WATER DISTRIBUTION NETWORK DESIGN BY PARTIAL ENUMERATION

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ABSTRACT

WATER DISTRIBUTION NETWORK DESIGN BY PARTIAL ENUMERATION

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Water distribution networks are being designed by traditional methods based on rules-of-thumb and personal experience of the designer. However, since there is no unique solution to any network design, namely there are various combinations of pipes, pumps, tanks all of which satisfy the same pressure and velocity restrictions, it is most probable that the design performed by traditional techniques is not the optimum one.

This study deals how an optimization technique can be a useful tool for a designer during the design to find a solution. The method used within the study is the partial enumeration technique developed by Gessler. The technique is applied by a commercially available software, i.e. WADISO SA. The study is focused on discrepancies between a network designed by traditional techniques and the same network designed by partial enumeration method. Attention is given to steps of enumeration, which are basically grouping of pipes, candidate pipe size and price function assignments, to demonstrate that the designers can control all the phases of optimization process. In this respect, special attention is given to price functions to show the effect of them on the result. The study also revealed that the cost of fitting materials cannot be included in the price function although it may have significant effect in a system composed of closely located junctions.

The results obtained from this study are useful to show that although optimization methods do not provide a definite solution; partial enumeration method can assist designers to select the optimum system combination.

Keywords: Water Distribution Networks, Optimization, Partial Enumeration Method, WADISO, Price Function.

ÖZ

KISMİ SAYIM İLE SU DAĞITIM ŞEBEKELERİ TASARIMI

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Su dağıtım şebekeleri belli ilkeler ve tasarımcının kişisel deneyimine dayanan geleneksel metotlarla tasarlanmaktadır. Ancak, su dağıtım şebekesi tasarımında tek bir çözüm olmamasından dolayı, aynı basınç ve hız limitlerini sağlayan bir çok boru, pompa, depo ve benzeri kombinasyon varlığından dolayı, geleneksel yöntemlerle yapılan tasarım büyük bir ihtimalle optimum sonuç olmayacaktır.

Bu çalışma, bir optimizasyon tekniğinin, sonuca ulaşmak isteyen tasarımcı için nasıl kullanışlı bir alet olduğunu irdelemiştir. Çalışmada kullanılan metot, Gessler tarafından geliştirilmiş kısmi sayım tekniğidir. Bu teknik, ticari olarak mevcut bir bilgisayar programı, WADISO SA, ile uygulanmıştır. Çalışma, geleneksel tekniklerle tasarlanmış bir sistem tasarımı ile aynı sistemin kısmi sayım metodu ile yapılan tasarımı arasındaki farklar üzerine eğilmiştir. Özellikle kısmi sayım metodunun temel olarak boru gruplandırma, aday boru çapları ve fiyat fonksiyonu olan kademelerine eğilinerek tasarımcısının optimizasyon sürecinin her aşamasını kontrol edebileceği gösterilmiştir. Bu bağlamda, fiyat fonksiyonu ile özel olarak ilgilenerek sonuç üzerindeki etkileri gösterilmiştir. Çalışma sonucunda, fiyat fonksiyonuna dahil edilemeyen boru bağlantı elemanlarının yoğun bağlantılara sahip bir sistemde toplam fiyat üzerinde önemli bir etkiye sahip olabilecekleri de elde edilmiştir.

Bu çalışmadan elde edilen sonuçlar, optimizasyon tekniklerinin kesin sonuç sağlamamalarına rağmen, kısmi sayım metodunun optimum sistem kombinasyonunu belirlemede tasarımcı için etkili bir yardımcı olduğunu göstermektedir.

Anahtar Kelimeler: Su Dağıtım Şebekeleri, Optimizasyon, Kısmi Sayım Metodu, WADISO, Fiyat Fonksiyonu.

To My Parents

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p	: pipes (links)
n	: nodes
r	: reservoirs
ΔQ	: flow rate correction
c_i	: characteristic pipe coefficient for pipe i
Q_i	: discharge in pipe i.
L	: length of pipe i.
D	: diameter of pipe i
Q_{i0}	: estimated flow rate in pipe i
Q_i	: the updated flow rate in pipe i
q	: difference between updated and estimated flow rate.
Q_{di}	: the amount of water withdrawn at node ,
A	: a very large number, for instance 10^5
H_{ri}	: required head at node i
ρ	: mass density of liquid
g	: gravitational acceleration
Q	: pumping flow rate
H	: Pump head
μ	: Pump efficiency
F_i	: Population at year i
k	: a coefficient

CHAPTER 1

INTRODUCTION

A water distribution network is a collection of elements such as pipes, valves, pumps, reservoir, tanks (buried, elevated, etc.) whose aim is to provide adequate amount of potable water with sufficient pressure at nodes where consumer demands (residential, industrial, commercial etc.) are extracted.

A water distribution system should be designed in such a way that it should be able to meet consumer demands at all times at a certain level, even during very extreme events, throughout its lifetime. There is no unique design for any water distribution system; even two completely different designs may provide the same required demands under the same pressure constraints but may vary dramatically in cost. New York City water supply tunnels may serve as an example to illustrate how essential optimization may be (Gessler, 1985). The work of Lai and Schaak (1969) led to a system with total cost 73,3 million dollars, where the study of Quindry, Brill and Liebman (1981) reduced this figure (using the same demands and minimum pressure requirements) to 63,6 million dollars. However, Gessler (1982) designed another technically feasible solution with total cost 41,2 million dollars.

According to Environmental Protection Agency – USA, total infrastructure investment need of United States for the next following twenty years in order to supply safe water to consumers is about 150,9 billion US Dollars, of which 83,2 billion US Dollars is required for transmission and distribution investment (raw water transmission, clean water transmission, distribution mains, service lines, flushing hydrants, valves, water meters etc.) (EPA, 2001).Similarly, for the capital city of Turkey, Ankara Municipality has reserved 55,000,000.-YTL (appr. 42,000,000.-$) for construction and maintenance of total of 641,181 meters of main supply lines and water distribution lines for Year 2006. These figures clearly demonstrates that water distribution system design should be handled very carefully since huge amount of money has been invested until now and also going to be invested in the future.

Despite these facts, the designs performed by professionals for real world water distribution systems do not take optimization techniques into account. Almost all of the designs are being performed by using traditional techniques based on rules of thumb and engineering experience disregarding any optimization technique. On the other hand, most of the optimization techniques do not permit designers' interference during the design. The aim of this study is to demonstrate design of a water distribution network by using an optimization technique, which allows designer to control whole process. The optimization technique used within the study is partial enumeration method developed by Gessler (1985). In this regard, a case study is conducted on North-8 (N8) pressure zone of Ankara Municipal water supply system.

In Chapter 2, a brief information on widely known optimization techniques and fundamentals of optimization process is presented. In Chapter 3, detailed information on partial enumeration method and guidelines on essential steps that are followed during optimization with partial enumeration method are introduced. In Chapter 4, the case study itself is given. Conclusions and recommendations are presented in Chapter 5.

CHAPTER 2

OPTIMIZATION OF WATER DISTRIBUTION NETWORKS

2.1 DEFINITION

To find the most economical solution to the water distribution systems has always been the ultimate goal of many designers and planners. Many studies have been conducted on this subject in the past (since Babbit and Doland (1931)) and many thesis studies performed in this subject (Selmanpakoğlu (1973), Soleyman (1976), Adıgüzel (1976), Tokalak (1976), İnözü (1977), Aygün (1978), Özer (1988)) in Water Resources Laboratory of Middle East Technical University with supervision of Prof. Dr. Doğan Altınbilek and Prof. Dr. Süha Sevük in addition to their published books (Sevük and Altınbilek (1976,1977)). The most recent thesis study belongs to Akdoğan (2005). Consequently, many techniques have been developed to assist designers. Since the optimization of water distribution systems is a multi-purpose aim (optimization of pipe diameters, tank sizing, pump selection and working time, etc.), there is not a single solution that can be gathered by using these techniques. Namely, there is always another “optimum” solution. The goal is to find the optimum that satisfies the requirements.

2.2 OPTIMIZATION METHODS

Within the optimization methods, many mathematical formulations and many problem solving techniques are utilized such as linear programming, dynamic programming, heuristic algorithms, gradient search methods, enumeration methods, genetic algorithms, simulated annealing etc. “The term optimization methods often refers to mathematical techniques used to automatically adjust the details of the system in such a way as to achieve the best possible system performance or, alternatively, the least-cost design that achieves a specified performance level." (Walski, et al., 2003) Using these said techniques, wide range of optimization methods are developed. Since the partial enumeration technique is the one that is used in this thesis study, special emphasize will be given to it in Chapter 3. However, in this chapter, brief description of partial enumeration technique and some other widely known and accepted techniques will be given.

2.2.1. Traditional (Trial-and-Error) Approach

In fact, traditional (trial-and-error) approach is not a systematic optimization method, but the method that has been widely used during system planning by designers. In this method, experienced engineers adopt some rules-of-thumb together with their past experience to design the system, then adjust the details after running series of hydraulic analysis. Some of the rules-of-thumb are as follows (Walski, 1985):

1. Velocities less than 8 ft/sec (~2,4 m/s) at peak flow
2. Velocities on the order of 2 ft/sec (~0,61m/s) at average flow
3. Pressures between 60 and 80 psi (4 and 5,4 atm) under normal conditions
4. Pressure at least 20 psi (~1,4 atm) during fire condition
5. Diameters at least 6 in (~150mm) for systems providing fire protection
6. Diameters at least 2 in. (~50mm) for systems without fire protection.
7. Adequate pumps such that design flow can be delivered with one pump out of service,
8. No dead end mains

Thus, designer needs not to try every possible solution, but only select the optimum from a few feasible solutions. Because this approach fully depends on the capabilities and experience of the designers; it may produce severely uneconomical solutions. Even if the designer is a unique engineer that has extensive knowledge on water distribution system design, some factors may also limit the possibility to find the optimum solution (Walski et al., 2003):

- Available time and financial resources would possibly limit the number of trials, that may lead to missing a more economical solution
- Due to nonlinear characteristics of the distribution networks, it is very hard to manually relate the influence of a particular change at one location on the other parts.

After all, since the designer adopts the rules-of-thumb and uses hydraulic analysis software, the design will most probably satisfy the design criteria in terms of pressure, velocity restrictions, but unfortunately, it is unlikely to be the most economical.

2.2.2 Linear Programming Methods

Linear programming approaches are used to reduce the complexity of the original nonlinear nature of the problem by solving a sequence of linear sub-problems (Alperovits and Shamir, 1977; Goulter and Morgan, 1985; Goulter and Coals (1986); and Fujiwara and Khang, 1990).

2.2.3 Nonlinear Programming Methods

These methods use partial derivatives of the objective function with respect to decision variables by assuming pipe diameters as continuous variables. This, however, leads the method to get stuck in the local optima.

2.2.4 Genetic Algorithms

The Genetic Algorithm uses a computer model of Darwinian evolution to "evolve" good designs or solutions to highly complex problems for which classical solution techniques are inadequate. The Genetic Algorithm incorporates ideas such as a population of solutions to a problem, survival of the fittest solutions within a population, birth, death, breeding, inheritance of genetic material (design parameters) by children from their parents, and occasional mutations of that material (thereby creating new design possibilities). (Walski, et al., 2003)

2.2.5 Partial Enumeration Technique

Optimization by enumeration, with the simplest description, is the trial of all the possible combinations as per the input data, and then finding the most economical one that meets the design criteria. The technique works fine for smaller systems, but as the system size increases, possible number of combinations increases exponentially, which results in huge amount of computation time, in the order of years. Due to these limitations of exhaustive enumeration, some criteria have been put by Gessler (1985) in order to reduce the number of possible combinations.

2.3 ADVANTAGES AND DISADVANTAGES OF OPTIMIZATION

The designers carry a huge responsibility towards public and decision-makers. The responsibility towards public is that people always want that when they open a tap, there will be adequate water with sufficient pressure. Fire fighters want that they will always have enough water when they attach their fire hoses to fire hydrants. Additionally, people want that in any case, for instance, during electrical shortage, main line breaks, huge fire in the town, to have water. In order to assure this, the designers have to give enough capacity to the system with enough redundancy and reliability. On the other hand, the decision makers and investors do not want to invest more than enough in the system. They oppose to unnecessary costs due to over-design. To meet all these requirements, the designers should design such a system that the required hydraulic restrictions (pressure etc.) can be met with the most economical combination of pipes, tanks, pumps etc. The optimization techniques can be very handy in this search. Since every technique has a systematic way, a designer with a good knowledge of hydraulics can use optimization techniques as an assistant to find the best solution.

