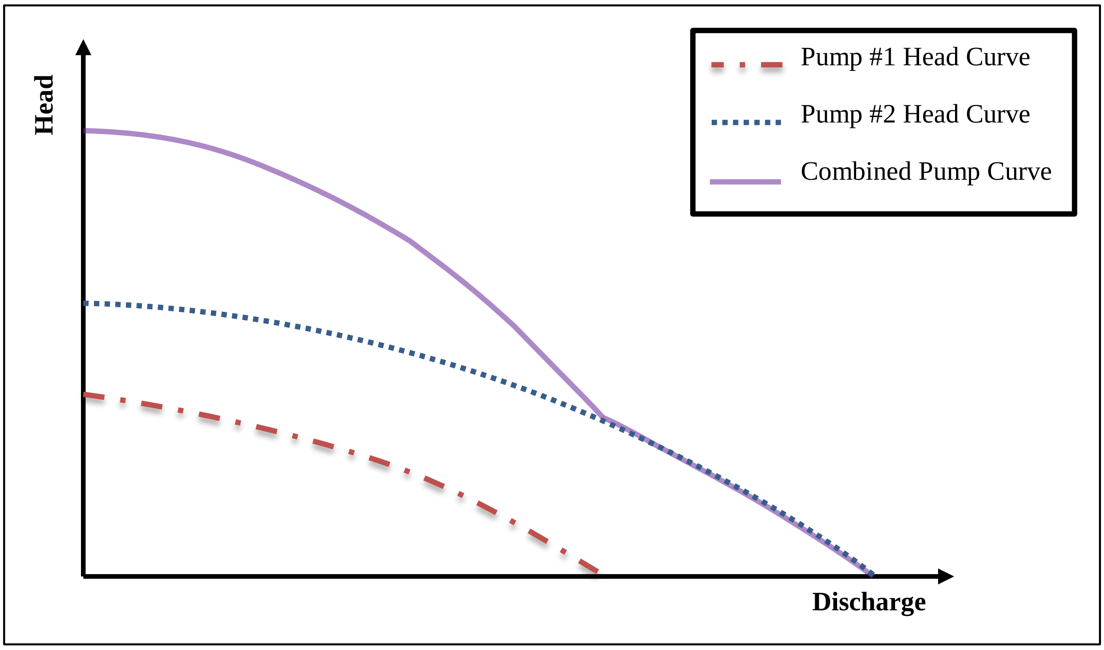


Figure 3.10. Head curve of pumps in series

3.1.4.2. Pumps in Parallel

It is possible to provide high pump flow by using multiple pumps in parallel having flow capacities small than resultant capacity. If two or more pumps are running in parallel, the head provided by each pump will be equal and united flow of pumps will be determined by summing flows of each pump depending on same head. Using pumps in parallel enable operator to provide water under variable flow rate requirements. In water distribution systems, demand varies by time (Qnight, Qaverage and Qpeak), thus to maintain good efficiency for pumping, pumps are commonly used in parallel form.

Combined head (H), flow (Q), efficiency (n) and power (p) values of parallel connected pumps are mathematically calculated by the following relations.

$$H = H_1 = H_2 = H_n \tag{3.7}$$

$$Q = Q_1 + Q_2 + Q_n \tag{3.8}$$

$$\eta = \left[\frac{Q_1+Q_2+Q_n}{\frac{Q_1}{\eta_1}+\frac{Q_2}{\eta_2}+\frac{Q_n}{\eta n}}\right] \tag{3.9}$$

$$P = \frac{\gamma \times H \times (Q_1+Q_2+Q_n)}{\eta} \tag{3.10}$$

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

The head curves of parallel connected pumps are determined by using equations 3.7 and 3.8. Summation of flow rates having same head values are plotted with varying heads to construct combined head curve of pump in parallel. Figure 3.11 illustrates graphical construction of head curve in parallel pumps.

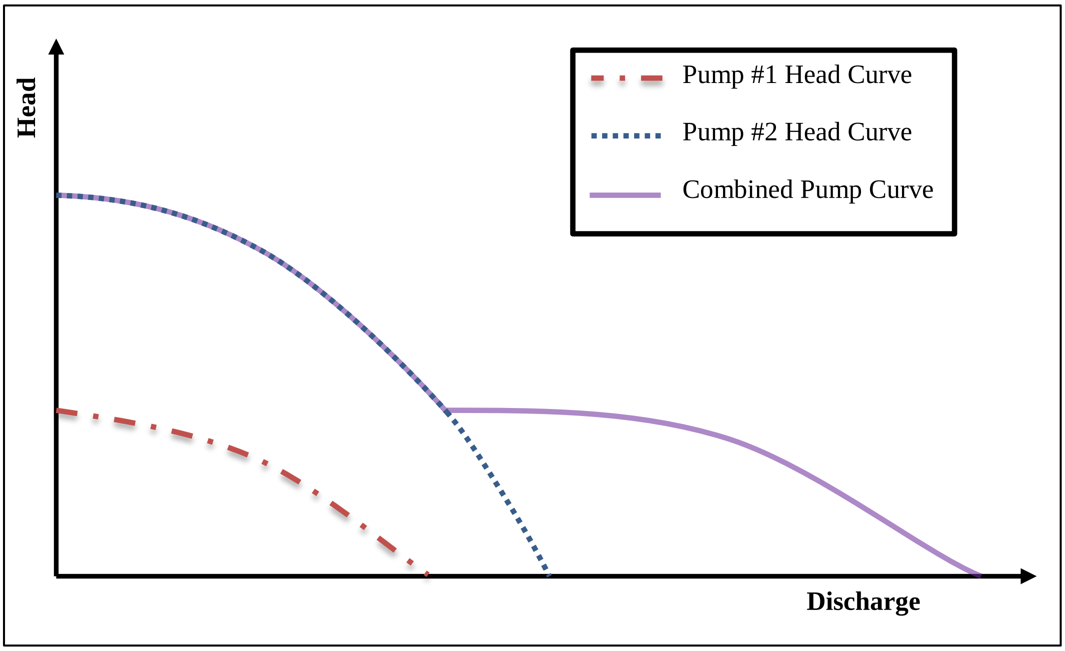


Figure 3.11. Head curve of pumps in parallel

CHAPTER 4

MODELING WATER SUPPLY SYSTEM

Today, modeling of water supply system by using hydraulic software is an essential process in planning, design and operation of water supply systems. By modeling the water supply system, a software based virtual water supply system is created which represents existing water supply system. With the help of modeling tools, engineers obtain much valuable information about the water supply system without constructing any real infrastructure. Modeling process is performed for many purposes. Modeling makes it possible for engineers to understand how water supply system operates under various conditions. The effects due to any changes of demand or flow in the system can be easily observed by engineer in water supply system model. Modeling process of water distribution network can be performed for any time interval; now or at any time in the future. Moreover, failure events such as pipe breaks, leakages, energy shortage of pumps, pump shut offs can be modeled and performance of the water supply system in these incidents can be determined by engineers with the help of water supply system model. Moreover, for an existing water supply system, models may be used by engineer to assess the impacts of proposed operation modifications, renewals, increments and developments (Gamtessa, 2008). Another purpose of modeling is to provide additional information for planning study of new water supply system. As mentioned above water supply planners use a range of models to support decision making.

In the creation of water supply system models, data of all components in the water supply system is required. A network model requires a wide range of inputs. These inputs are physical location information within the network, characteristics of water supply system components and system parameters like demand data. The quality of model is directly related with input data. If the data provided are erroneous or incomplete, the model will not function as desired and will not represent the existing water supply system in the field.

4.1. Building Physical Water Network Skeleton

Modeling of water supply system starts with building physical water network skeleton that exist in the field. In this process; all components such as pipes, connection nodes, valves, sub DMA’s, reservoirs, storage tanks and pump stations are modeled in software according the their characteristics and physical data (location, elevation, etc) known or obtained from field study.

4.1.1. Modeling Pipes

Pipes are the most encountered element in the water supply system. Therefore, huge amount of different data comes into consideration for pipes. Required pipe data for the model are pipe location information (coordinates), lengths, diameter, roughness coefficient, materials and also age of pipe for different modeling purposes.

Until the last few years, pipes in a water distribution network were drawn on tracing paper and these papers were stored in water utility archives. Moreover, some pipes which were installed long time ago were not even drawn on paper and nobody knows enough information about them. In this situation, unknown pipe information may be obtained by making excavations in the field.

Today, computer based software enables water utilities to store pipe information in computer aided draft (CAD) and geographic information system (GIS) environments. All the existing pipe information drawn on paper in archives were scanned, digitized and transferred into GIS environment including spatial data. Moreover, new projects are preferred in CAD environment by the water utilities to make sure data is easily accessible and accurately stored in archives. Therefore, today all the pipe data needed for the model are easily obtained from GIS database of water utility directly.

The roughness coefficients of used pipes are not easy to determine. Therefore, these data can be determined by making a detailed study in the field which is called calibration. Roughness coefficient of unused new pipes can be obtained from pipe manufactures. After accessing the all pipe data, pipe model is created in the modeling software.

4.1.2. Modeling Nodes

In water supply system model, every pipe is created by two nodes which are the start and end nodes. To provide flow in a group of pipes, connectivity of nodes must be achieved. Moreover, inflow and outflow points in the system are modeled with the help of connection nodes. The required data for modeling them are location (coordinates) and elevation data.

Elevation and location information of all connection nodes are also obtained from GIS database of water utility like pipes. Connectivity of nodes can be automatically done by modeling software with a tolerance assigned by user. For example, if the tolerance is 1 meter then software automatically creates connection between nodes when the distance between two nodes is less than 1 meter. However, this process also causes to create connection between two nodes which are close but not actually connected. Therefore, while using automatic connectivity feature, user must carefully select tolerance and after implementation must check the connection of nodes in the network to prevent redundant connections.

4.1.3. Modeling Reservoirs and Storage Tanks

In water supply system model, reservoirs and storage tanks are placed as a node connected to the system. The inflow and outflow of reservoirs and storage tanks are performed on this node.

Storage tanks may have different shapes. Base area of storage tank can be circular or non – circular. Generally, cross section area of storage tanks does not change depending on level which means that cross section area of storage tank remains constant from base level to max level. However, in some cases storage tank cross section area vary along the level. Therefore, while modeling the storage tanks required data which are location, volume, base area, base elevation, initial water elevation, operating levels (maximum and minimum water elevations) and if the cross-section has variable area, cross section curve is needed. Without these data, storage tanks cannot be represented in a realistic way.

Similarly, reservoirs have different shapes like storage tanks. Volume of reservoirs is larger than other water sources in water supply systems. Due to huge water volume in reservoirs, water level does not change significantly hour by hour or day by day. Therefore, reservoirs are modeled as unlimited water source and which has constant water level. Location and elevation data of reservoir is sufficient to model. If the reservoir level changes dynamically, reservoir can be modeled as storage tank.

4.1.4. Modeling Pump Stations

Pumps stations are facilities housing pumps to transfer water from one place to another. In pump stations, multiple pumps can be operated in different combinations (in parallel or in series). So that, pump stations are the most complex infrastructure elements of water supply system. During the modeling process of pump station, location and elevation data are needed. Modeling of pumps in pumps stations will be discussed in the following sections.

4.1.5. Modeling Valves

As mentioned in previous chapters valves are used to control flow in pipeline. Some of the valves are operated manually. These valves are adjusted by the operator and their set position does not change dynamically by the running system such as gate valve, butterfly valves, isolation valves, discharge valve and etc. However, some type of valves works dynamically in the running system such as check valves, air valves, pressure reducing valves and etc. Because of these valves having different behaviors and different responsibilities, every type of valves is specifically defined in modeling software. When the valve type is changed, the parameters that must be entered are changed. Location, elevation and diameters are the minimal data required for modeling valves.

CHAPTER 5

GENETIC ALGORITHM

Pump station is composed of a set of same or different type of pumps that pumps water to the system and one or more storage tanks. These pumps are operated at the same time or different times with various combinations in order to pump necessary amount of water. Today growing population increases water demands and leads to formation of larger and more complicated water supply systems. In other words, water supply systems become more complex systems with the combination of several pumps and tanks working together. This complexity causes operation of water supply systems to be more difficult. Operator of water supply system should know which pump or pumps are to be used and which periods of the day pumps are to be in switched on position while satisfying hydraulic requirements of water supply system. Process of choosing which pumps in pump station are to be used in which time period is called pump scheduling (Mäckle et al. 1995). Main objective of pump scheduling is to minimize pumping energy costs. However while minimizing pumping energy cost, physical and operation constraints should be taken into consideration. Some of these constraints are consumer demands, storage capacities and nodal pressures of the water supply systems. These constraints directly effects pump schedule. For instance, due to variation of demands, some pumps may be working while others not. Moreover, if the water level of storage tank reaches to maximum limit all or some of the running pumps should be switched to off position at that time. Therefore, to efficiently operate pumps in pump station, pump scheduling process should be performed. In this study, minimizing energy cost of pumps in pump station is the main objective and for this objective optimal pump schedule will be tried to be determined. In order to achieve this objective, optimal control formulations have been developed by several researchers and different optimization methods have been used to find optimal pump schedules. Mäckle et al. (1995) emphasizes that main methods applied at present were linear programing, dynamic programming, network flow programing and non-linear programming. It was mentioned that none of these optimization methods totally succeed for all types of pump scheduling problems. Therefore which method is best to perform cannot be determined or a general advice cannot be made. All these methods can be used on a small distribution network successfully. However when the size of network increases the success of these methods is reduced due to encountered difficulties in larger systems. Solving capacity of these optimization methods may become insufficient when more than two storage tanks, several different pump combinations are used or more complex constraints are included into water supply system. The amount of required calculation for optimization is directly related to complexity of the system. Thus, as number of reservoirs, storage tanks and possible pump combination used in the system increase, the amount of necessary calculations increase rapidly too. To overcome these limitations and solve complex problems another method using mathematically based artificial evolution was explored and developed by researchers. Today these evolutionary computation techniques are the most widely used techniques in the study of optimum pump scheduling problem. In this study Genetic algorithm based pump scheduling tool WaterCAD Darwin Scheduler developed by Bentley was used to optimize pump energy cost while satisfying system requirements. This algorithm simply works as local search method to optimize objective which is minimizing electric energy cost of pump while considering system constraints by establishing penalties.

5.1. What is Genetic Algorithm

Genetic algorithm is one of the most favorite searching and optimization method running similarly as evolutionary process observed in nature. This algorithm searches for the overall best solution in complex multi-dimensional search space based on the principle of survival of the fittest. Genetic algorithm has been explored by John Holland in 1975 by implementing Darwin’s evolution theory in optimization applications. In genetic algorithm optimization technique, successive populations of trial solutions are randomly generated. These generated trial solutions are assigned as strings which are called chromosomes. Each chromosome is composed of a series of characteristic or features similarly as biological genes found in DNA (Strafaci, 2001). Main objective of pump scheduling is to determine optimum pump schedule with minimum energy costs. Thus, solution of pump scheduling analysis shows that which of the pumps should be used in which time interval during optimization period. In genetic algorithm solving process user needs to code decision variables of the system, such as pump settings, pipe diameter and tank water levels as “genes”. Every different variable should be coded with unique binary code. For example in pump scheduling optimization running state of pump (running or not) should be defined by unique binary code. There are only two situations for each pump: pump is running or not running. If pump is running then binary code of this pump is defined as “1” if not it is defined as “0”. In water supply systems generally 24 hours extended period simulation is performed. Because after reaching successive solution for 24 hours period, this solution may be repeated in consecutive days if the system has similar characteristics in each day. For example, similar daily demand may observe in ongoing days. In extended period simulation of water supply system any time step can be selected. But selecting smaller time step causes huge solving time for the simulation and optimization process. In general, one hour time step is used for running extended period simulation of water supply systems. In this study optimal pump schedule for 24 hours with one hour time increments were performed. It is mentioned that pump status is represented by bit’s value. If the bit’s value equals to zero, pump is in switched off position. If the value is one, pump is in switched on position and running. The time step of pump schedule is defined as one hour. Therefore, solution chromosome for each pump consists of 24 bits. If the total number of pumps to be optimized is three then a string composed of 24x3 total 72 bits forms the solution of system. An example of trial solution coded in binary for system composed of 3 pumps is represented in Table 5.1.

Table 5.1. First Trial Solution Coded in Binary

Pump #	Time Periods (hour)																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Pump #1	1	0	0	1	0	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	0	1	1	1
Pump #2	1	1	1	1	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	1	1	1	1
Pump #3	0	0	0	1	0	0	1	1	1	0	1	0	0	0	1	1	0	1	0	1	0	0	1	0

Full String → | Pump #1 | Pump #2 | Pump #3 |

Total number of all possible solutions to the pump scheduling of three pumps is 2^{72}. If one more pump is included to the system, total number of solution rises to 2^{96}. Total solution number of system composed of 4 pumps is approximately equal to 16 million times of system composed of three pumps.

A fitness function is developed by Mäckle et al. (1995) that aggregates energy cost of pumps and penalties for violation of the system constraints defined before. Fitness function can be mathematically expressed as:

$$Ce + \sum Penalty \tag{5.1}$$

where Ce represents total energy cost of pumps in 24 hours; $\sum Penalty$ is the total penalty due to violations of system constraints.

In this study two different tariffs were used for energy prices. Therefore two different cost functions were used for constant and multi tariff priced systems. Mathematical expression of total energy cost Ce for constant and multi tariff energy prices are represented equation 5.2 and 5.3 respectively.

$$Ce_{constant\ tariff} = \sum_{n=1}^{N}[\sum_{t=0}^{T} E_n(t)Cc] \tag{5.2}$$

$$Ce_{multi\ tariff} = \sum_{n=1}^{N}[\sum_{t=0}^{5} E_n(t)Cn + \sum_{t=6}^{16} E_n(t)Cd + \sum_{t=17}^{21} E_n(t)Cp + \sum_{t=22}^{23} E_n(t)Cn] \tag{5.3}$$

where N represents total number of pumps; T is the control time span; Cc is the unit energy cost of constant tariff; Cd, Cp, Cn are multi tariff energy prices in day, peak, night periods respectively and $E_n(t)$ is the pump energy consumption during schedule time interval from t to t+1. In some places maximum demand charges is included into total energy cost thus extra equation enters to the total cost equation (Boulos et al. 2001).

$$Ce_{constant\ tariff} = \sum_{n=1}^{N}\left[\sum_{t=0}^{T} E_n(t)Cc + \sum_{bp=1}^{NBPn} Emax_n^{Bp}Cn(bp)\right] \tag{5.4}$$

$$Ce_{multi\ tariff} = \sum_{n=1}^{N}\left[\sum_{t=0}^{5} E_n(t)Cn + \sum_{t=6}^{16} E_n(t)Cd + \sum_{t=17}^{21} E_n(t)Cp + \sum_{t=22}^{23} E_n(t)Cn + \sum_{bp=1}^{NBPn} Emax_n^{Bp}Cn(bp)\right] \tag{5.5}$$

where $Emax_n^{Bp}$ represents maximum energy consumption of pump number n during billing period bp; $Cn(bp)$ is the maximum demand charge TL/max.kW for pump number n during billing period bp; and number of billing period is defined by $NBPn$.

Objective function of pump scheduling process is minimization of total energy costs mentioned above. Objective cost function can be mathematically expressed as:

For constant tariff energy price

$$\text{minimize} \quad [\sum_{n=1}^{N}[\sum_{t=0}^{T} E_n(t)Cc]] \tag{5.6}$$

For multi tariff energy prices:

$$\text{minimize} \quad [\sum_{n=1}^{N}[\sum_{t=0}^{5} E_n(t)Cn + \sum_{t=6}^{16} E_n(t)Cd + \sum_{t=17}^{21} E_n(t)Cp + \sum_{t=22}^{23} E_n(t)Cn]] \tag{5.7}$$

According to trial solutions, these cost functions are automatically computed and minimization process is performed while satisfying system constraints. These constraints are divided into three different types by Boules et al. (2001). These are implicit system constraints, implicit bound constraints and explicit variable constraints. Implicit system constraints are used to define hydraulic equilibrium state of the water supply system. Conservation of mass equilibrium in each nodes and conservation of energy equilibrium around loop in distribution network is defined by implicit system constraints. For each decision variable of trail solutions, water supply system model is executed and equilibrium solution of system; pipe flow velocities, nodal pressures, hydraulic grade line of pipes and water level in storage tanks are determined in simulated steady state. Four different implicit bound constraints are implemented into the system. These constraints are defined by operator and represent performance criteria of the water supply system. Pressure on nodes, flow velocities in pipes, water level in storage tanks and pump switch operations are implicit bound constraints of water supply systems.

I. Nodal Constraints:

Pressure at any node for any operational time interval may be restricted between maximum and minimum pressure values. This can be mathematically expressed as:

$$Pmin_i \leq P_i(t) \leq Pmax_i \qquad \forall i, \forall t \tag{5.8}$$

where $P_i(t)$ is the pressure at node i at time t; $Pmin_i$ is the minimum pressure limit at node i; and $Pmax_i$ is the maximum pressure limit at node i.

II. Pipe Constraints:

Maximum flow rate in any pipe during any time interval can be restricted with selected value. This restriction is expressed as:

$$V_j(t) \leq Vmax_j \qquad \forall j, \forall t \tag{5.9}$$

where $V_j(t)$ represents water flow velocity in pipe j during time interval t and $Vmax_j$ is the maximum flow velocity permitted in pipe j.

III. Storage Tank Constraints:

For each operation time interval, water level in storage tank may be bounded between a maximum and minimum values (constant cross section tanks). This can be expressed as:

$$TLmin_k \leq TL_k(t) \leq TLmax_k \qquad \forall k, \forall t \tag{5.10}$$

where $TLmin_k$ is the minimum allowable water level in storage tank k; $TL_k(t)$ is the water level in storage tank k at time t; $TLmax_k$ designates maximum water level limit in storage tank k. If the cross section of storage tank is not constant, instead of water level constraints storage tank volume may be used as constraints. To maintain hydraulic periodicity and continue repetitive simulation for coming time intervals, at the end of pump scheduling period final water level in storage tank should be bigger or equal to initial water level in storage tank. This criterion is expressed as:

$$\left|TL_k^{final} - TL_k^{initial}\right| \leq \Delta TL_k \qquad \forall k, \tag{5.11}$$

Where TL_k^{final} represents final water level of storage tank k; $TL_k^{initial}$ is the initial water level of storage tank k; and ΔTL_k designates allowable tolerance of the final water level for storage tank k. In general, initial and final water levels in storage tank should be equal to provide efficient periodicity for the next operating period.

IV. Pump switch constraints:

Addition to energy cost, maintenance cost of pump is another important factor in water supply systems. Increasing number of pumps switches causes high wear effect on pump and increases maintenance cost of pumps. The wear effect occurs on pumps cannot be quantified easily. Thus, only a directly proportional relation can be applied between pump switches and maintenance cost. In other words, it can be assumed that as number of pump switch is increased, maintenance cost of pump will be increased. A pump switch is defined by Lansey and Awumah (1994) as "turning on a pump that was not operating in the previous period". To prevent increase of maintenance cost of pumps caused by wear effect, number of pump switches should be limited by using pump switch constraints. Expression of this constrains is given as:

$$PS_k \leq PSmax_k \qquad \forall k \tag{5.12}$$

where PS_k designates number of pump switch for pump k; and $PSmax_k$ is the maximum allowable number of pump switched permitted for pump k.

If the determined or random selected trial solution does not satisfy given implicit bound constraints, a penalty is applied due occurred violations. Then calculated penalty cost is added to objective cost functions expressed in equation 5.6 and 5.7 to penalize violations and forcing genetic algorithm search process towards the region of feasible solutions space.

In explicit variable constraints pump control setting values of pumps are defined in new pump schedule run. In general pumps are grouped together according to their known physical characteristics which are location, control tank and pump capacity. However each pump within a group has identical operating policy. Thus for each pump group, the pump control settings should be defined with on or off at specific time period t (Boulos et al. 2001). This constraint is expressed as:

$$\forall k, \forall t, \forall S_k(t) \epsilon S^0 = \{1, 0\} \qquad (5.13)$$

where $S_k(t)$ represents the control setting of pump k at time period t.

Starting with initial trial solutions optimization process continues in network solver to satisfy implicit system constraints and evaluate implicit bound constraints. Then objective function and penalty functions are evaluated according to results taken from network solver. Fitness value of each trial solution is calculated to perform optimization process and generate new chromosomes. New chromosomes, the "fittest" of which survive to breed and evolve increasingly desirable offspring are generated. The fitness evaluation is performed according to success of generated trial solution. The success of trial solution is based on how the trial solution meets the optimization objective function or goals. Therefore, the fitness of chromosomes decides whether it survives or is eliminated. Similarly as in nature, weakest one is eliminated strongest ones survives and continue to be spread in next population.

In genetic algorithm new trial solutions, chromosomes are generated by some special operators. These operators are selection, crossover, mutation and elitism. Next generations are formed from current generations by these operators. Selection operator is used to eliminate weak chromosomes due to their low fitness. Thus, before running selection operator, all chromosomes should be evaluated. After evaluation process, a certain number of chromosomes having low fitness are replaced by new chromosomes having higher fitness. The crossover operation is performed by making partial replacement of characteristic information series of chromosomes between parent strings to form two offspring strings (Figure 5.1).

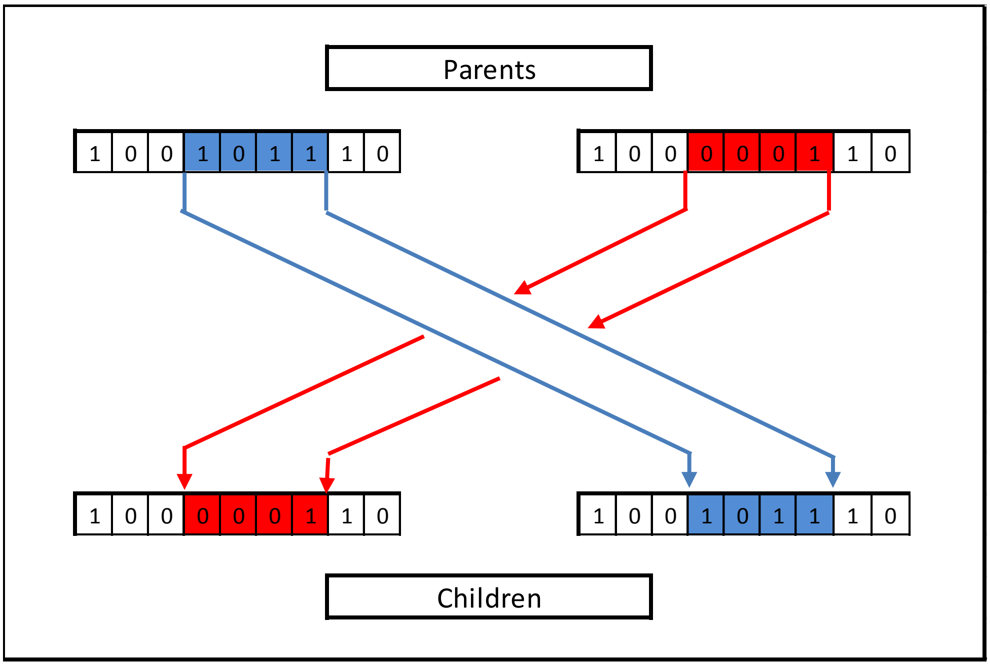


Figure 5.1. Crossover

Two solutions are randomly selected for breeding process. Rate of crossover is a predefined parameter which is selected by user. There are various types of crossovers. Most common types are single point, two point and multi point crossovers. In single point crossover type, chromosomes are divided from a single point and crossover process is applied. In two point and multi point type crossover, chromosomes are divided in to three or more parts with these points and then crossover process is applied. In all crossover processes, crossover points are randomly selected. Function of mutation operator is to truly simulate nature by producing random mistakes in genetic process. Randomly some gene values in chromosomes are changed to generate a new chromosome (Figure 5.2).

Figure 5.2. Mutation

Thus, one of the trial solutions may disappear which may be remain as final solution. Moreover, after mutation process is performed, a good solution may be generated from solutions having low fitness. In other words, this operator creates the chance to catch disappeared chromosomes again. Last operator elitism is used to prevent mutation and crossover operations to be performed on the fittest chromosomes. Therefore, best fittest chromosomes can be protected and survive in next generation.

Search process of genetic algorithm is stopped according to predefined stopping criteria. These stopping criteria are maximum generation, maximum trials and maximum non improvement generations. Iterative calculations are stopped if one of the stopping criteria is achieved. Solution trials having smaller fitness value is selected as optimal pump schedule for a given water supply system. A flow chart of pump scheduling process based on genetic algorithm is represented in Figure 5.3 to emphasis working mechanism of pump scheduling visually.

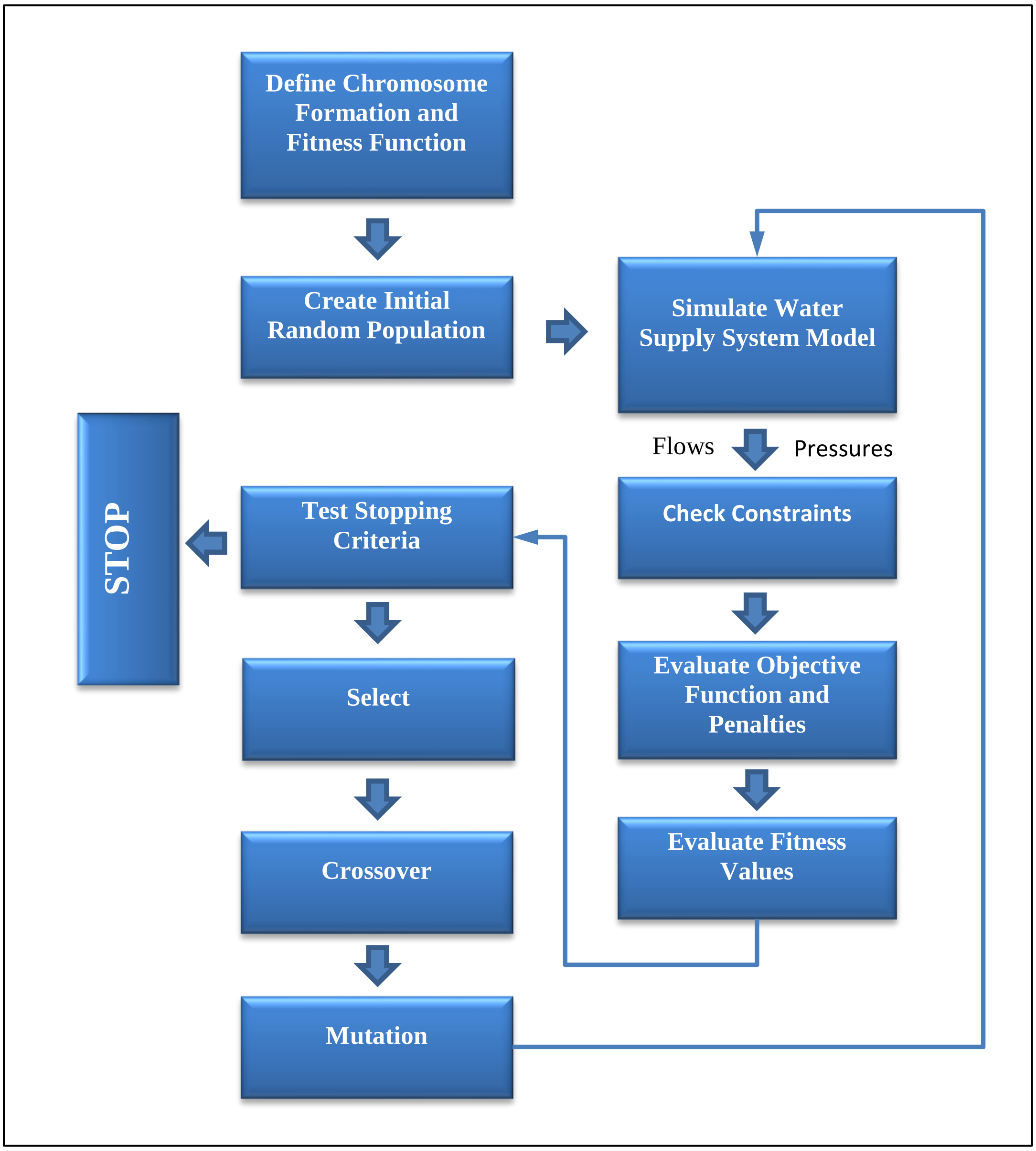


Figure 5.3. Flow Chart of Pump Scheduling

5.2. Genetic Algorithm Parameters and Definitions

In this study simple genetic algorithm was used. Default values were used for genetic algorithm parameters in WaterCAD Darwin Scheduler. Parameters of genetic algorithm are selected as follows (Bentley WaterCAD V8i User's Guide, 2009):

Population Size = 100 : Number of generated genetic algorithm solutions in each step.

Elite Population Size = 10 : Sets the number of elite population of trail solutions in the main generic algorithm population.

Number of Crossover Points = 4 : The number of cut points in each parent chromosome while crossing over with the other parent.

Probability of Crossover = 95 % : The probability of crossover operation being performed at the cut point in the genetic algorithm.

Probability of Mutation = 1,5 % : The probability of random change in Genetic Algorithm solution.

Probability of Creeping Mutation = 0,1 % : The occurrence probability of creeping mutation to generate child chromosome.

Probability of Creeping Down = 65 % : The probability that a decision value in child chromosome will mutate and result to a smaller value.

Probability of Elite Mate = 0.5 : The selection probability of an elite chromosome for the usage in next generation in the genetic algorithm.

Probability of Tournament Winner = 95% : The probability of selecting the most fit chromosome within a two chromosome tournament in the process of parent selection.

Stopping Criteria:

Maximum Generations = 1000 : The maximum generation number that is allowed to conduct the genetic algorithm process.

Maximum Trials = 100000 : The maximum number of optimized run trials.

Maximum Non Improvement Generations = 200 : The maximum number of generations which result in non-improvement fitness.