However, if optimization techniques are considered as “automatic” searches that guarantee the best solution without any interference of the designer, they may be very dangerous in the hands of individuals who do not understand water distribution design, and blindly implement the poor decisions of optimization models without awareness of the real issues. The users should be aware of the shortcomings resulted from cost minimization. The optimization techniques try to eliminate as many pipes as they can to reduce costs. They do also try to install diameters that can barely satisfy the requirements, which means reduction of system capacity and reliability. If optimization modelers were to ask water distribution operators, they would find that capacity in a water system is a good thing not an evil to be eliminated, especially since the marginal cost of adding capacity is relatively small due to the significant economic scale in pipe capacity (Walski, 1998). Operators prefer spending money on capacity in order to compensate the uncertainty in demands and to increase the reliability of the system.

In addition to above, there are some aspects of water distribution network design, that are unfortunately cannot be included in the optimization techniques and should be performed and decided by the designers such as (Walski,1995) :

- No optimization models address the question of how to set pressure zone boundaries and optimal nominal heads.
- Optimization models do not include change of the route of a pipe in order to reduce the cost, for instance, they do not compare a main line with 500m long crossing a heavily loaded motorway with an alternative main line with 2000m long but laid in open land.
- Decisions about the location of tie-ins, i.e. connections of subdivisions to main lines, are generally not addressed by optimization models.
- If the required pressure at a node is insufficient, people adopt alternatives according to their needs such as fire flow with sprinkler systems, internal booster pumps and storage tanks, nonaqeous fire-suppression systems, fire walls etc. No optimization methods take these into consideration.

As the result of these, optimization techniques should be regarded as a powerful tool for designers that help to make decisions; but at the same time a tool that should not be left alone and every step of which should be pursued and interacted carefully.

2.4 GRADUAL (STAGED) EXPANSION OF NETWORKS

During system design of a new water distribution network or rehabilitation / expansion of an existing network, future demands are predicted by means of some statistical methods. The demands that are going to be used within design process are those that will occur at the end of service life. For instance, if a system is going to be designed in year 2000 considering 20 years of operating period, the design demands are the demands of year 2020. Then, according to these demands, design is finished and construction activities are done. However, because the present demands are much lower than year 2020 demands, there will occur problems within the system. As a result of this, gradual expansion of networks is a phenomenon that should be considered during design stage.

In the design phase, designer should assign the crucial elements that are required during whole service life. These can be the storage tanks, main lines etc. Then, the elements that are of secondary importance and can be installed later when the system capacity is not sufficient should be determined. These can be parallel main lines, branches to newly developed areas etc. By the aid of this concept, the initial cost of the system is reduced and distributed over the service life.

In addition to reduction of initial cost, gradual expansion of networks is also required due to uncertainty of future demands. The main problem of water distribution system design is predicting future demands. Optimization models have treated demands as a given, provided by some outside source, and known with certainty (Walski, 2001). Unfortunately, this is not true in real world. Distribution systems evolve over many decades in response to demands that the original system designers may or may not have anticipated (Walski, et al., 2003). Especially for smaller systems, change of demands may have very significant effect on the network. For example, if a large factory within a small network is closed down after 5 years of network design, the demands will fall far below design demands, and the “optimum solution” gathered in design process will not be valid.

In the design stage, designer may try to overcome uncertainty in demands by applying conservative design with large pipes. However, this will result in high capital costs as well as low quality water due to low velocity in large pipes. On the other hand, if the demands exceed the design demands, namely if the design happens to be under-design, there will be low pressure problems, inadequate fire flows and requirement to immediate system expansion which was not considered by the decision makers beforehand.

In addition, unexpected events may occur during the service life of the water distribution system, such as closure of a factory that affect the demands of pipes, which is unfortunately not considered during the design stage. It is assumed that the demands will occur as predicted regardless of the system capacity. In reality, on the contrary to this, demands are affected by the constructed pipe sizes, which is actually a form of "self-fulfilling prophecy". More simply stated, "If you build it, they will come (within reason)." (Walski, 2001). Consider a developing town in which large pipes are constructed in the southern part and relatively small pipes are in the northern part. Due to available capacity in the southern part, development will be much rapidly. Investors will select locations where distribution capacity is available. Thus, demands in the southern part will rapidly exceed the design demands due to new / unexpected developments.

To overcome the aforementioned issues, gradual expansion of networks can be a useful tool for designers.

CHAPTER 3

PARTIAL ENUMARATION USING WADISO

3.1 HISTORY

WADISO (Water Distribution Simulation and Optimization) is a software which dates back to 1980s. In early 1980s, Thomas Walski was an engineer who has recognized the value of a user-friendly program to optimally select pipe sizes and decided that the most convenient approach for optimization is the algorithm developed by Gessler in 1985. With cooperation of Gessler and Walski and additions by Sjostrom, first edition of WADISO was produced in 1980s. This first edition was applied to a number of water systems worldwide and presented to public with a manual. This first edition of WADISO was “user-friendly” for 1980s~1990s; it was working on DOS environment in the computers; it was “old-fashioned” as compared to today’s hydraulic software having Graphical User Interfaces (GUI), working with databases in connection with Geographical Information Systems (GIS). In 1990s, a commercial version of WADISO was developed by GLS Software, South Africa in which the WADISO is revised in terms of “user-friendly” applications. Since then, several new versions of WADISO have been developed by GLS, the most recent one being WADISO 5. WADISO 5 is equipped with a Graphical User Interface, has connection to Geographical Information Systems and many more user-friendly applications, the algorithm is the same with the original WADISO. The network solver is based on node method, and basics of partial enumeration given in Section 3.3 remain unchanged in all versions of WADISO.

3.2 REASONS FOR AN ENUMARATION ALGORITHM

The optimization process for water networks is very hard due to discrete characteristics of pipe diameters. Some optimization techniques assume variables as continuous. However, the discrete cost function can be quite irregular and difficult to approximate by a continuous function. Additionally, most of the optimization procedures proposed so far are essentially gradient search techniques, some in a continuous variable space, some in a discrete space. Such algorithms can only guarantee local minima. Finally, a solution developed in a continuous space requires an additional space after the execution of the optimization algorithm, in which pipe sizes are “rounded” to nearest commercially available pipe sizes. Indeed, it is possible that the globally optimal discrete solution may not even be in the neighborhood of the globally optimal solution using continuous pipe sizes, but could be associated with a local minimum. Due to this, it is quite logical to perform optimization in the discrete space from the beginning.

Optimization by enumeration of all possible pipe size combinations with some user specified constraints will diminish all the said shortcomings of other optimization techniques and will guarantee that the solution is the global minimum of the discrete space. Additionally, generation of a queue of Pareto Optimal solutions can also be available, which is very handy for decision makers.

3.3 ALGORITHM USED IN WADISO

The most significant shortcoming of the enumeration technique is that it may require huge amount of processing time, some may even in the order of tens of years. To overcome this, the candidate pipe size combinations have to be reduced.

The first thing to do before running the software is the data input. Data input stage contains identification of the following:

- Pipes that are going to be optimized: The user defines which pipes are going to be included in the optimization process. In some cases, the user may not need all of the pipes be optimized.
- Assignment of groups: Each of the pipes to be sized must be assigned to a group. All pipes in the same group will be assigned the same diameter A detailed discussion is given in Section 3.5.1 regarding grouping of pipes. In brief, since it is not desirable to have pipe sizes change at every block in a network, the user groups pipes that are to be assigned same diameter. This reduces the number of combinations considerably.
- Assignment of candidate pipe sizes: For each of the groups, a list of candidate pipe sizes needs to be specified. This list may include elimination of the group as an alternative and/or cleaning of the old pipes which run parallel to the new pipes.
- Assignment of cost functions: For every group, which cost function should be used by the software is assigned. The cost functions represents various conditions related to the construction and installation of pipes. The pipes within a group can be assigned to different cost functions.
- Assignment of demands and pressure constraints at the nodes: The required output at all nodes and the pressure, which needs to be maintained, are specified.

After data input stage, WADISO follows the schematic flowchart of the procedure, which is given in Figure 3.1. First, WADISO selects a pipe size combination that meets the design criteria, i.e. pressure constraints, regardless of its cost. This is **"Best Solution".** For the next size combination, it first computes the total cost of the combination. If the total cost of this new combination is more than that of **"Best Solution",** it is omitted and another size combination is selected. If it passes, following tests are applied to the new combination:

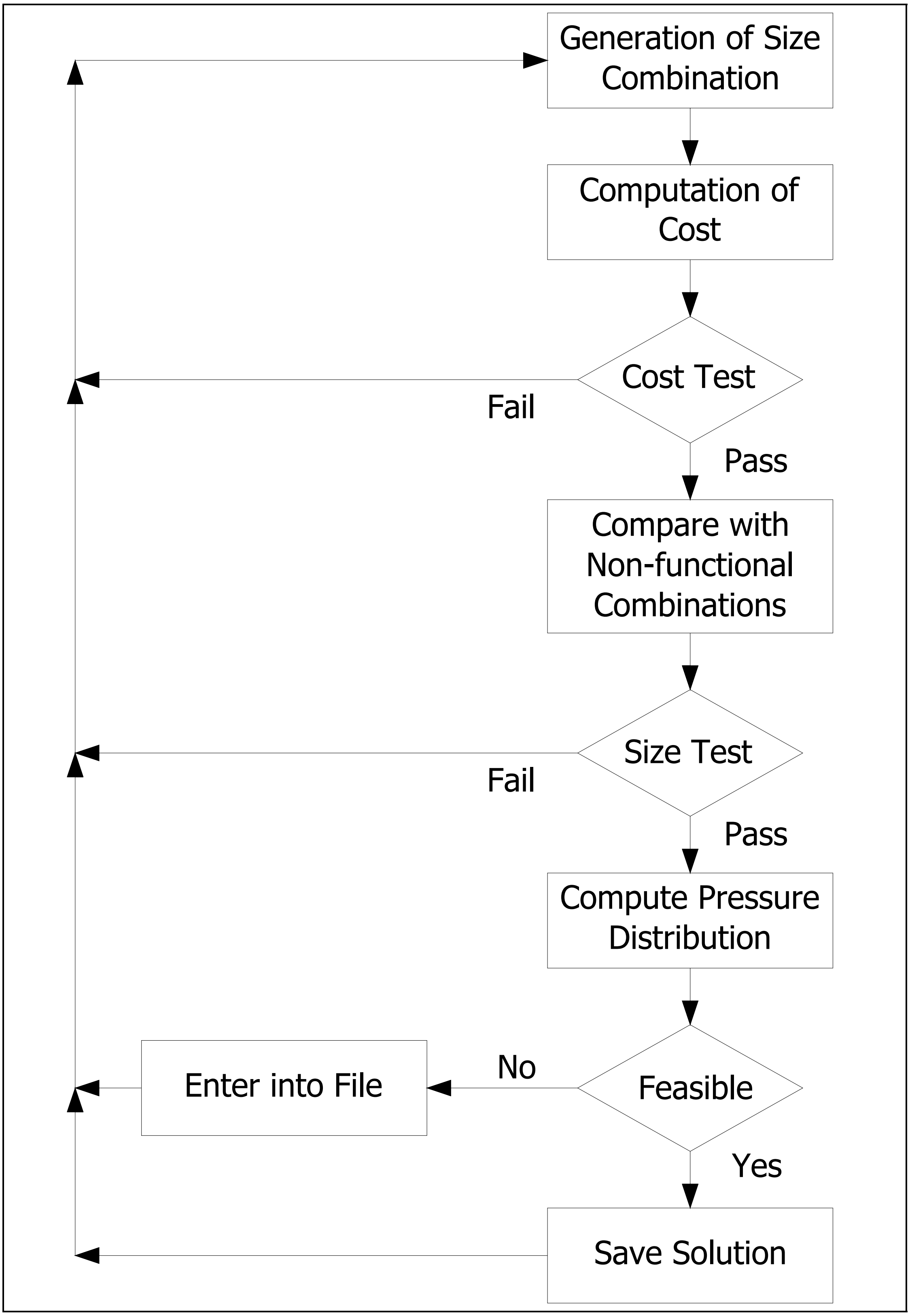

Figure 3.1: Schematic Flowchart for Partial Enumeration Technique

Test on Size Range: The number of pipe size combinations to be tested is equal to the product of the number of candidate sizes in each group. To reduce the number of pipe combinations, it is required to test whether the candidate pipe sizes assigned for groups are appropriate or some can be eliminated. To verify this, a combination consisting of the smallest size in a group combined with the largest sizes in all other groups is built and checked if the pressure requirement is fulfilled. If not, tested smallest pipe size is eliminated which in turn eliminates many infeasible pipe combinations reducing the computation time.

Cost Test: After a size combination has been found that meets all pressure requirements, there is no need to test any other size combination that is more expensive than this functional solution (Gessler, 1985). This cost test is most effective in eliminating candidate solutions if it is possible to find a relatively inexpensive functional inexpensive solution early on. Only the combinations within Pareto optimal specifications are allowed to pass cost test. For each pipe size combination, the program will first calculate the total cost (excluding pump cost). If the construction cost is already more than the total cost of a previously found and functional solution, the program will disregard this combination and proceed with the next one.

Size Test: If a certain pipe size combination does not meet the pressure requirement, no pipe size combination with all pipes equal or smaller than the ones of this combination can meet the pressure requirement (Gessler, 1985). In order to perform the size test, WADISO maintains a queue of nonfunctional combinations. This queue is not allowed to grow too long. Otherwise, the testing of a particular size combination against all entries in the queue requires more computation time than evaluation of pressure distribution. During the enumeration process, the program maintains a file of pipe size combinations that failed to meet the pressure requirements. In brief, it will not be necessary to calculate the pressure distribution for a combination in which all sizes are equal or less than the sizes of the corresponding pipes in a combination stored in this file, because it could not meet pressure requirements either.

If a combination passes these tests, the pressure distribution within the network is calculated as per the given loading patterns. According to the results of this computation, a combination is either “non-functional” or “new best solution”

Non-functional Solution: During pressure distribution computations, if it is encountered that pressure requirement at a node cannot be satisfied, computations are terminated, then, the combination is entered into the file of non-functional combinations and the program proceeds with the next size combination.

New Best Solution: If the pressure requirement is met at all nodes, the algorithm has found a solution better than an other one previously encountered. Then, it is stored as the new best solution and the program proceeds with the next size combination. If there are pumps, present worth of pumping cost is added to construction cost.
The procedure continues until all combinations have been enumerated. By the help of this algorithm, the best solution will always be the global minimum in the cost function.

Effectiveness of Tests: The effectiveness of these tests is illustrated by the following numbers (Gessler, 1982). The percentage of combinations passing the cost test may be around 20% for a relatively small number of combinations and may drop to around 10% when the number of combinations reaches 100,000. The percentage of combinations for which the pressure distribution needs to be evaluated may be as high as 10% for small number of combinations and drops to less than 1% for large numbers. Obviously, these numbers will vary from network to network. They are provided here as a guideline only.

3.4. HYDRAULIC NETWORK ANALYSIS

In the optimization algorithm of WADISO, the hydraulic constraints are defined as the minimum pressures that should be satisfied at every node. After size and cost tests, the software calculates the pressure distribution within the network. For network analysis, two methods are available suggested by Hardy Cross (1936): loop and node methods. In WADISO, node method is applied. The terminology that will be used hereafter is as follows:

Links : Pipes, pumps, pressure reducing valves
Nodes : Junctions between links

In a system with p links and n nodes, among which are r reservoirs, the problem has the following unknowns:

p links (flow rates)
n-r heads
Total of p+n-r unknowns.

To find these unknowns, following equations are built:

- The energy equation between any two directly connected nodes (friction loss equation for pipes, or characteristics curve of pumps)
- The continuity equation at all nodes, excluding the constant head nodes.

Therefore, the total number of available equations is p+n-r.

The uniqueness of the solution will not be discussed in detail herein, but simply, a network that consists of only pipes and nodes has a single solution. In case of pumps and valve inclusion, as long as the first derivative of the characteristic pump curve is negative for all discharges, the uniqueness is also guaranteed.

3.4.1 Loop Method

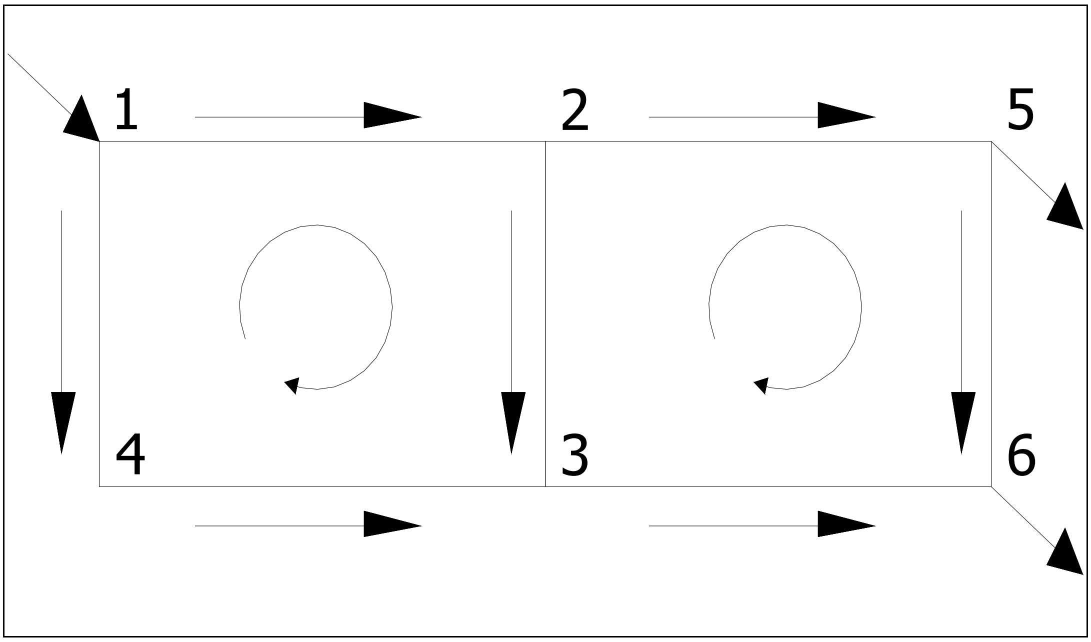

Figure 3.2: A simple looped network

In the loop method, procedure is initiated by assuming flow rates and directions for each pipe so that the continuity is satisfied at all nodes, i.e. inflow into the nodes are equal to the outflows, as given in Figure 3.2. Then, for every loop, friction loss is calculated in the selected direction, clockwise in Figure 3.2. For the first trial, it is most likely that the total headloss calculated will not be equal to zero. The key concept in loop method is to superimpose a flowrate correction ΔQ in all pipes of a loop either with the sense of the loop or against it. In other words, for pipes with a positive friction loss the flow correction is added to the discharge, and in pipes with a negative friction loss the flow correction is subtracted, or vice versa. After application of flow rate correction to the estimated flow rates, the continuity equations at all nodes still will be met.

Hardy Cross (1936) solved these equations for ΔQ one at a time using a Taylor expansion of hydraulic loss equation, keeping the first two terms only. However, convergence is very slow and gets worse with the increasing system size with this application.

3.4.2 Node Method

The node method requires solving as many equations as there are nodes with unknown heads. In the node method, the heads at the nodes are estimated, and flow rate in each link is calculated based on these estimates. Then, the continuity at the nodes is checked. Nevertheless, based on the head estimates, the sum will be a residual flow rate. Cross then proceeded by assuming the heads at adjacent nodes to be correct. One can then adjust the head at the node under consideration such that the flow rates will balance. The resulting non-linear equations are solved by linearization.

3.4.3 Comparison of Loop and Node Methods

- The node method has a simpler topology. This may be of particular importance when it is necessary to temporarily eliminate a link. This may be required if the status of a valve is changed from open to closed. In loop method, this requires re-establishing of loops.
- In the node method, one directly solves the equations for the unknown pressures. In the loop method, pressures are calculated at the end of whole processes with extra calculations.
- Inclusion of pumps, pressure reducing or check valves are much easier in node method since the devices are pressure controlled. The status of these devices can be checked after each iteration.

3.4.4 Node Method Used in WADISO

WADISO uses the Hazen Williams friction loss equation to calculate the losses in the pipes (Walski et al, 1990).

$$h_i = c_i * Q_i^{1,85} \qquad \textbf{(3.1)}$$

$$c_i = \frac{10.68 * L_i}{C_i^{1.85} * D_i^{4.87}} \qquad \textbf{(3.2)}$$

where h_i is the friction loss in pipe i in m.

C_i is the characteristic pipe coefficient for pipe i

Q_i is discharge in pipe i in m^3/s.

L is the length of pipe i in m.

D is the diameter of pipe i in m

Equation 3.1 can be linearized in regard to correction on the discharge to read

$$H_j - H_k = c_i(Q_{i0}^{1.85} + 1.85Q_{i0}^{0.85}q) \quad \textbf{(3.3)}$$

where H_j and H_k are total heads at the beginning and ending node of pipe i with

$H_j > H_i$

Q_{i0} = estimated flow rate in pipe i

And $Q_i = Q_{i0} + q$ **(3.4)**

where Q_i is the updated flow rate in pipe i

q is the difference between updated and estimated flow rate.

Combining equations 3.3 and 3.4 to eliminate q,

$$Q_i = 0.46Q_{i0} + 0.54\frac{H_j - H_k}{c_i Q_{i0}^{0.85}} \quad \textbf{(3.5)}$$

Then the continuity equation is written, e.g. for node 2 in Figure 3.2,

$$-0.46Q_{1o} - 0.54\frac{H1 - H2}{c_1 Q_{1o}^{0.85}} + 0.46Q_{2o} + 0.54\frac{H_2 - H_3}{c_2 Q_{2o}^{0.85}} + 0.46Q_{5o} + 0.54\frac{H_2 - H_5}{c_5 Q_{5o}^{0.85}} + Q_{d2} = 0 \quad \textbf{(3.6)}$$

where Q_{d2} is the amount of water withdrawn at node 2. If the estimated flow rates are close to the correct flow rates then

$$-0.46Q_{1o} + 0.46Q_{2o} + 0.46Q_{5o} + Q_{d2} \cong 0 \qquad \textbf{(3.7)}$$

which allows us to simplify Equation 3.7 as

$$-\frac{1}{c_1 Q_{1o}^{\ 0.85}} H_1 + \left(\frac{1}{c_1 Q_{1o}^{\ 0.85}} + \frac{1}{c2 Q_{2o}^{\ 0.85}} + \frac{1}{c_5 Q_{5o}^{\ 0.85}}\right) H_2 - \frac{1}{c2 Q_{2o}^{\ 0.85}} H_3 - \frac{1}{c_5 Q_{5o}^{\ 0.85}} H_5 = -Q_{d2} \qquad \textbf{(3.8)}$$

This is the linearized continuity equation, i.e. an equation with exponents of 1 on unknown heads H, in terms of the unknown heads at the adjacent nodes and at node 2, as well as in terms of estimated flow rates leading to node 2.
For the nodes with constant heads, e.g. for node 1, the equation is revised as:

$$A * H_1 - \frac{1}{c_1 Q_{1o}^{\ 0.85}} H_2 - \frac{1}{c_4 Q_{4o}^{\ 0.85}} H_4 = A * H_{r1} \qquad \textbf{(3.9)}$$

where A is a very large number, for instance 10^5
H_{r1}= required head at node 1.

When all continuity equations are formulated and the proper equations at the constant head nodes are inserted, the resulting coefficient matrix is always symmetrical and for large networks extremely sparse. Gessler (1985) showed that the symmetry is also preserved when pump and/or Pressure Reducing Valves are present. The algorithm of WADISO takes advantage of both the symmetry and sparseness when solving the continuity equations simultaneously.

3.5 STEPS OF PARTIAL ENUMARATION WITH WADISO

3.5.1 Pipe Grouping

Pipe grouping is the most useful and at the same time most critical step of the system setup with WADISO. It is useful because by the aid of pipe grouping concept, amount of candidate pipe combinations are reduced which in turn reduces the computation time significantly. It is critical at the same time, because if the groups are built in hands of people that have little knowledge on hydraulics, it may lead to very unrealistic "optimum" solutions.

Generally, optimization of every pipe within a system is not required; on the contrary, it is sometimes not desirable. For example, it is not desirable to have a main line whose diameter changes at every junction. Similarly, a designer would not prefer a loop with one leg's diameter is 200mm while the parallel leg is optimized as 80mm. Consequently, designers have some common rules such as the mains and tributaries are easily observed, having same diameters in the parallel legs of loops in order to increase reliability of the system, etc. Thus, some pipes should have the same diameters. With pipe grouping concept in WADISO, this can be achieved. By this way, not only the above concepts are fulfilled, but also the computation time is reduced.