Penalty Factors:

Pressure Penalty : 1000

Velocity Penalty : 1000

Pump Starts Penalty : 10000

Tank Final Level Penalty : 10000

Tank High/Low Level Penalty : 1000

CHAPTER 6

CASE STUDY

6.1. Study Area

Ankara is the second largest city of Turkey by a population of 4,890,893 (Web 2). Water treatment plants serve Ankara by pumping approximately 1,000,000 m^3 water per day. According to these values, Ankara water consumption is roughly 205 liter per day per capita. This value is calculated by dividing total water consumption to total population. This value may not indicate exact water consumption of person per day. Because all water losses and other water usages such as industrial and agricultural water uses are included in this value. However, everyday this amount of water per person is given to the city to provide water supply system to work and meet direct and indirect water consumption of population. In a city, every home is connected to water supply system. Water is given to each home to use in lots of ways. Some are very obvious; for example washing, cleaning and drinking. Some are less obvious such as leaks at household water pipeline, dripping taps, watering of house plants, etc. Water consumption due to these needs is direct water consumption of population. Water consumption of city water in industrial plants, factories and agricultural applications, etc. is indirect water consumption of population. Each water usage is important for the survival of the people. Therefore, average 205 liters water consumption can be accepted as water consumption per person per day in Ankara.

Water consumption of some countries is shown in Figure 6.1 (Web 3). Climate, economy and water resources availability of a country have great influences on municipal water consumption. Balling et al. (2006) informs that changes in temperature, precipitation and/or drought conditions have significant effects on water consumptions; therefore, water consumption of countries which have hot temperature climate would be higher. In fact, water consumption at Australia having tropical climate is higher with respect to other countries having colder climates in general. Uganda is another country having hot tropical climate; however, its water consumption is approximately 15 liters per day per capita which is almost thirty times smaller than Australia water consumption. For decades, destructive economic policies and instabilities make Uganda as one of the world’s poorest countries (Web4). Therefore, poor economy prevented governments in Uganda to make investment in water supply system. As seen in Figure 6.1, developed countries are in the range of high water consumer in the world. Ankara has 205 liter per day capita water consumption and it is in the range of developed countries concerning water consumptions. In Figure 6.1, average water use per person per day of Ankara is plotted with red dashed line to emphasize Ankara water usage with respect to other countries.

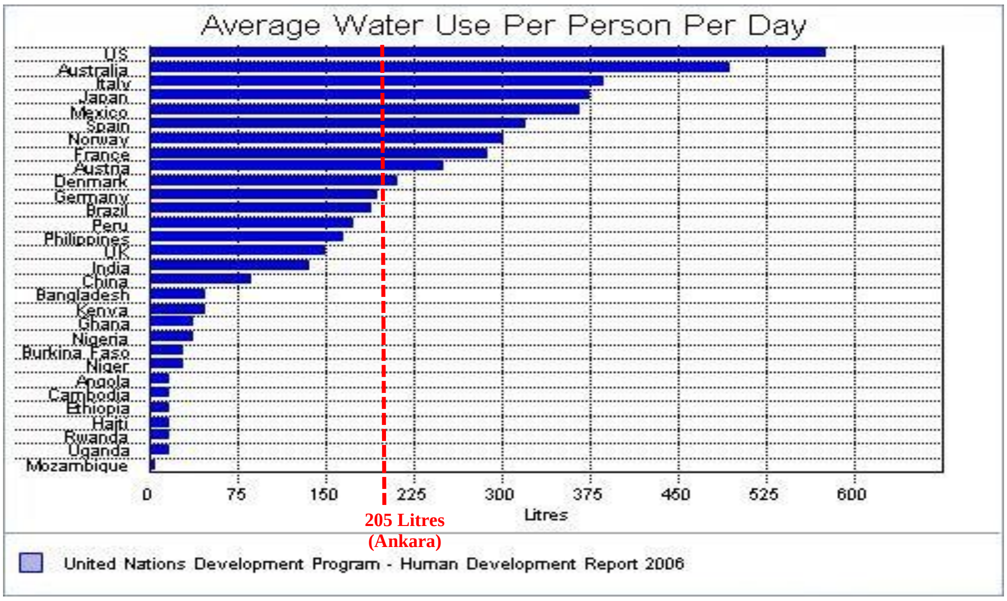


Figure 6.1. Average water use per person per day (Web 3)

Water supply system of Ankara takes water from six dams which are Akyar, Çubuk 2, Eğrekkaya, Kurtboğazı, Kavşakkaya, and Çamlıdere dams. These dams are shown in Figure 6.2. Çamlıdere dam is the major water resource of Ankara water supply system according to water capacity. Water capacities and ratios of all dams are listed in Table 6.1.

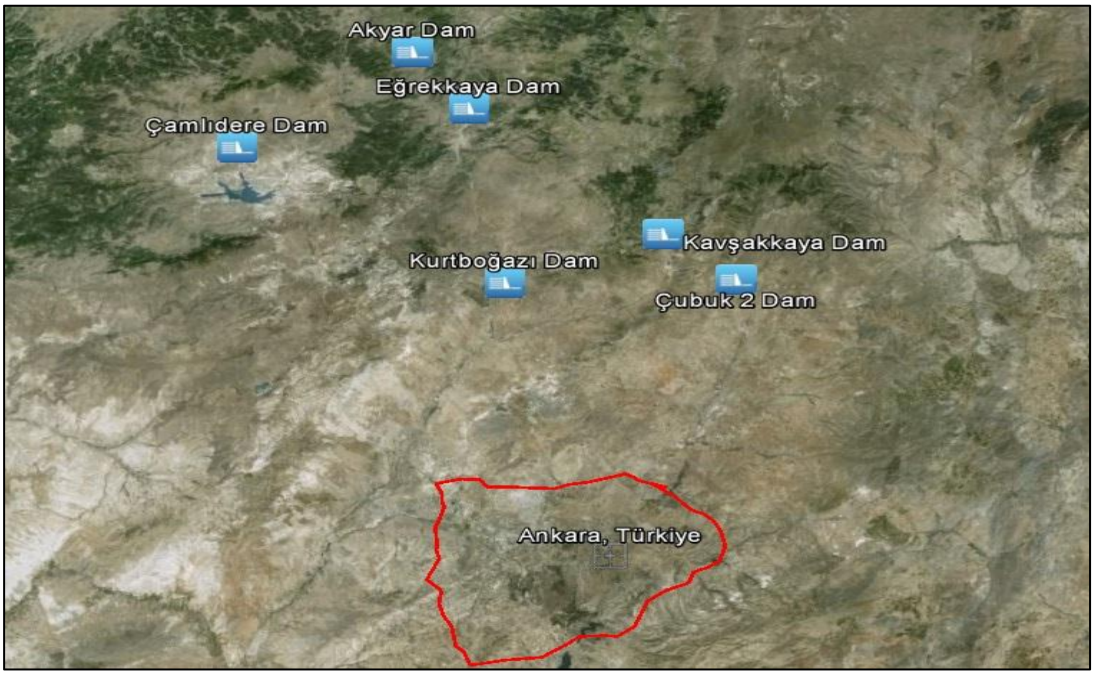


Figure 6.2. Water Resources of Ankara City

Table 6.1. Water Capacities of Ankara Dams

Name of Dam	Water Capacity (m^3)	Capacity Ratio
Akyar Dam	56 000 000	3.54%
Çamlıdere Dam	1 220 150 000	77.04%
Çubuk 2 Dam	22 445 000	1.42%
Eğrekkaya Dam	112 300 000	7.09%
Kavşakkaya Dam	80 835 000	5.10%
Kurtboğazı Dam	92 053 000	5.81%
Total Capacity	1 583 783 000	100.00%

Raw water taken from these dams is treated at İvedik, Pursaklar, Çubuk and Kazan treatment plants. Treated water at these treatment plants is supplied to the distribution system at different points. The treatment capacity of Pursaklar, Çubuk and Kazan treatment plants are too lower than İvedik treatment plant. Therefore, main treatment plant of Ankara water supply system is İvedik treatment plant having capacity approximately 1 000 000 m^3 per day; 94% of total water given to Ankara is treated only by Ivedik treatment plant.

Water distribution system of Ankara is managed under seven main supply zones (Ankara Potable Water Distribution System – Long Term Concept and Feasibility Study, 2000). These main supply zones are named according to their region orientations in Ankara. For instance, zone which is located in the northern part of the city was named as Northern supply zone. Each main supply zone provides water to various locations and having different elevation intervals.

These supply zones and their service elevations are;

- Central and Western Supply Zone (C: 830-870 m and W: 785-830 m)
- Northern Supply Zone (N:870-1295)
- Eastern and South Eastern Supply Zone (E: 870-1190 m and SE: 915-1185 m)
- Southern Supply Zone (S:870-1295 m)
- South Western Supply Zone (SW: 870-1250 m)
- New-South-Western Supply Zone (N-SW: 870-1295 m)
- Gölbaşı Supply Zone (G: 870-1250 m)

These supply zones are divided into several pressure zones of 40-50 m elevation intervals as follows:

1. Central –Western supply zone is divided in to two pressure zones named C2 and W1.
2. Northern supply zone is divided into eight pressure zones named from N3 to N10.
3. Eastern and South Eastern Supply Zone has seven pressure zones at east location being E3-E9 and six pressure zones ant south east location being SE4-SE9.
4. Southern Supply Zone is divided into ten pressure zones being S3-S12.
5. South Western Supply Zone contains nine pressure zones called SW3-SW11
6. New-South-Western Supply Zone has ten pressure zones named from N-SW3 to N-SW12.
7. Gölbaşı supply zone is divided into six pressure zones being G5-G10.

Pressure zones and elevation interval of supply zones are given in Table 6.2.

Table 6.2. Pressure Zones and Elevation Intervals of Supply Zones

	Supply Zones and Pressure Zones											
Name	1	2	3	4	5	6	7	8	9	10	11	12
	Elevation Intervals (m)											
Central-Western Supply Zone (between W1 and C2)												
Elevation Intervals	785 830	830 870										
Tank Levels	865	905										
Northern Supply Zone (between N3 and N10)												
Elevation Intervals			870 915	915 955	955 995	995 1035	1035 1075	1075 1115	1115 1160	1160 1205		
Tank Levels			950	990	1030	1070	1110	1150	1195	1240		
Easthern Supply Zone (between E3 and E9)												
Elevation Intervals			870 915	915 960	960 1005	1005 1055	1055 1105	1105 1150	1150 1190			
Tank Levels			950	995	1040	1090	1140	1185	1225			
South-Eastern Supply Zone (between SE4-SE9)												
Mamak (SE4, 5, 6, 7)				915 960	960 1005	1005 1050	1050 1095					
Dostlar (SE6, 7)						1005 1050	1050 1095					
Bayındır (SE5, 6)					960 1005	1005 1050						
Doğukent (SE5, 6, 7, 8, 9)					960 1005	1005 1050	1050 1095	1095 1140	1140 1185			
Tank Levels				950	1040	1085	1130	1175	1220			
Southern Supply Zone (between S3-S12)												
Elevation Intervals			870 915	915 955	955 995	995 1035	1035 1075	1075 1115	1115 1160	1160 1205	1205 1250	1250 1295
Tank Levels			950	990	1030	1070	1110	1150	1195	1240	1285	1330
South-Western Supply Zone (between SW3-SW11)												
SW.a (SW3, 4, 5, 6, 7)			870 915	915 955	955 995	995 1035	1035 1075					
SW.b (SW3, 4, 5, 6, 7, 8, 9, 10, 11)			870 915	915 955	955 995	995 1035	1035 1075	1075 1115	1115 1160	1160 1205	1205 1250	
SW.c (SW3, 4, 5, 6, 7, 8)			870 915	915 955	955 995	995 1035	1035 1075	1075 1115				
SW.d (SW7, 8, 9, 10, 11)							1035 1075	1075 1115	1115 1160	1160 1205	1205 1250	
Tank Levels			950	990	1030	1070	1110	1150	1195	1240	1285	
New South-Western Supply Zone (between N-SW3 - N-SW12)												
N-SW.a (N-SW3, 4, 5, 6)			870 915	915 955	955 995	995 1035						
N-SW.b (N-SW4, 5, 6, 7, 8, 9, 10)				915 955	955 995	995 1035	1035 1075	1075 1115	1115 1160	1160 1205		
N-SW.c (N-SW8, 9, 10, 11, 12)								1075 1115	1115 1160	1160 1205	1205 1250	1250 1295
Tank Levels			950	990	1030	1070	1110	1150	1195	1240	1285	1330
Gölbaşı Supply Zone (betwen G5-G10)												
G.a (G5, 6, 7, 8, 9, 10)					955 995	995 1035	1035 1075	1075 1115	1115 1160	1160 1205		
G.b (G5, 6, 7, 8)					955 995	995 1035	1035 1075	1075 1115				
Tank Levels					1030	1070	1110	1150	1195	1240	1285	1330

Water distribution system of Ankara contains 108 pump stations and 62 storage tanks; seven main zones are divided into 89 sub pressure zones to manage them efficiently.

In this study, two pressure zones of Northern Pressure Zone which are N8.3 and N7 pressure zones are selected to create realistic water distribution network model. Optimal pump scheduling study will be performed on established water distribution network models. As shown in

Table 6.2, northern supply zone consists of eight pressure zones named N3-N10. N8.3 and N7 are the third and fourth highest pressure zones at north of Ankara municipal water supply system.

N8.3 and N7 are consecutive pressure zones and elevation intervals are 1075 m – 1115 m and 1035 m - 1075 m respectively (Figure 6.3). Moreover, N8.3 and N7 Pressure zones are located at the intersection of two districts of Ankara which are Yenimahalle and Keçirören districts.

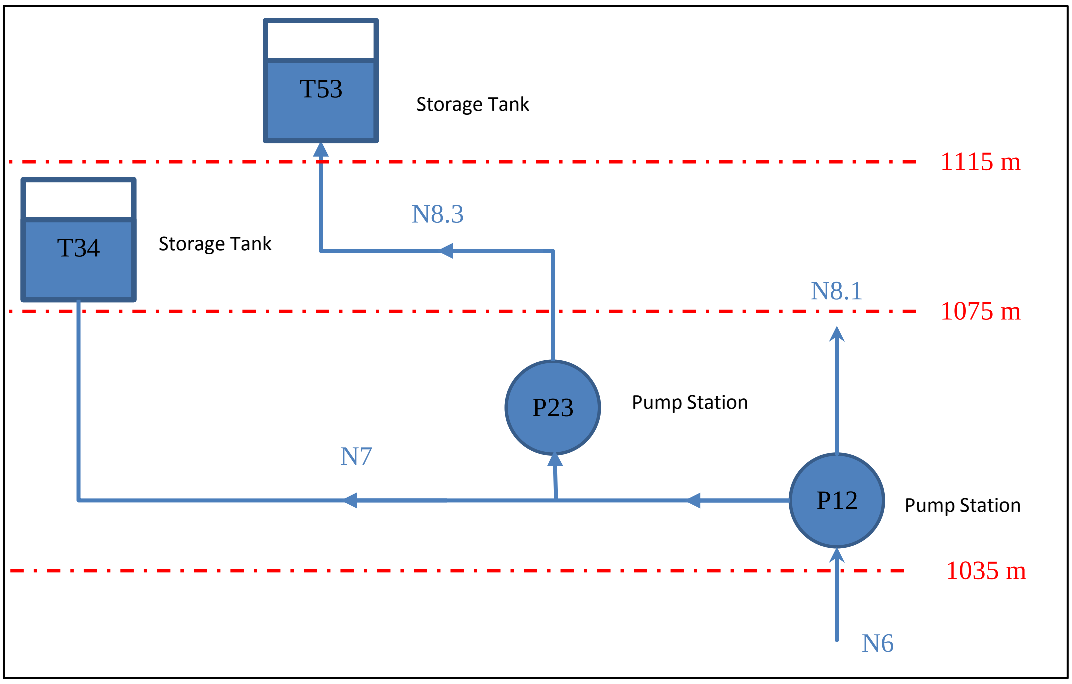


Figure 6.3. N8.3 and N7 Pressure Zones and Elevation Intervals

N7 pressure zone feed customers who are located at 1075 m – 1115 m elevation interval. In addition, N7 pressure zone provides water to N8.3 pressure zone. This pressure zone supplies water to eleven quarters shown in Figure 6.4 which are Şehit Kubilay , Sancaktepe, Çiğdemtepe, Yayla, Avcılar, Kaletepe, Kayalar, Barıştepe, Burç, Güventepe, Atapark quarters.

Figure 6.4. N7 Distribution Network

N7 pressure zone is composed of one pump station which is called P12 and one storage tank called T34; a schematic view of N7 pressure zone is presented in Figure 6.5. Water taken from N6 pressure zone is lifted with the help of pumps in P12 Pump station. In P12 pump station there are two groups of pumps (Figure 6.6). Pumps are in parallel position in each group and each pump can be run at the same time or at different times. First pump group (Pump # 1-2-3) contains three similar pumps running to supply water for N7 pressure zone. Second pump group (Pump # 4-5-6) is composed of another three similar pumps running for N8.1 sub pressure zone. Therefore, P12 pump station is a multi-purpose pump station which means that, this pump station serves N7 and N8.1 pressure zones at the same time. Water pumped by P12 pump station is transported to the N7 pressure zone by using the transmission line. T34 storage tank and distribution network of N7 pressure zone is supplied by this transmission line. At a specific node on transmission line, P23 pump station takes water from this transmission line and pumps water to N8.3 pressure zone. Elevation of P12 pump station is 1017.60 m. Storage tank T34 has 5000 m^3 volume, 6.5 meter height and its base elevation is 1106.99 m; base cross section of T34 storage tank is rectangular.

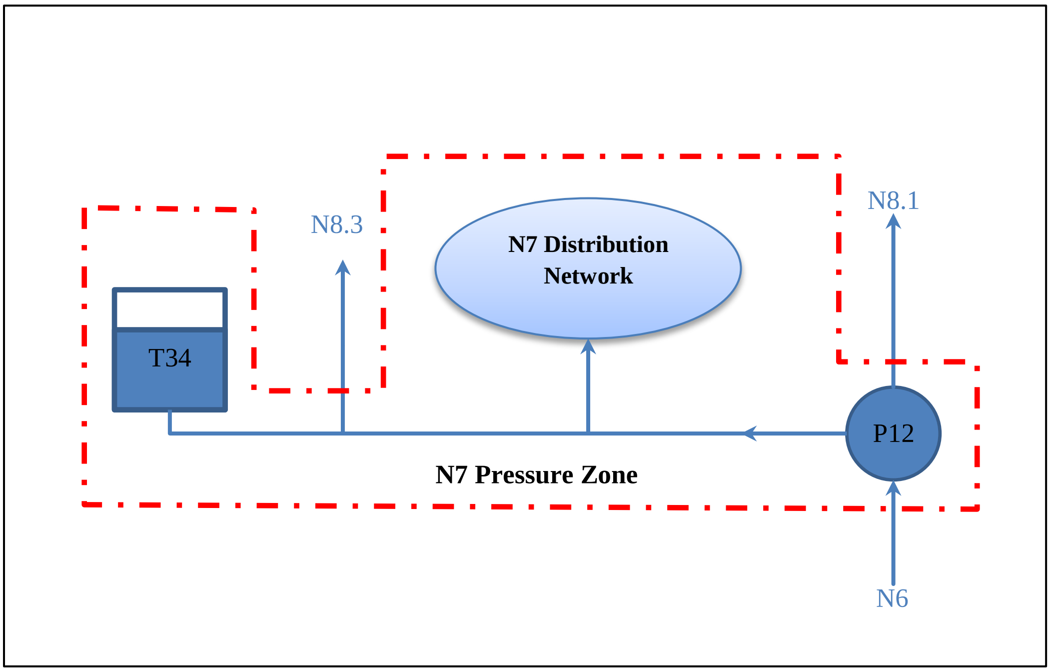


Figure 6.5. Schematic View of N7 Pressure Zone

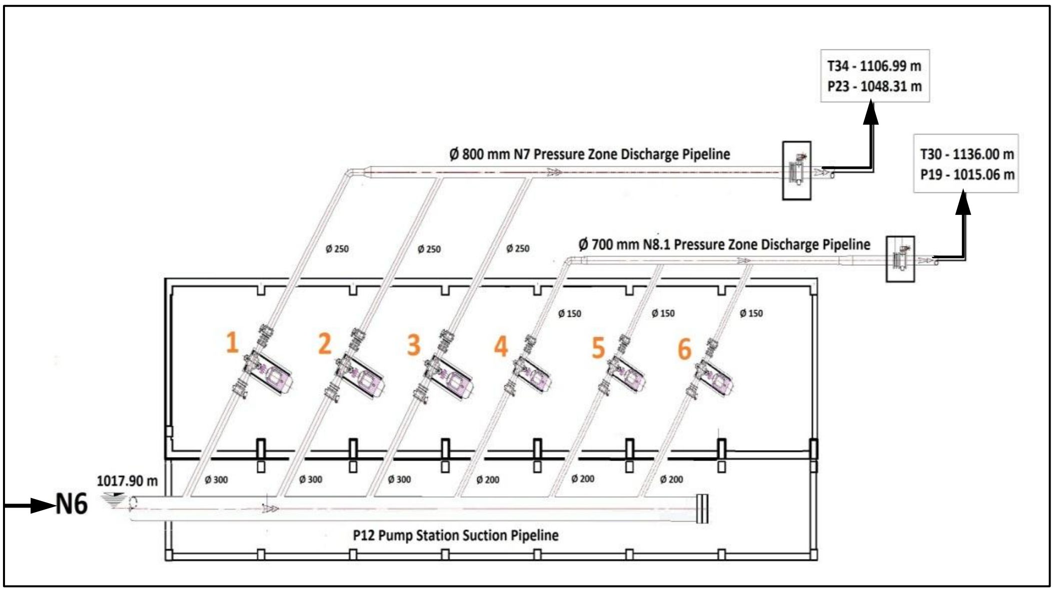


Figure 6.6. Pump placement in P12 Pump Station

N8 pressure zone is divided into two separated subzones called N8.1 and N8.3. Both N8.3 and N8.1 sub pressure zones feed the consumers which are located in 1075-1115 m elevation intervals. Although N8.3 sub pressure zone takes water from N7 pressure zone, N8.1 pressure zone takes water from N6 pressure zone through P12 pump station. Thus different pump stations are used to supply these sub pressure zones. Şehit Kubilay, Sancaktepe, Çiğdemtepe and Yayla quarters form the service area of N8.3 pressure zone (Figure 6.7). This region is a rapidly developing area and new high buildings are constructed. Therefore, total water consumption of the pressure is increasing day by day due to increasing population. Today, the population of N8.3 is approximately 50,000.

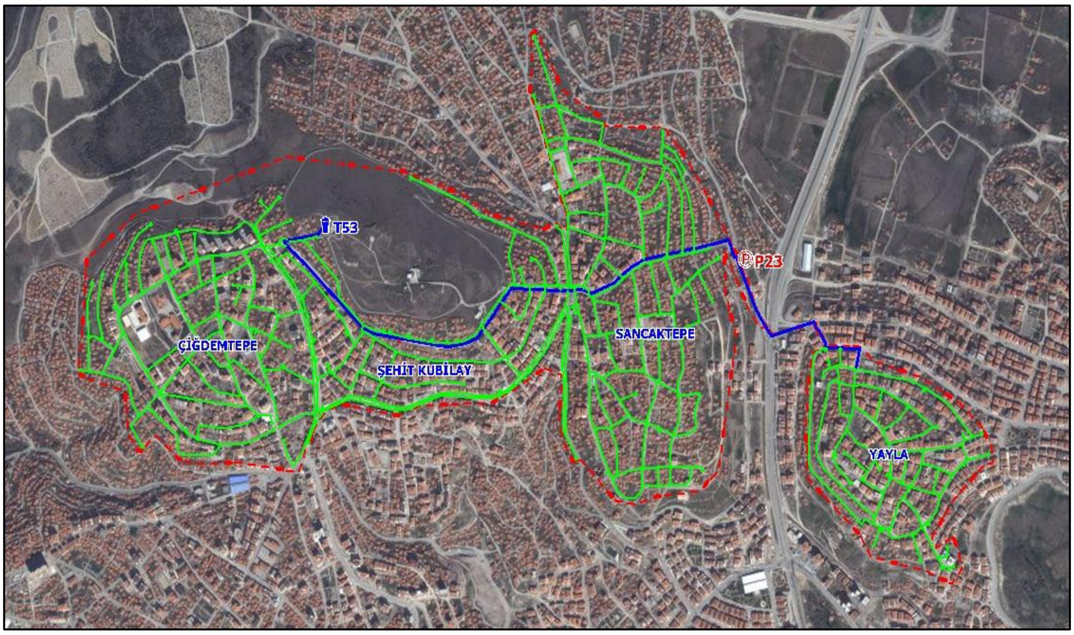


Figure 6.7. N8.3 Distribution Network

N8.3 pressure zone contains one pump station which is called P23 and one storage tank called T53. It is indicated in Figure 6.8 that water comes from N7 pressure zone is pumped to N8.3 sub pressure zone by P23 pump station. Then, main transmission pipeline transmits water to N8.3 distribution network and T53 storage tank. P23 pump station contains three pumps which two pumps are same and other one is different. Elevation of pump station is 1048.31 m. Pump placements in P23 pump station is shown in Figure 6.9. Pumps are in parallel position and each can be used at the same time or at different times.

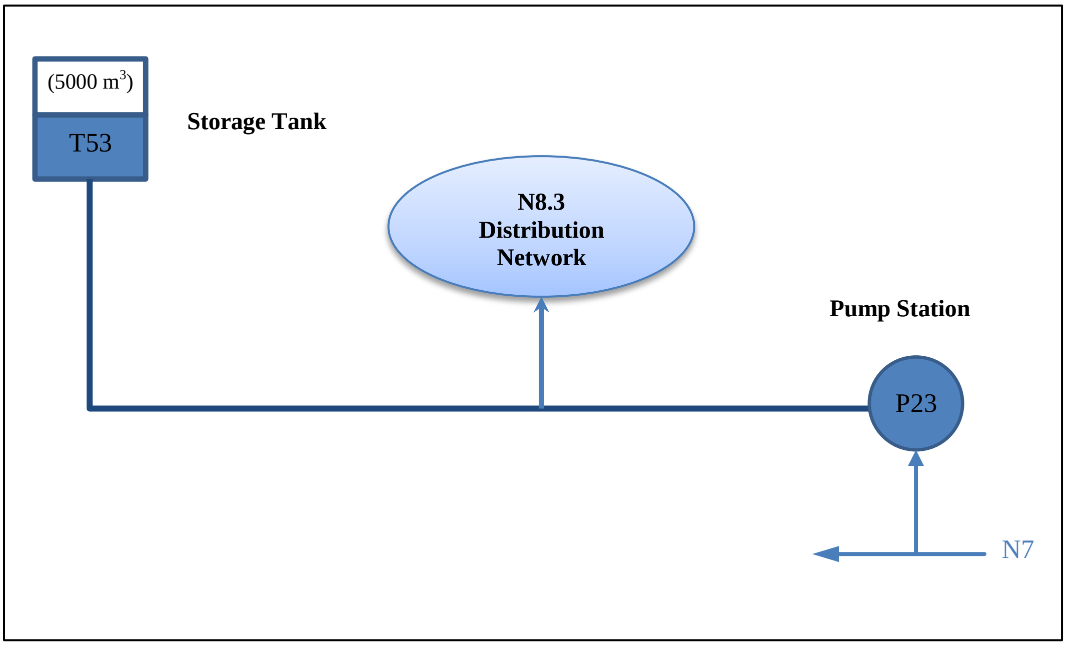


Figure 6.8. Schematic View of N8.3 Sub Pressure Zone

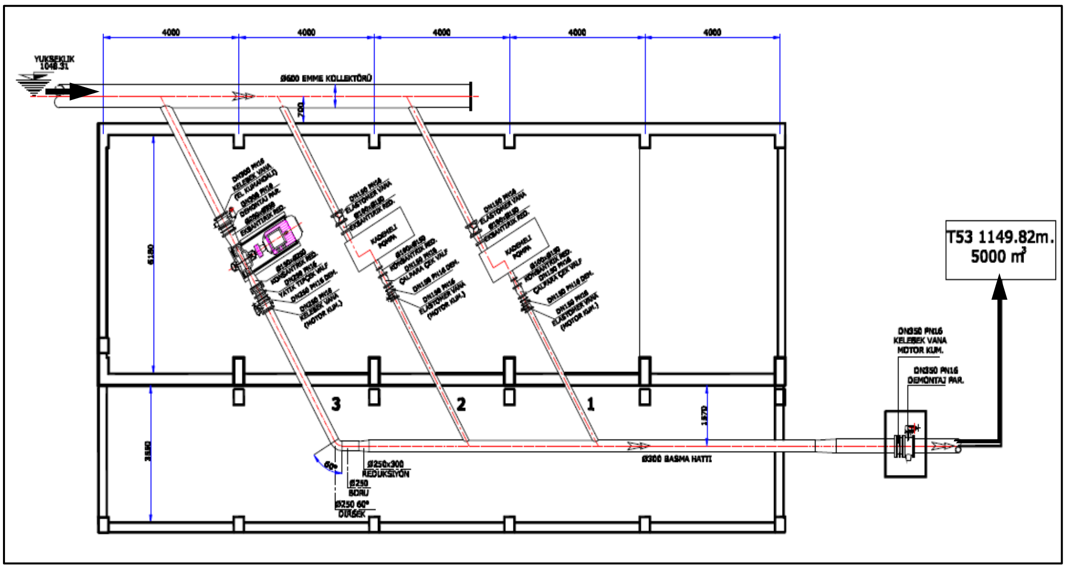


Figure 6.9. Pump Placement in P23 Pump Station

Base elevation of T53 storage tank is 1149.83 m. Base cross-section of tank is rectangular. It has 5000 m^3 volume and 6.5 m height.

Figure 6.10 illustrates schematically that N7 and N8.3 pressure zones are part of the Northern main supply zones. Additionally water flow path of these zone are represented as follows. Firstly, treated water at Ivedik treatment plant is pumped by P1 pump station to N4 pressure zone. By P2 pump station water is lifted from N4 pressure zone to N6 pressure zone. Then, incoming water to P12 pump station inlet is pumped to N7 and N8.1 pressure zones. Finally, P23 pump station takes water from N7 pressure zone and pumps the water to N8.3 Pressure zone. Thus, water coming from dams is treated at Ivedik treatment plant and transmitted to N7 pressure zone by following path P1, P2 and

P12. For N8.3 pressure zone similar path is used with additional P23 pump station, thus P1, P2, P12 and P23 flow path is used.

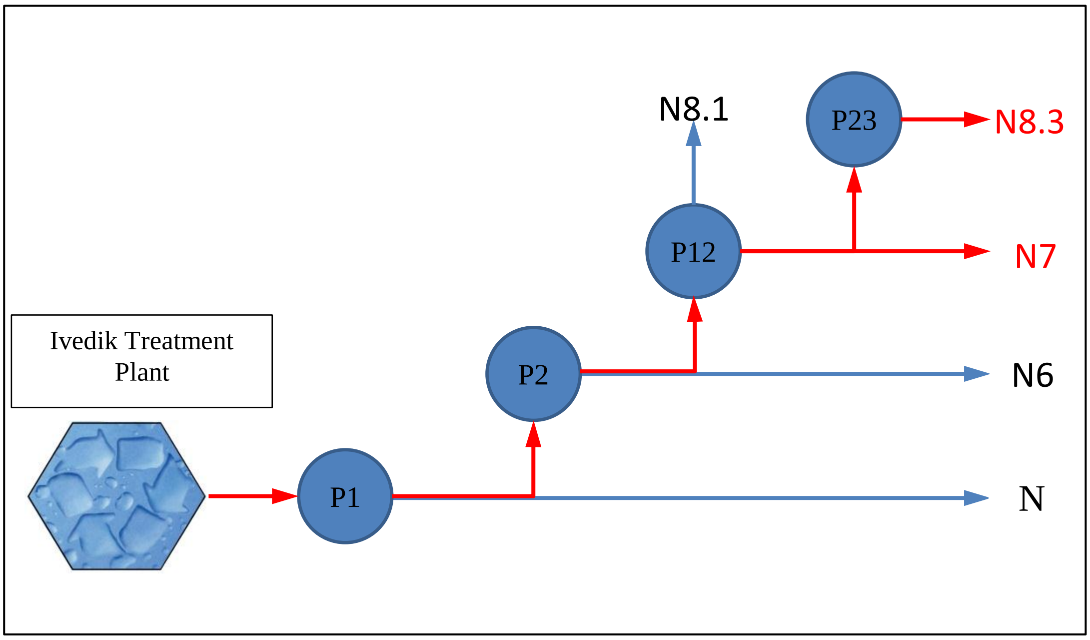


Figure 6.10. Water Flow Path of N8.3 and N7 Pressure Zones

N8.3 and N7 pressure zones are selected for applying this study, because N8.3 and N7 pressure zones consist of district metered areas (DMA) to measure demands and water level in tank, pump flows and pressures are observed and recorded by SCADA (Supervisory Control and Data Acquisition) system installed at this site. The data needed to run model can be easily obtained from SCADA and DMA's measurements. Therefore, N8.3 and N7 pressure zone have been chosen in order to maintain optimal pump schedule for minimizing the total energy costs.

6.2. Modeling the System

6.2.1. System Characteristics

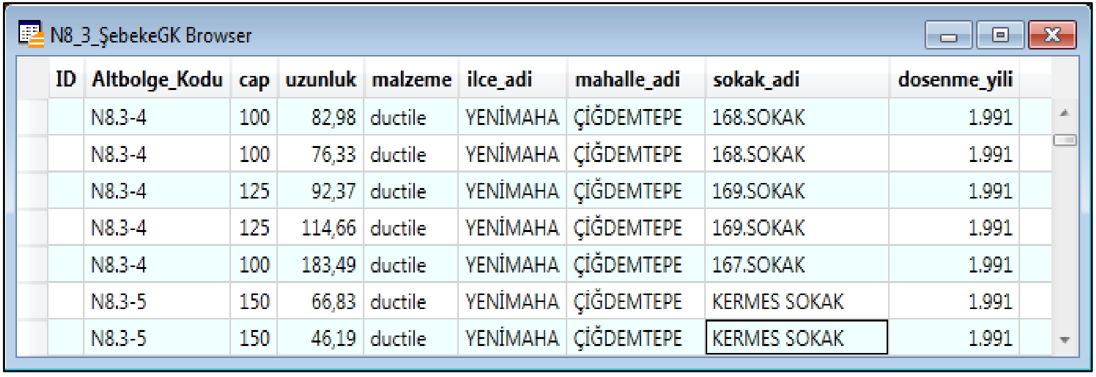
Before modeling the water distribution system, all component characteristics should be known. During the study, necessary data was collected from difference sources and from field studies; these are pipes, nodes, tanks, reservoirs, valves, district metered areas (DMAs) and pump station data. Main data sources are Operation, Facilities and Data Processing Departments of Ankara Water and Sewerage Administration (ASKİ).

Several software tools were used to generate data proper for modeling (MapInfo, MapBasic, Microsoft Office Excel and WaterCAD). Moreover, an Excel macro code and Map Basic code were developed for this study; the purpose of these codes will be described in related parts.

6.2.1.1. Pipes and Nodes

Pipe data were obtained in MapInfo format according to Data Processing Department of ASKI standards; a pipe is drawn in polyline and contains district metered area code, diameter, length, material, installation year and also district and quarter data where pipe is located (Table 6.3). The database containing all GIS data about Ankara water supply system is called AYBİS (ASKI Altyapı Bilgi Sistemi); there are some missing pipe data in the database. Therefore, the missing data were completed according to pipe plans which are taken from Operation Department of ASKI archives. From gathered data, it is observed that pipes in N8.3 pressure zone were constructed in 1991 and material of all pipes is ductile iron (Table 6.3). Similarly, N7 pressure zone was constructed in 1991 and material of pipes are ductile iron and steel. Minimum pipe diameters are 100 mm in both N8.3 and N7 pressure zones. Maximum pipe diameters are 500 mm and 800 mm in N8.3 and N7 pressure zones respectively.

Table 6.3. Example of Pipe Data



N8_3_ŞebekeGK Browser

ID	Altbolge_Kodu	cap	uzunluk	malzeme	ilce_adi	mahalle_adi	sokak_adi	dosenme_yili
	N8.3-4	100	82,98	ductile	YENİMAHA	ÇİĞDEMTEPE	168.SOKAK	1.991
	N8.3-4	100	76,33	ductile	YENİMAHA	ÇİĞDEMTEPE	168.SOKAK	1.991
	N8.3-4	125	92,37	ductile	YENİMAHA	ÇİĞDEMTEPE	169.SOKAK	1.991
	N8.3-4	125	114,66	ductile	YENİMAHA	ÇİĞDEMTEPE	169.SOKAK	1.991
	N8.3-4	100	183,49	ductile	YENİMAHA	ÇİĞDEMTEPE	167.SOKAK	1.991
	N8.3-5	150	66,83	ductile	YENİMAHA	ÇİĞDEMTEPE	KERMES SOKAK	1.991
	N8.3-5	150	46,19	ductile	YENİMAHA	ÇİĞDEMTEPE	KERMES SOKAK	1.991

Nodes are the connection point of consecutive two pipes or where pipes are connected to each other (T junctions) and demand - discharge points on pipes. The information about customer service pipes and consumer connection nodes are not available in AYBİS database. All the data about consumer connections are drawn and written on formatted paper and conserved in archives; in other words, data related about customer connections are recorded only on plain papers and physically stored at archives of Customer Department. Therefore, digitizing customer service pipes and customer connection nodes from recorded paper into database is difficult and time consuming process due to huge number of current connections. As already mentioned in section 4.1.2, every pipe is created by two nodes which are start and end node. After carefully examining the pipe data, it has been observed that many of pipes were drawn as one pipe without any nodes containing except start and end nodes. This means that, a group of connected pipes having same diameter and having total length of 50 m, were drawn as a single 50 m long polyline. This situation causes some complications when using nodes as consumer connection points. Lack of consumer connection nodes on a 50 m long pipe decreases the reliability of the model. Therefore, for this study service connection nodes are produced by a tool written in MapBasic code.

In this tool, every polyline which is a part of distribution network pipes is divided into smaller lines by integrating new consumer connection nodes at every break point of polyline. The code is called as **pipesplitter**. In Figure 6.11, it is observed that red colored 125 mm diameter pipe is integrated to database as a polyline which is a group of pipes in the existing distribution network. After running pipesplitter tool, same pipe is divided into eight pipes and integrated to system as lines with new connection nodes between each line (Figure 6.12). Generated connection nodes are not exact points of service connection but they can provide more homogenous distribution for demand.

Figure 6.11. Polyline pipe view

Figure 6.12 Split pipe view

After checking all pipe data, pipes and created nodes are exported to shape files by MapInfo universal translator tools. Then, created shape files are imported to WaterCAD to create water distribution network model of pipes and nodes.

6.2.1.2. Tanks and Reservoirs

In study area part, it was already mentioned that N8.3 pressure zone consists of one storage tank T53 and one pump station P23. N7 pressure zone contains one storage tank T34 and one pump station P12. To model storage tank volume, cross-section area and type, height, base elevation data are needed. During the study, location and elevation data were taken from AYBIS database. Volume, Cross section and height of T53 and T34 storage tanks were gathered from plans which are stored at Operation Department of ASKI (Table 6.4).

Table 6.4. T53 and T34 Storage Tanks Information

Storage Tank	**T53**	**T34**
Volume	5000 m^3	5000 m^3
Cross-Section Type	Rectangular	Rectangular
Cross-Section Area	800 m^2	800 m^2
Height	6.5 m	6.5 m
Base Elevation	1.149.83 m	1106.99 m

N8.3 pressure zone takes water directly from N7 pressure zone’s transmission line by P23 pump station. Thus, N7 pressure zone is water supplier of N8.3 pressure zone Therefore, in the model the inlet sides of the pump station P23 have to be modeled in order to run the system of N8.3 pressure zone. According to SCADA data of pump stations taken from Facilities Department of ASKI, it was seen that inlet pressure remains continuously constant except if there is not power cut at P12 pump station which transfers water to P23 pump station.

While modeling inlet pressure, reservoir was used to supply constant pressure to the system (Figure 6.13). P23 was connected to the reservoir and the elevation of reservoir is selected as 1.106.81 m to provide 5.85 bar constant pressure at P23 pump station inlet. Same operation was done for N7 pressure zone and P12 pumps station inlet was modeled as reservoir having elevation 1063.53 m and inlet pressure is assigned as 4.70 bars.

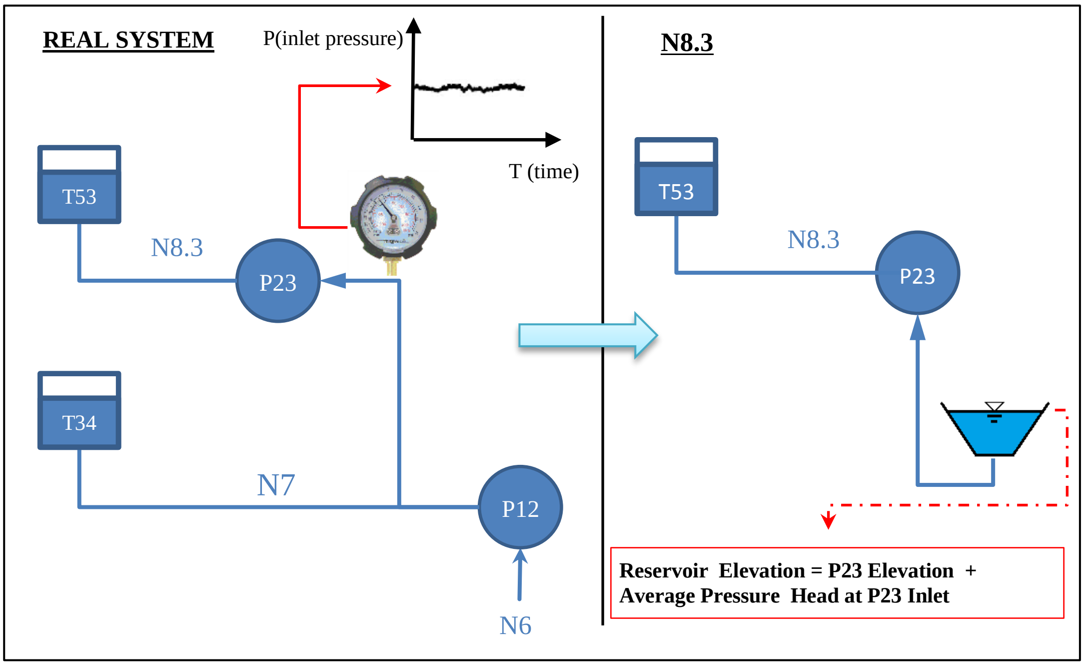


Figure 6.13. Modeling P23 Inlet

6.2.1.3. Valves

Isolation valves and check valves were created in the model. Check valves were used at outlet of each pump in pump stations P23 and P12. These valves prevent water flow in reverse direction. Thus, by using these valves water flow generated by one pump to backward through pump which is in off position is prevented. Isolation valve were used to create isolated DMAs in the model. Each DMA is separated from each other by these isolation valves. There are 22 and 19 isolation valves in N7 and N8.3 pressure zones respectively. All valve locations were taken from AYBIS and integrated to model by connecting them to related pipes.

6.2.1.4. DMAs

In year 2009 one District Metered Area (DMA) had been constructed in N8.3 pressure zone to maintain preliminary study of leakage control. This study was extended and totally 14 DMAs was constructed in year 2010; six of DMAs are located in N8.3 and remaining eight DMAs in N7 pressure zone. The distribution networks of N8.3 and N7 pressure zones were divided into DMAs by using isolation valves. DMAs are physically connected at each pressure zone in the field but isolation valves are closed to block flow between DMAs. DMAs are named with respect to surrounding quarters. Some of DMAs are located at intersection of several quarters, for that reason they were named as location of DMA’s measurement point like street name. Unique code and name of the DMAs are given below.

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

- N7-1 Aydan Street DMA
- N7-2 Sorgu Street DMA
- N7-3 Karahöyük Street DMA
- N7-4 Seval Street DMA
- N7-5 Şehit Kubilay DMA
- N7-6 Yükseltepe DMA
- N7-7 Yayla DMA
- N7-8 Aşıkveysel DMA

Distribution of N8.3 and N7 Pressure zone DMAs are presented in Figure 6.14a and 6.14b.

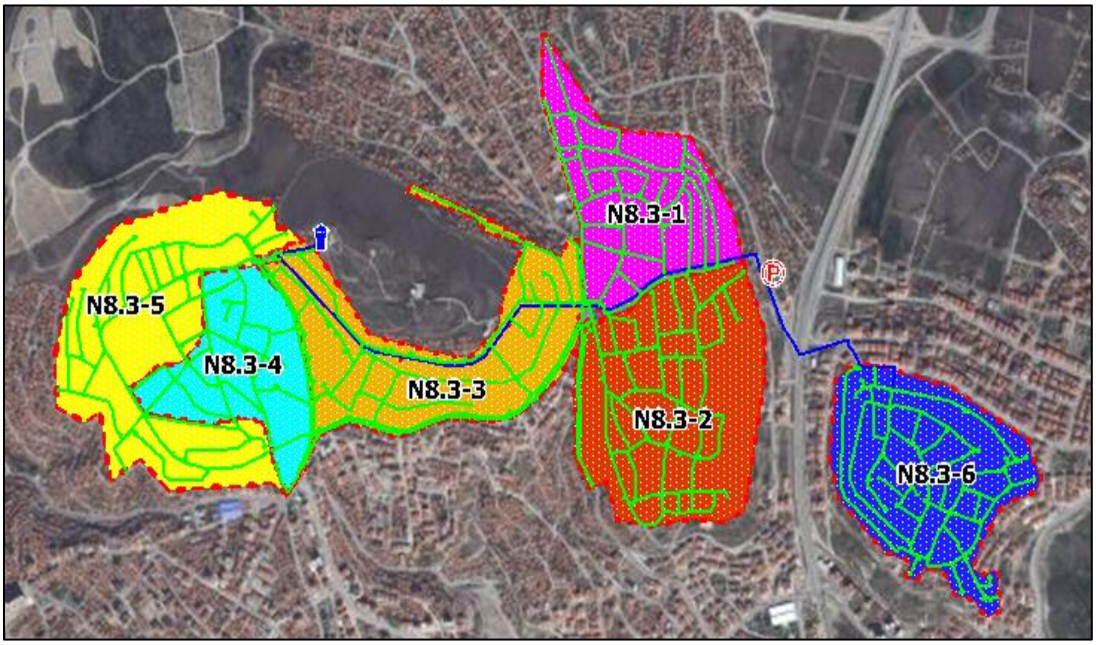


Figure 6.14a. N8.3 Pressure Zone DMA Distribution

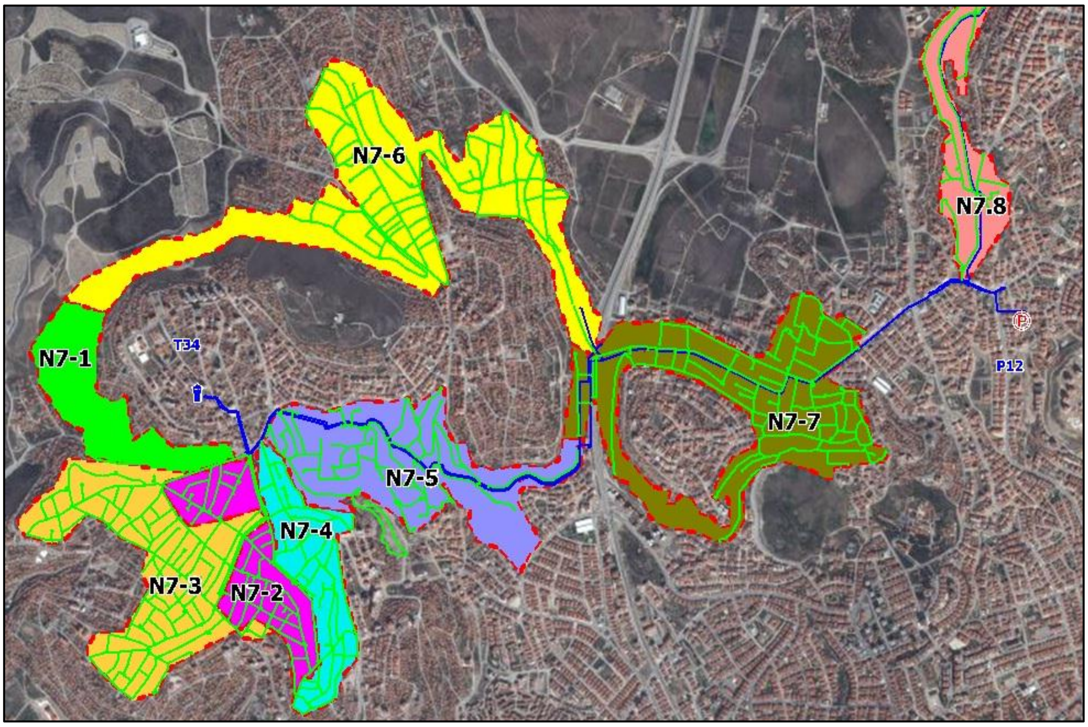
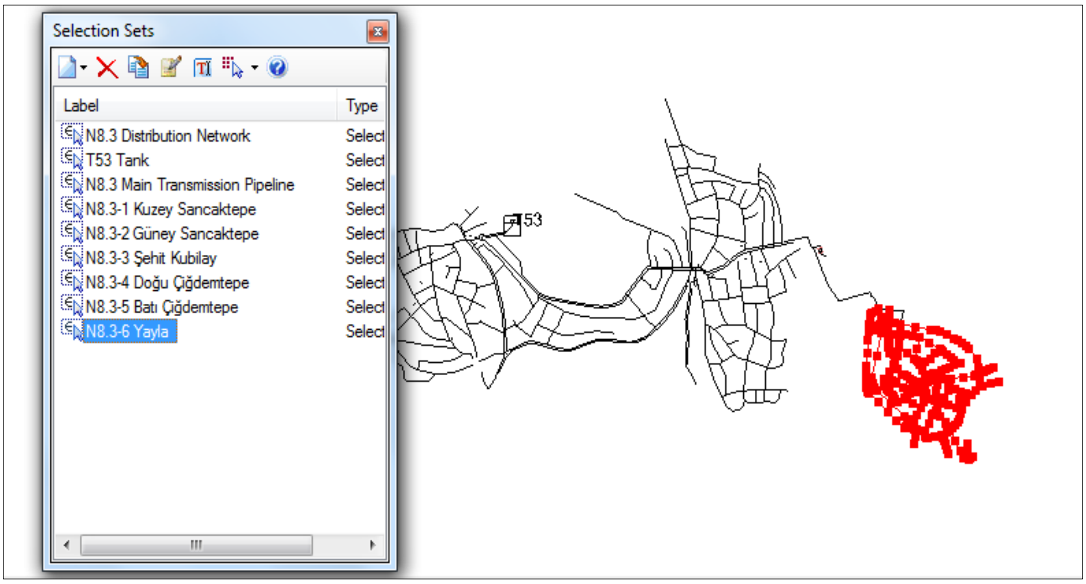


Figure 6.14b. N7 Pressure Zone DMA Distribution

In WaterCAD modeling software, it is important to easily select required nodes from huge number of nodes to attach nodal demands in DMA accurately and as quickly as possible. Thus, selection set tool of WaterCAD is used. Selection set is the predefined choose operation to select any group of components automatically any time you need. In this study selection sets were created to easily distribute related demands to the nodes in each DMA. Such as nodes located in N8.3-6 Yayla DMA is selected by selection sets created before as shown in Figure 6.15.



Selection Sets

Label	Type
N8.3 Distribution Network	Select
T53 Tank	Select
N8.3 Main Transmission Pipeline	Select
N8.3-1 Kuzey Sancaktepe	Select
N8.3-2 Güney Sancaktepe	Select
N8.3-3 Şehit Kubilay	Select
N8.3-4 Doğu Çiğdemtepe	Select
N8.3-5 Batı Çiğdemtepe	Select
N8.3-6 Yayla	Select

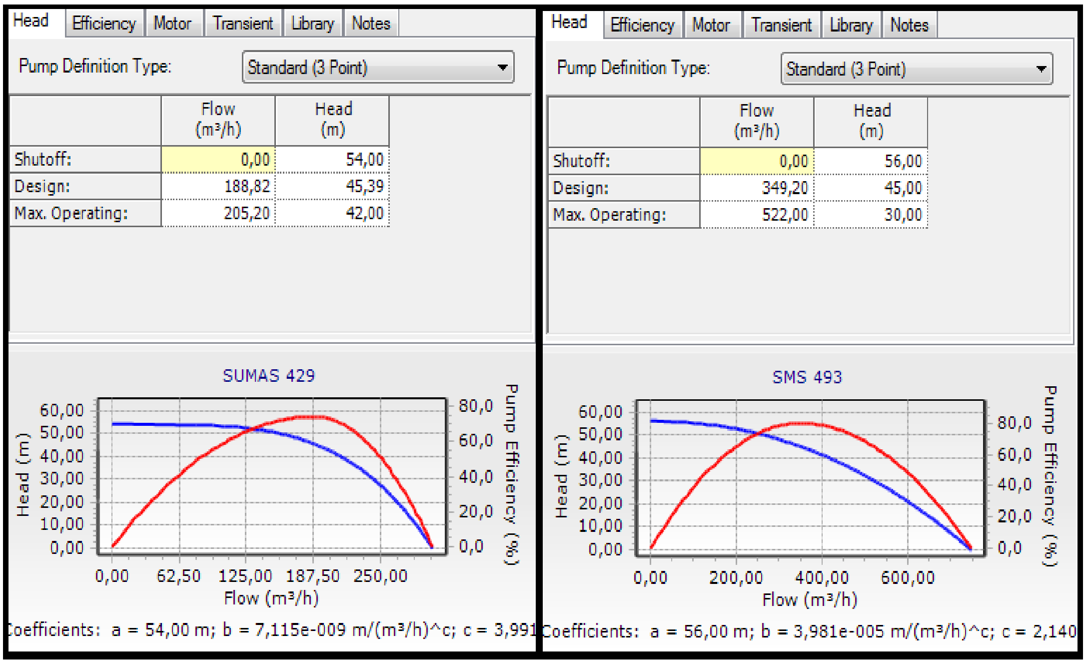
Figure 6.15. Selection Sets

6.2.1.5. Pumps in Pump Stations

P23 pump station contains three pumps which two of them are same. Pump#1 and Pump#2 had been produced by SUMAS firm. Pump#3 had been produced by SMS (Samsun Makina Sanayi). Design capacities of two types of pumps are given in following Table 6.5. Orientations of pumps in pump stations are shown in Figure 6.6 and 6.9. P12 pump station contains same type of three pumps running to supply N7 pressure zone. In Table 6.5 required basic pump data which are design flow, design head, pump efficiency and inlet-outlet diameter of pumps are tabulated. These given data are not sufficient to run model properly. Pump characteristic curves are also needed to define pump successfully. These curves are: (i) pump head-discharge curve, (ii) pump power curve and (iii) pump efficiency curve. All curves were obtained from Operation Department of ASKI; according to these curves, pump definitions were entered in WaterCAD Model. By using head discharge curve all pumps were defined in WaterCAD model with three point type. In three point type, head and flow values of each pump at shutoff design and maximum operating condition are entered in model as show in Figure 6.16 and 6.17. Blue plotted curves are pump head-discharge curves and red plotted curved are pump efficiency curves.

Table 6.5. Pump Information of P23 and P12

Pump Station	**P23**		**P12**
Pump Number	**Pump #1 and #2**	**Pump # 3**	**Pump #1, #2 and #3**
Manufacturer	SUMAS	SMS	KSB
Type	SP 125	SP 150-400/493	OMEGA 250 /480B
Design Flow	188 m^3/h	350 m^3/h	792 m^3/h
Design Head	45 m	45 m	52
Pump Efficiency	74%	80%	83%
Inlet Diameter	150 mm	200 mm	300
Outlet Diameter	125 mm	150 mm	250



Pump Definition Type: Standard (3 Point)

	Flow (m³/h)	Head (m)
Shutoff:	0,00	54,00
Design:	188,82	45,39
Max. Operating:	205,20	42,00

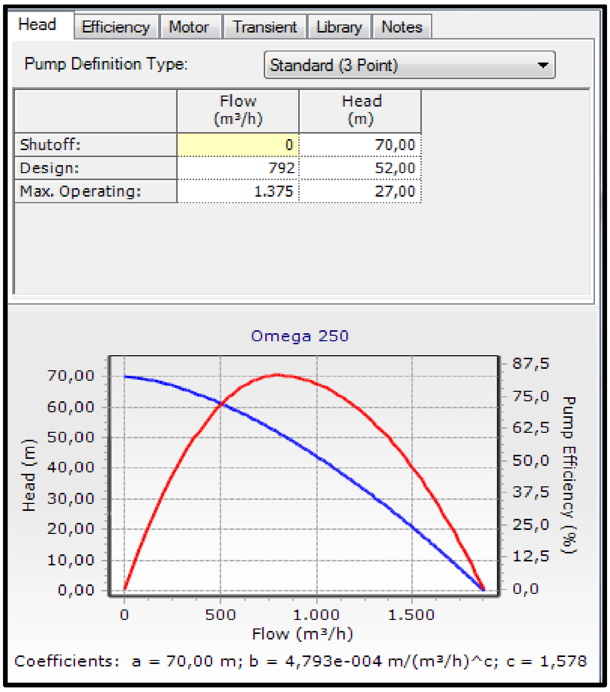
oefficients: a = 54,00 m; b = 7,115e-009 m/(m³/h)^c; c = 3,991

Pump Definition Type: Standard (3 Point)

	Flow (m³/h)	Head (m)
Shutoff:	0,00	56,00
Design:	349,20	45,00
Max. Operating:	522,00	30,00

Coefficients: a = 56,00 m; b = 3,981e-005 m/(m³/h)^c; c = 2,140

Figure 6.16. P23 Pumps Definitions in Model



Pump Definition Type: Standard (3 Point)

	Flow (m³/h)	Head (m)
Shutoff:	0	70,00
Design:	792	52,00
Max. Operating:	1.375	27,00

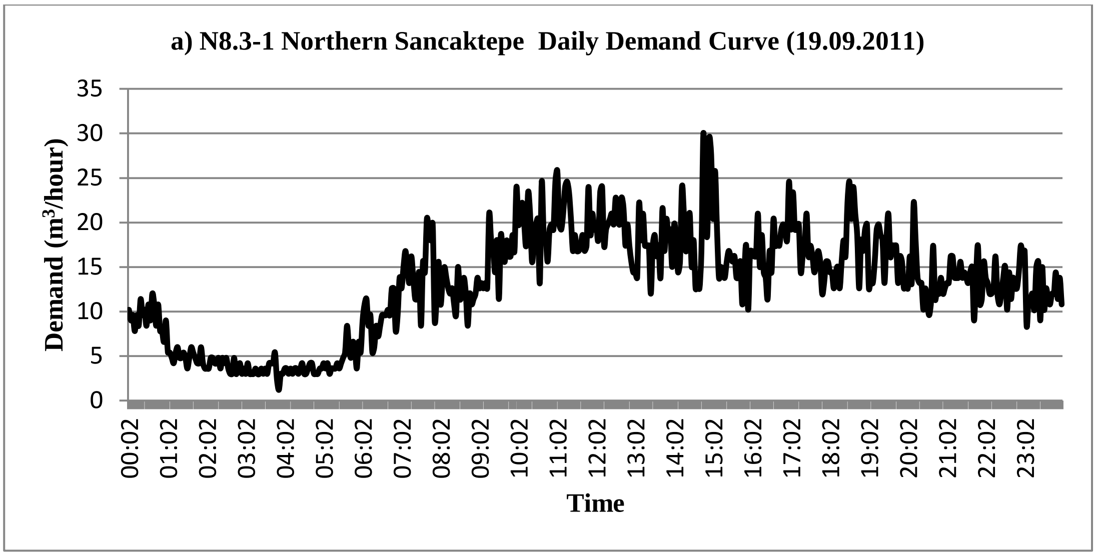
Coefficients: a = 70,00 m; b = 4,793e-004 m/(m³/h)^c; c = 1,578

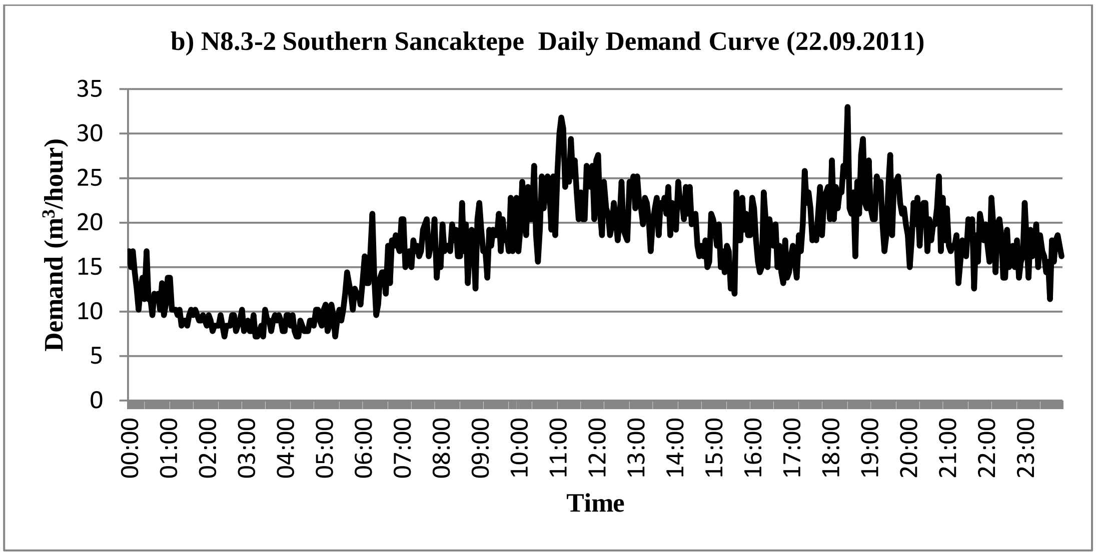
Figure 6.17. P12 Pumps Definitions in Model

Locations and elevations of pumps are taken from AYBIS database as other system components. In addition efficiency and supplying motor information were entered.

6.2.2. Demand Pattern

As mentioned in previous DMA part, N8.3 pressure zone consists of 6 DMAs and N7 pressure zone consists of 8 DMAs. Each DMA is connected to transmission line at one branch pipe. Moreover, 14 measuring manholes had been constructed for each DMA. Constructed measuring manholes enable operators to measure water consumption of DMAs by using portable ultrasonic flow meters. Thus, Daily Demands Curves of each DMA were plotted according to measurement done before. For this study, demand flow of each DMA was measured and flow values were recorded for 24 hours with 3 minute time intervals. Measurement records are given in Figure 6.18 and Figure 6.19.


a) N8.3-1 Northern Sancaktepe Daily Demand Curve (19.09.2011)


b) N8.3-2 Southern Sancaktepe Daily Demand Curve (22.09.2011)

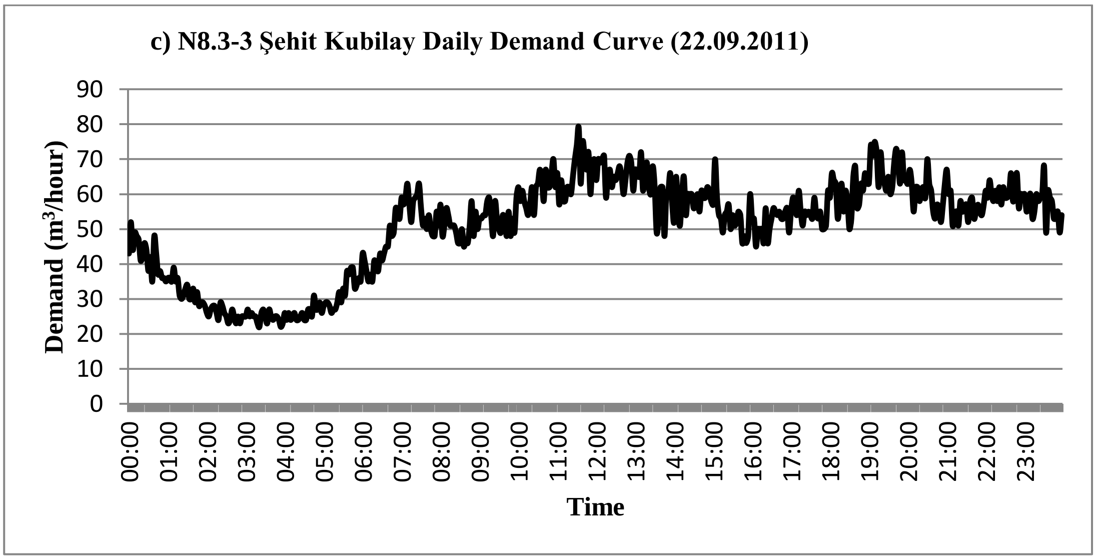
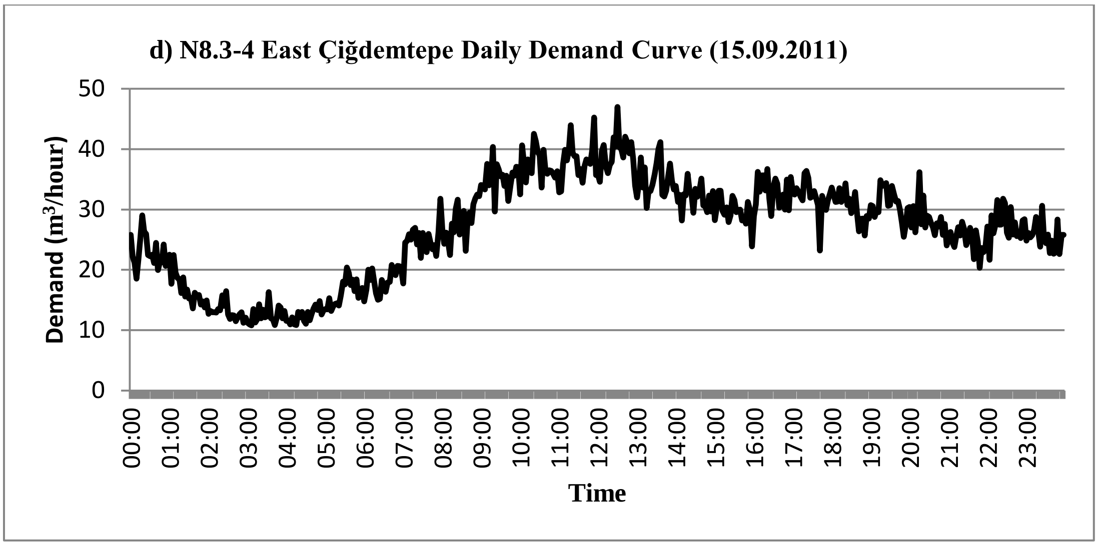
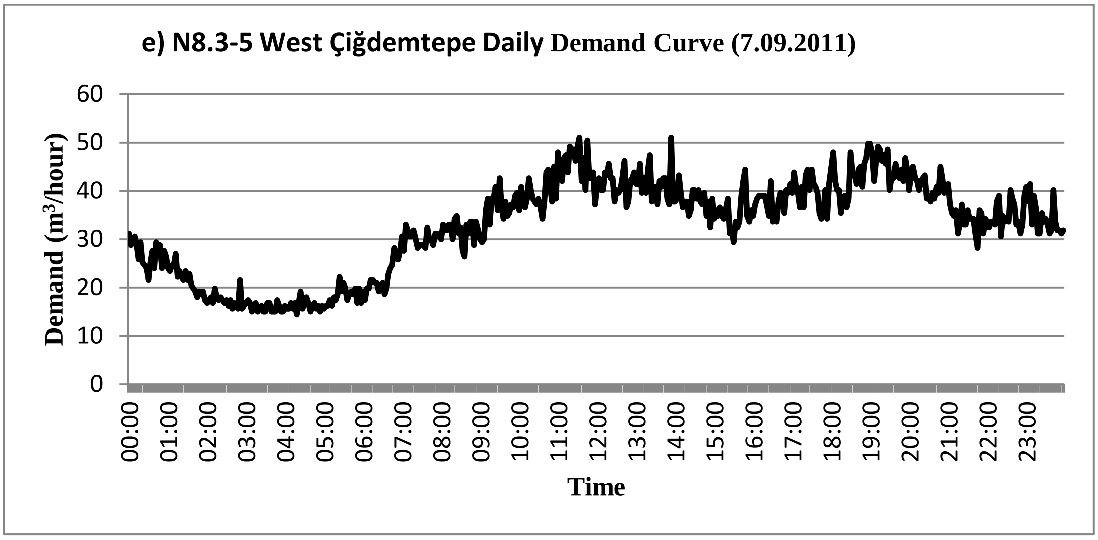

c) N8.3-3 Şehit Kubilay Daily Demand Curve (22.09.2011)