In WADISO, grouping of pipes is accomplished by the user before the optimization procedure starts. The user specifies which pipes should have the same diameter. For this purpose, following concepts are useful:

- The main lines feeding whole system, i.e. taking water directly from tank, reservoir, pump and end at another source, are grouped individually (Figure 3.3).

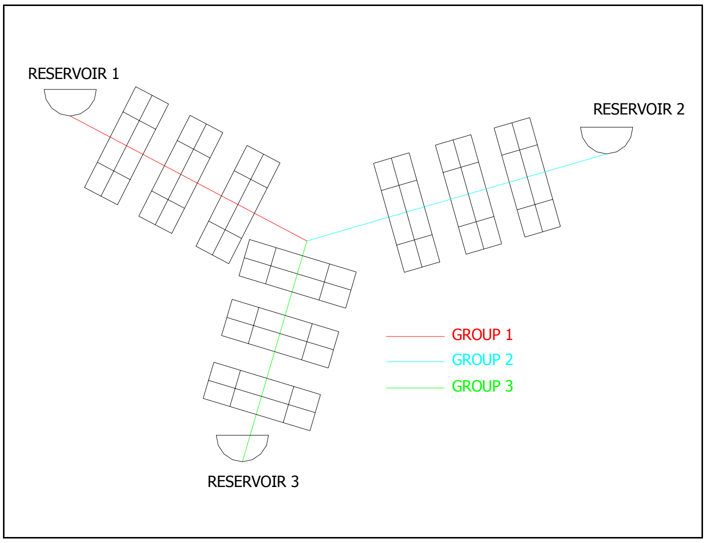

Figure 3.3: Grouping of main lines

* Main tributaries feeding sub-zones form individual groups (Figure 3.4).

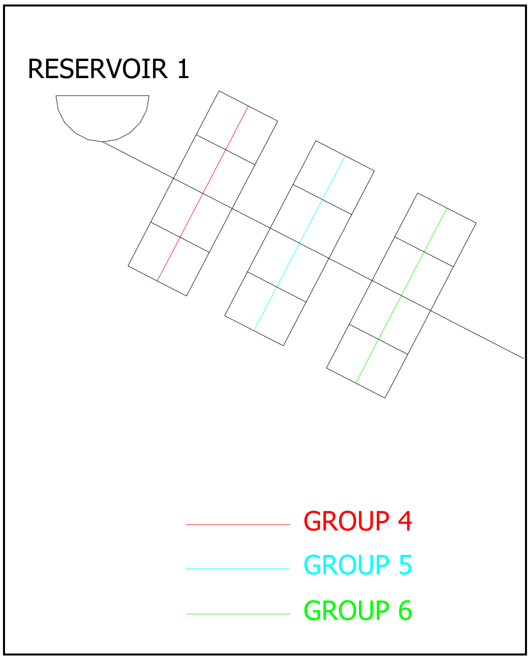

Figure 3.4: Grouping of main tributaries

* Parallel legs of a loop form one group (Figure 3.5).

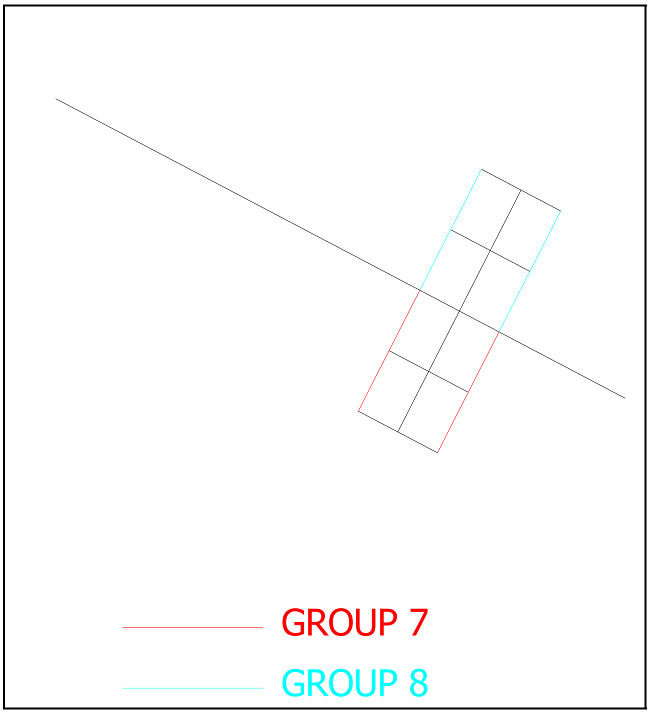

Figure 3.5: Grouping of parallel pipes

The groups may include any number of pipes, even if a single pipe can form a group if it is desired to be optimized. However, number of groups within WADISO is limited to 15, i.e. maximum number of groups that can be formed is equal to 15. This is again to reduce computation time. Due to this limitation, pipe groups should be selected very carefully, only those pipes that have significant effect on the global cost of the system should be included in groups. In other words, the smaller branches need not be included in the procedure. The change of a pipe's diameter from 125mm to 100mm will not be very significant on the global cost. However, the reduction of a 3000m-long main line's diameter from 1000mm to 800mm will produce great cost savings.

Pipe grouping concept reduces computation time and provides a clear conveyance layout to the system. However, pipe grouping should be handled carefully with hydraulic principles kept in mind. As stated before, all the pipes in a group will have the same diameter at the end of optimization. As an example, Figure 3.6 is given. Region 1 is an industrial zone where demands are higher requiring larger diameters. On the other hand, Region 3 is a commercial zone with moderate demands and Region 2 is composed of residential dwellings, which requires relatively low demands as compared to Region 1, which results in smaller diameters. If all the pipes in the three main lines are assigned to the same group, they will have the same diameter at the end of optimization. Since the demands are higher at Region 1, larger diameter main line will be assigned by WADISO due to pressure requirements. Although the demands are smaller for Region 2 and 3, because they are in the same group with Main Line 1, they will be assigned the same diameter of main line 1. In this case, the diameter of Main Line 1 will be governing one; main lines 2 and 3 will be unnecessarily assigned larger diameters. However, if all main lines are assigned to individual groups, they will have different diameters as per demands of the corresponding regions, Main Line 1 having the largest diameter where Main Line 2 has the smallest.

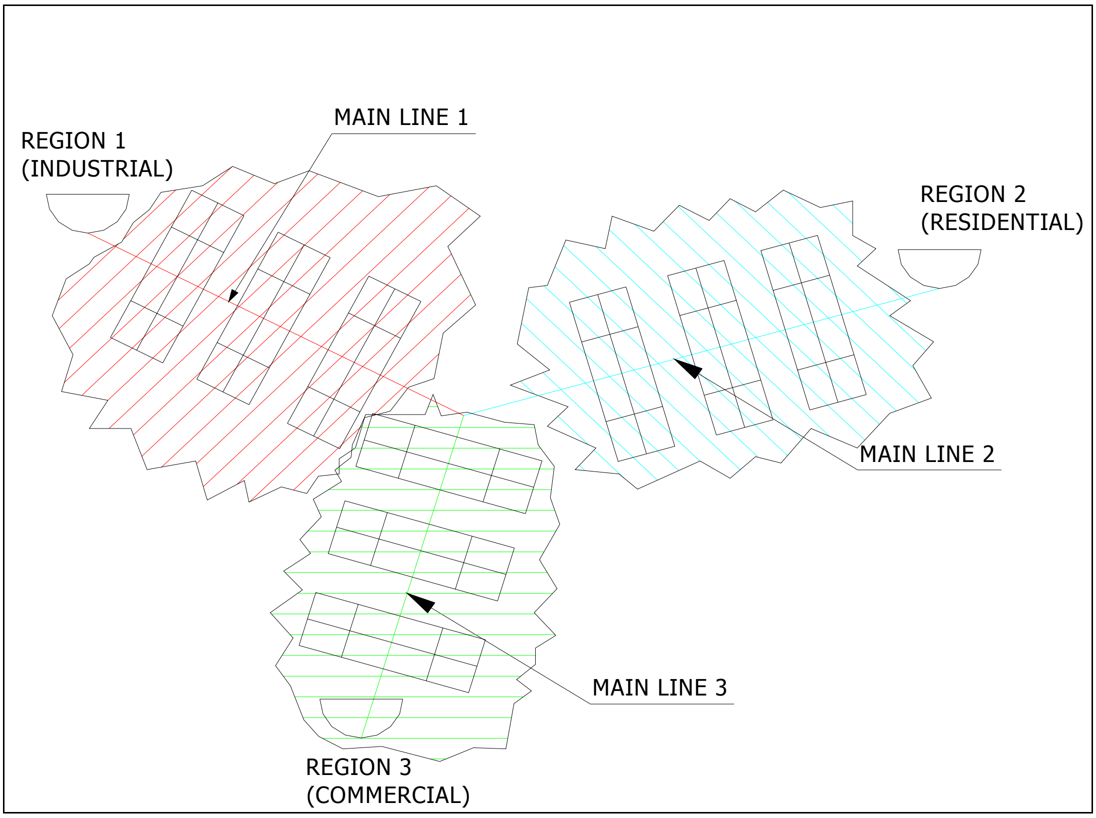

Figure 3.6: Sample Network For Pipe Grouping

3.5.2 Pipe Size Assignment

In the pipe size assignment step, the candidate pipe sizes for each group are listed. Although it is possible, the list for a group does not need to include all commercially available pipe sizes, since having too many candidate pipe sizes for groups will increase computation time. Thus, the candidate pipe sizes should be "reasonable". To find the reasonable candidate pipe sizes, following procedure can be followed:

- Using rules-of-thumb and experience and trial-and-error method, assign preliminary pipe sizes for every pipe in the system. This is also a pre-requisite for WADISO. Before running optimization module, program tries to balance the system, thus in the very beginning, preliminary diameters of all pipes should be assigned.

- Assign one lower and one upper commercially available pipe diameter together with the preliminary diameter for every group and run the first optimization trial (Table 3.1). This will last for 4~12 hours depending on the system size and number of groups.

Table 3.1: Candidate pipe sizes for first run

PRELIMINARY DIAMETERS	200,00	110,00	500,00	250,00	200,00
CANDIDATE DIAMETERS (mm)	**GROUP1**	**GROUP2**	**GROUP3**	**GROUP4**	**GROUP5**
	180,00	90,00	450,00	225,00	180,00
	200,00	110,00	500,00	250,00	200,00
	225,00	125,00	560,00	280,00	225,00
OPTIMUM DIAMETERS (mm)	180,00	110,00	450,00	225,00	180,00

- Check the results of the optimization. Identify the groups in which program assigns the lowest available candidate size. This may mean that if there were lower diameters, the program may assign it (lower) to the group. To ensure the results and to give relaxation for the program, assign two more lower diameters. Similarly, if the program assigns the upper diameter for a group, assign two more upper diameters. (Table 3.2.)

Table 3.2: Revised Candidate Pipe Sizes for Second Run

PREVIOUS OPTIMUM DIAMETERS (mm)	180,00	110,00	450,00	225,00	180,00
CANDIDATE DIAMETERS (mm)	GROUP1	GROUP2	GROUP3	GROUP4	GROUP5
	140,00	90,00	355,00	180,00	140,00
	160,00	110,00	400,00	200,00	160,00
	180,00	125,00	450,00	225,00	180,00
	200,00		500,00	250,00	200,00
OPTIMUM DIAMETERS (mm)	160,00	110,00	400,00	250,00	160,00

- Perform the optimization and repeat the previous step until the program assigns diameters to group that are neither the available upper nor the lower ones (Table 3.3).

Table 3.3: Final Candidate Diameters and Optimum Sizes

PREVIOUS OPTIMUM DIAMETERS (mm)	160,00	110,00	400,00	250,00	160,00
CANDIDATE DIAMETERS (mm)	GROUP1	GROUP2	GROUP3	GROUP4	GROUP5
	140,00	90,00	355,00	180,00	140,00
	160,00	110,00	400,00	200,00	160,00
	180,00	125,00	450,00	225,00	180,00
				250,00	
				280,00	
OPTIMUM DIAMETERS (mm)	160,00	110,00	400,00	250,00	160,00

As can be seen from Table 3.1, for the first run, due to available candidate pipe sizes, WADISO assigned 180mm for Group 1 and 225mm for Group 4, which are the main lines of the system. Then in the second run program assigns 160mm for Group 1 and 250mm for Group 4 since there are more available diameters. Finally, to check if more changes would have occurred when 280mm were in the candidate sizes, it is included in the candidate sizes list. At the same time, to reduce computation time, candidate sizes from Groups 3 and 5 are reduced to three, and according the results, WADISO assigned all the diameters for the groups that were neither the lowest nor the highest available ones.