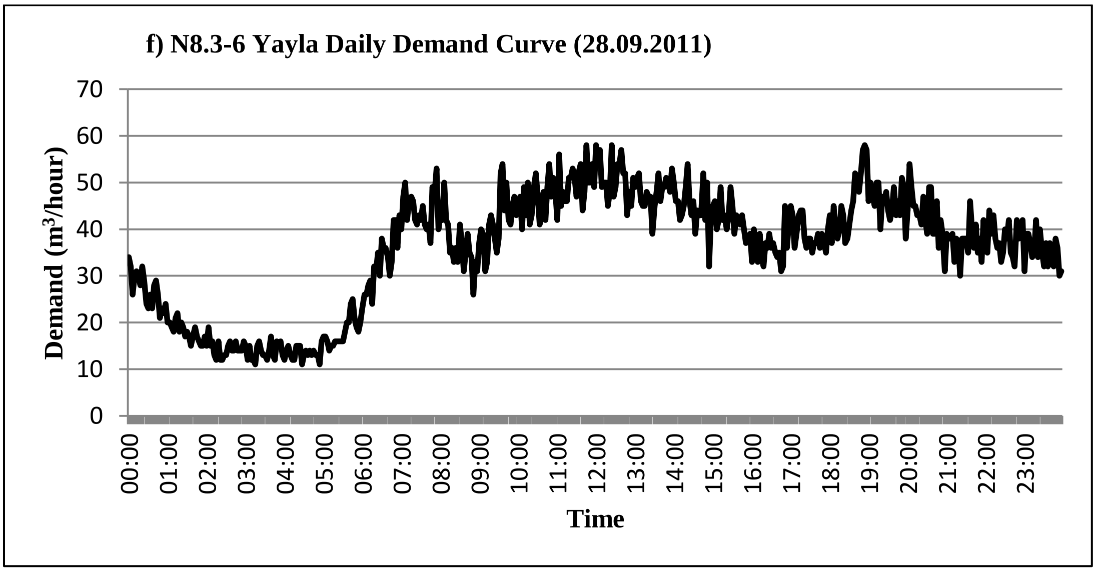
Figure 6.18. Daily Demand Curves of N8.3 Pressure Zone DMAs



d) N8.3-4 East Çiğdemtepe Daily Demand Curve (15.09.2011)



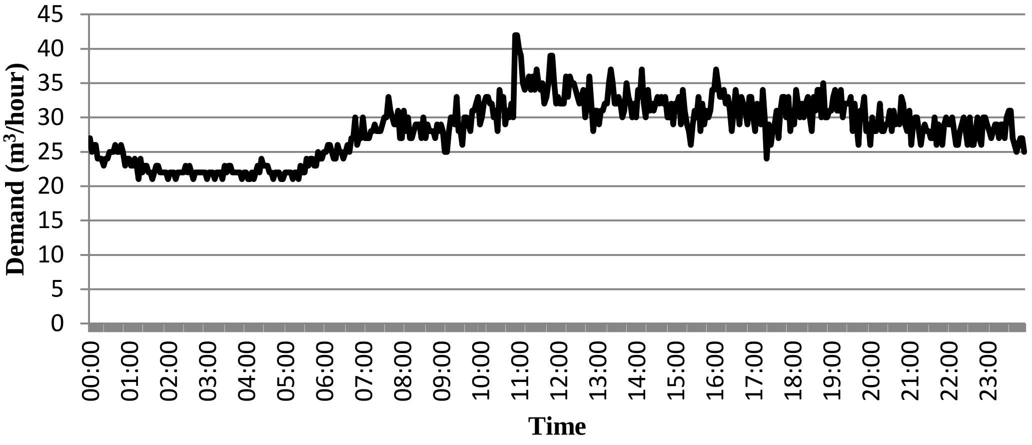
e) N8.3-5 West Çiğdemtepe Daily Demand Curve (7.09.2011)



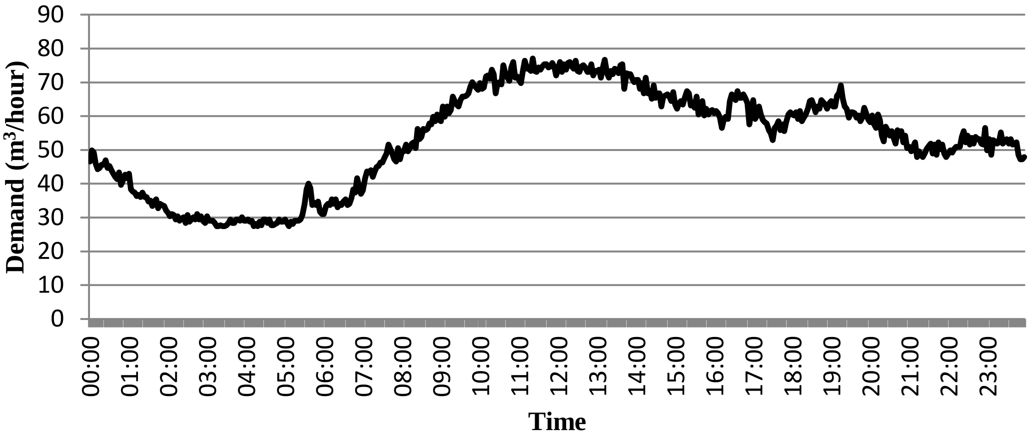
f) N8.3-6 Yayla Daily Demand Curve (28.09.2011)

Figure 6.18. Daily Demand Curves of N8.3 Pressure Zone (Continued)

a) N7-1 Aydan Caddesi Daily Demand Curve (22.09.2011)



b) N7-2 Sorgun Sokak Daily Demand Curve (16.09.2011)



c) N7-3 Karahöyük Caddesi Daily Demand Curve (16.09.2011)

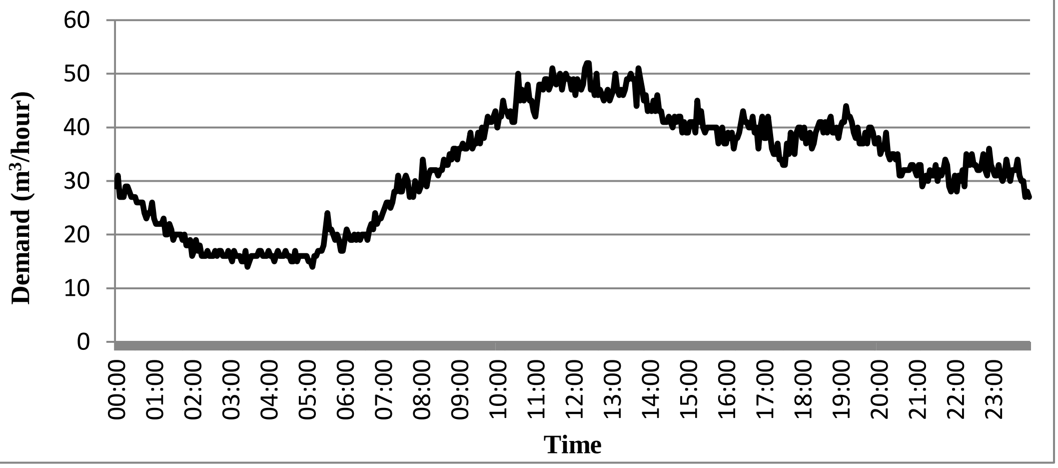
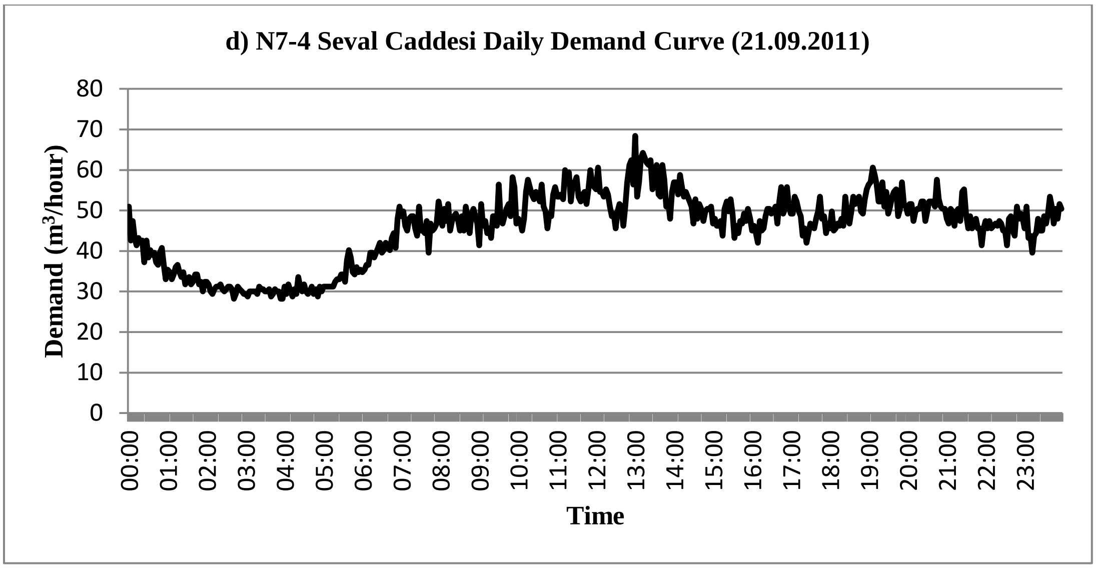
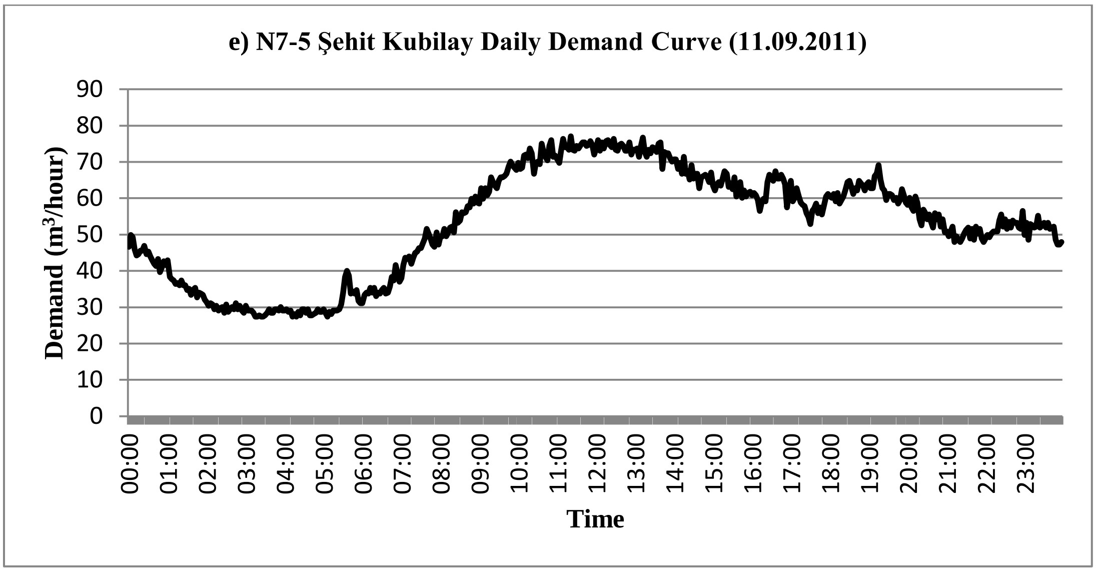


Figure 6.19. Daily Demand Curves of N7 Pressure Zone DMAs





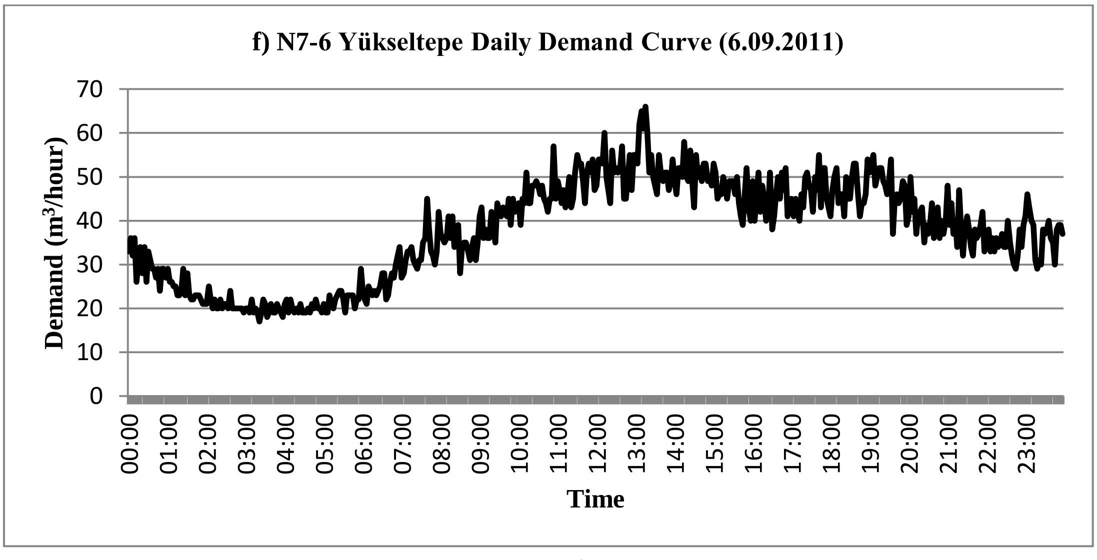
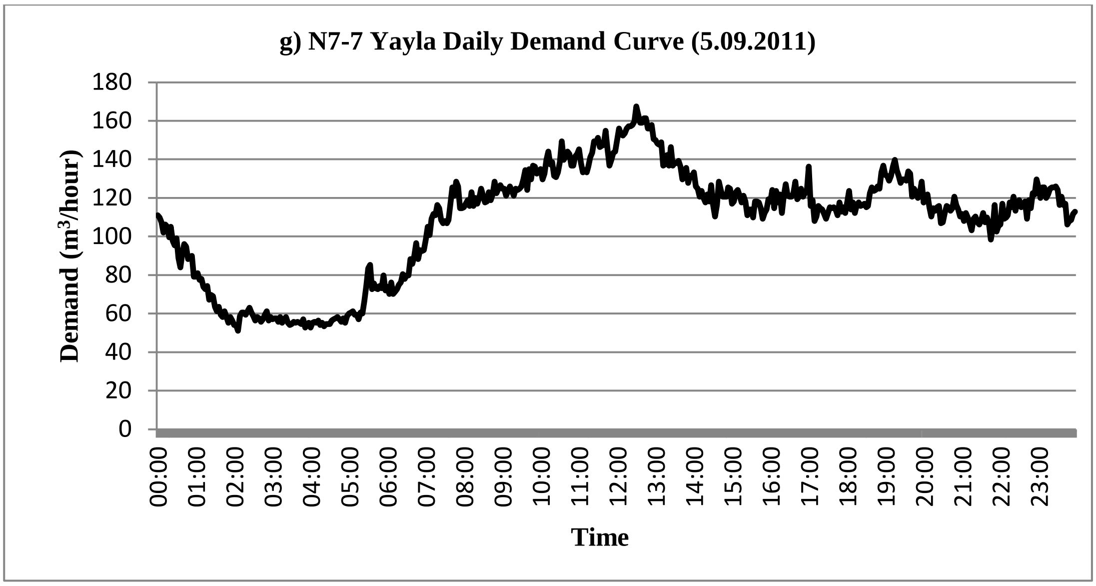


Figure 6.19 Daily Demand Curves of N7 Pressure Zone (Continued)



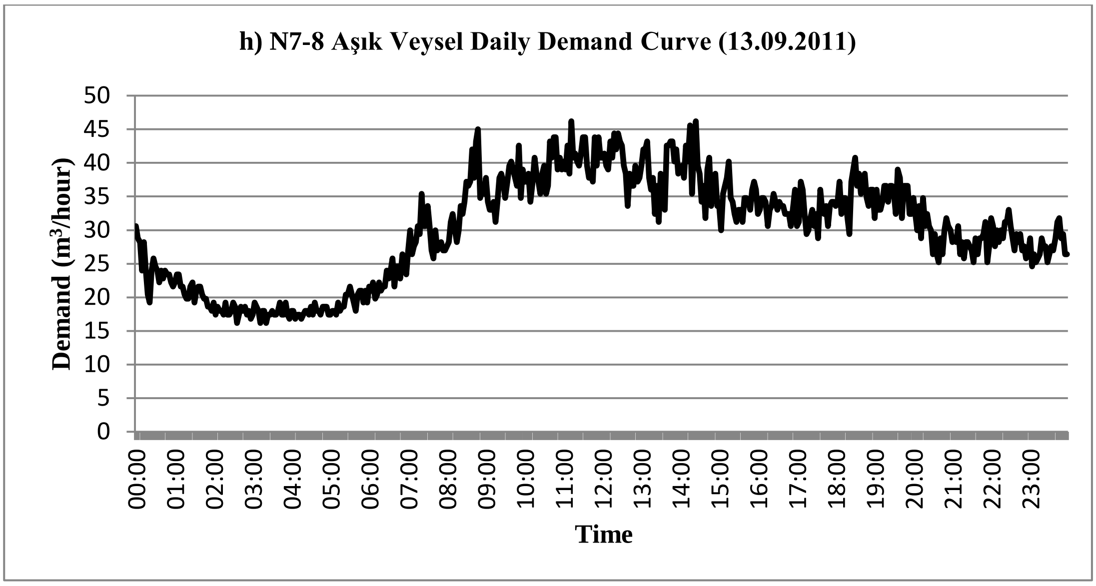


Figure 6.19. Daily Demand Curves of N7 Pressure Zone (Continued)

Daily demand curves shown in Figure 6.18 and in Figure 6.19 were simplified by calculating the average of measurement values for each hour. In addition, mean daily demands were calculated. Although total daily demands of each DMA are known, flow rates of customer connection nodes created before are unknown. The total demand of DMA must be distributed to each customer connection nodes in meaningful way; in order to handle this task (distribution of total demand to nodes) a particular methodology was developed.

Regional properties of N8.3 and N7 pressure zones which consist of almost residential areas show that distribution of buildings is homogeneous. Moreover, water consumption in this pressure zone is nearly homogeneous. Therefore, demand at customer connection points were determined by developed methodology according to pipe lengths connected to each nodes. Almost in all streets distribution network pipes are available. Application of this methodology starts with determination of demand per meter pipe. So that average demand of DMA is divided by total pipe length of DMA. Every pipe is created by two nodes which are start and end node in the model. If these two nodes are assumed as customer connection nodes, the demand at both nodes is calculated by multiplication of half of the total length of pipe with demand per meter pipe value which was determined before. This means that demand at one customer connection point is determined according to the half-length of pipes connected to that node. In Figure 6.20, a schematic of simple distribution network is shown. The demand at node 5 is calculated by given equations as follows;

$$D_x(Demand\ per\ meter\ pipe) = {}^{D_t}/_{\sum Li} \tag{6.1}$$

$$D_{N5}(demand\ \ at\ node\ 5) = \left(\frac{L_4}{2} + \frac{L_5}{2} + \frac{L_6}{2} + \frac{L_7}{2}\right) \times D_x \tag{6.2}$$

where:

D_t: Average demand measured at DMA inlet node.

Li: Pipe Length

Dx: Demand per meter pipe

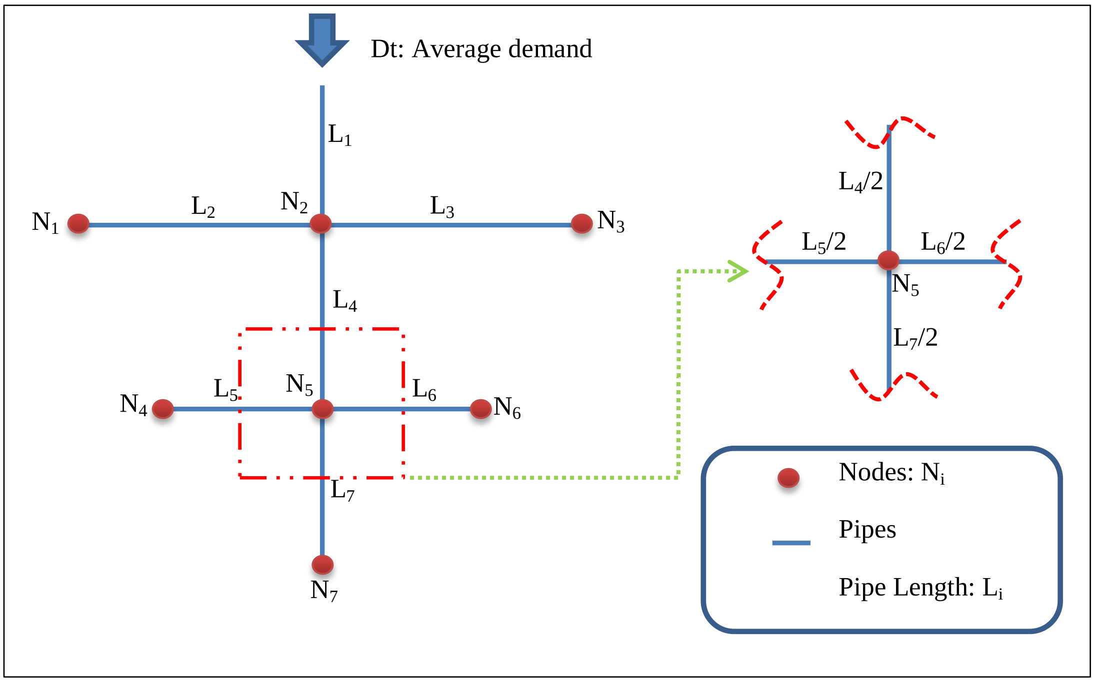
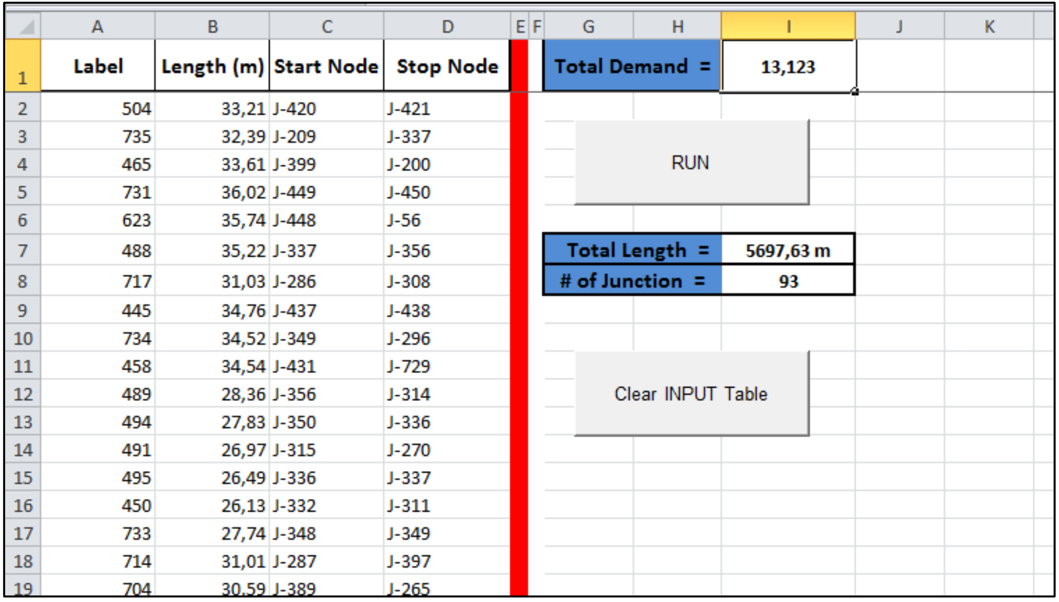


Figure 6.20. Spatial Distribution of Average Demand

N8.3 and N7 pressure zone DMAs contain hundreds of nodes which are connected to various number of pipes. Thus, this methodology is not easy to apply for each customer connection nodes in the system. A Microsoft Excel macro code was developed to overcome this difficulty. This macro was named as Demand Distributer. Various types of data are needed to run this tool which is named as Demand Distributer. These required data contains pipe ID, pipe length, pipe start-end nodes which are customer connection nodes and finally total water flow measured at DMA. A view of input page is shown in Table 6.6. In output page of Demand Distributer, calculated node demands are presented with related node id. Then, these node demands can be easily imported to WaterCAD model by using model builder wizard. Up to that point, demands of each node were imported. Now, model is ready to run in steady state mode.

Table 6.6. Demand Distributer Input Page



Label	Length (m)	Start Node	Stop Node
504	33,21	J-420	J-421
735	32,39	J-209	J-337
465	33,61	J-399	J-200
731	36,02	J-449	J-450
623	35,74	J-448	J-56
488	35,22	J-337	J-356
717	31,03	J-286	J-308
445	34,76	J-437	J-438
734	34,52	J-349	J-296
458	34,54	J-431	J-729
489	28,36	J-356	J-314
494	27,83	J-350	J-336
491	26,97	J-315	J-270
495	26,49	J-336	J-337
450	26,13	J-332	J-311
733	27,74	J-348	J-349
714	31,01	J-287	J-397
704	30,59	J-389	J-265

Total Demand = 13,123

Total Length = 5697,63 m

# of Junction = 93

Daily demand curves in Figure 6.18 and Figure 6.19 show that water consumption of DMAs varies as a function of time as expected. Distributed demands have to fluctuate as DMA demand to provide realistic simulation. Thus, demand pattern of each DMA was created to reflect fluctuations in extended period simulation. Hourly demands were divided by average hourly consumption of DMA to determine demand pattern of each DMA; for example, hourly demands of N8.3-1 Northern Sancaktepe DMA are given in Table 6.7.

Table 6.7. Hourly Demands of N8.3-1 Northern Sancaktepe DMA

Time	**00:00**	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**
Discharge (m^3/hr)	**9,36**	**4,89**	**3,96**	**3,33**	**3,45**	**4,77**	**9,48**	**14,58**	**12,15**	**16,23**	**19,59**	**20,01**
Time	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
Discharge (m^3/hr)	**19,74**	**17,43**	**19,29**	**15,78**	**17,43**	**16,92**	**17,52**	**16,14**	**13,44**	**13,92**	**13,32**	**12,21**

Average demand of N8.3-1 Northern Sancaktepe DMA is calculated as 13.123 m^3 per hour. Each hourly demand was divided by 13.123 m^3/hour to determine demand pattern of DMA. By using these values, demand pattern of N8.3-1 Northern Sancaktepe DMA is plotted in Figure 6.21. Then, in WaterCAD pattern was defined. Each multiplier value was entered for the pattern (Figure 6.22). This process was repeated for all DMAs.

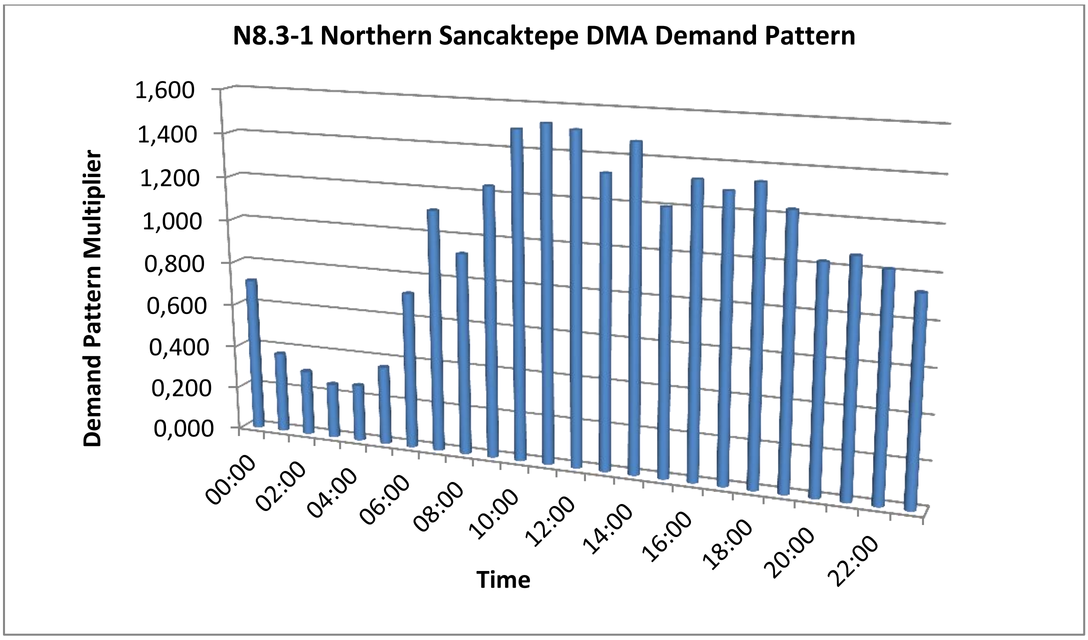
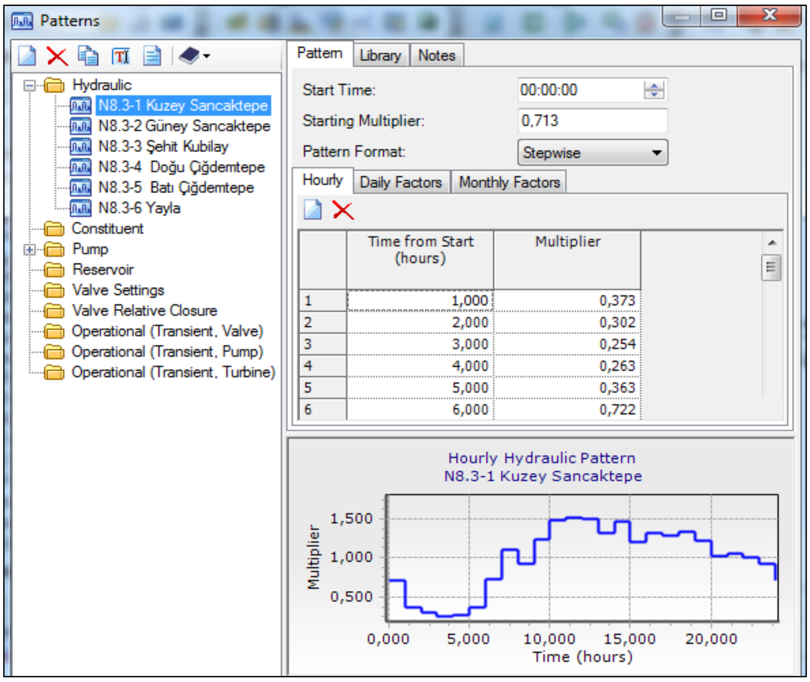


Figure 6.21. N8.3-1 Northern Sancaktepe DMA Demand Pattern



- Hydraulic
  - N8.3-1 Kuzey Sancaktepe
  - N8.3-2 Güney Sancaktepe
  - N8.3-3 Şehit Kubilay
  - N8.3-4 Doğu Çiğdemtepe
  - N8.3-5 Batı Çiğdemtepe
  - N8.3-6 Yayla
- Constituent
- Pump
- Reservoir
- Valve Settings
- Valve Relative Closure
- Operational (Transient, Valve)
- Operational (Transient, Pump)
- Operational (Transient, Turbine)

Start Time: 00:00:00
Starting Multiplier: 0,713
Pattern Format: Stepwise

	Time from Start (hours)	Multiplier
1	1,000	0,373
2	2,000	0,302
3	3,000	0,254
4	4,000	0,263
5	5,000	0,363
6	6,000	0,722

Figure 6.22. WaterCAD Input Pattern

6.2.3. Extended Period Simulation

The behavior of a water distribution system through time can be simulated by using an extended period simulation (EPS). An EPS can be conducted for any duration specified by operator. System conditions are computed over the given duration at a specified time increment. Some of the types of system behaviors that can be analyzed using an EPS include how tank levels fluctuate, when pumps are running, whether valves are open or closed, and how demands change throughout the day. There are many inputs required to run extended period simulation. Thus, huge amount of input data must be integrated carefully by modeler to increase reliability of the created model. Also modeler may need to perform additional actions during calibration, analysis, design and schedule processes. Therefore it is highly recommended by Walski et al. (2003) that a model should be analyzed in steady-state situations before running system in extended period simulation to overcome operator errors. Once steady-state analysis is performed successfully, shifting system from steady-state to extended period simulation is much easier. In this study EPS was used to analyze different scenarios to determine optimal pump schedule for 24 hours with one hour time increments.

6.2.4. Energy Price

Multi and single tariffs were used in N8.3 and N7 pressure zone models. Single tariff has constant value. In multi tariff, prices change in different time interval. Multi tariff is based on three phase. These are day, peak and night prices. Energy prices used in model were obtained from Enerjisa Başkent Electricity Distribution Inc. are shown in Table 6.8 (October 2011 electricity price).

Table 6.8. Energy Prices

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

6.2.5. Constraints

N8.3 pressure zone had been designed to service consumers who are located in 1075-1115 m elevation intervals. However, some consumers are located above 1115 m elevation. Ankara water utility provides water service to consumers with minimum 2.5 bar pressure. Thus, while running optimal pump scheduling analysis min pressure constraint was selected as 2.5 bar and customer connection nodes having higher elevation than 1115 m were not included in this constraint. Similarly, there are consumers located above service elevation interval of N7 pressure zone which is 1035-1075 m. As in N8.3 pressure zone pressure constraints of nodes connected to this consumer are not taken into consideration.

Another constraint is minimum tank levels. To perform continuity of model final water level of tank should be equal or higher than initial water level of tank. Initial water level was selected as 2.5 m at 00:00 hour and also final water level was selected as minimum 2.5 m. Allowable minimum water level of tank was selected as 1.75 m to supply water for fire and emergency situations. Both N7 and N8.3 pressure zone’s storage tanks are used with these constraints in the model.

Third constraint is the velocity constraint. Maximum velocity in distribution pipelines is selected as 1.3 meter per second. Last constraint is pump start. This constraint is the global maximum number of pump starts allowed. In this study, fluctuation of daily demand is lower. Thus, maximum pump start was selected as 3.

6.3. Scenarios and Alternatives

Scenarios and alternatives are important features of water distribution network modeling tools. Scenarios allow user to calculate multiple “What If?” situations in a single model. User may wish to try several designs and compare the results, or analyze an existing system using several different demand alternatives and compare the resulting system pressures without constructing additional models.

A scenario is a set of Alternatives, while alternatives are groups of actual model data. For example, different demand pattern data (demand #1 and demand #2) at same nodes can be used separately in the same model. By creating two scenarios, each alternative which are (demand #1 and demand #2) are used separately and result are determined for each alternative. Thus, alternatives contain different model data, Scenarios decide which alternatives to use.

In this study, different combinations of pumps were used in model. In addition, entire system was analyzed in 14 isolated DMAs and as a whole. Running system as a whole or with an isolated DMA, isolation valve positions of each case were entered as a different alternative. Eight different pump combinations, two different tariffs and two different networks which were insulated and uninsulated were examined in this study. Totally, 32 different scenarios were created. In order to define scenarios in a simple way and avoid confusions, a terminology is developed.

6.3.1. Terminology

Each scenario was presented with a different code using the developed terminology; sequence of the terms in codes as follows:

1. Isolation Condition
2. Pump Number
3. Pump Type
4. Tariff Type

All terms are described in details as follows,

- INS: Insulated: System is running with isolated DMAs. Isolation valves are closed.
- UNINS: Uninsulated: All isolation valves are open and DMAs are interconnected.
- #PMP: # represents number of pipe active. (1-2-3)
- SM: Small capacity pump which is SUMAS SP 125 in P23 pump station is active.
- LG: Large capacity pump which is SMS SP 150-400 in P23 pump station is active.
- CT: Constant tariff energy price is used.
- MT: Multi tariff energy price is used.

By using this terminology optimal pump scheduling scenarios for N8.3 pressure zone are created. For N7 pressure zone, pump type terms which are SM and LG are not required, because type of pumps in P12 pump station are same; thus, only isolation condition, pump number and tariff type are used while creating scenarios. Scenarios of combined system of N8.3 and N7 pressure zones are defined by another terminology. New terms are generated to describe combined scenarios effectively. These terms are;

- Isolation condition
- N8.3 Pressure Zone Pumps Status (1 = active , 0 = passive)
- N7 Pressure Zone Pumps Status (1 = active , 0 = passive)
- Tariff Type

6.3.2. Considered Scenarios

First scenario of N8.3 pressure zone (Table 6.10) is running model in insulated condition with one small pump with constant tariff energy prices. Generated code by previously defined terminology is represented in Figure 6.23. Totally 20 different scenarios were simulated for N8.3 pressure zone.

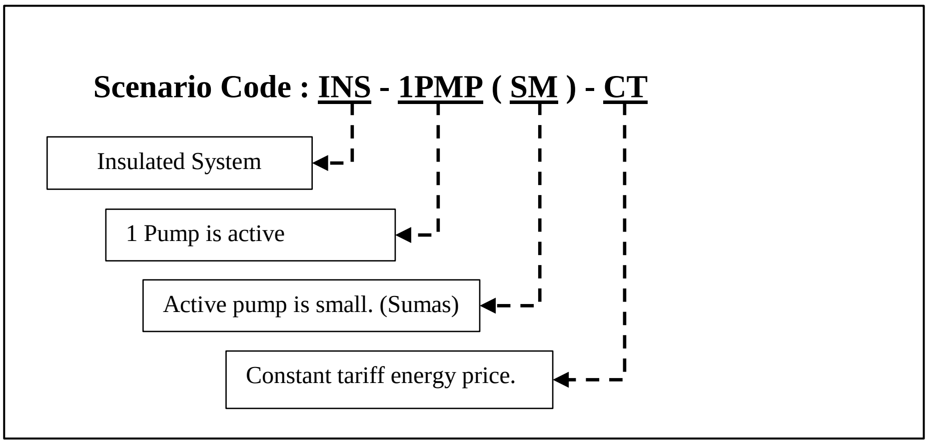


Figure 6.23. First Scenario Code of N8.3 Pressure zone

N7 pressure zone first scenario (Table 6.9) is similar as N8.3 pressure zone first scenario. Scenario is running model in insulated condition with one of the pump in P12 pump station by using constant tariff energy prices. In Figure 6.24, generated first scenario code of N7 pressure zone is shown. Due to similar type of pumps in P12 pump station, 12 different scenarios were created and analyzed for N7 pressure zone.

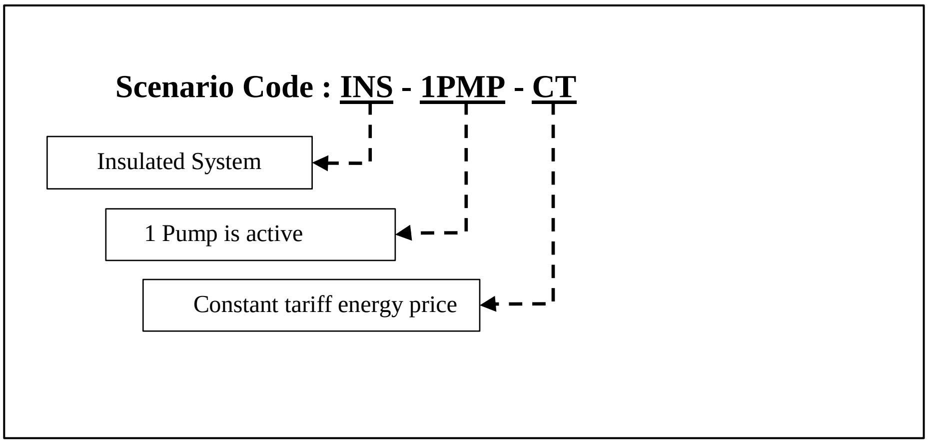


Figure 6.24. First Scenario Code of N7 Pressure zone

Remaining individual scenario codes of N7 and N8.3 pressure zones and their definition are shown in the following tables (Table 6.9 and Table 6.10). Results of scenarios will be presented according to these generated codes.

Table 6.9. Scenario Codes and their Definitions of N7 Pressure Zone

	Scenario Codes of N7		Scenario No	Insulated System	Uninsulated System	# of Active Pump	Constant Tariff	Multi Tariff
INSULATED SYSTEM	INS-1PMP-CT	CONSTANT TARIFF	1	X		1	X	
	INS-2PMP-CT		2	X		2	X	
	INS-3PMP-CT		3	X		3	X	
	INS-1PMP-MT	MULTI TARIFF	4	X		1		X
	INS-2PMP-MT		5	X		2		X
	INS-3PMP-MT		6	X		3		X
UNINSULATED SYSTEM	UNINS-1PMP-CT	CONSTANT TARIFF	7		X	1	X	
	UNINS-2PMP-CT		8		X	2	X	
	UNINS-3PMP-CT		9		X	3	X	
	UNINS-1PMP-MT	MULTI TARIFF	10		X	1		X
	UNINS-2PMP-MT		11		X	2		X
	UNINS-3PMP-MT		12		X	3		X

Table 6.10. Scenario Codes and their Definitions of N8.3 Pressure Zone

▨	Scenario Codes of N8.3	▨	Scenario No	Insulated System	Uninsulated System	# of Active Pump	Pump #1 SM-SUMAS	Pump #2 SM-SUMAS	Pump #3 LG-SMS	Constant Tariff	Multi Tariff
INSULATED SYSTEM	INS-1PMP(SM)-CT	CONSTANT TARIFF	1	X		1	X			X	
	INS-1PMP(LG)-CT		2	X		1			X	X	
	INS-2PMP(SM+SM)-CT		3	X		2	X	X		X	
	INS-2PMP(SM+LG)-CT		4	X		2	X		X	X	
	INS-3PMP(SM+SM+LG)-CT		5	X		3	X	X	X	X	
	INS-1PMP(SM)-MT	MULTI TARIFF	6	X		1	X				X
	INS-1PMP(LG)-MT		7	X		1			X		X
	INS-2PMP(SM+SM)-MT		8	X		2	X	X			X
	INS-2PMP(SM+LG)-MT		9	X		2	X		X		X
	INS-3PMP(SM+SM+LG)-MT		10	X		3	X	X	X		X
UNINSULATED SYSTEM	UNINS-1PMP(SM)-CT	CONSTANT TARIFF	11		X	1	X			X	
	UNINS-1PMP(LG)-CT		12		X	1			X	X	
	UNINS-2PMP(SM+SM)-CT		13		X	2	X	X		X	
	UNINS-2PMP(SM+LG)-CT		14		X	2	X		X	X	
	UNINS-3PMP(SM+SM+LG)-CT		15		X	3	X	X	X	X	
	UNINS-1PMP(SM)-MT	MULTI TARIFF	16		X	1	X				X
	UNINS-1PMP(LG)-MT		17		X	1			X		X
	UNINS-2PMP(SM+SM)-MT		18		X	2	X	X			X
	UNINS-2PMP(SM+LG)-MT		19		X	2	X		X		X
	UNINS-3PMP(SM+SM+LG)-MT		20		X	3	X	X	X		X

6.4. Results

Optimum pump scheduling study of N8.3 and N7 pressure zones were established with the different pump combinations, isolation conditions and tariffs (constant and multi tariff). Water level in tanks T53, T34 and pump flow rates for 24 hours extended simulation will be represented. Best three solution costs will be shown for each scenario.

6.4.1. N8.3 Pressure Zone

6.4.1.1. Constant Tariff Insulated Systems:

N8.3-Scenario # 1 - INS-1PMP(SM)-CT

Best three solutions are represented in Table 6.11. Total energy cost of best solution is calculated as 195.254 TL. It is observed that pump # 1 continuously runs from 01:00 to 24:00 to provide water to the system while satisfying target hydraulic requirements (Figure 6.25). This situation shows that small pump in P23 pump station should run almost 24 hours a day to supply system water requirement. If P23 pump station operation policy is assumed as using one pump at the same time (for example due to insufficient electricity system while running two or more pump at the same time), small pump will not satisfy its mission in near future by not providing required water to system. In this scenario constant tariff is selected. Thus, while calculating optimal pump schedule, genetic algorithm is concentrated only on hydraulic requirements and total energy use. Small pump runs continuously and water in T53 storage tank fluctuates due to hourly demand changes. Extended period Simulation (EPS) is started with 2.5 meters water level in T53 storage tank. At the end of the 24 hours it is observed in Figure 6.25 that water level is calculated as approximately 2.6 meters. Final water level is higher than initial water level thus this optimal pump schedule can be applied with daily cycles.

Table 6.11. Energy Costs of Best Solutions in Scenario INS-1PMP(SM)-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	196.126	0	196.126
Solution 2	196.230	0	195.254
Solution 3	196.253	0	195.276

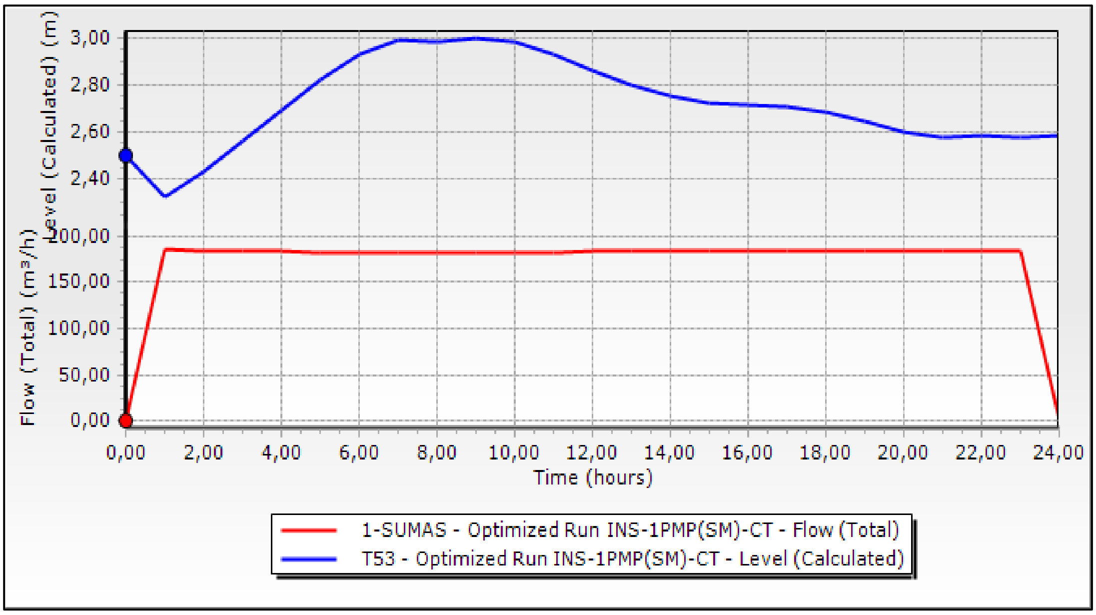


Figure 6.25. Pump Flows and Water Level in T53 Storage Tank versus Time INS-1PMP(SM)-CT

N8.3-Scenario # 2 - INS-1PMP(LG)-CT

INS-1PMP(LG)-CT scenario is simulated by operating only large pump in P23 Pump Station with constant tariff in insulated network condition. Optimum pump operation of this scenario was determined and energy cost of the pump station is calculated as 171.610 TL which is solution 1 shown in Table 6.12.

Table 6.12. Energy Costs of Best Solutions in Scenario INS-1PMP(LG)-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	174.037	0	171.610
Solution 2	174.338	0	171.907
Solution 3	174.475	0	172.042

Water level in tank T53 and pump flow rates for 24 hours extended simulation for the INS-1PMP(LG)-CT Scenario is plotted in Figure 6.26. On- off operation of pump is observed. It is seen that pump # 1 continuously runs from 06:00 to 12:00 and from 16:00 to 23:00 to provide water to the system while satisfying target hydraulic requirements (Figure 6.26). Maximum peak demand is observed at 11:00. However, large pump in P23 pump station stops at this hour in given optimal pump schedule. This means that in N8.3 pressure zone hydraulic pressure requirement can be satisfied with certain water level in T53 storage tank at peak demand hours. Thus, solve mechanism of optimal pump scheduling tries to minimize energy use and decide when the pump switches on or off. At the end of the simulation water level in T53 storage tank is calculated as 2.8 meters. This water level is higher than water level calculated in scenario # 1 which is discussed earlier. Total energy cost of scenario #2 is significantly smaller than scenario # 1 which means that scenario #2 is more economical. In addition, final water level in scenario # 2 is higher; water level difference is 0.2 meter. Consequently, net difference is 20.516 TL (196.126 TL – 171.610 TL) and extra 0.2 meter water height in storage tank T53. 0.2 meter water height can be considered as small value but due to large base cross section area of T53 tank which is 800 m^2 it is transformed to 160 m^3 extra water volume. As mentioned in section 6.2.1.5 that small pump SUMAS SP 125 in P23 pump station has 188 m^3/hour design flow capacity. Therefore, this amount of extra water volume can be pumped by SUMAS SP 125 in approximately one hour. For this reason, final water level in storage tanks should be taken into consideration while comparing energy costs.

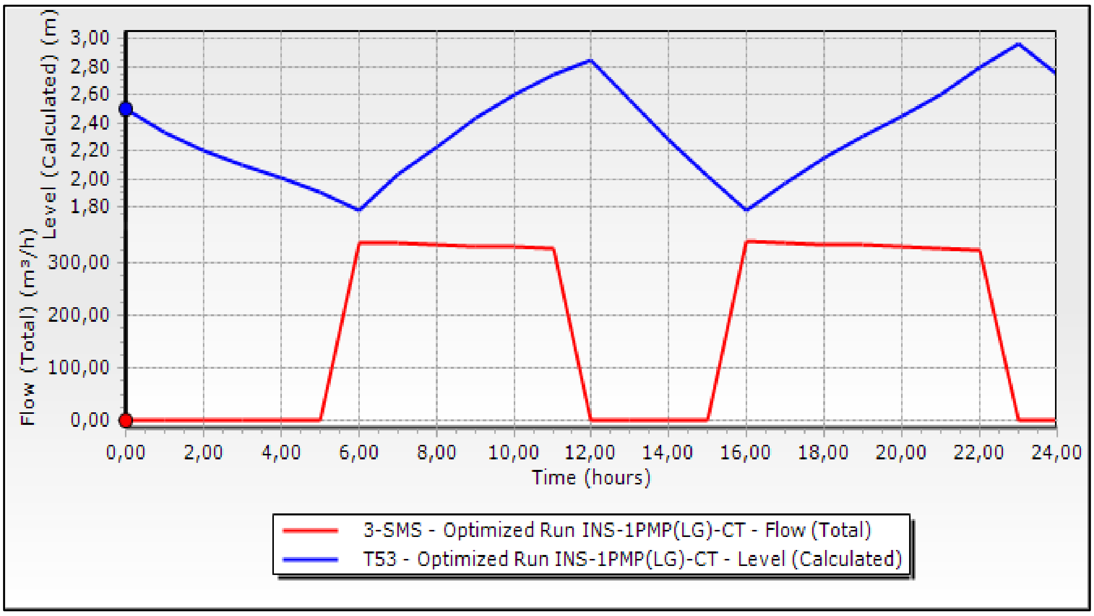


Figure 6.26. Pump Flows and Water Level in T53 Storage Tank versus Time INS-1PMP(LG)-CT

N8.3-Scenario # 3 - INS-2PMP(SM+SM)-CT

Optimal pump scheduling operation was performed with combined two similar pumps in P23 pump station in isolated distribution state with constant tariff. In Figure 6.27 it is observed that two pumps run with different schedules. Pump number one is started to run at time 19:00 and stopped at 01:00. Second pump runs between 07:00 and 23:00 time interval. At 19:00 and 22:00 time interval both pumps are working at the same times. At this point, final water level constraint force pumps to fill the tank; providing final water level in storage tank to be higher than 2.5 meters. At time between 12:00 and 19:00 hours water level in storage tank T53 is observed as fixed and 1.75 meters. While creating water supply system model, minimum water level in the tank is restrained for the emergency operations thus model does not permit flow from storage tank to the distribution network. Required water for the demand is supplied only by pumps at these hours.

Minimum energy cost calculated for this scenario is 186.718 TL (Table 6.13). Energy cost of scenario #3 is smaller than scenario #1 (#3:INS-2PMP(SM+SM)-CT: 186.718 TL and #1:INS-1PMP(SM)-CT: 196.126 TL). Optimal pump schedule of combined similar pumps is more economical then single pump.

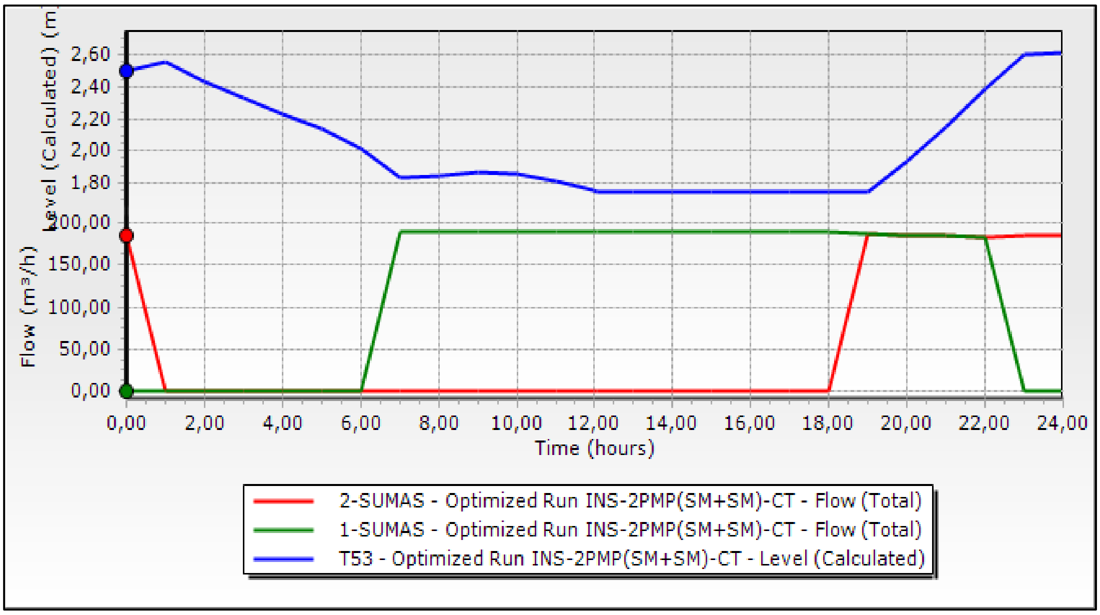


Figure 6.27. Pump Flows and Water Level in T53 Storage Tank versus Time INS-2PMP(SM+SM)-CT

Table 6.13. Energy Costs of Best Solutions in Scenario INS-2PMP(SM+SM)-CT

Solution ID	**Fitness**	**Violation (Total)**	**Energy Cost (Net Total) (TL)**
Solution 1	189.359	0	186.718
Solution 2	189.653	0	187.009
Solution 3	190.703	0	188.044

N8.3-Scenario # 4 - INS-2PMP(SM+LG)-CT

Scenario number four is created by running small and large pump in P23 pump station in isolated distribution network. Constant tariff is used for this optimization. Calculated optimal pump schedule shows that best solution is reached by using only large pump in P23 pump station. Large pump SMS made two on off operation during the day. On the other hand small pump SUMAS continuously remained in switched off position throughout the day. Time versus pumps flows are plotted in Figure 6.28. Running hours of large pump are 05:00 – 08:00 and 11:00 – 21:00. These hours coincide with peak daily demand hours thus large pump starts to provide water for the required demand of the system.

Energy cost of best three solutions calculated by optimal pump scheduling analysis is tabulated in Table 6.14. Minimum energy cost is 172.364 TL. Energy cost of this scenario and scenario number two which is performed by using only large pump are approximately equal. Because best solution of this scenario is occurred by using only large pump; while minimizing energy cost small pump is left outside the schedule and remained switched off position.

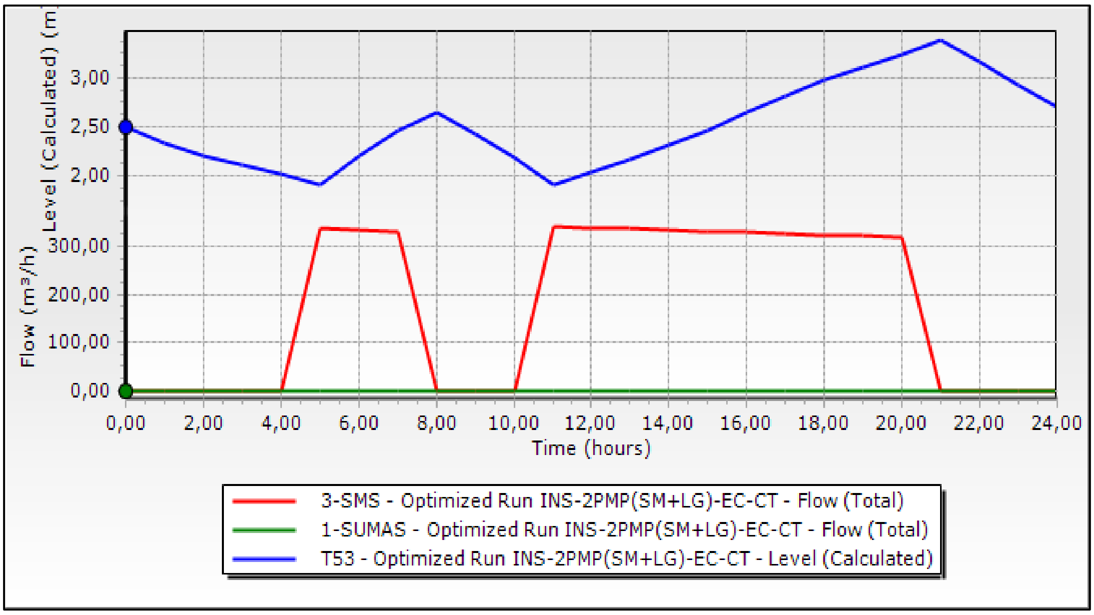


Figure 6.28. Pump Flows and Water Level in T53 Storage Tank versus Time INS-2PMP(SM+LG)-CT

Table 6.14. Energy Costs of Best Solutions in Scenario INS-2PMP(SM+LG)-CT

Solution ID	**Fitness**	**Violation (Total)**	**Energy Cost (Net Total) (TL)**
Solution 1	174.801	0	172.364
Solution 2	174.979	0	172.539
Solution 3	175.112	0	172.670

N8.3-Scenario # 5 - INS-3PMP(SM+SM+LG)-CT

Two small and one large pump located in P23 pump station are included in to the system at the same time while determining cost effective pump schedule. Optimizing all pumps at the same time tremendously increases solution size and extends solving time. Moreover, increased solution size decreases genetic algorithm solving efficiency. Default parameters of genetic algorithm should be changed to reach good solution. In this study, genetic algorithm is used only with default values. Although scenario number five contains all solution alternatives, calculated energy cost of optimized pump schedule did not give the best solution.

Optimization study of N8.3 pressure zone in insulated distribution network was performed and optimum pump schedules of three pumps were determined by using constant energy tariff. Water levels in T53 storage tank and pump flows versus time graphs are represented in Figure 6.29 according to best pump schedule solution determined. In Figure 6.29, it is observed that 3 pumps in P23 pump stations are operated. It is noticed that water level in T53 storage tank is almost equal to minimum water level limit 1.75 meters at hours between 12:00 and 20:00. Although pump #1 SUMAS is running at these hours water level in T53 storage tank remains unchanged. Total demand at these hours is directly supplied by pump # 1 and water level in storage tank T53 remains at minimum water level limit. It is observed from Figure 6.29 that after 20:00 o'clock, pump #2 and pump #3 are activated to provide final minimum water level limit 2.5 meters at 24:00 o'clock.

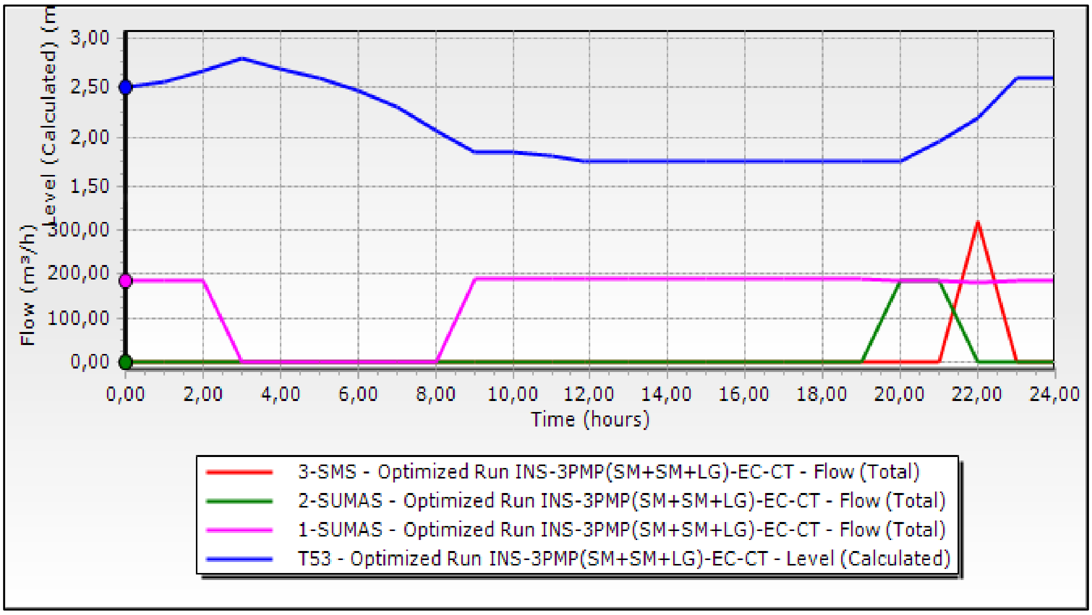


Figure 6.29. Pump Flows and Water Level in T53 Storage Tank versus Time INS-2PMP(SM+SM+LG)-CT

Using optimum pump schedules, extended period simulation of N8.3 pressure zone was made. From the simulation results total energy cost is calculated as 183.411 TL with respect to optimum pump schedule determined. Two more alternative pump schedules that are close to best one were determined. Energy costs of each alternative solution are tabulated in Table 6.15. In each pump schedule all hydraulic requirements were satisfied thus violation was not occurred.

Table 6.15. Energy Costs of Best Solutions in Scenario INS-3PMP(SM+SM+LG)-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	187.481	0	184.867
Solution 2	188.176	0	183.411
Solution 3	188.341	0	183.571

6.4.1.2. Multi Tariff Insulated Systems:

N8.3-Scenario # 6 - INS-1PMP(SM)-MT

In this scenario, optimal pump schedule of small pump (SUMAS 125) in P23 pump station was determined while running system in isolated state with multi tariff. Multi tariff prices and their time interval are presented in Section 6.2.4. If the multi tariff and constant tariff are deeply examined, it can be observed that changing tariff will have significant effect on optimal pump schedule. Comparison of multi and constant tariff is presented in Table 6.16. For instance, electricity is % 43.04 more expensive in multi tariff than constant tariff between 17:00 – 22:00 hours. Thus, in optimal pump schedule study pumps will run as short as possible time period due to high energy prices. Scenario number six can be a good example; small pump is in switched off position only hours between 17:00 and 18:00 (Figure 6.30) in a day which its one hour is in the expensive price period. However, in scenario number one (INS-1PMP(SM)-CT) which was simulated by constant tariff, same pump is not used in hours between 23:00 and 01:00; these hours remain in low night price interval in multi tariff.

Best three optimal pump schedules of scenario # six were analyzed and their energy cost is tabulated in Table 6.17. Minimum energy use of distribution network is determined as 176.663 TL. Optimal pump schedule study of same configuration with constant tariff was performed in scenario # one and best solution was 196.126 TL. Using multi tariff with same system configuration caused approximately %11 cost savings.

Table 6.16. Comparison of Tariffs

Time Interval	Energy Price (TL/kWh)		% Difference
	Constant Tariff	Multi Tariff	
Day 06:00-17:00	0.2486	0.2336	-6.03
Peak 17:00-22:00	0.2486	0.3556	43.04
Night 22:00-06:00	0.2486	0.1456	-41.43

Table 6.17. Energy Costs of Best Solutions in Scenario INS-1PMP(SM)-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	177.546	0	176.663
Solution 2	177.581	0	176.698
Solution 3	177.618	0	176.734

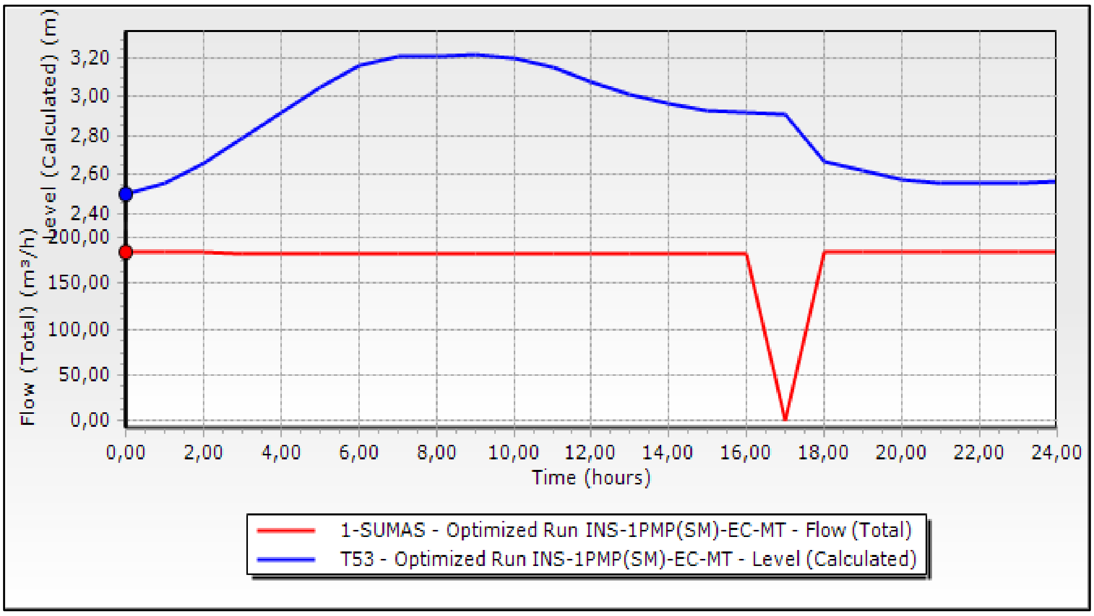


Figure 6.30. Pump Flows and Water Level in T53 Storage Tank versus Time INS-1PMP(SM)-MT

N8.3-Scenario # 7 - INS-1PMP(LG)-MT

N8.3 isolated distribution network was simulated and optimum pump schedule of large pump in P23 pump station was determined under multi tariff energy prices. All hydraulic requirements (pressure, flow, demand, water level and etc.) were established while making optimal pump scheduling process. Flow of large pump SMS outlet versus time and water level in T53 storage tank versus time graphs are plotted in Figure 6.31. Optimal operation schedule of SMS pump is gathered from flow versus time plot; working time intervals are 12:00 – 17:00 and 22:00 – 06:00. Same as previous multi tariff scenario (N8.3-Scenario # 6 - INS-1PMP(SM)-MT) large SMS pump remained switched off where expensive tariff (peak time interval) is active. Again, this shows that tariff and its characteristic has great effect on optimal pump scheduling study.

Energy cost of best pump schedule is calculated as 126.353 TL. And energy costs of subsequent alternatives are given in Table 6.18. After making both constant and multi tariff analysis, it is observed that using multi tariff with pump schedule causes energy cost reduction. For this scenario configuration multi tariff provided approximately %26 cost saving with respect to constant tariff.