As discussed previously, cleaning / rehabilitation is also an alternative for new pipe installation. One can assign this option during optimization with WADISO. In this case, the preliminary diameters should be the real world diameter of the group. Then, assumed Hazen Williams coefficient of pipes after cleaning is given to program together with its associated price function. In this option, WADISO determines if it will be more economical when the constructed system is cleaned and rehabilitated or the existing pipes should be replaced by new ones.

One of the drawbacks of optimization methods is to reduce the reliability of the system to save costs. If the designer decides that, some groups formed in the previous steps can be eliminated, then this option can also be introduced into WADISO. Then, the program will test all the combinations including elimination of the said groups. As the result, it may produce results including elimination provided that the specified pressure restraints at nodes are all satisfied. However, it should be kept in mind that these pressure constraints are satisfied with the given steady state loading pattern(s). The reliability of the system should be checked with Extended Period Simulation Analysis and with other critical Steady State Loading Patterns.

3.5.3 Price Functions

Within the optimization process with enumeration, number of combinations of pipes are built, and then compared with each other to find the most economical combination that meets the restrictions. Within this process, pipes are valued by multiplication of their lengths times the assigned price function, - price function of a pipe is the cost per meter of the pipe - and finally all the costs of pipes are added resulting in the cost of the whole system. Thus, the only cost related part of optimization with WADISO is the price function. This obviously requires that the price functions should not only be considered as the pipe material costs, but should also include construction costs (excavation, fill, bedding transportation etc.), special crossing costs (crossing under a heavily loaded motorway, river etc.), pipe fittings' costs (elbows, collars, branching fittings, dead-end fittings etc.) and all the other costs specific to the projects.

In the past, various attempts have been made to find the price functions of the pipes to assist planners and developers such as Clark, et al. (2002), or the outcome of the survey performed by American Environmental Protection Agency (2001). Although all these gives rough estimates that can be used for master planning stage, detailed cost analysis should be performed for each project considering the latest market conditions (e.g. rise of steel prices, advances in pipe material chemistry, new construction technologies etc.).

In the recent years, there have been advances in pipe chemistry that enables designers to use different kinds of pipes within their designs, such as GRP (glass fiber reinforced polyester), HDPE (high density polyethylene), ductile iron etc. All of these pipe materials have advantages depending on the point of view. One material may have very well hydraulic properties (such as low friction loss), but another one may have dramatically low prices. Thus, there is not a universal law that rules the use of material in water distribution networks.

In addition to cost perspective, other factors limit the use of a material in every aspect of design. For example, GRP pipes can be very well applied in water transmission lines. However, due to their brittle characteristics, they are not advised for distribution lines. In short, there are factors that cannot be represented in mathematical cost functions but which dictates the use of a material.

All pipe materials have different material characteristics and they do also have different construction methodologies, fittings installation etc. A brief summary for three basic types of pipe materials is as follows:

GRP (Glass fiber reinforced polyester):

Commercially available GRP pipes are produced within range of 300mm~2400mm. GRP Pipes and Fittings are designed to be used in underground and above ground piping systems to transport sewage, sea water, aggressive chemicals, and potable water under pressure and gravity flow. GRP pipes are used in the following fields:

- Main pipes and branch lines for potable water systems
- Pipes for sewage systems. Main and subsidiary sewage collectors to pressure and gravity flow
- Pipes for waste water systems
- Pipes for cooling systems of power stations (also sea water)
- Pipes for submarine systems
- Pipes for systems in chemical plants

The followings are the advantageous properties GRP pipes that are given by the manufacturers (Table 3.4).

Table 3.4: Advantageous properties of GRP pipes (www.superlit.com)

Non-metalic material, inert chemically resistant	Long effective service life.
	No need for cathodic protection systems.
	No need for internal and external coatings.
	Particularly low maintenance costs.
	Smooth inner surface provides good hydraulic properties, unchanged throughout its working life.
Couplings are chemically resistant and watertight	Easy to assemble, saves time.
	Effective sealing under pressure and vacuum.
	Coupling enabling angular deflection, allowing change of direction without requiring additional fittings.

Table 3.4 Continued

Low weight (about 1/10 of a concrete pipe, 1/4 of steel pipe)	Quick and easy installation. There is no need for heavy equipment to transport pipes.
	Cheap transportation.
Long pipe sections	Few connections, very fast installation.
Excellent inner smoothness	High Hazen-Williams factor, significant energy savings.
	The energy savings in time may be equivalent to the purchase cost of the pipe.

Figure 3.7 Connection of GRP Pipes (www.superlit.com)

Figure 3.8 GRP Water Transmission Line (www.superlit.com)

HDPE (High density polyethylene pipes): HDPE pipe diameters vary between 75mm up to 1600mm depending on the pressure class. HDPE pipes are applied in the following fields:

- Surface and Underground Drinking Water Networks
- Natural Gas Systems and Networks
- Irrigation Systems
- Drainage and Sewerage Systems
- Sea Discharging Systems
- Waste Water Systems
- Solid Waste Drainage Systems
- Fire Water and Cooling Water Systems
- Geothermal Systems
- Pharmaceutical and Chemical Industry / Sanitary Appliances
- Aggressive Fluid Systems

Basic properties of HDPE pipes, which make them advantageous among others, given by manufacturers are as follows (www.superlit.com):

- 50 years of service life guarantee
- Perfect corrosion resistance
- High resistance to chemical agents
- Good flexibility
- Light weight, easy transport, loading, unloading and installation
- Various jointing methods
- Capability of assembling in and/or out of channel during installation
- High elasticity (18-20 times of its diameter) , minimum fittings usage
- Perfect adaptation to the field conditions, suitable for seismic area
- Perfect welding and leak-proof characteristic
- Resistance to UV rays and low temperature conductivity
- High resistance to cracking and impact
- Production of all pressure classes between 2,5 bars and 32 bars ,
- and also optional production according to the clients' requirements
- Resistant to the sudden pressure increases known as " Water Hammer "
- Low operating cost
- Easy repairs by strangle technique
- Mobile production facility for huge projects

HDPE pipes are classified according to pressure class as SDR value. SDR value stands for the "Standard Diameter Ratio" which is the outside diameter divided by the wall thickness. A 2" SDR 7 product would have the outside diameter of 2.375" and a wall thickness of 0.339" (2.375/0.339 = 7).

Pipe jointing methods used for HDPE pipes are butt-welding method, electrofusion welding, electrofusion coupling, edge welding and flanged (Figure 3.10).

Butt-welding can be performed for PE Pipes with wall thickness greater than 4mm. The two pipes that are going to be welded should have the same wall thickness.

Welding can be performed inside or outside the trench. However, considering the width of welding machine, trench should be excavated larger than required to perform welding inside. General application is giving a reasonable radius (approximately 18 x pipe diameter) to the PE pipe inside of the trench to take the edge out of the trench, and then perform welding outside of the trench. No extra fittings are required for butt-welding.

Electrofusion welding can be used for pipes up to Ø110mm for pipes having different wall thickness.

When butt-welding cannot be carried out, the electrofusion-coupler is the ideal for big diameters and long pipe lengths. The electrofusion coupler is a joint with an incorporated heating element that (connected to the automatic welding machine) absorbs the necessary heat for welding (Figure 3.9). Inside the coupler, there are notches for the insertion of the pieces to be welded, which will join up in the middle to make the surface more sliding. (These notches can be removed by a knife) The welding pressure is given by the coupler which shrinks because of the temperature. During welding, in order to avoid the softening of material that causes contractions on the pipe, the external and central areas of the coupler do not melt. The contraction is uniformly distributed during welding.

Figure 3.9 Electrofusion coupling of PE Pipes (www.superlit.com)

Edge welding and flanged jointing are applied for gravity pipelines.

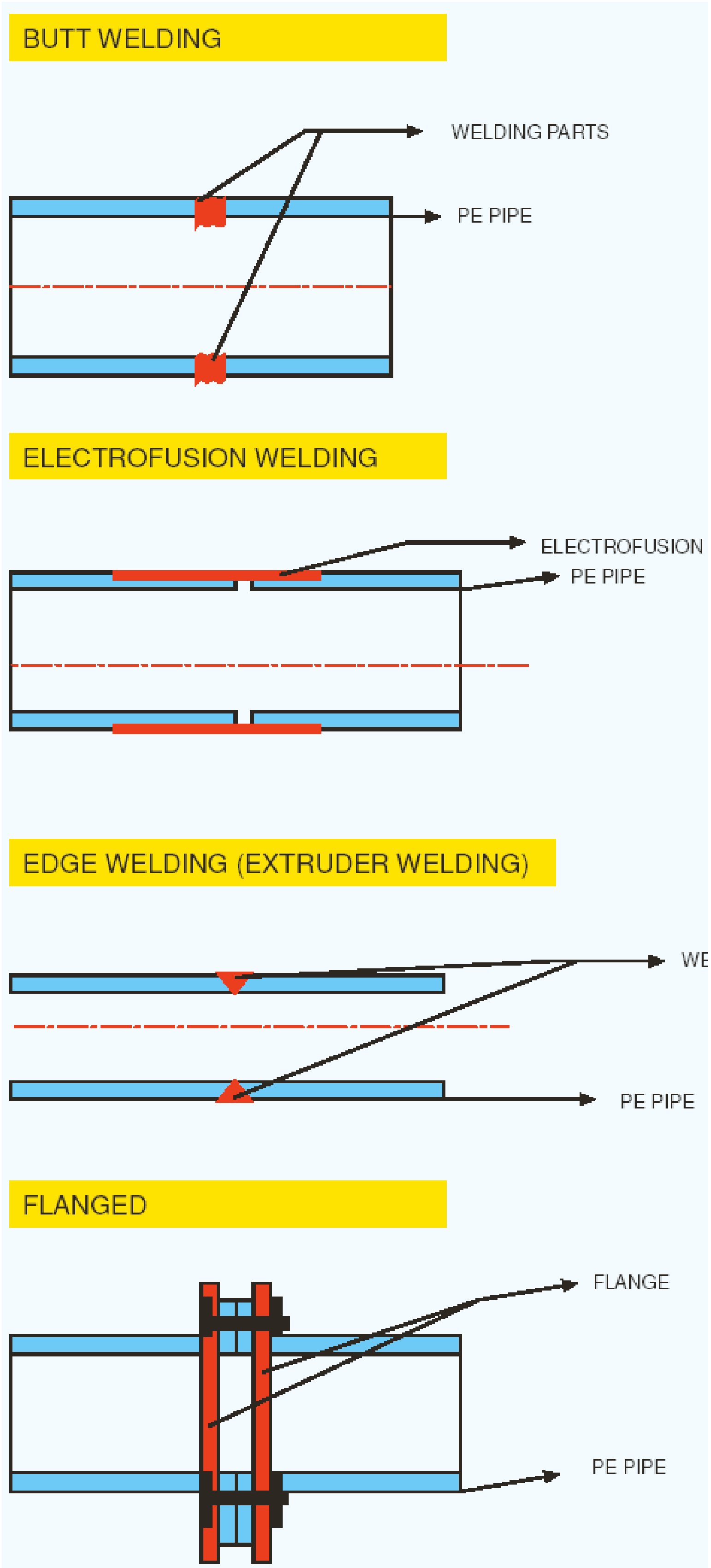

Figure 3.10 Pipe jointing methods for PE Pipes (www.superlit.com)

Ductile Iron Pipes: Since its first introduction into the market in 1955, ductile iron has been extensively used in wide range of sectors including water and waste water systems (Figure 3.11).