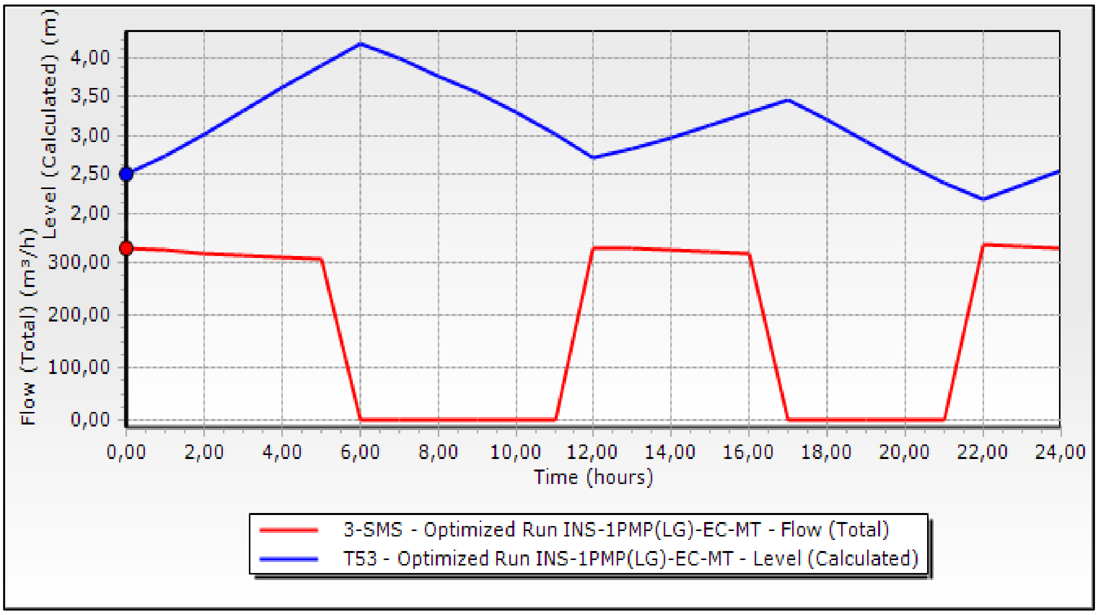


Figure 6.31. Pump Flows and Water Level in T53 Storage Tank versus Time INS-1PMP(LG)-MT

Table 6.18. Energy Costs of Best Solutions in Scenario INS-1PMP(LG)-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	128.140	0	126.353
Solution 2	128.373	0	126.583
Solution 3	128.433	0	126.642

N8.3-Scenario # 8 - INS-2PMP(SM+SM)-MT

Two similar pumps (SUMAS SP 125 #1 and #2) in P23 pump station were allowed to run in this scenario. Water distribution network was modeled in isolated condition and optimum schedule of these pumps were determined while using multi tariff energy prices. According to optimum scheduling analysis it is observed that two pumps are working at the same time between 00:00 and 06:00 hours when the energy prices are lowest. System starts to fill the tank at these hours and uses stored water when energy prices are high to minimize energy costs. In Figure 6.32 it is clearly seen that both pumps are in switch off position 17:00 – 22:00 time intervals when the energy prices are highest. However, hours between 11:00 and 17:00 one of the pumps is working. The reason of running pump at these hours is to provide required water to system and provide hydraulic requirements. Moreover, these hours are coincided with peak demand hours of N8.3 Pressure Zone which is given in section 6.2.2.

The costs of best three solutions are tabulated at Table 6.19. Minimum energy cost of optimized pump schedule is calculated as 140.724 TL. Using two small pumps at the same time instead of one and scheduling them minimize energy cost approximately %30. Because by using two pumps at the same time increases store more water in the system at low energy price interval. Thus, storage capacity is an important factor while using multi tariff energy prices.

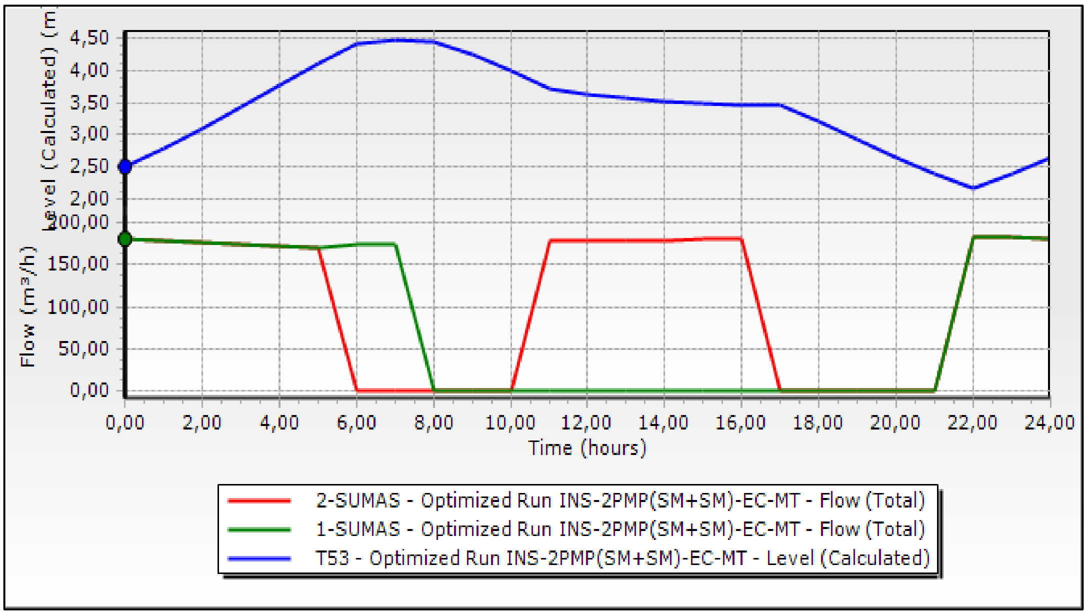


Figure 6.32. Pump Flows and Water Level in T53 Storage Tank versus Time INS-2PMP(SM+SM)-MT

Table 6.19. Energy Costs of Best Solutions in Scenario INS-2PMP(SM+SM)-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	144.380	0	140.724
Solution 2	144.468	0	140.809
Solution 3	144.565	0	140.904

N8.3-Scenario # 9 - INS-2PMP(SM+LG)-MT

Optimal schedule of one small and one large pump are determined in this scenario. Similarly as previous scenario, both pumps are allowed to work at the same time or different times. Flow capacity of large pump in P23 pump station is approximately twice of small pump. Thus, total pumping capacity of this scenario is higher than INS-2PMP(SM+SM)-MT scenario. Due to this excess capacity total pumping time of the system is reduced. Again, at low energy price hours (22:00 – 06:00), both pumps are working and T53 storage tank is filling. At hours between 13:00 and 16:00 only large pump is working to provide peak hour demands. It is observed in Figure 6.33 that water in T53 storage tank fluctuates and final water level remains as 2.5 meters which is assigned as final minimum water level. Therefore, simulation can be repeated for ongoing days.

Energy cost using by optimal pump schedule of this scenario is expected as lower than energy cost by using optimal pump schedule of two small pumps. The results are shown in Table 6.20; energy cost of best solution is calculated as 124.667 TL and lower than energy cost of previous scenario which is 140.724 TL. For the second pump, using large pump instead of small pump provides % 13 cost reductions in N8.3 pressure zone with optimum pump schedule. Thus capacity of pumps is another important factor while using pumps with multi tariff energy prices.

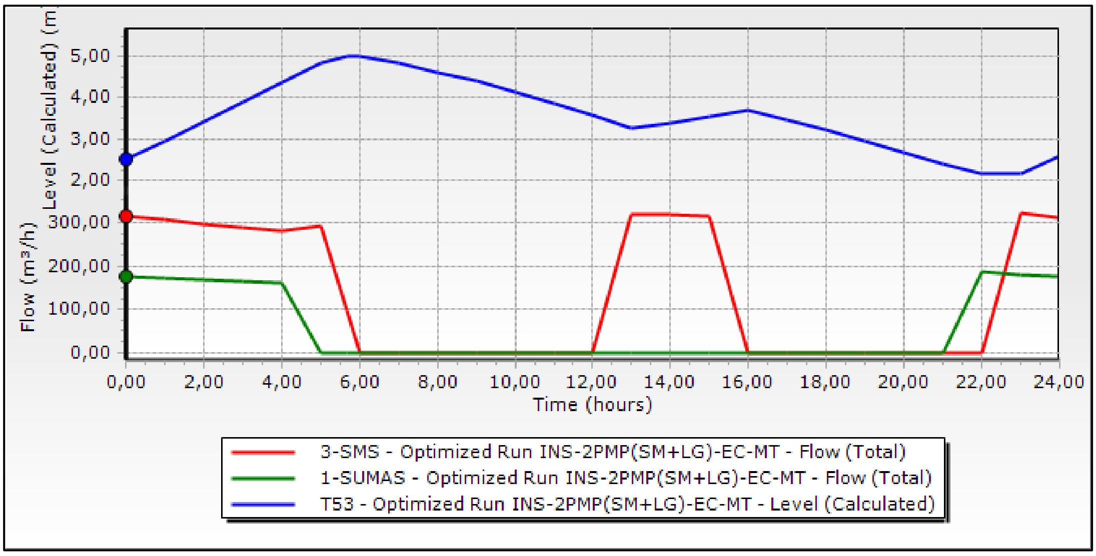


Figure 6.33. Pump Flows and Water Level in T53 Storage Tank versus Time INS-2PMP(SM+LG)-MT

Table 6.20. Energy Costs of Best Solutions in Scenario INS-2PMP(SM+LG)-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	127.906	0	124.667
Solution 2	128.050	0	124.807
Solution 3	128.213	0	124.966

N8.3-Scenario # 10 - INS-2PMP(SM+SM+LG)-MT

Last scenario of the insulated system with multi tariff energy prices is created by operating all pumps in P23 pump station. All pumps in pump station are included in optimization process. Thus solution space of this scenario contains all different possibilities of other pump combinations. Solving time of Genetic algorithm based software increases as solution size expands. Therefore, solution process of this scenario spends more time than other scenarios. Flow versus time of each pump in P23 pump station and water level versus time in T53 storage tank are plotted in Figure 6.34.

Determined pumps schedule of last three scenarios #8, #9 and #10 shows that they have similar pump schedule characteristic. For instance, in each scenario roughly pumps are running at hours between 22:00 and 06:00 (night tariff). In addition, at peak demand hours, pumps are switched on again. It can be inferred from pumps schedules that running duration of pumps is inversely proportional with total capacity of operated pumps. While total flow capacity of operated pumps decreases, duration of running pumps increases to provide sufficient water at peak demand hours.

Energy cost of pumps by using determined optimal pump schedule is calculated as 123.456 TL and best three solution is given in Table 6.21. This value is best solution for the insulated system using multi tariff energy prices. Energy cost of each pump combination were examined and it is observed that operating large pump single or combined with small pump or pumps results similar energy costs (Table 6.22). However, operating one small pump or two small pumps cause %12 and %25 rise in energy cost respectively. In other words, for this type of water distribution system replacing small pumps with new pumps having larger flow capacity can lead to save significant energy cost while using tariff energy costs.

Table 6.21. Energy Costs of Best Solutions in Scenario INS-3PMP(SM+SM+LG)-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	129.675	0	124.688
Solution 2	130.358	0	123.456
Solution 3	130.359	0	123.458

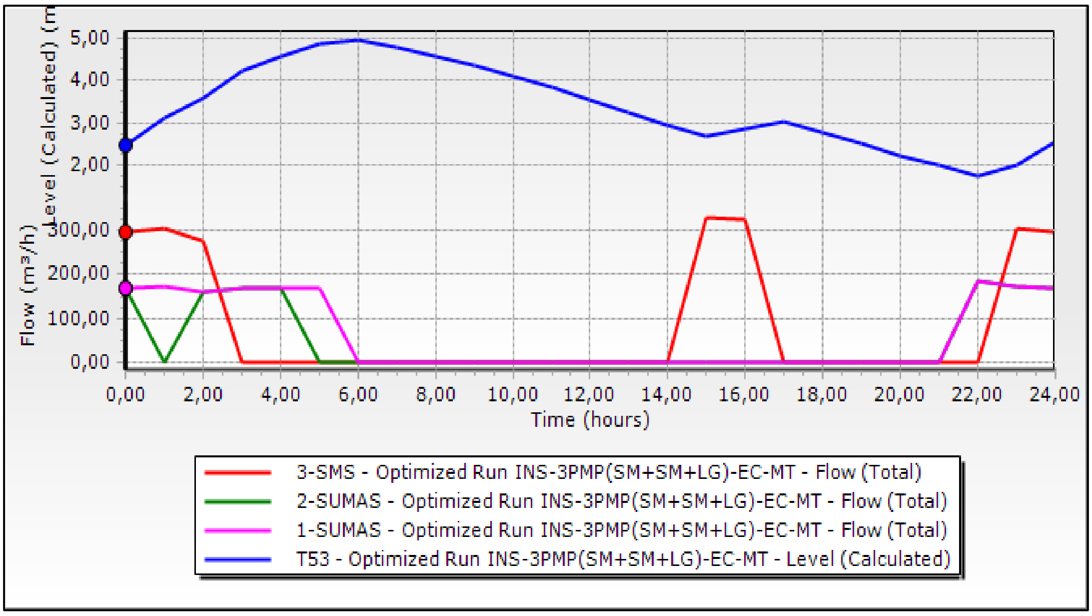


Figure 6.34. Pump Flows and Water Level in T53 Storage Tank versus Time INS-3PMP(SM+SM+LG)-MT

Table 6.22. Energy Costs of Insulated System with Multi Tariff Energy Prices

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

6.4.1.3. Constant Tariff Uninsulated Systems:

Optimal pump scheduling study of N8.3 Pressure Zone in isolated system condition was performed and all pumps combinations were analyzed in constant - multi tariff separately in Section 6.4.1.1 and 6.4.1.2. The results of isolated system are discussed in previous scenarios. Same configurations with uninsulated system condition with constant energy prices were analyzed. Pumps were optimized and their pumps schedules were determined. The pump schedules and fluctuation of T53 storage tank water level in insulated system condition and uninsulated system condition were compared. It is observed that changing water network system from insulated to uninsulated condition or vice versa usually causes small or no change in pump schedule. Comparison of different isolation conditions are represented in Figure 6.35. Optimal pump schedule of first three scenarios (#1/#2/#3 and #11/#12/#13) are exactly same. Last two scenarios (#4/#5 and #14/#15) have different pump schedules in insulated and uninsulated system state. In these scenarios two pump types (small and large pumps in P23 pump station) are operated at the same time. Thus, different pump combinations can provide alternative pump schedules for approximately equal total energy costs.

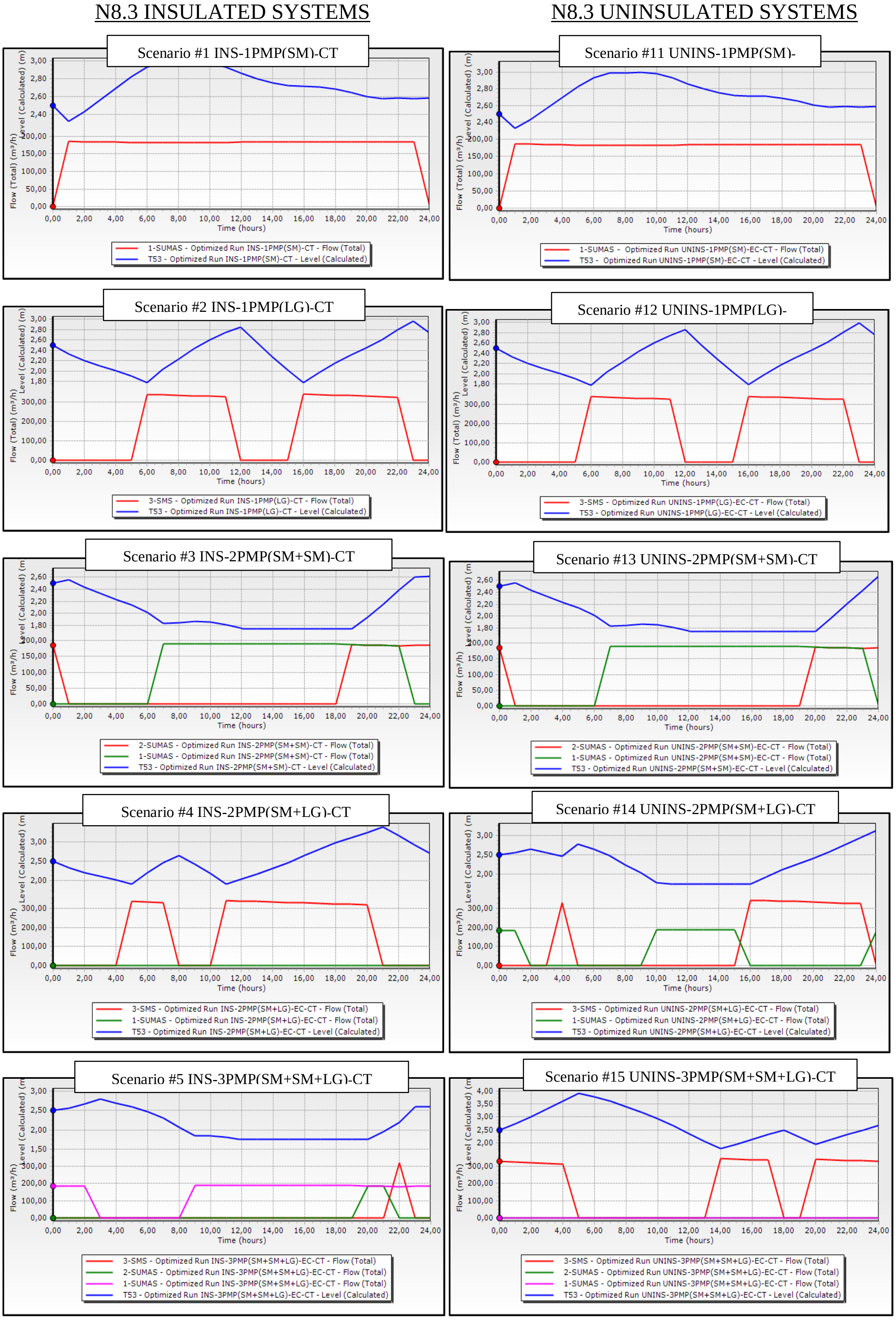


Figure 6.35. Comparison of N8.3 Pumping Schedules for Insulated and Uninsulated Conditions with Constant Tariff

Total energy costs of scenarios were calculated according to determined optimal pump schedules. Results show that using system in uninsulated condition instead of insulated condition causes approximately % 1.3 cost saving for N8.3 pressure zone. This value can be considered as small; however, cost reduction on large water distribution networks can be huge. In year 2011, total energy cost of all pump stations in Ankara Water Supply System was calculated as 39,323,316 TL. If entire water distribution network is operated in uninsulated condition instead of insulated condition, total energy cost saving in one year can be approximately 500,000 TL. Optimal pump schedules were determined and calculated energy costs of five different pump combinations are represented in Table 6.23. In each optimization process hydraulic constraints are provided. Most economical pump schedule of uninsulated system with constant tariff energy prices was determined in UNINS-1PMP(LG)-CT scenario. The total energy cost was calculated as 171.321 TL. Energy costs of determined optimal pump schedule in UNINS-2PMP(SM+LG)-CT and UNINS-3PMP(SM+SM+LG)-CT scenarios are close to energy costs of most economical pump schedule. Their daily energy costs are 172.164 and 172.461 TL respectively. After analyzing in detailed it was realized that using large pump in P23 pump station causes significant reduction in energy cost while using electricity with constant tariff.

Table 6.23. Energy Costs of Optimal Pump Schedule in Different Pump Combinations

Scenario No	Scenario Code	Energy Cost
11	UNINS-1PMP(SM)-CT	195.176 TL
12	UNINS-1PMP(LG)-CT	171.321 TL
13	UNINS-2PMP(SM+SM)-CT	184.955 TL
14	UNINS-2PMP(SM+LG)-CT	173.414 TL
15	UNINS-3PMP(SM+SM+LG)-CT	172.461 TL

6.4.1.4. Multi Tariff Uninsulated Systems:

Isolation valves that restrict flow between DMAs will be remained in open position and N8.3 pressure zone will be analyzed in uninsulated system condition. In other words boundary of DMAs will be removed and N8.3 Pressure Zone will work as a whole system. All pump combinations that can be created were modeled in scenarios and optimal pump schedules were determined. According to optimal pump schedules, extended period simulations were performed and pump flows and water level in T53 storage tank are calculated for both insulated and uninsulated system and plotted in Figure 6.36. Results show that determined optimum pump schedules of multi tariff scenarios created by single small pump, single large pump and two small pumps are exactly same in both insulated and uninsulated systems (Scenarios #6-#7-#8 and Scenarios #16-#17-#18). Thus pump scheduling analysis results with same pump schedule while remaining water distribution network isolated or not.

Total energy costs of these scenarios were compared and results were determined similar as expected because of same pump schedules in in both insulated and uninsulated scenarios mentioned above. Difference of total energy costs of scenarios having same pump combinations are tabulated in Table 6.24. Maximum difference % 1.229 is observed at scenario created by single small pump.

Table 6.24. Total Energy Costs of Different Scenarios with Same Pump Combination

	Insulated System	Total Energy Cost (TL)	Uninsulated System	Total Energy Cost (TL)	Energy Cost Difference %
Scenario Codes	**#6 INS-1PMP(SM)-MT**	176.663	**#16 UNINS-1PMP(SM)-MT**	178.835	1.229
	#7 INS-1PMP(LG)-MT	126.353	**#17 UNINS-1PMP(LG)-MT**	126.108	0.194
	#8 INS-2PMP(SM+SM)-MT	140.724	**#18 UNINS-2PMP(SM+SM)-MT**	140.486	0.169

Scenario # 19 UNINS-2PMP(SM+LG)-MT was optimized and optimum pump schedule was determined. Daily schedule of pumps are represented in Table 6.25 with used energy prices. It is observed that pump #1 and #3 are running at the same time between 00:00 and 03:00 when energy prices are lowest. At the point optimization process force system to pump water when energy price is low and fill the tank to provide water to the system when energy prices are higher. In Figure 6.36, water levels versus time graph of Scenario UNINS-2PMP(SM+LG)-MT shows that filling tank starts at 00:00 and stops at 06:00 due to maximum storage capacity is provided.

Table 6.25. Pump Schedule - Energy Prices of Scenario #19 UNINS-2PMP(SM+LG)-MT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓	✓	✓																				✓	
Pump #3	✓	✓	✓	✓	✓										✓	✓							✓	✓
	✓ : Pump is switched on.																							
	🟨	:Night Period Energy Price							🟩	:Day Period Energy Price								🟥	:Peak Period Energy Price					

Scenario # 20 UNINS-2PMP(SM+SM+LG)-MT was optimized and optimum pump schedule was determined. Solution space of this scenario contains all solutions of multi tariff energy priced uninsulated system. Daily schedule of pumps are represented in Table 6.26 with used energy prices. It is observed that pump #1, #2 and #3 are running at the same time between 23:00 and 01:00 when energy prices are lowest. At the point similarly as previous scenario, optimization process force system to pump water when energy price is low and fill the tank to provide water to the system when energy prices are higher. In Figure 6.36 water levels versus time graph of Scenario UNINS-3PMP(SM+SM+LG)-MT shows that filling tank starts at 00:00 and stops at 05:00 due to maximum storage capacity is provided.

Table 6.26. Pump Schedule - Energy Prices of Scenario #20 UNINS-3PMP(SM+SM+LG)-MT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓	✓	✓	✓	✓																		✓	✓
Pump #2	✓	✓	✓	✓										✓	✓								✓	✓
Pump #3	✓																✓							✓
	✓ : Pump is switched on.																							
	🟨	:Night Period Energy Price							🟩	:Day Period Energy Price								🟥	:Peak Period Energy Price					

Total energy cost of all pump combinations with multi tariff energy prices and uninsulated system conditions are represented in Table 6.27. According to total energy cost best multi tariff pump schedule is selected as optimum pump schedule of UNINS-2PMP(SM+LG)-MT in uninsulated system conditions; Total energy cost is 122.334 TL.

Table 6.27. Energy Costs of Optimal Multi Tariff Pump Schedules of Uninsulated N8.3 Pressure Zone

Scenario Codes	Violation (Total)	Energy Cost of Best Solution (TL)
UNINS-1PMP(SM)-MT	0	178.835
UNINS-1PMP(LG)-MT	0	126.108
UNINS-2PMP(SM+SM)-MT	0	140.486
UNINS-2PMP(SM+LG)-MT	0	122.334
UNINS-3PMP(SM+SM+LG)-MT	0	126.693

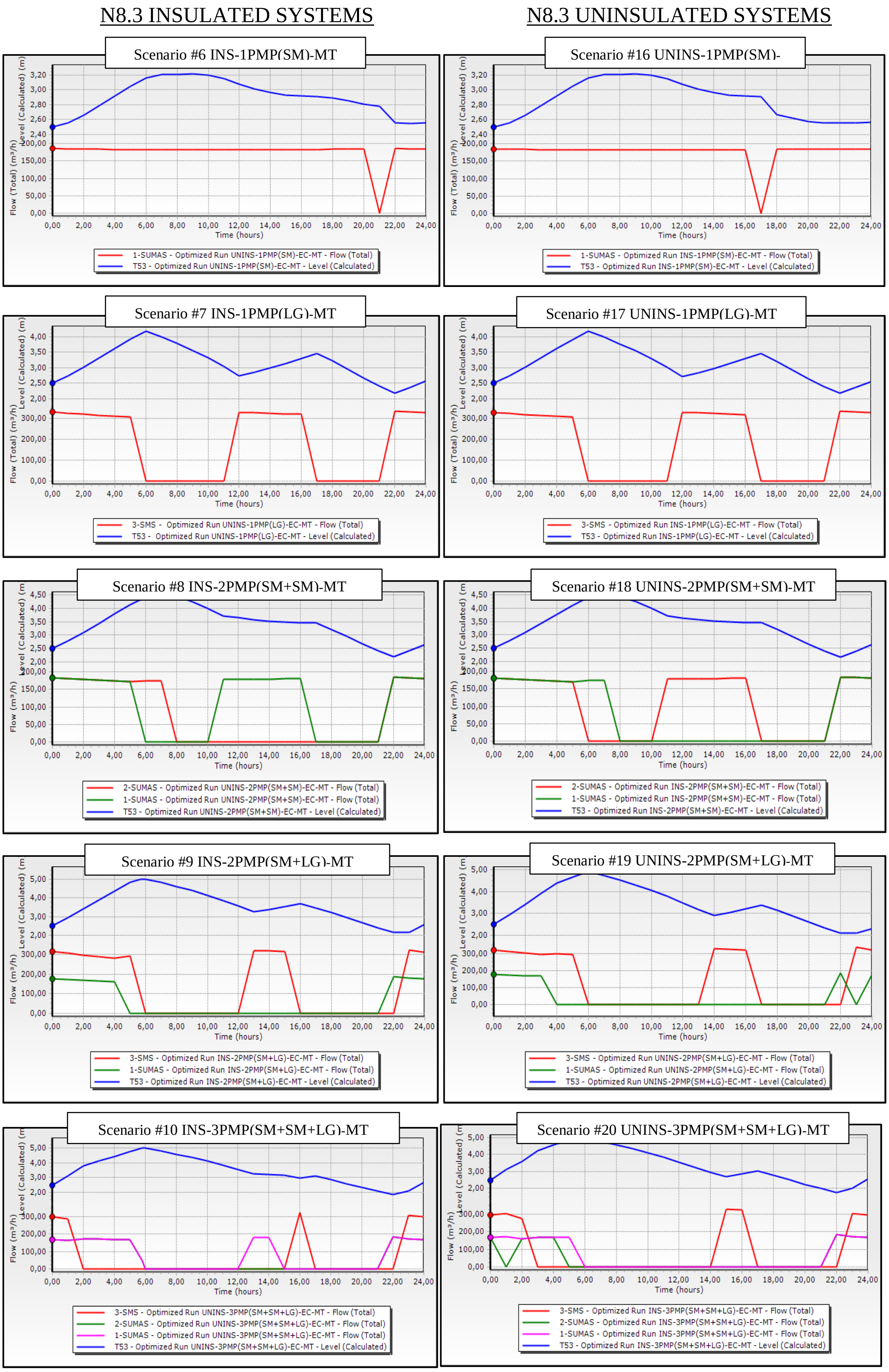


Figure 6.36. Pump Flow and Water Level in T53 Storage Tank versus Time in N8.3 Pressure Zone with Multi tariff

6.4.2. N7 Pressure Zone

N7 pressure zone contains one pump station P12 and one storage tank T34. Two pump groups are working in P12 pump station. First pump group boosts water taken from N6 pressure zone to provide water to N7 pressure zone. Second pump group is working for N8.1 pressure zone. N8.1 pressure zone is not included in this study. Thus only first pump group connected to N7 pressure zone is used in the optimization analysis. This pump group consists of three pumps having same pump characteristics. Therefore, only three different pump combinations can be created; one, two or three pumps. All pumps in first pump group are same thus which pump is operated does not matter; only number of operated pumps is important. For N7 pressure zone 12 different scenarios were created and modeled (Table 6.9). For three different pump combinations optimal pump schedules were determined with multi tariff and constant tariff prices while running water network system in both insulated and uninsulated condition. Optimal pump schedule of each scenario will be discussed below.

6.4.2.1. Constant Tariff Insulated Systems:

N7-Scenario # 1 - INS-1PMP-CT

N7 pressure zone was modeled as insulated system and then optimal pump schedule was determined using constant tariff energy prices. According to optimal pump schedule, one of the pumps (pump #1, #2 or #3) in P12 pump station should be operated in 06:00 – 13:00 and 16:00 – 01:00 time intervals (Figure 6.37). Pump is operated with constant energy prices thus energy price does not vary by time. Optimum pump schedule was determined by minimizing energy cost of the pump while satisfying hydraulic system requirements which are integrated as constraints in genetic algorithm (Section 5.1). For instance, water demands in the distribution network should be met by pumping enough water to the system. Moreover, predefined final water level in storage tank should be satisfied. Therefore, pump schedule is directly controlled by hydraulic requirements of the system. Demand characteristic of N7 pressure zone (Figure 6.19) is examined and it is observed that optimum pump schedule and daily demand curves has similar behavior during the day. At peak demand hours pump is working however, at low demand hours pump is not working. In other words, pump operations is effectively controlled by the system demand. Total daily demand curve of N7 pressure zone is plotted in Figure 6.38. It is observed that low demand hours are seen in 01:00 – 06:00 time interval. This time interval overlaps with determined optimum pump schedule switch off hours. Similarly, in peak demand hours pump is in switched on position according to pump schedule.

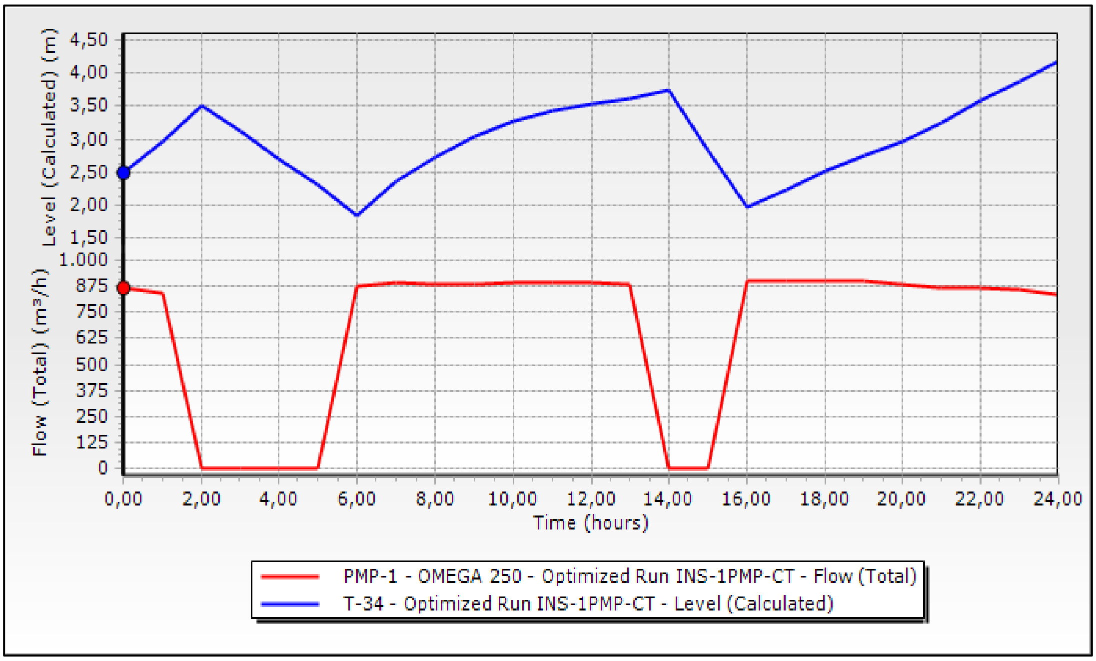


Figure 6.37. Pump Flow and Water Level in T34 Storage Tank versus Time - INS-1PMP-CT

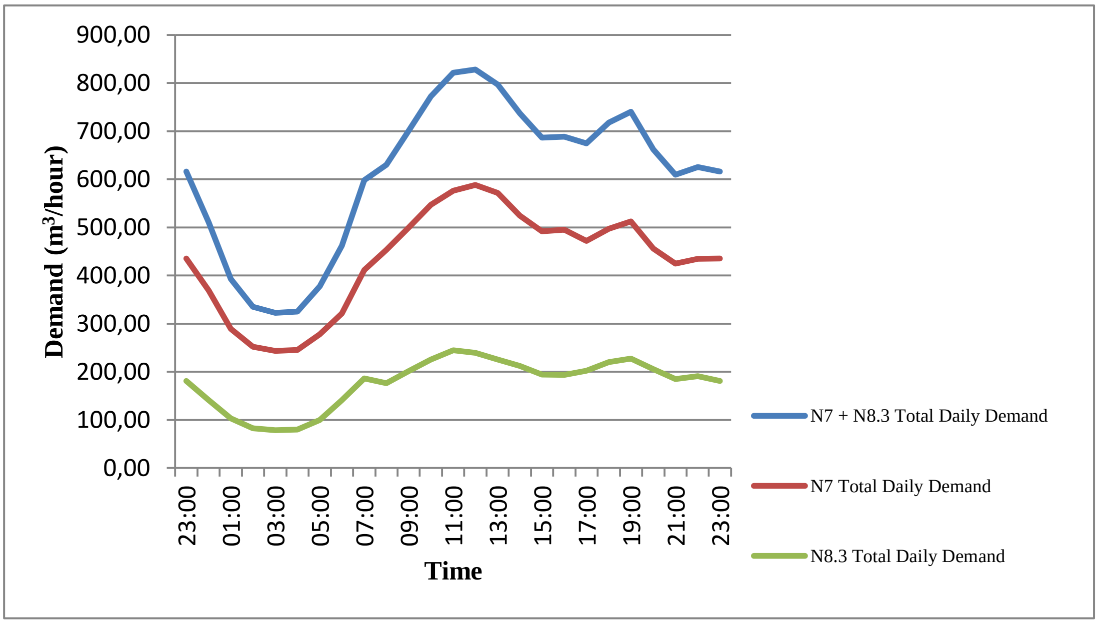


Figure 6.38. N7 and N8.3 Pressure Zone Daily Demand Curves

At the end of optimum pump scheduling analysis total energy cost of INS-1PMP-CT scenario was calculated as 643.971 TL. Energy costs of alternative best three solutions are tabulated in Table 6.28. It is observed that while satisfying system requirements any penalty did not occur; violations are zero.

Table 6.28. Energy Costs of Best Solutions in Scenario INS-1PMP-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	652.281	0	649.036
Solution 2	653.078	0	643.971
Solution 3	653.912	0	644.793

N7-Scenario # 2 - INS-2PMP-CT

In this scenario, one more pump is added into pump scheduling analysis. Two pumps in P12 pump station are permitted to operate. However it is observed that second pump is not operated according to determined best optimum pump schedule. Pump number two remains in switched off position during the day. This situation shows that using only one pump with constant tariff energy price is economical and sufficient to provide each requirement of the water supply system. Similarly as in scenario #1, pump is operated parallel to water demand of the system. 09:00 - 17:00 and 20:00 – 03:00 time intervals pump #1 in P12 pump station is running to supply water to the system. All hydraulic system requirements are satisfied and final water level in T34 storage tank is approximately 3 m which is above predefined final water level constraint. Pump flow versus time according to determined pump schedule and water level fluctuations are plotted in Figure 6.39.

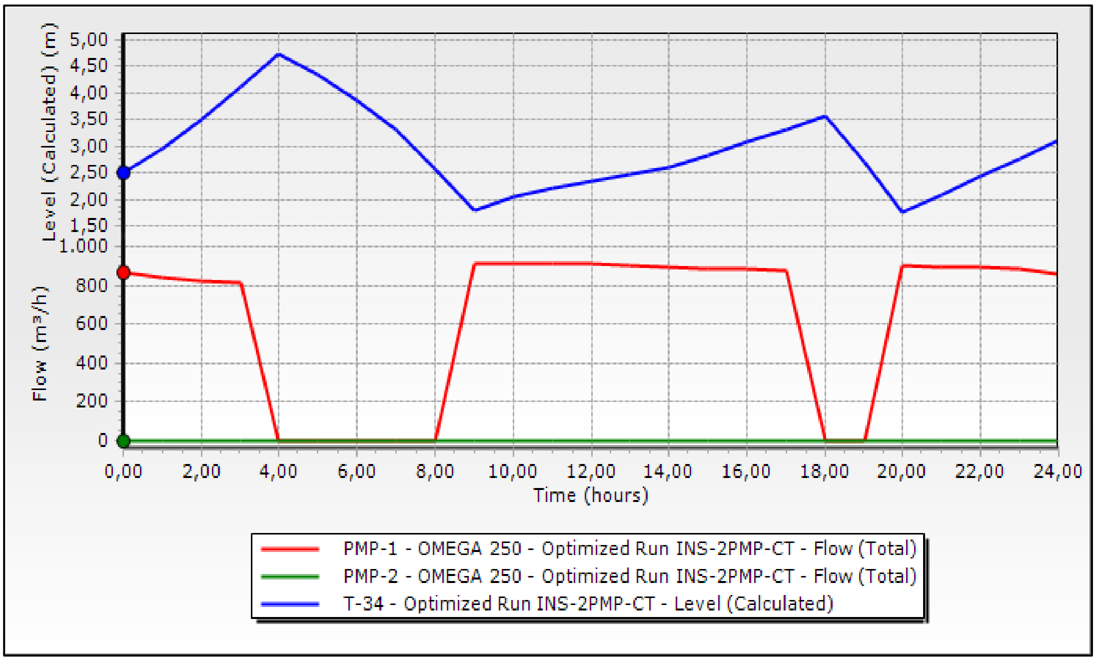


Figure 6.39. Pump Flow and Water Level in T34 Storage Tank versus Time - INS-2PMP-CT

Minimum energy cost was calculated as 643.457 by using determined best pump schedule of scenario #2 – INS-2PMP-CT. Energy costs of following best two solutions are given in Table 6.29. Constant tariff energy price was used in pump scheduling process. As mentioned before only one pump is operated according to optimal pump schedule. Thus, energy cost of scenario #1 and #2 is expected to be equal. Results shows that energy cost difference of scenario #1 and #2 is % 0.08 and energy costs of both scenarios can be accepted as equal.

Table 6.29. Energy Costs of Best Solutions in Scenario INS-2PMP-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	652.281	0	649.036
Solution 2	652.557	0	643.457
Solution 3	653.025	0	643.919

N7-Scenario # 3 - INS-3PMP-CT

All pumps (#1, #2 and #3) in P12 pump station are included in optimization process and optimal pump schedule of those pumps are determined. According to determined pump schedules, it is observed that three pumps were operated with different schedules. Moreover, pumps are not working at the same time. This means that same combined schedule can be applied by using only one pump. In Figure 6.40, it is noticed that pump working hours which can be understood from pump flows graph do not coincide. Running hours of pump #1 is 01:00 – 02:00, pump #2 is 06:00 – 13:00 / 20:00 – 23:00 and pumps #3 is 16:00 – 18:00. Although this total schedule can be provided by using only one pump, this schedule cannot be solution for this optimization study. Because while defining optimization constraints, each pump is restrained to make maximum 3 pump starts; pump can only make three start till the day. In determined pump schedule, totally four pump start is observed. Thus, to simulate same schedule with one pump, pump start constraint should be four or more.

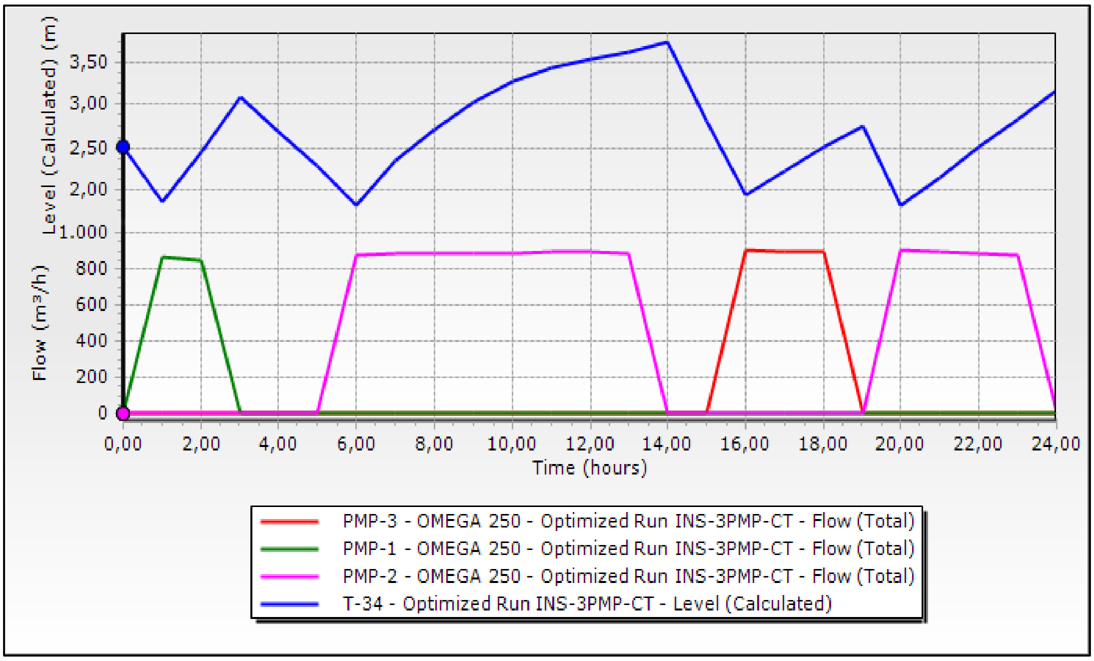


Figure 6.40. Pump Flow and Water Level in T34 Storage Tank versus Time - INS-3PMP-CT

Scenario #1, #2 and #3 are created with insulated water distribution network and constant tariff energy price is used in each scenario. Energy price does not vary by time thus it does not have any effect on pump schedule. In scenario #1 and #2 only one pump is operated according to best pump schedules. If pump start constraint is excluded from the optimization analysis, optimum pump schedule of scenario #3 can be performed by one pump. Therefore, in each scenario it is observed that only one pump is sufficient to supply N7 pressure zone system requirements. In addition, all pumps in P12 pump station are same and which pump is used does not matter while applying optimum pump schedule analysis for N7 pressure zone. Total energy cost of best pump schedule was calculated as 643.238 TL. Energy cost of second and third alternatives are given in Table 6.30. Calculated energy costs of scenario #1, #2 and #3 are approximately same and difference is lower than %0.08.

Table 6.30. Energy Costs of Best Solutions in Scenario INS-3PMP-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	668.165	0	642.466
Solution 2	668.968	0	643.238
Solution 3	668.990	0	643.259

6.4.2.2. Multi Tariff Insulated Systems:

N7-Scenario # 4 - INS-1PMP-MT

Scenario # 4 is created by modeling N7 pressure zone in insulated condition and only one pump is permitted to run. By using multi tariff energy prices pump schedule was determined. Optimum pump schedule analysis is performed while minimizing total energy cost of water supply system. Thus time dependent changes in energy price have significant effect on pump schedule and calculated energy cost according to this pump schedule. In Section 6.2.4 time periods and values of multi tariff energy prices are discussed. Multi tariff energy price is combination of three time depended different prices. Price periods are named as day, peak and night period. Day period energy price is approximately equal to constant energy price. Peak period energy price is the most expensive and night period energy price is cheapest energy price. Therefore, till the end of 24 hours simulation different energy prices are used. Main objective is minimizing total energy cost thus multi tariff are becoming more important while achieving most economical pump schedule for the water supply system.

In Figure 6.41 water levels in storage tank and pump flows are plotted for 24 hours model simulation. It is observed that after 04:00 time T34 storage tank is completely full filled; water level reaches maximum 5 meters limit. After this point no more water can be stored in T34 storage tank. Moreover, pump should be stopped due to storage shortage of the water supply system. Time period of lowest energy prices (night period) is between 22:00 and 06:00 hours. Thus, storing water when energy price is lowest and using stored water when needed can be more economical operation if the storage capacity is enough to supply system when the pumps are not working. At 00:00 time water level in T34 storage tank is predefined as 2.5 meters. Simulation starts by using cheapest energy price which will be ended at 06:00 hour. Daily demands of N7 pressure zone were examined and it is observed that demands are generally lower at this time interval. Thus, running pumps at these hours fill storage tank more rapidly. In determined optimum pumps schedule of INS-1PMP-MT scenario, pump #1 in P12 pump station is running in 22:00 – 06:00, 08:00 – 18:00 and 20:00 -21:00 time intervals. According to this pumps schedule pump was operated eight hours with night period energy price, nine hours with day period energy price and two hours peak period energy price which is most expensive. At the end of the extended period simulation final water level of T34 storage tank is calculated a 2.5 meter which is final minimum water level limit. Although at time 20:00 N7 pressure demand is not high as peak demand, pump # 1 is running at this hour. The reason of running pump at this hour is to provide required final water level in storage tank.

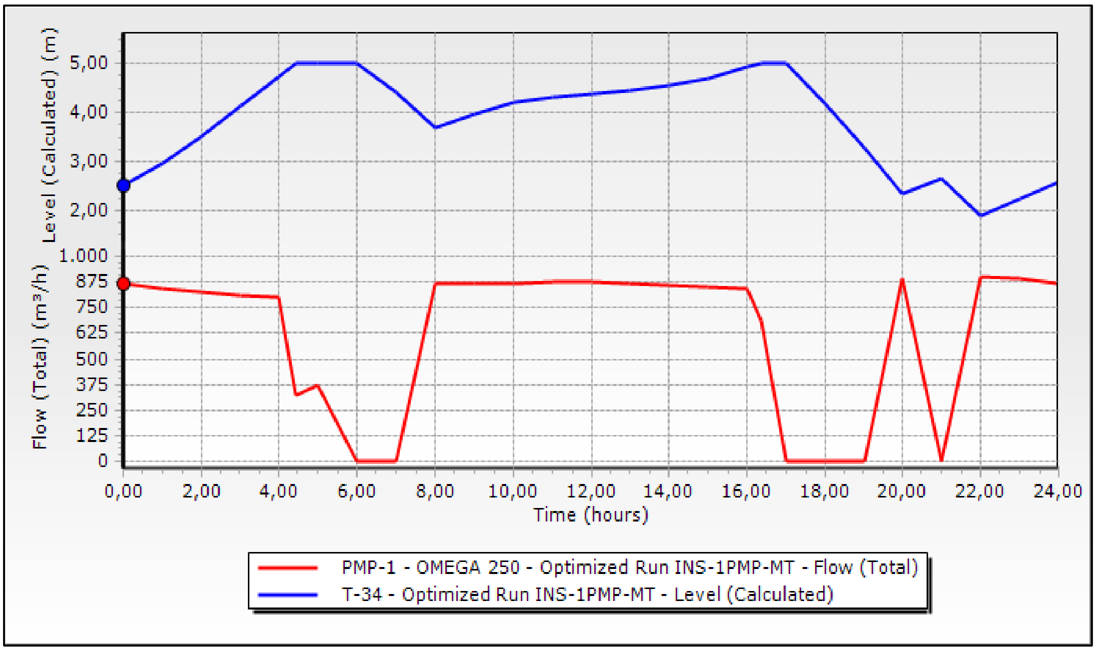


Figure 6.41. Pump Flow and Water Level in T34 Storage Tank versus Time - INS-1PMP-MT

Three best optimum pump schedules were determined and total energy cost of each pump schedule in scenario INS-1PMP-MT were calculated. Minimum energy cost of best pump schedule is 551.749 TL. Energy cost of following pump schedules are tabulated in Table 6.31. All hydraulic requirements are provided and all defined constraints are achieved thus in optimization process violations is not occurred.

Table 6.31. Energy Costs of Best Solutions in Scenario INS-1PMP-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	566.084	0	551.749
Solution 2	566.157	0	551.820
Solution 3	566.268	0	551.929

N7-Scenario # 5 - INS-2PMP-MT

Scenario #5 is created same as scenario #4 except instead of one pump, two pumps are operated and optimum pump schedule of these pumps are expected to be determined. Distribution network was modeled as a combination of insulated DMAs and multi tariff energy prices were used while operating pump #1 and pump #2 in P12 pump station. Pump flows and water level versus time graph is plotted in Figure 6.42. Pump schedule of best solution is tabulated in Table 6.32. It is observed that pumps are not working at the same time. Only one pump is active in each hour. In addition, total number of pump start is four. Pump #1 made 3 pump starts and pump #2 made one pump start. All pumps working for N7 pressure zone in P12 pump station are same. Therefore same pump schedule can be simulated by one pump if total pump start constraint is chosen as four. In this study, more than three pump starts is not permitted and more than three pump starts are punished with penalty in pump schedule optimization process. So that same schedule cannot be performed by single pump.

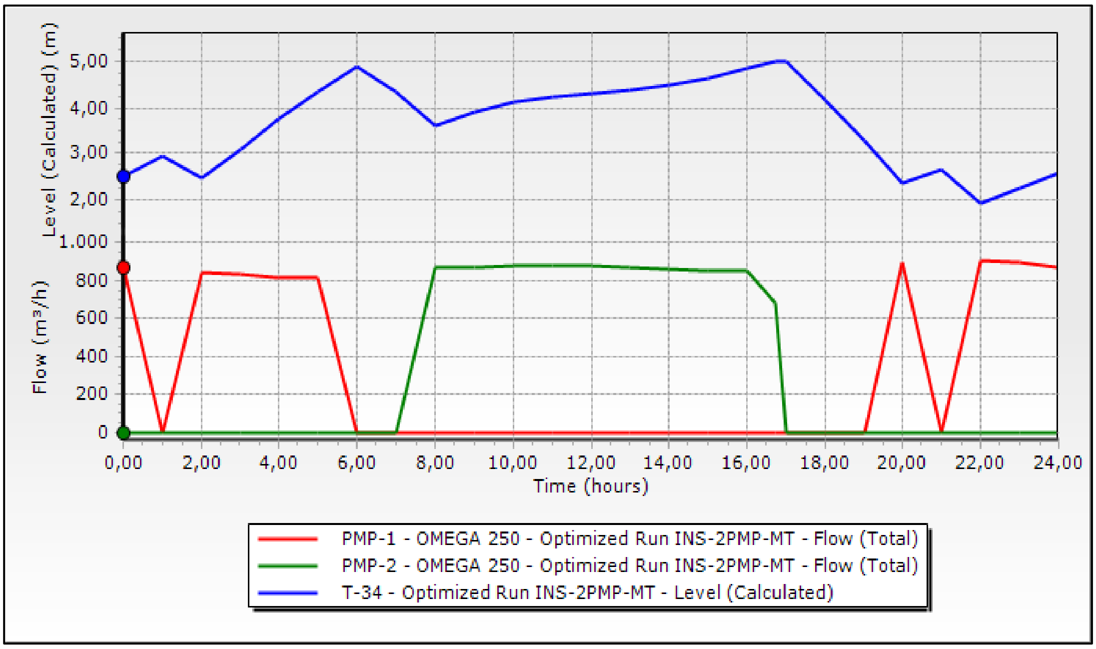


Figure 6.42. Pump Flow and Water Level in T34 Storage Tank versus Time - INS-2PMP-MT

Table 6.32. Optimum Pump Schedule of Scenario INS-2PMP-MT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓		✓	✓	✓	✓															✓		✓	✓
Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓							
✓ : Pump is switched on.																								

Water level in T34 storage tank fluctuates till the 24 hours simulation and final water level is calculated as approximately 2.5 m which is minimum water level limit at the end of extended period simulation. Pump schedules and used energy price at each running hour of pumps are represented in Table 6.33. Pump #1 was operated eight hours with night period energy price and one hour with peak period energy price. Second pump was operated nine hours only with day period energy prices. Totally both pumps were operated 15 hours till the day.

Table 6.33. Pump Schedule - Energy Prices

	🟨 00:00	🟨 01:00	🟨 02:00	🟨 03:00	🟨 04:00	🟨 05:00	🟩 06:00	🟩 07:00	🟩 08:00	🟩 09:00	🟩 10:00	🟩 11:00	🟩 12:00	🟩 13:00	🟩 14:00	🟩 15:00	🟩 16:00	🟥 17:00	🟥 18:00	🟥 19:00	🟥 20:00	🟥 21:00	🟨 22:00	🟨 23:00
Pump #1	✓		✓	✓	✓	✓															✓		✓	✓
Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓							
	✓ : Pump is switched on.																							
	🟨 :Night Period Energy Price								🟩 :Day Period Energy Price								🟥 :Peak Period Energy Price							

Total energy cost of N7 pressure zone is calculated by using determined optimum schedules of each pump and result is found as 538,451 TL. Energy cost of alternative optimum pump schedules are given in Table 6.34; costs are close enough to the each other. This means that minimum energy cost of N7 pressure zone can be achieved with alternative pump schedules. In Table 6.35 alternative pump schedules are tabulated. Although total energy cost of each alternative are equal, pumps schedule are different. Total running hours are same and 17 hours. Moreover, total pumping hours in night, day and peak pricing period are same.

Table 6.34. Energy Costs of Best Solutions in Scenario INS-2PMP-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	559.989	0	538.451
Solution 2	559.989	0	538.451
Solution 3	559.991	0	538.453

Table 6.35. Comparison of Pump Schedule Alternatives

Time		00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total Energy Cost (TL)
Solution 1	**Pump #1**	✓		✓	✓	✓	✓															✓		✓	✓	538.451
	Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓								
Solution 2	**Pump #1**	✓	✓		✓	✓	✓															✓		✓	✓	538.451
	Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓								
Solution 3	**Pump #1**	✓		✓	✓	✓	✓																	✓	✓	538.453
	Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓				✓				

✓ : Pump is switched on.

🟨 :Night Period Energy Price 🟩 :Day Period Energy Price 🟥 :Peak Period Energy Price

N7-Scenario # 6 - INS-3PMP-MT

Last scenario of multi tariff insulated system is operating three pumps in P12 pump station at the same time. Pump schedule of each pump is expected to be determined. Determination of pump schedules of three pumps in multi tariff is a difficult mission. Because increasing number of pumps to be optimized expands solution space and reduce solving success of genetic algorithm. Solution space of this scenario contains all solutions of Scenario # 4 - INS-1PMP-MT and Scenario # 5 - INS-2.PMP-MT. Thus optimizing pumps pump station independently can achieve a better solution if that is a reasonable thing to do hydraulically in the system being optimized. Pump scheduling process of Scenario # 6 - INS-3PMP-MT was performed in WaterCad Darwin Scheduler and results are represented in Table 6.36. It was observed that there is a significant difference between total energy costs of best three solutions. Although energy costs of solution number 1 and 2 are approximately equal, energy cost of solution number 3 is different than others. The difference is approximately % 3 which can be accepted as a good cost saving.

Table 6.36. Energy Costs of Best Solutions in Scenario INS-3PMP-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	568,447	0	554,052
Solution 2	568,733	0	554,331
Solution 3	568,782	0	538,670

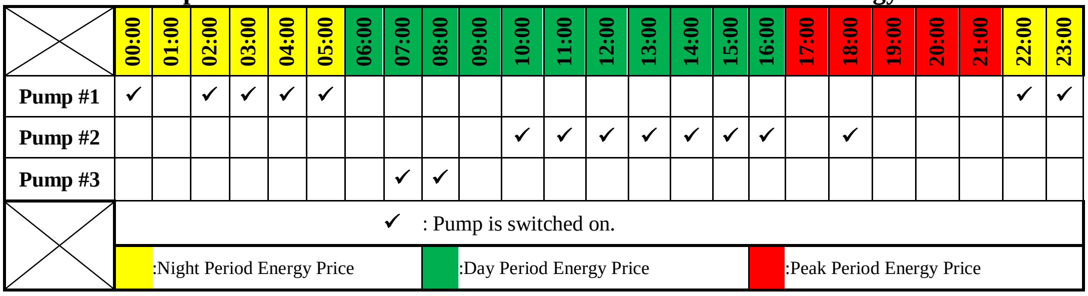
Pump schedule and related energy prices of solution number 3 which is most economical one are represented in Table 6.37. Similarly as in Scenario # 5 - INS-2.PMP-MT, it is seen that three pumps are not running at the same hour. If the maximum number of pumps stars limit is removed while optimizing pump schedule, combined pump schedules of three pumps can be simulated by single pump only. This situation shows that operating N7 pressure zone with single pump only is sufficient to provide hydraulic requirements of the water supply system if maximum pump start limit is ignored. Total running hours of single pump will be 17 hours.

Table 6.37. Optimal Pump Schedule of Scenario INS-3PMP-MT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓		✓	✓	✓	✓																✓	✓	✓
Pump #2												✓	✓	✓	✓	✓	✓		✓					
Pump #3								✓	✓															
	✓ : Pump is switched on.																							

Pump schedules of each pump and used energy prices are superposed in Table 6.38. According to best pump schedule pump #1 is operated with only night period energy prices, pump #2 is operated with both day and peak period energy prices and pump #3 is only operated with day period energy prices.

Table 6.38. Pump Schedule of N7 Scenario #6 INS-3PMP-MT and Used Energy Prices



	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓		✓	✓	✓	✓																	✓	✓
Pump #2											✓	✓	✓	✓	✓	✓	✓		✓					
Pump #3								✓	✓															
	✓ : Pump is switched on.																							
	🟨 :Night Period Energy Price								🟩 :Day Period Energy Price									🟥 :Peak Period Energy Price						

Initial water level of T34 storage tank is defined as 2.5 meters. Then extended period simulation of N7 pressure zone with most economical pump schedule was performed. At the end of extended period simulation final water level in T34 storage tank is calculated as 2.56 m which is higher than final minimum water level constraint 2.5 meter. During the extended period simulation water level in T34 storage fluctuated and final minimum water level limit has been exceeded (Figure

6.43). This shows that using determined optimum pump schedule 24 hours extended period can be repeated for the next days.

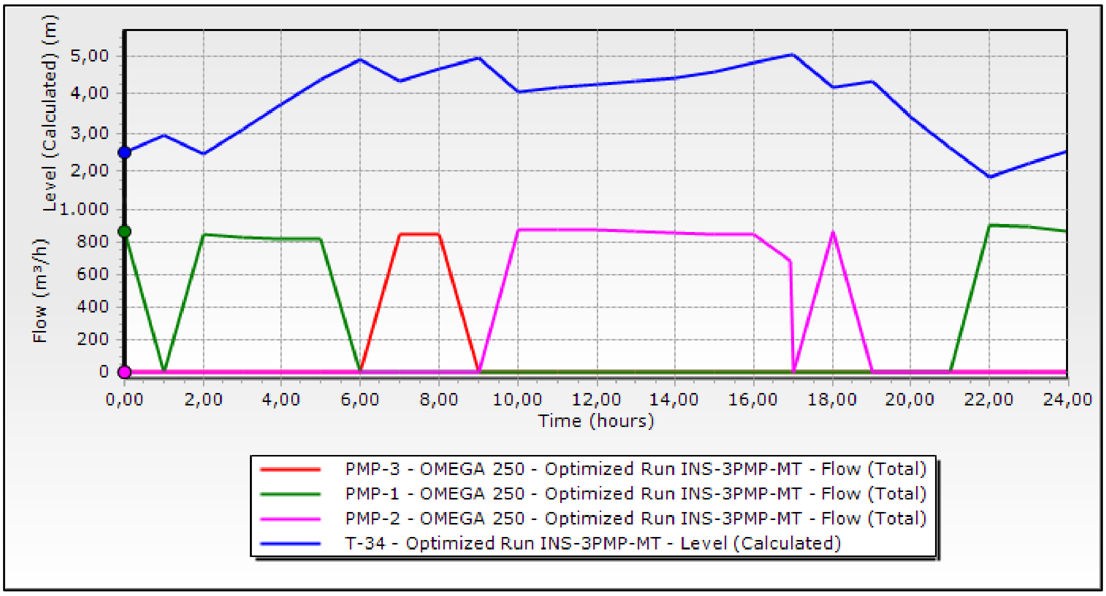


Figure 6.43. Pump Flow and Water Level in T34 Storage Tank versus Time - INS-3PMP-MT

6.4.2.3. Constant Tariff Uninsulated Systems:

In section 6.4.2.1, N7 pressures zone was divided in to DMAs which are insulated from each other by closing isolation valves and using constant tariff energy price all different pump combinations were simulated in insulated distribution network condition. According to created water distribution model optimum pumps schedules of each pump combination was determined. In the current section, all isolation valves that remain distribution network in insulated conditions will be opened and same pump combinations will be analyzed to reach optimum pump schedules under constant tariff energy price.

N7-Scenario # 7 - UNINS-1PMP-CT

In this scenario, N7 pressure zone was simulated as a whole network by permitting water flows between each DMA. Only one pump (pump #1, pump #2 or pump #3) in P12 pump station was allowed to run while providing water to the system. Optimization process was performed in Darwin Scheduler and best pump schedule is determined; optimum pump schedule is represented in Table 6.39. Only two pump start operation is observed in pump schedule. Pump #1 works for 17 hours a day to provide system requirements.

Table 6.39. Optimal Pump Schedule of Scenario UNINS-1PMP-CT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓	✓	✓	✓						✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓
✓ : Pump is switched on.																								

Pump remains in switched off position at two different time interval. First time interval starts with 04:00 and ends with 09:00. It is observed in Figure 6.44 that at 04:00 o'clock T34 storage tank is almost full. Due to volume constraints of storage tank, running pump is stopped. The second time interval is between 18:00 and 20:00. At 20:00 o'clock, water level of T34 storage tank is very close to minimum water level limit of T34 storage tank; 1.75 meters. Pump # 1 is started to run again and at the end of 24 hours final minimum water level is provided. As expected at time interval 09:00 – 15:00 which is roughly peak demand hours of N7 pressure zone, pump in P12 pump station is remained in switched on position.

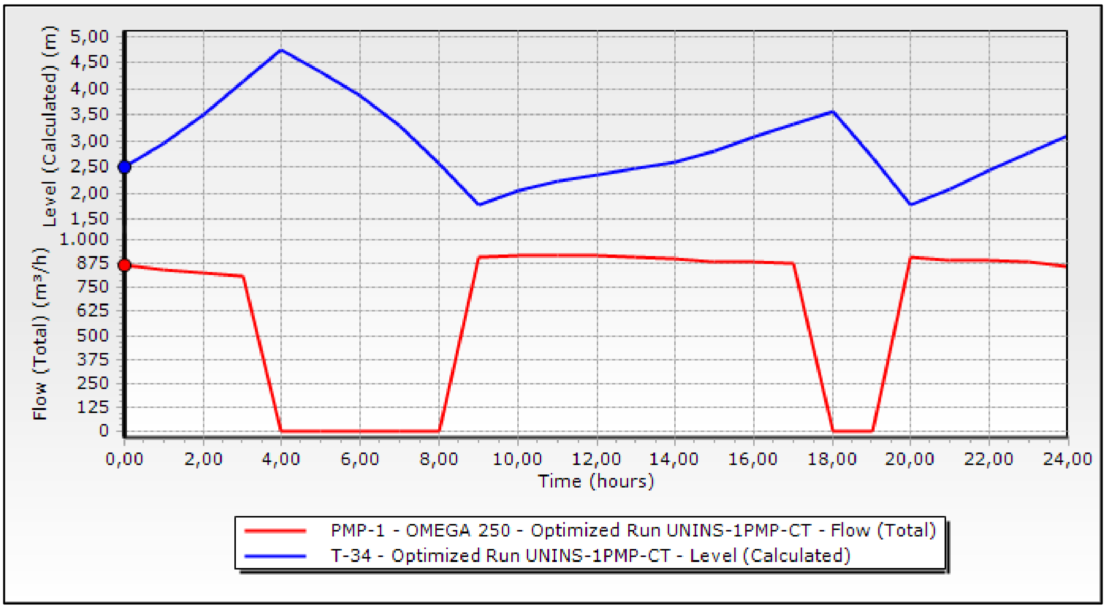


Figure 6.44. Pump Flow and Water Level in T34 Storage Tank versus Time - UNINS-1PMP-CT

At the end of optimization process, best three different alternative pump schedules were determined. Total energy cost of each pump schedule is calculated in

Table 6.40. It is indicated in Table 6.40 that in pump schedule solution 3, violation is occurred thus penalty is applied. Extend period simulation of solution 3 was performed again and it is observed that violation is occurred due to exceeding minimum water level limit of T34 storage tank. Total energy cost of best pump schedule is calculated as 643.457 TL. This value is too close to energy cost of N7-Scenario # 1 - INS-1PMP-CT; 643.971 TL. As expected operating water distribution network in uninsulated condition is more economical but the difference is not too much.

Table 6.40. Energy Costs of Best Solutions in Scenario UNINS-1PMP-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	652.557	0	643.457
Solution 2	653.025	0	643.919
Solution 3	653.031	0.749	649.036

N7-Scenario # 8 - UNINS-2PMP-CT

Scenario 8 is created by permitting two pumps in P12 pump station to work. Moreover, two pumps are operated by using constant energy prices and distribution network is modeled in uninsulated system condition. According to optimization process, optimum pump schedule is determined as tabulated in Table 6.41.

Table 6.41. Optimal Pump Schedule of Scenario UNINS-2PMP-CT

	00:00	**01:00**	**02:00**	**03:00**	**04:00**	**05:00**	**06:00**	**07:00**	**08:00**	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
Pump #1	✓	✓	✓	✓						✓	✓	✓	✓	✓	✓	✓					✓	✓	✓	✓
Pump #2																		✓	✓					
✓ : Pump is switched on.																								

It is observed that two pumps in P12 pump station are not working at the same time. Pump flows and water levels in T34 storage tank versus time graphs are plotted in Figure 6.45. Fluctuating water level in T34 storage tank indicates that two times, water level in T34 storage tank is approached to minimum water level limit 1.75 meters; at 09:00 and 20:00 o'clock. At these hours pump # 1 is started to fill the tank again to provide hydraulic system requirements. According to optimum pump schedule, total working hours of pumps is calculated as 17 which is same as in scenario # 7 - UNINS-1PMP-CT. Total energy cost of best pump schedule is calculated as 642.639 TL. Due to equality of total working hours of pumps in scenario # 7 - UNINS-1PMP-CT and # 8 - UNINS-2PMP-CT, total energy cost in each scenario is found as approximately equal as expected. Best three alternative pump schedules were determined and extended period simulation of N7 pressure zone was performed according to each determined pump schedule. Total energy cost of these alternative pump schedules are represented in Table 6.42. The results are too close to each other.

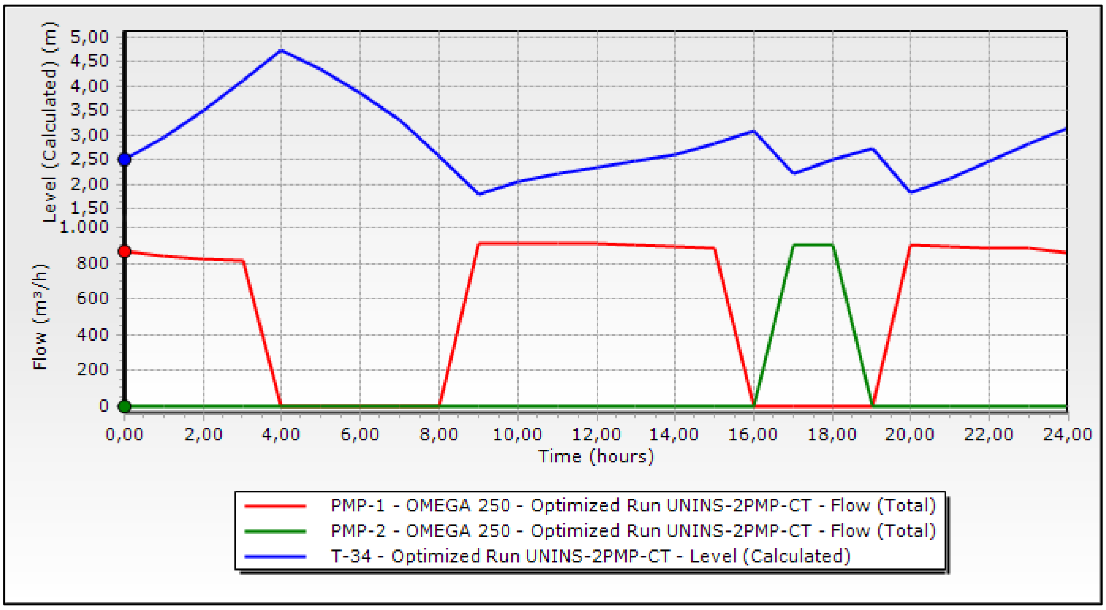


Figure 6.45. Pump Flows and Water Level in T34 Storage Tank versus Time - UNINS-2PMP-CT

Table 6.42. Energy Costs of Best Solutions in Scenario UNINS-2PMP-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	659.335	0	642.639
Solution 2	659.514	0	642.813
Solution 3	659.689	0	642.984

Pump Schedules of each alternative are tabulated in Table 6.43. Although pump schedules are different in each solution, total energy costs are approximately equal. In addition, total working hours of pumps in each solution are equal and 17 hours. Therefore by using constant energy tariff, total energy cost in each solution is calculated as approximately equal as expected.