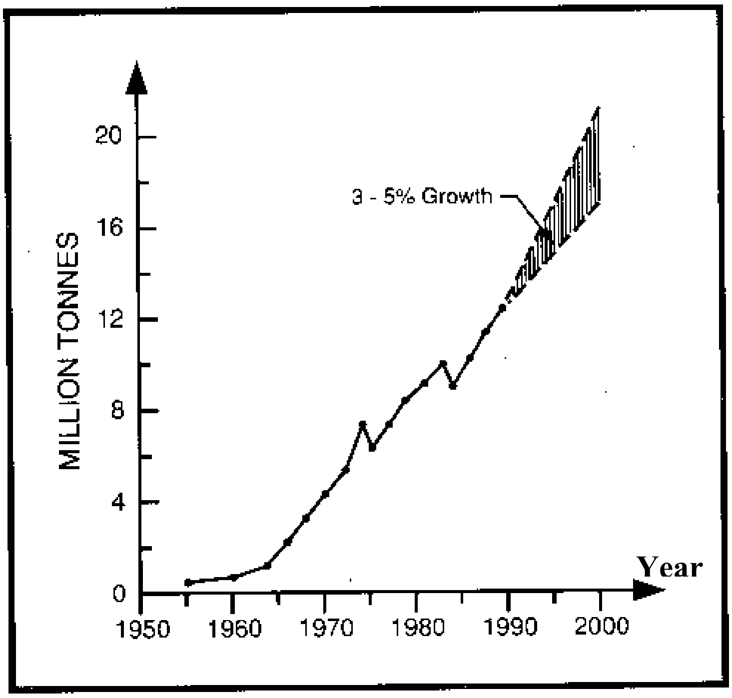

Figure 3.11 Ductile Iron production in the past for all sectors (www.ductile.org)

Ductile Iron not only retains all of Cast Iron's attractive qualities, such as machinability and corrosion resistance, but also provides additional strength, toughness, and ductility. It is lighter, stronger, more durable and more cost effective than Cast Iron. Although its chemical properties are similar to those of Cast Iron, Ductile Iron incorporates significant casting refinements, additional metallurgical processes, and superior quality control. Ductile Iron's improved qualities are derived from an improved manufacturing process that changes the character of the graphite content of the iron. Ductile Iron's graphite form is spheroidal, or nodular, instead of the flake form found in Cast Iron (Figure 3.12). This change in graphite form is accomplished by adding an inoculant, usually magnesium, to molten iron of appropriate composition during manufacture.

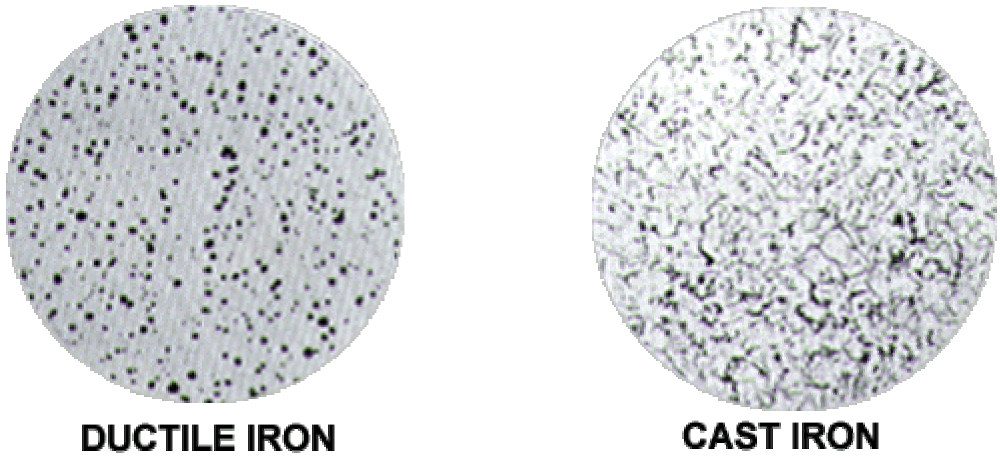

Figure 3.12 Ductile and Cast Iron under microscope (www.ductile.org)

Due to its spheroidal graphite form, Ductile Iron has approximately twice the strength of Cast Iron as determined by tensile, beam, ring bending, and bursting tests. Its impact strength and elongation are many times greater than Cast Iron's. Ductile's high degree of dependability is primarily due to its high strength, durability, and impact and corrosion resistance.

The first cast iron water lines were installed without lining. However, in time it was observed that inner side of pipe could be affected by the water. Thus, researches were conducted on inner lining of cast irons and linings such as cement-mortar lining have been developed. Cement-mortar-lined Ductile Iron pipe provides a Hazen-Williams flow coefficient, or "C" value, of 140 — a realistic value that is maintained over the life of the pipe. This standard lining, which is furnished in accordance with ANSI/AWWA C104/A21.4, continues its tradition of dependable, trouble-free service (BONDS, 1989). Comparison of ductile iron (ANSI/AWWA C150/A21.50 and ANSI/AWWA C151/A21.51) and PE pipe (ANSI/AWWA C906) standards is as follows (Bonds, 2000):

Table 3.5: Comparison of ductile iron (ANSI/AWWA C150/A21.50 and ANSI/AWWA C151/A21.51) and PE pipe (ANSI/AWWA C906) standards

TOPIC	Ductile Iron Pipe ANSI/AWWA C150/A21.50 ANSI/AWWA C151/A21.51	HDPE Pipe ANSI/AWWA C906
Sizes	3”-64”	4”-63”
Laying Lengths	18’, 20’	40’
Pressure Class / Ratings	Rated up to 350 psi. Pressure Class 150, 200, 250, 300, & 350. Higher pressures may be designed.	Dependent on material code: 40 to 198 psi for PE 2406 or PE 3406; 51 to 254 psi for PE 3408.Rated up to 254 psi for 20-inch diameter and smaller. Due to manufacturers limited extrusion capabilities for wall thicknesses >3-inches, ratings may be progressively reduced with increasing sizes greater than 20-inches in diameter.
Method of Design	Designed as a flexible conduit. Separate design for internal pressure (hoop stress equation) and external load (bending stress and deflection). Casting tolerance and service allowance added to net thickness.	Flexible material; internal pressure design only. External load design is not covered by a standard.
Internal Pressure Design	Pressure Class: stress due to working pressure plus surge pressure cannot exceed the minimum yield strength of 42,000 psi ÷ 2.0 safety factor.	Pressure Rating: Stress due to working pressure cannot exceed the Hydrostatic Design Basis (1,600 psi) ÷ 2.0 safety factor (Hydrostatic Design Stress = 800 psi) for PE 3408. Any surge pressure compromises the safety factor.
Surge Allowance	Nominal surge allowance is 100 psi (based on an instantaneous velocity change of approximately 2 fps), however, actual anticipated surge pressures should be used.	Not Included. Surge pressures are allowed to compromise the “design factor” which results in a reduction in the safety factor below 2.0.
External Load Design	Prism load + truck load. Ring bending stress limited to 48,000 psi, which is 1/2 the minimum ultimate bending strength. Deflection is limited to 3% of the outside diameter of the pipe, which is 1/2 of the deflection that might damage the cement-mortar lining. The larger of these two thicknesses governs and is taken as the net thickness.	None discussed in standard.
Live Load	AASHTO H20, assuming a single 16,000 lb. concentrated wheel load. Impact factor is 1.5 for all depths.	None discussed in standard.

Table 3.5 Continued

Factor of Safety	Pressure Design: 2.0 (including surge) based on minimum tensile yield strength of 42,000 psi.	A "Design Factor" is used in the internal pressure design formula. This factor is simply the inverse of the more common "Safety Factor." This "Design Factor," in reality, is not a constant number. The design formula for hdpe pipe ignores surge pressures by merely increasing the "Design Factor," thereby, reducing the "Safety Factor," to compensate for them.
	External Load Design: 2.0 for bending based on minimum ultimate ring bending strength of 96,000 psi, or 1.5 for bending based on minimum ring yield bending strength of 72,000 psi. 2.0 for deflection for cement-mortar-lined pipe. Note: Actual safety factors are greater than the nominal safety factors due to the addition of the service allowance and casting tolerance in the design procedure.	Ignoring surge pressures, the "Design Factor" is 0.5 ("Safety Factor" is 2.0). Acknowledging surge pressures, the "Design Factor" is >0.5 ("Safety Factor" is < 2.0).
Specified Trench Conditions	Five specified laying conditions (Types 1-5).	None.
	Conservative E' and soil strength parameters listed. Type 1 (flat bottom trench, loose backfill) or Type 2 (flat bottom trench, backfill lightly consolidated to centerline of pipe) are adequate for most applications.	
Hydrostatic Testing	Each pipe tested to a minimum of 500 psi for at least 10 seconds at full pressure.	Only one pipe size from three size ranges (4- to 12-, 14- to 20-, and ≥ 24-inch) are subjected to an elevated temperature sustained pressure test semiannually. Also, only one pipe per production run may be subject to a quick burst test. A ring tensile test or a five-second pressure test can be substituted for this test.
Factory Tests	At least one sample during each casting period of approximately 3 hours shall be tested for tensile strength; must show minimum yield of 42,000 psi, minimum ultimate of 60,000 psi and a minimum elongation of 10%. At least one Charpy impact sample shall be taken per hour (minimum 7 ft-lb.), with an additional low-temperature impact test (minimum 3 ft-lb.) made from at least 10% of the sample coupons taken for the normal Charpy impact test.	Bend-back or elongation-at-break; once per production run. Ring tensile, quick burst, or fivesecond pressure test; once per production run.Melt flow index; once per day. Density; once per day. Carbon black content; once per production run.

Pipe Fittings: In the most simplest form, pipe fittings are the materials that are used to join pipes or used to provide junctions for branching pipes. There are numerous kinds of pipe fittings, the common ones being (www.superlit.com):

- Flanges (Figure 3.13)

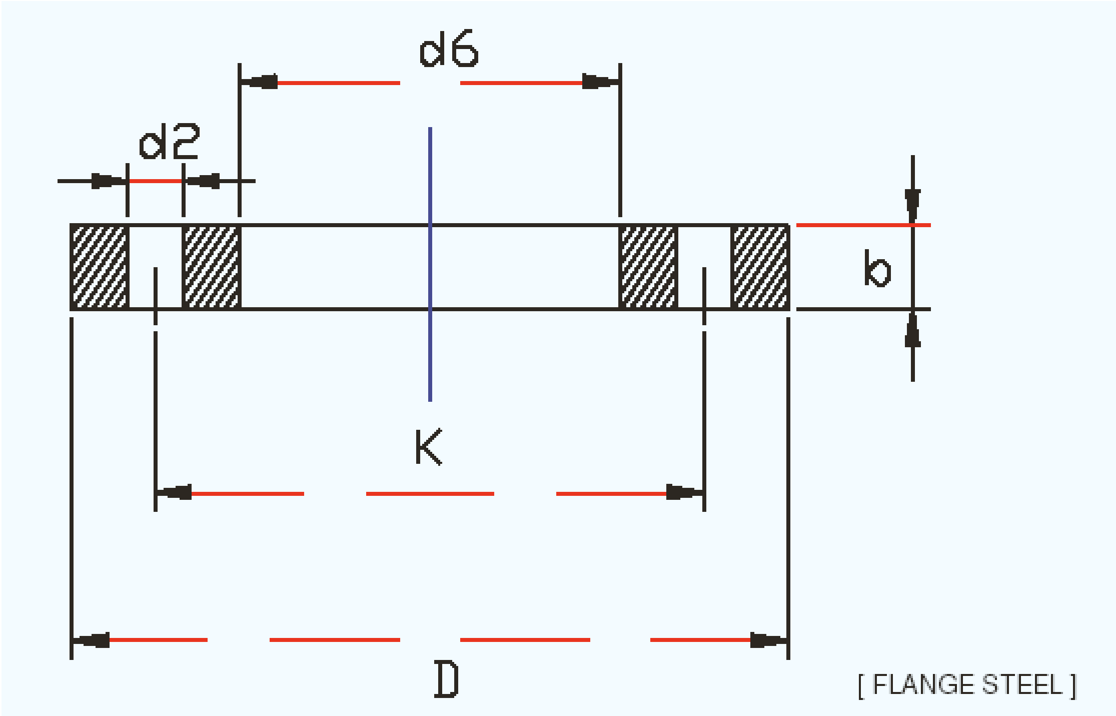

Figure 3.13: Flanges

- Bends (45°, 90°), to provide deflection from alignment (Figures 3.14, 3.15)

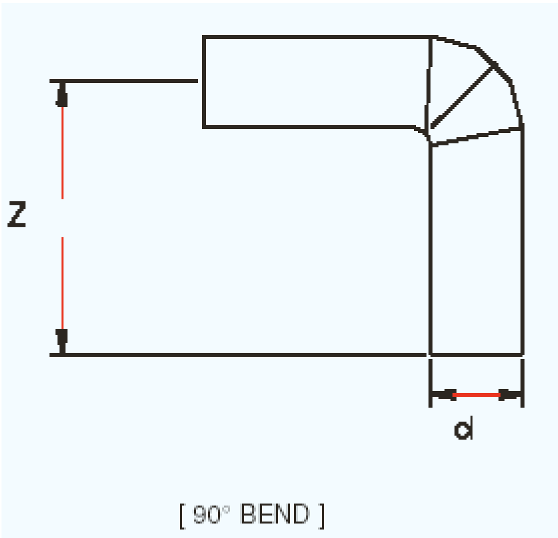

Figure 3.14: Bends (90°)

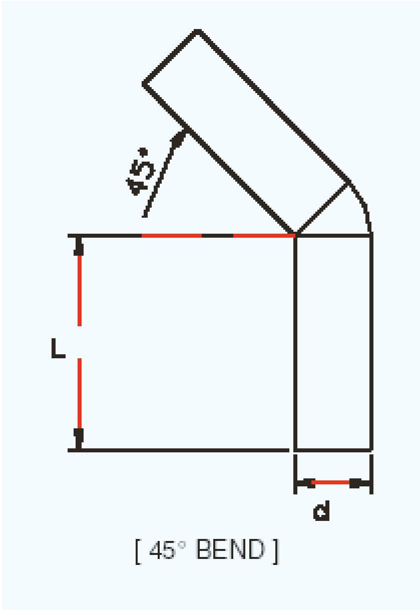

Figure 3.15: Bends (45°)

- Tees, to provide 90° junction (Figures 3.16, 3.17)

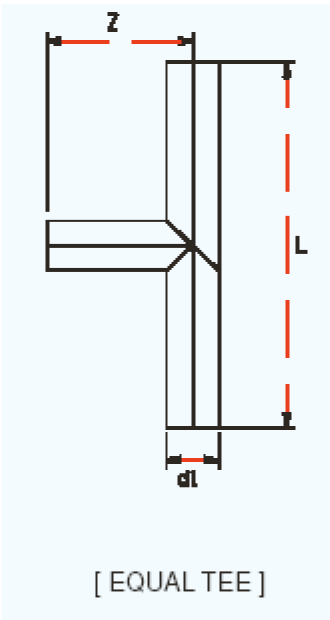

Figure 3.16: Equal Tee

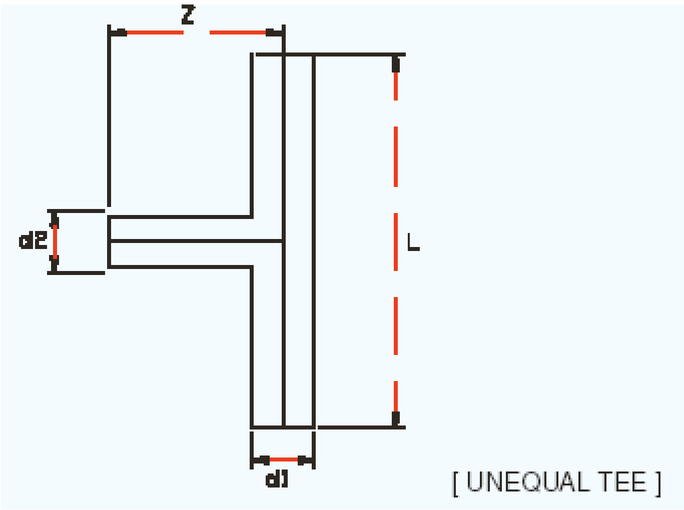

Figure 3.17: Unequal tee

- Reducers, to connect a larger diameter with a smaller one in series (Figure3.18)

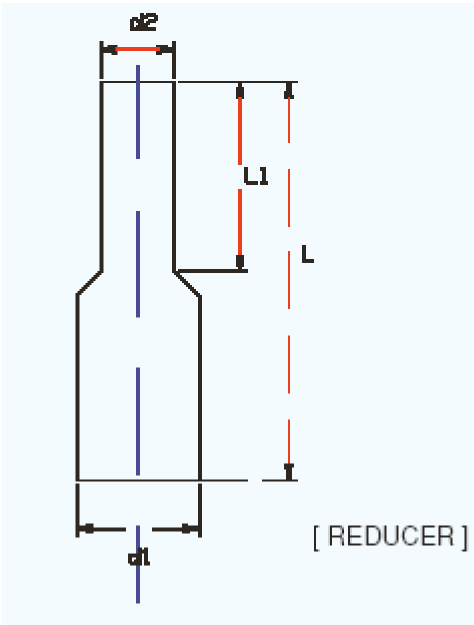

Figure 3.18: Reducer

Depending on the need, there are also other fittings such as:

- Flange Tees
- Blind Flanges
- Saddle service tees
- Hydrant Connections

- Adapters

The prices of fittings depends on the following:

- Material types of connecting pipes
- Required pressure strength
- Diameters of connecting pipes
- Methodology to connect pipes and fittings (e.g. for HDPE pipes connection with electrofusion or welding)

As an example, a simple junction is given in Figure 3.19.

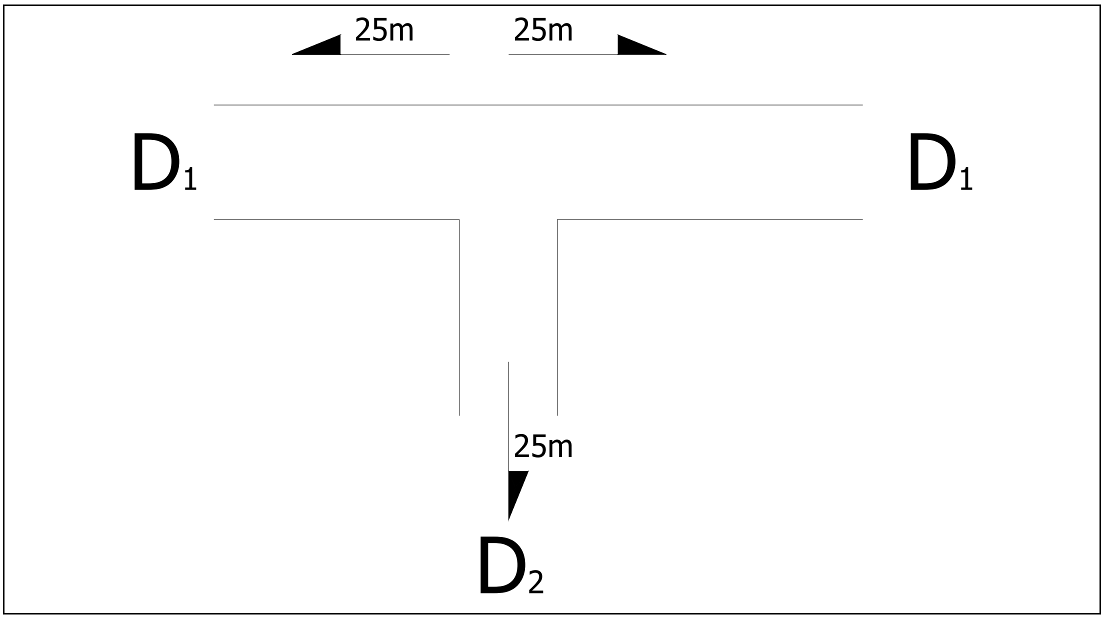

Figure 3.19: Example Fitting Layout (with unequal tee)

According to Unit Prices announced by Bank of Provinces (İller Bankası) and State Hydraulic Works (DSİ) for year 2004, the total cost of the system with various diameters are given in Table 3.6 and Figure 3.20

Table 3.6: The total cost of the system (fitting with unequal tee)

D1	D2	COST OF PIPES	COST WITH TEE
110	90	414.35 YTL	484.57 YTL
125	90	494.20 YTL	579.33 YTL
140	90	588.08 YTL	708.45 YTL
160	90	713.23 YTL	863.48 YTL
180	90	864.33 YTL	1,055.44 YTL
200	90	1,015.43 YTL	1,272.45 YTL
225	90	1,248.43 YTL	1,578.78 YTL
250	90	1,481.45 YTL	1,922.06 YTL
280	90	1,837.70 YTL	2,429.93 YTL
315	90	2,253.38 YTL	2,910.81 YTL

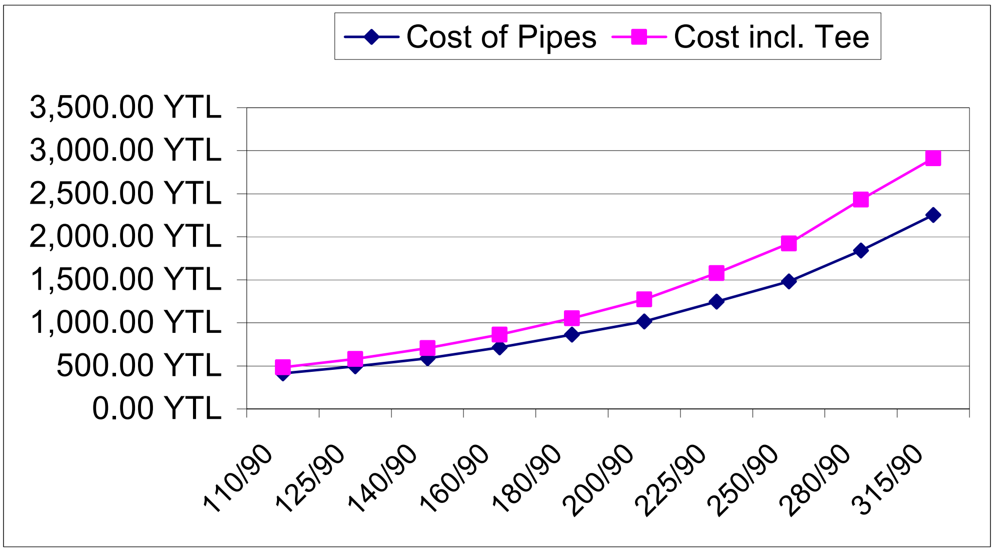

Figure 3.20: The total cost of the system (fitting with unequal tee)

As it is observed from Figure 3.20, the total cost may increase up to 30% with inclusion of the cost of tee.

In order to include the effect of fittings in the optimization procedure with any software below steps has to followed:

- Every fitting has to be selected as per the pressure class individually; there should be no over-design such as installing a SDR 7,4 and PN25 atm fitting for PE pipes where SDR 17 and PN10 atm is sufficient. Similarly, no under-design should be allowed to prevent damages.

- While selecting pipe sizes for the system, price of fittings should also be considered.

In WADISO, the price functions are input to the software as the price per length. However, as given above, the price of fittings are dependent on pressure classes and the diameters of pipes connected to them. This creates a vicious circle: in order to include the price of fitting, diameters have to be known, but the optimization, i.e. inclusion of fitting prices in price function, is performed to determine the diameters. As the result, since there is no mathematical relationship between the fittings and the pipes, it is almost impossible to consider effect of fittings during optimization with WADISO.

As the conclusion, in order to have a reasonable optimum solution with WADISO, designer should have a good knowledge on available pipe materials, their conformity to his project area, recent market prices, construction and installation technologies and their corresponding prices. For a general design of a water distribution system with WADISO, the following items can be included in price functions for the design of a system:

Table 3.7: Activities / materials for HDPE Price Function

EXCAVATION WORKS Trench excavation (without explosives) Fill Bedding & Compaction
PIPE RELATED Pressure Test Before Laying Connection of HDPE Pipes with Butt Welding Laying of HDPE Pipes HDPE Pipe material

Table 3.8 Activities / materials for Steel or Ductile Price Function

EXCAVATION WORKS
Trench excavation (with/without explosives)
Fill
Bedding & Compaction
PIPE WORKS
Pressure Test Before Laying
Welding
Inner insulation of welded ends
Outer insulation of welded ends
Laying
Price of pipe material
Cathodic protection (~2% of pipe price)

However, it should be kept in mind that the effects that cannot be included in price functions should be checked by the designer manually.

3.5.3.1 Price Functions for the Case Study

To use in the Case Study presented in Chapter 4, three types of materials are selected as suitable for the network and their corresponding price functions are built.

- HDPE (High density polyethylene)
- Steel Pipe
- Ductile Iron Pipe

To calculate the price function of each material in YTL/m, unit prices announced by Devlet Su İşleri (DSİ-State Hydraulic Works) and İller Bankası (Bank of Provinces) are used. Additionally, a market search has been performed including major pipe manufacturers and approximate market prices of pipe materials are gathered. Further to above, unit prices given by United States Environmental Agency as the result of a broad survey performed within USA are also used.

HDPE Pipes Price Function: Standard diameters available for HDPE Pipes vary between 16mm up to 1600mm depending on the pressure class. Because the pressures are less than 100m, pipes with PN10 - SDR11 are selected for the study. Price analyses are performed for pipe diameters 90, 110,125, 140, 160, 180, 200, 225, 250, 280, 315, 355, 400, 450, 500, 560 and 630mm.

According to information gathered from hydraulic designers, typical trench cross-section for HDPE Pipes is given in Figure 3.21. From Figure 3.21, calculated excavation, bedding and fill volumes are given in Table 3.9, for the mentioned diameters.