Table 6.43. Comparison of Pump Schedule Alternatives

Time		00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total Energy Cost (TL)
Solution 1	Pump #1	✓	✓	✓	✓						✓	✓	✓	✓	✓	✓	✓					✓	✓	✓	✓	642.639
	Pump #2																		✓	✓						
Solution 2	Pump #1	✓	✓	✓	✓						✓	✓	✓	✓	✓	✓	✓						✓	✓	✓	642.813
	Pump #2																		✓	✓	✓					
Solution 3	Pump #1	✓	✓	✓	✓						✓	✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	642.984
	Pump #2																				✓					

✓ : Pump is switched on.

N7-Scenario # 9 - UNINS-3PMP-CT

Last scenario of N7 pressure zone with uninsulated distribution network condition and constant energy price is UNINS-3PMP-CT. In this scenario all pumps in P12 pump station (pump #1, pump #2 and pump #3) are included in to optimization process. Optimum pump schedule of each pump is expected to be determined. Solution space of this scenario contains all alternative solutions of other scenario UNINS-1PMP-CT and UNINS-PMP-CT. Optimization process was performed in Darwin Scheduler and best solution was determined. According to determined results pump schedules of each pump were established. Pump schedules of operated pumps are tabulated in Table 6.44. By chance as in previous scenario, it is observed that pumps are not running at the same time. Pump schedules of scenario UNINS-3PMP-CT shows that pump #1, pump #2 and pump #3 make two, one and one pump start respectively. Thus 3 pump start limit is not exceed in each pump.

Table 6.44. Optimal Pump Schedule of Scenario UNINS-3PMP-CT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓	✓								✓	✓	✓	✓	✓								✓	✓	✓
Pump #2							✓	✓																
Pump #3																✓	✓	✓	✓	✓				

✓ : Pump is switched on.

Determined optimum pump schedule was integrated to the N7 pressure zone and 24 hours extended period simulation was performed. Water flows in each pump outlet and water level in T34 storage tank versus time graphs are plotted in Figure 6.46 according to extended period simulation. It is noticed that water level in T34 storage tank fluctuates more than in other scenarios. The reason of this situation is due to number of pump starts. In this scenario 3 pumps are operated and total 4 pump starts are observed. Thus more frequent on-off operation of pumps causes water in T33 storage tank fluctuates more.

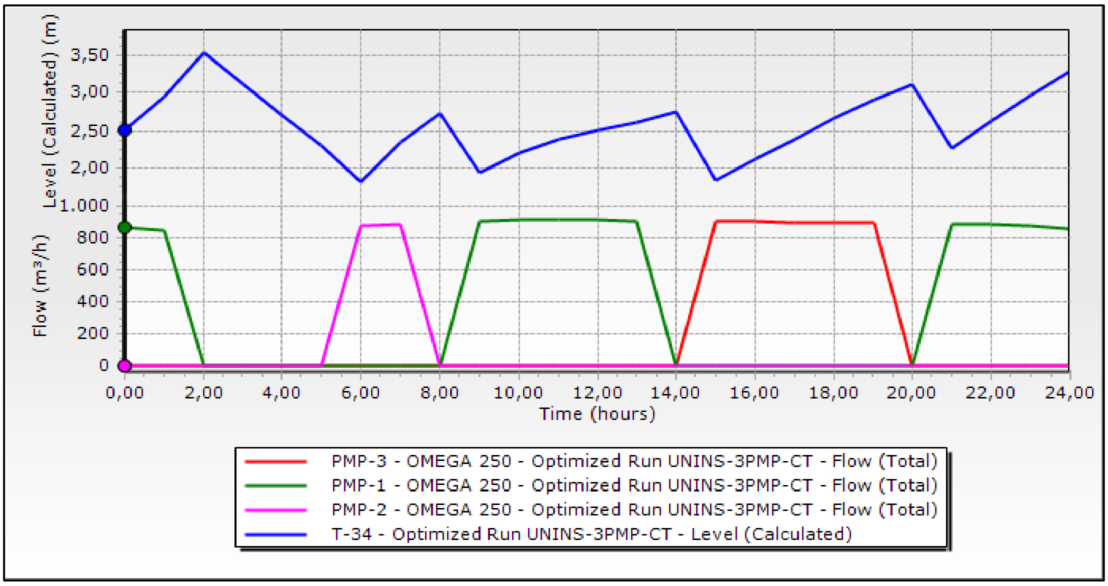


Figure 6.46. Pump Flows and Water Level in T34 Storage Tank versus Time - UNINS-3PMP-CT

At the end of optimization analysis, best three alternative pump schedules for scenario UNINS-3PMP-CT were determined. Pre-defined constraints were not exceeded in each solution thus penalty was not applied in optimization process. Total energy cost of best solution alternative number 1 was calculated as 640.048 TL. Energy costs of alternative pumps schedule solutions are tabulated in Table 6.45. In addition fitness values of best three solutions are included in this table.

Table 6.45. Energy Costs of Best Solutions in Scenario UNINS-3PMP-CT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	665.649	0	640.048
Solution 2	666.275	0	640.649
Solution 3	667.975	0	642.284

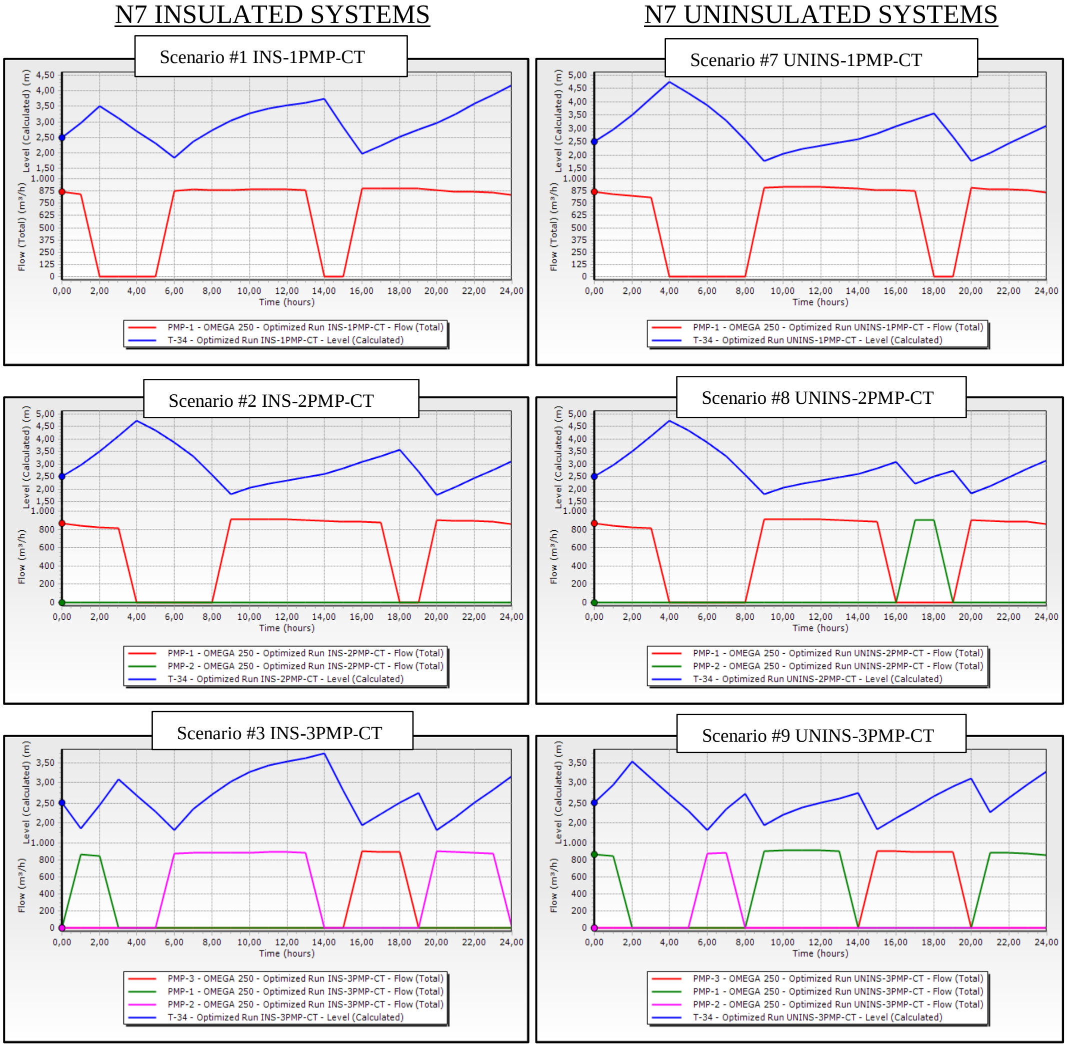


Figure 6.47. Pump Flow and Water Level in T34 Storage Tank versus Time in N7 Pressure Zone with Constant tariff

6.4.2.4. Multi Tariff Uninsulated Systems:

In section 6.4.2.2 all pump combinations created in N7 Pressure Zone were optimized with multi tariff energy prices under insulated distribution network condition. In current section N7 Pressure Zone's DMAs will be permitted to be interconnected to each other by opening isolation valves placed at connected points. Optimization study will be performed with uninsulated distribution network of N7 Pressure Zone. Again multi tariff energy prices will be used and three different pump combinations will be optimized by creating pump schedules. Only difference from section 6.4.2.1 is the isolation state of distribution network.

N7-Scenario # 10 - UNINS-1PMP-MT

N7 pressure zone is modeled same as N7-Scenario # 4 - INS-1PMP-MT except distribution network remained in uninsulated condition. Optimization study was performed and pumps schedule of pump #1 in P12 pump station is determined (Table 6.46). Due to similarity between Scenario # 4 - INS-1PMP-MT and Scenario # 10 - UNINS-1PMP-MT, optimum pump schedules were compared. It was observed that optimum pump schedules of both scenarios are nearly the same. Thus changing isolation condition of N7 Pressure Zone did not create more significant effect on pump schedule. The difference on pump schedules is represented in Table 6.47. In scenario INS-1PMP-MT pump was running one hour at time 20:00 however in scenario UNINS-1PMP-MT one hour running time interval of pumps shifts to time 19:00. In both hours energy prices are same thus change in total energy cost is not expected.

Table 6.46. Optimal Pump Schedule of Scenario UNINS-1PMP-MT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		✓	✓
	✓: Pump is switched on.																							

Table 6.47. Pump Schedule Comparison of Scenario UNINS-1PMP-MT and INS-1PMP-MT

Scenario Code	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
INS-1PMP-MT	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		✓	✓
UNINS-1PMP-MT	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓
	✓: Pump is switched on. ←																							

Total energy cost of scenario UNINS-1PMP-MT with determined optimum pump schedule was calculated as 551.820 TL. This value can be accepted same as 551.749 TL total energy cost of scenario INS-1PMP-MT. Energy costs of alternative pump schedules are tabulated in Table 6.48. In each alternative pump schedules, all hydraulic requirements were provided and violations were not occurred.

Table 6.48. Energy Costs of Best Solutions in Scenario UNINS-1PMP-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	566.156	0	551.820
Solution 2	566.335	0	551.993
Solution 3	568.116	0	553.729

N7-Scenario # 11 - UNINS-2PMP-MT

One more pump is added to N7 pressure zone model and optimization process is continued. At the end of Darwin Scheduler iterations optimum pumps schedules of pumps #1 and #2 were determined (Table 6.49). Optimum pump schedule of this scenario was compared with previously discussed pump schedule of scenario #5 INS-2PMP-MT having same system configuration except isolated distribution network condition. It is observed that pump schedules of two pumps are exactly same in both scenarios (Table 6.50).

Table 6.49. Optimal Pump Schedule of Scenario UNINS-2PMP-MT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓		✓	✓	✓	✓															✓		✓	✓
Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓							
	✓ : Pump is switched on.																							

Table 6.50. Pump Schedule Comparison of Scenario UNINS-2PMP-MT and INS-2PMP-MT

Scenario Code	**Time** **Pump #**	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
INS-2PMP-MT	**Pump #1**	✓		✓	✓	✓	✓															✓		✓	✓
	Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓							
UNINS-2PMP-MT	**Pump #1**	✓		✓	✓	✓	✓															✓		✓	✓
	Pump #2									✓	✓	✓	✓	✓	✓	✓	✓	✓							

As expected, total energy cost of two insulated and uninsulated scenarios with optimum pump schedules are calculated as completely equal. Total energy cost is 538.451 TL in both scenarios. Total energy costs of best three pump schedules are represented in Table 6.51. In each alternative pump schedules, all hydraulic requirements were provided and violations were not occurred.

Table 6.51. Energy Costs of Best Solutions in Scenario UNINS-2PMP-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	559.989	0	538.451
Solution 2	559.991	0	538.453
Solution 3	559.991	0	538.453

N7-Scenario # 12 - UNINS-3PMP-MT

Scenario # 12 UNINS-3PMP-MT is a model of N7 Pressure zone distribution network in uninsulated condition. All pumps in P12 pump station are included pump scheduling process and multi tariff is used. Similarly as in previous scenario, same system configuration of this scenario with isolated distribution condition was discussed in previous section 6.4.2.2. Only gate position of isolation valves were changed from closed position to open position. Thus interconnected distribution network between DMAs are provided and water flow is permitted between connected DMAs.

For minimum energy cost created model was optimized with WaterCad Darwin Scheduler and best pump schedule of each pump in P12 pump station was determined. Like in previous scenarios, optimized pumps are not running at the same time according to determined optimum pump schedules (Table 6.52).

Table 6.52. Optimal Pump Schedule of Scenario UNINS-3PMP-MT

	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Pump #1	✓	✓	✓		✓	✓					✓	✓	✓	✓	✓								✓	✓
Pump #2																✓	✓		✓					
Pump #3									✓	✓														
	✓ : Pump is switched on.																							

Optimum pump schedule of this scenario was compared with Scenario # 6 INS-3PMP-MT and at first sight pump schedules were seen as different. As mentioned earlier, all pumps in P12 pump station are same. Therefore, by ignoring maximum pump start constraints, optimum pump schedules of Scenario # 6 INS-3PMP-MT and Scenario # 12 UNINS-3PMP-MT are remodeled as single pump and same pump schedule can be simulated. Modified single pump schedules were compared and it is seen that modified pump schedules are more similar to each other (Table 6.53). Total running hours of pumps with different energy prices are equal. In both schedules single pump is running seven hours with night period, nine hours with day period and one hour with peak period energy prices.

Table 6.53. Modified Single Pump Schedule of Scenarios UNINS-3PMP-MT and INS-3PMP-MT

Time Isolation	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Uninsulated	✓	✓	✓		✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				✓	✓
Insulated	✓		✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓		✓					✓	✓
	✓ : Pump is switched on.																							

Total energy cost is calculated as 538.709 TL according to determined optimum pumps schedules of scenario UNINS-3PMP-MT. Energy costs of alternative pump schedules are tabulated in Table 6.54. In each alternative pump schedules, all hydraulic requirements were provided and violations were not occurred.

Table 6.54. Energy Costs of Best Solutions in Scenario UNINS-3PMP-MT

Solution ID	Fitness	Violation (Total)	Energy Cost (Net Total) (TL)
Solution 1	576.502	0	554.329
Solution 2	578.296	0	538.709
Solution 3	578.350	0	538.759

Water level of T34 storage tank and pump flows versus time graphs of all scenarios with multi tariff optimized pump schedules are plotted in Figure 6.48. In insulated and uninsulated systems, extended period simulation of optimum pump schedules shows similar behaviors in N7 pressure zone.

N7 INSULATED SYSTEMS N7 UNINSULATED SYSTEMS

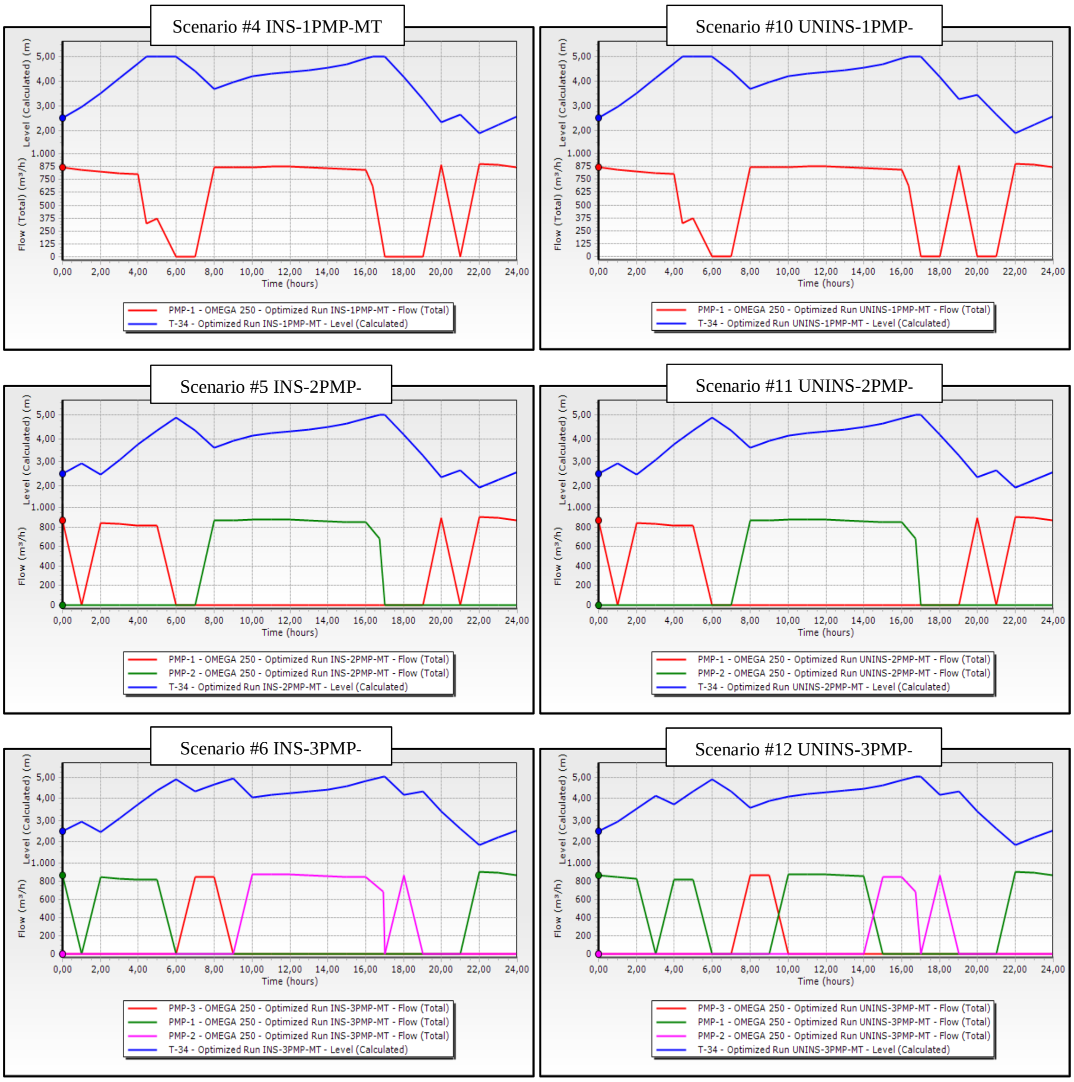


Figure 6.48. Pump Flow and Water Level in T34 Storage Tank versus Time in N7 Pressure Zone with Multi tariff

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

In Chapter 6, optimum pump scheduling analysis of two pressure zones in different scenarios were studied. It has been observed in each scenario that determined pump schedules satisfy hydraulic system requirements at every time. Hydraulic system requirements are the constraints that define minimum service quality provided at water supply system. Pump schedules are prepared considering hydraulic system requirements thus pressures at any nodes, water level in storage tank, flow in pipes will always be in the range of acceptable interval. Therefore, failure events such as; pressure reductions, water shortage, fully depletion of storage tank, extreme flows in pipes and etc. do not occur in the system. This ability of pumping scheduling process helps system operator to operate pumps in water supply system with efficient operation policy and to carry on a certain service quality. In addition to this, minimization of total energy consumed by pumps while satisfying hydraulic system requirement is the second ability of pump scheduling process. The determination of pump schedule minimizing energy cost is the first objective. Thus, total energy consumptions of pumps have been calculated in each scenario and the results have been compared.

According to results, best pump combination in N8.3 pressure Zone was determined as running Small (Sumas SP 125) and Large (SMS SP 150-400) pumps in parallel for both insulated and uninsulated cases by using multi tariff energy price. However, running model with constant tariff energy prices, optimum pump combination was determined as using only large pump in P23 pump stations. Using multi tariff energy price instead of constant tariff energy price causes approximately 30% cost savings (Table 7.1). In N7 pressure zone best pump combination was determined as running two Omega 250 pumps in parallel for both insulated and uninsulated system condition. Total energy consumptions of pump combinations created by using two and three pumps are almost equal in both insulated and uninsulated systems while using multi tariff energy prices. However, energy consumption of system running with only one pump is higher than other two pump combinations while using multi tariff energy prices. At low energy price interval, pump starts to fill the tank as much as possible. When the storage tank is fully filled, overall internal pressure of the system reaches to its maximum. Therefore, system curve is modified and operation point of pump is changed. Moreover, new efficiency point comes into consideration. When the efficiency of pump is decreased due to these reasons, pump needs more energy to provide new operation flow for the system. If the energy consumption of multi tariff and constant tariff based scenarios running according to optimum pump schedules are compared, it is observed that using multi tariff energy price instead of constant energy price in pump station of N7 pressure zone is approximately % 15 more economical (Table 7.2). Thus, operating water distribution network under multi tariff energy prices with respect to optimized pump schedule provides significant amount of cost to be saved. Both demand and energy prices are time dependent. Controlling system and deciding optimum operation program under fluctuating demands and multi tariff is difficult process to maintain. If water utility uses multi tariff energy prices, pump scheduling analysis must be performed, to find optimum operation policy of pumps by considering these time dependent variables. Because, operating pump station using multi tariff energy prices can be effectively kept running by using optimal pump scheduling. Till the end of the life time, pumps should be operated by pump schedules. Thus determination of on-off operation policy of pumps in a pump station can be performed by developing daily pump schedules.

In the case study, pressure zones were physically divided into DMA’s and pump scheduling study was performed with insulated system condition. Moreover, same pressure zones were modeled as an entire system and system was studied in uninsulated system condition. Result of Insulated or uninsulated cases shows that the cost difference is approximately % 1.3 in N8.3 pressure zone and % 0.2 in N7 pressure zone. % 0.2 cost saving is not small quantity for such water distribution network. Running system in uninsulated condition is more economical than in insulated condition. Thus, remaining system in uninsulated state and isolating the DMA’s by closing isolation valves whenever the DMA flow measurement is needed will be more economical operation for the system.

Table 7.1. Cost Comparisons of Scenarios Performed in N8.3 Pressure Zone

Scenario Number	Scenario Code	Best Solution Number	Energy Cost of Best Solution (TL)
1	INS-1PMP(SM)-CT	20	195,254
2	INS-1PMP(LG)-CT	10	171,610
3	INS-2PMP(SM+SM)-CT	18	186,718
4	INS-2PMP(SM+LG)-CT	11	172,364
5	INS-3PMP(SM+SM+LG)-CT	16	183,411
6	INS-1PMP(SM)-MT	14	176,663
7	INS-1PMP(LG)-MT	5	126,353
8	INS-2PMP(SM+SM)-MT	8	140,724
9	INS-2PMP(SM+LG)-MT	2	124,667
10	INS-3PMP(SM+SM+LG)-MT	3	124,688
11	UNINS-1PMP(SM)-CT	19	195,176
12	UNINS-1PMP(LG)-CT	9	171,321
13	UNINS-2PMP(SM+SM)-CT	17	184,955
14	UNINS-2PMP(SM+LG)-CT	13	173,414
15	UNINS-3PMP(SM+SM+LG)-CT	12	172,461
16	UNINS-1PMP(SM)-MT	15	178,835
17	UNINS-1PMP(LG)-MT	4	126,108
18	UNINS-2PMP(SM+SM)-MT	7	140,486
19	UNINS-2PMP(SM+LG)-MT	1	122,334
20	UNINS-3PMP(SM+SM+LG)-MT	6	126,693

Table 7.2. Cost Comparisons of Scenarios Performed in N7 Pressure Zone

Scenario Number	Scenario Code	Best Solution Number	Energy Cost of Best Solution (TL)
1	**INS-1PMP-CT**	**12**	643.971
2	**INS-2PMP-CT**	**10**	643.457
3	**INS-3PMP-CT**	**8**	642.466
4	**INS-1PMP-MT**	**5**	551.749
5	**INS-2PMP-MT**	**1**	538.451
6	**INS-3PMP-MT**	**3**	538.670
7	**UNINS-1PMP-CT**	**11**	643.457
8	**UNINS-2PMP-CT**	**9**	642.639
9	**UNINS-3PMP-CT**	**7**	640.048
10	**UNINS-1PMP-MT**	**6**	551.820
11	**UNINS-2PMP-MT**	**2**	538.451
12	**UNINS-3PMP-MT**	**4**	538.709

Today, in order to fulfill the task of providing adequate quantity and quality of drinking water to Ankara, ASKI monitors and controls facilities of water supply system with the help of supervisory control and data acquisition (SCADA) unit. Many different kinds of system components such as pumps, valves, tanks can be controlled remotely by operator from SCADA unit of ASKI. Totally 108 pump stations containing 233 pumps, 62 storage tanks and 93 measurement points are connected to SCADA System. Moreover, various types of data such as water level in storage tanks, pump discharges, pressures at some important nodes, (pressures at pump inlet, pump outlet or critical nodes at high or low elevations) and etc. are gathered from the system, recorded and evaluated by the operators. These recorded data can be used any time for various analysis and studies.

Related data for N7 and N8.3 pressure zones were obtained from SCADA unit to simulate current water supply system. Water level in storage tanks, pump discharges, pressures at pump inlet-outlet and pump status (switched on or off) were taken from SCADA archives with three minutes time intervals. In section 6.2.2, it is mentioned that daily demand curves of each DMAs in N7 and N8.3 pressure zones were plotted according to measurement made by portable flow meters in September 2011. Therefore, SCADA data recorded in September 2011 were used to make efficient and consistent comparison between energy costs of current pressure zones and energy costs obtained by optimum pump schedules determined in this study. Taken data from SCADA unit were revised and their reliabilities were checked. By using portable pressure gauges and flow meters, pressure and flow values of pumps stations were measured in field and gathered data were compared with data read by SCADA system. Moreover, water levels read by SCADA systems were also checked in the field for both T34 and T53 storage tanks. Pressures and flows data read from SCADA were found as close enough to data gathered by field measurement. However, it is observed that storage tank water level data are erroneous and not reliable enough.

In both N7 and N8.3 pressure zones, storage tanks are two-celled type storage tanks. Two cells of storage tank are connected in parallel. For that reason, water levels in both cells are expected to be equal. In T34 storage tank which provides service for N7 pressure zone, water level in cells are not equal and they fluctuate randomly according to SCADA data. Moreover, there is a significant difference between water level in cells and this difference is not constant. Table 7.3 illustrates random change of water level in cells of T34 storage tank.

Table 7.3. Water levels in T34 Storage Tank Cells

DATE-TIME	CELL 1 (m)		CELL 2 (m)		Difference (m)
20.09.2011 22:30	lev1	1,70	lev2	2,29	0,59
20.09.2011 22:33	lev1	1,72	lev2	2,28	0,57
20.09.2011 22:36	lev1	0,86	lev2	1,13	0,27
20.09.2011 22:39	lev1	0,00	lev2	0,00	0,00
20.09.2011 22:42	lev1	0,00	lev2	0,00	0,00
20.09.2011 22:45	lev1	0,00	lev2	0,00	0,00
20.09.2011 22:48	lev1	0,00	lev2	1,24	1,24
20.09.2011 22:51	lev1	0,00	lev2	2,28	2,28
20.09.2011 22:54	lev1	0,00	lev2	2,28	2,28
20.09.2011 22:57	lev1	0,68	lev2	2,28	1,60
20.09.2011 23:00	lev1	1,74	lev2	2,28	0,54

Erroneous water level data of T34 storage tank were analyzed and values were modified and corrected as much as possible. However, a balanced system simulation could not be reached by using modified data. For that reason comparison study of N7 pressure zone was not performed. In T53 storage tank which provides service for N8.3 pressure zone, water level difference between cells are approximately 0.03 meters: this difference can be acceptable value for reliable system simulation.

5 different days of September month in 2011 were selected randomly and 24 hours extended period simulation of N8.3 pressure zone was performed according to ASKI operation policy of the related days. Multi tariff energy prices have been used by ASKI in pump stations for a while. Therefore, multi tariff energy prices were integrated in to simulation model while calculating energy costs. N8.3 pressure zone was simulated one by one that reflects same operation at selected days. Pump energy costs of N8.3 pressure zone in each selected days were calculated. In addition, at the end of each 24 hours simulation, initial and final water levels in T53 storage tank were taken into consideration and storage costs due to filled or emptied tank were calculated. Pump, storage and net energy usage cost of N8.3 pressure zone according to 5 different days of current system simulation and best pump schedule determined by study are tabulated in Table 7.4. Total daily demand of N8.3 pressure zone was calculated as 4238 m^3 with respect to DMA's flow measurement. However, in selected days total daily demands varies. Therefore, while comparing energy costs and determining cost savings, energy cost of N8.3 pressure zone according to best pump schedule was proportionally increased with respected to different daily demands. Minimum % 14.65 daily cost saving has been observed according to best pumps schedule determined by the study. Cost savings for different days are represented in Table 7.4.

Table 7.4. Energy Cost Comparison of Current System and Optimized System

Simulation Date	Tank Levels (m)		Tariff	Pump Cost (TL)	Storage Cost (TL)	Usage Cost (TL)	Used Pumps	Total Daily Demand (m^3)	Demand Difference %	Cost Saving %
	Initial	Final								
16.09.2011	1.21	1.86	Multi	197.435	-19.020	178.415	1-2-3	4910	+ 13.69%	19.05%
20.09.2011	2.93	2.19	Multi	146.394	22.087	168.481	1-2	4505	+ 5.93%	21.34%
22.09.2011	1.80	3.02	Multi	220.074	-39.316	180.758	1-2	4657	+ 9.00%	24.21%
24.09.2011	2.21	2.16	Multi	184.780	1.439	186.219	1-2	5200	+ 18.50%	17.86%
28.09.2011	3.20	2.41	Multi	133.387	21.907	155.294	1-2	4506	+ 5.95%	14.65%
Best Pump Schedule	2.50	2.58	Multi	126.496	-1.829	124.667	1-3	4238	0.00%	0.00%

ASKI controls pumps in pump stations with the help of SCADA system. Some of the pumps are working continuously 24 hours a day. Thus, daily pump schedule is not necessary for these pumps. However, if the storage capacity is low or demand fluctuations are high then pumps may not be used continuously. For that reason, pumps are operated by switching on and off from time to time. This task is carried out by the ASKI SCADA unit operators. Pumps are operated 24 hours seven day by three operators manually. There aren't any exact pump schedules for pumps in pump stations. Then, a question is arised: How do the operators decide when the pumps will be switched on or off? To overcome this situation, ASKI defined minimum and maximum storage levels in SCADA system. When the limit are exceed, the system is alarming and operator decides to switch on or off the related pump. Moreover, to minimize energy cost, operators strive to run pumps in low energy price time interval (22:00-06:00) and avoid to run pumps in high energy price time interval (17:00-22:00). It is a difficult mission for the operators to provide all of these criteria at the same time for a large number of pumps. In addition, energy cost minimization effort of operator sometimes causes water shortage in the system. Because, operator tries to start pumps after 22:00 o'clock and storage tanks can be fully emptied before 22:00 o'clock due to unpredictable demand. Therefore, consumers cannot get water until the system is fully filled with required amount of water again. Moreover, serious pressure reductions may be occurred. All these faults decrease water supply system quality which is one of the most important tasks of water utility.

In case study section, it is observed that using large pump SMS 493 is more economical for N8.3 pressure zone. However, used pumps column in Table 7.4 indicates that operators prefer to use large pump more rarely. At that point, pump scheduling process can provide more efficient, consistent and economical operation policy. Moreover, hydraulic system requirements are achieved every time and the quality of water supply system is kept at a certain level. To determine efficient pump schedule, water utility should monitor demands sensitively and estimate more robust demand prediction.

Finally, it was found that alternatives and scenarios have strong effect on pump scheduling optimization process time and efficiency. Optimizing every component at the same time increases the solution space and causes difficulty to reach optimal solution effectively. Thus, while performing pump scheduling optimization study, flowing setting up process should be considered (Bentley WaterCAD V8i User's Guide, 2009).

- Keeping the number of pumps being optimized at the same time as minimum as possible.
- Optimizing different pump stations independently if that is an acceptable process to perform hydraulically in the water supply system being analyzed.
- Keeping hydraulic time step of extended period simulation larger; if coarser times step are selected such as 2 hours or more, size of the solution space will be significantly reduced and initial optimization process will be completed in a shorter time.
- Keeping duration of extended period simulation shorter; generally, 24 hours duration for EPS is sufficient for optimization analysis of pumps in water supply system. Because, 24 hours simulation can provide repeatable solution for optimized pumps in water supply systems for the next days.

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