To calculate the corresponding construction related works, unit prices of State Hydraulic Works are used for the following items:

- Trench excavation (without explosives)
- Fill
- Bedding & Compaction

Regarding pipe related works, the following items are taken from both State Hydraulic Works and Bank of Provinces Unit Price Books:

- Pressure Test before Laying
- Connection of HDPE Pipes with Butt Welding
- Laying of HDPE Pipes
- HDPE Pipe resistant to 10 atm

As discussed in Section 3.5.3, there are various methods for joining pipes. In this study, because all the pipes are of the same material and assuming that all pipes have the same wall thickness, jointing method is assumed as butt welding. Unfortunately, due to reasons g iven in the same section, price of fittings and jointing costs at fittings cannot be included in the optimization.

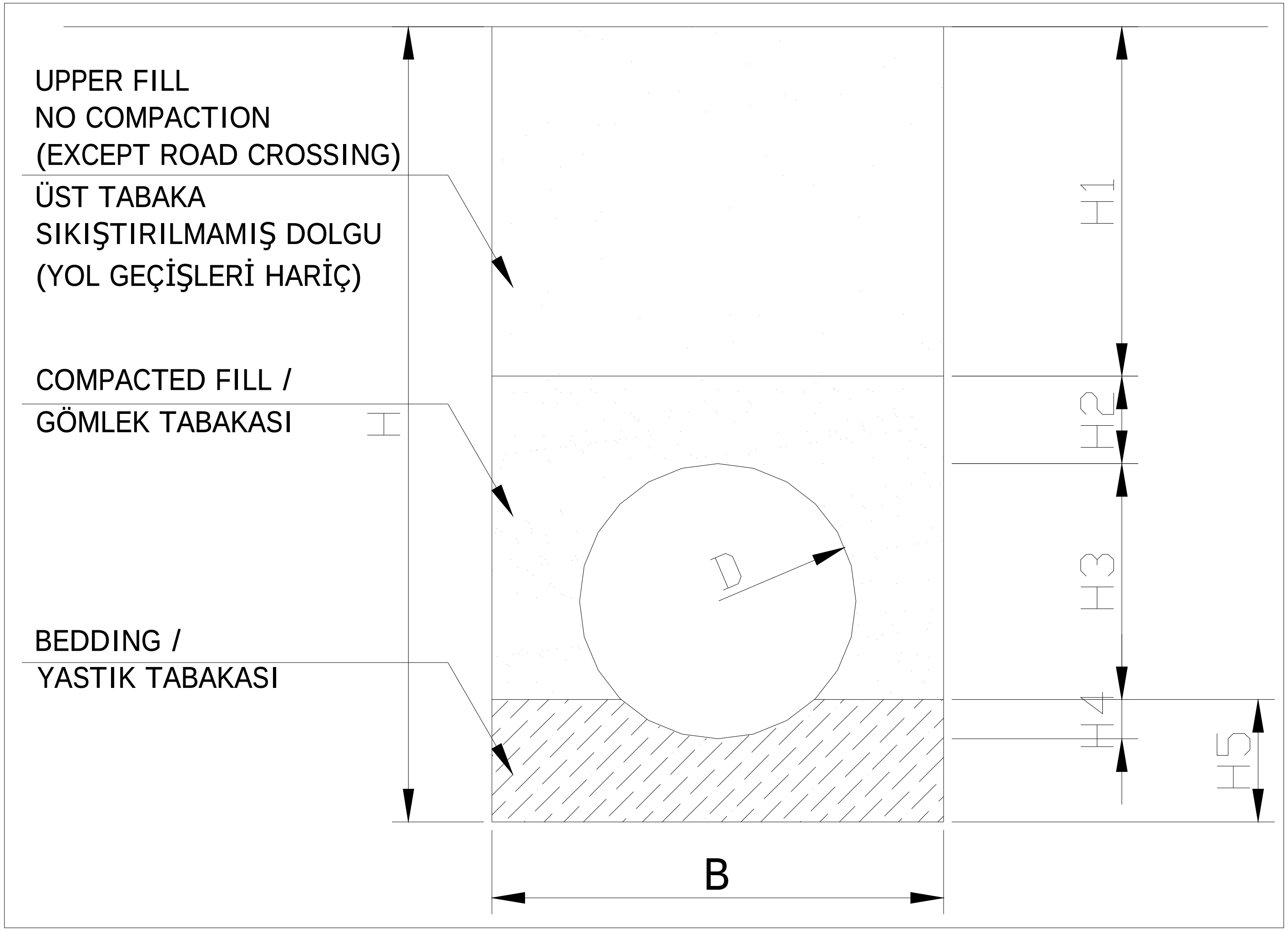

Figure 3.21: Typical trench cross-section for HDPE Pipes

Table 3.9: Trench dimensions and excavation, bedding and fill volumes for HDPE Pipes

DIMENSIONS							VOLUME (for 1 meter length)		
Diameter	B	H1	H2	H3	H4	H5	EXCAVATION	BEDDING	FILL
mm	cm	cm	cm	cm	cm	cm	m3	m3	m3
90	39	100	20	7	2	11	0,54	0,04	0,49
110	41	100	20	9	2	12	0,58	0,05	0,52
125	43	100	20	10	3	12	0,61	0,05	0,55
140	44	100	20	12	2	12	0,63	0,05	0,57
160	46	100	20	14	2	12	0,67	0,06	0,60
180	48	100	20	15	3	13	0,71	0,06	0,62
200	50	100	20	17	3	13	0,75	0,07	0,65
225	53	100	20	19	4	13	0,81	0,07	0,70
250	55	100	20	21	4	14	0,85	0,08	0,73
280	58	100	20	24	4	14	0,92	0,08	0,77
315	62	100	20	27	5	15	1,00	0,09	0,83
355	66	100	20	30	6	15	1,09	0,10	0,89
400	70	100	20	34	6	16	1,19	0,11	0,95
450	75	100	20	38	7	17	1,31	0,13	1,03
500	80	100	20	42	8	18	1,44	0,14	1,10
560	86	100	20	48	8	18	1,60	0,15	1,20
630	103	100	20	54	9	19	1,99	0,20	1,48

As a summary, HDPE pipe price functions for diameters between 90~630mm are calculated as given in Table 3.10. These prices include the cost of pipe material, laying, excavation, bedding, fill and connection of pipes. Hazen-Williams C coefficient for friction loss calculation is taken as 150.

Table 3.10: Price Function for HDPE Pipes (according to State Institutes Unit Price Books)

Diameter	Price
(mm)	(YTL/m)
90	11,64
110	14,76
125	18,26
140	22,51
160	28,12
180	34,48
200	40,88
225	51,08
250	61,19
280	76,08
315	94,01
355	118,75
400	146,52
450	185,84
500	223,27
560	281,31
630	351,83

As an alternative to unit prices announced by State Institutes, price functions are re-calculated considering data gathered from manufacturers. However, it should be noted that the used material prices are listing prices, which means that they may further decrease depending on the extent of the project, transportation distance etc. Although the material prices are taken from the market, no price analysis could be done for either for construction or other pipe related items. The cost of each item changes from project to project depending on many factors such as geological formations encountered, traffic and public density, available time scope, available machinery of the contractor etc. Thus, remaining unit prices, i.e. unit prices except the pipe material price, are kept unchanged. Price functions calculated according to market data are given in Table 3.11. It is observed that these unit prices are lower than the ones obtained from state unit price books.

Table 3.11: Price Function for HDPE Pipes according to market data

Dia	Price
mm	**YTL/m**
90	9,87
110	12,75
125	15,27
140	18,08
160	22,47
180	26,98
200	32,08
225	39,63
250	47,53
280	61,40
315	76,54
355	95,27
400	118,41
450	148,12
500	179,26
560	222,33
630	282,06

Steel Pipes Price Function: An alternative to HDPE pipes given in the aforementioned unit price books is steel pipes. However, there were two difficulties: available unit prices for steel pipes in State Hydraulic Works unit price book starts from pipes with diameter equal to 500mm. and secondly the minimum pressure class is 16atm. To find the unit prices for the diameters used in the previous optimizations, a polyline is fitted to available data and extrapolation is done for lower diameters. The pressure class is kept as 16atm since there is no data available regarding the relationship of 10atm pressure class and 16atm pressure class prices of same diameters. Material unit prices obtained by this method are given in Table 3.12 and Figure 3.22.

Table 3.12: Material unit prices for steel

Dia	Price
mm	YTL/m
80	8,52
100	11,05
125	14,4375
150	18,075
200	26,1
225	30,4875
250	35,125
300	45,15
350	56,175
400	68,2
450	81,225
500	95,25
600	126,3
650	143,325
700	161,35
750	180,375
800	200,4
850	221,425
900	243,45
1000	290,5

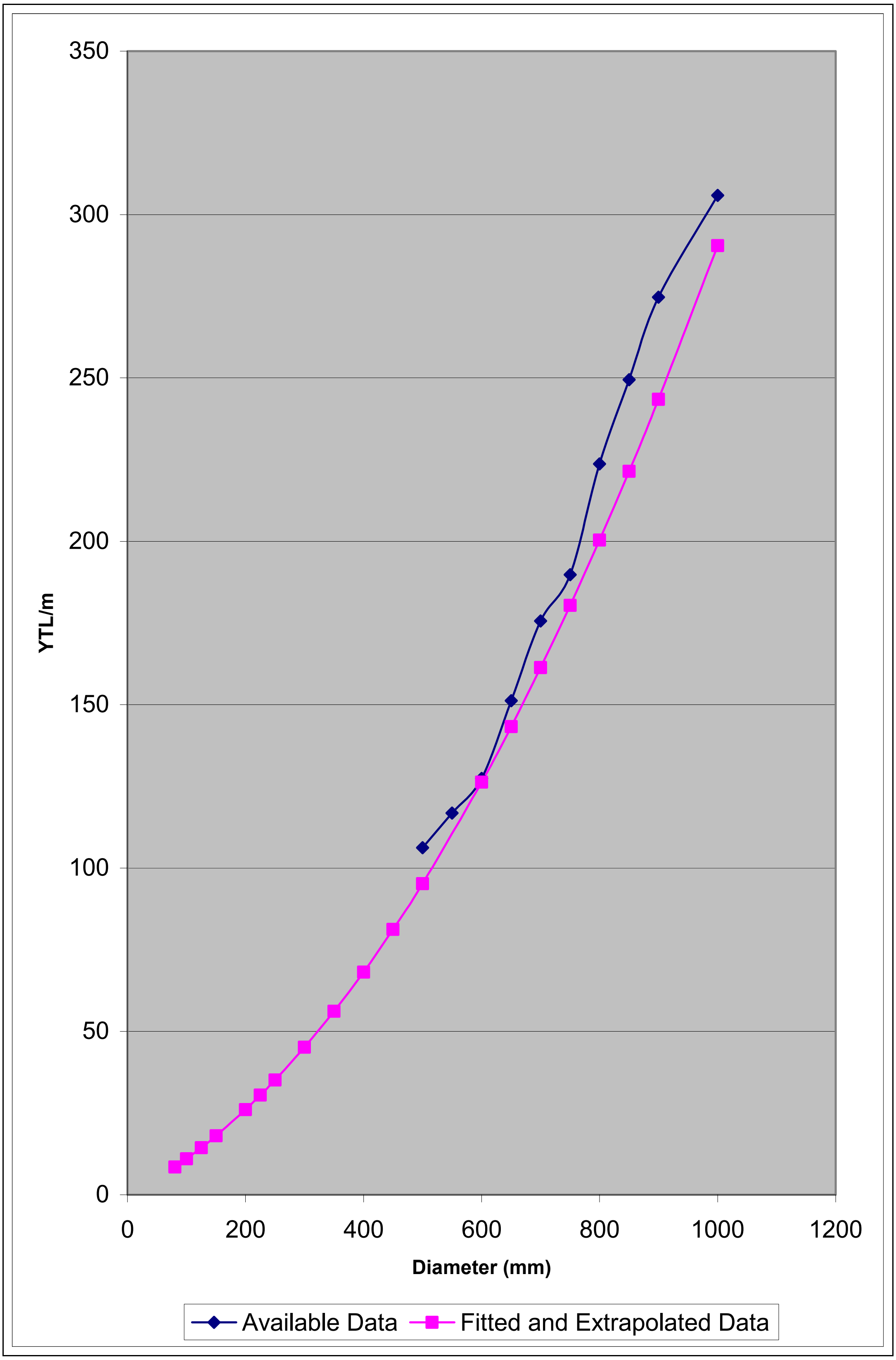

Figure 3.22: Material unit prices for steel

Similar to HDPE, pipes, typical trench cross-section for steel pipes is gathered from professions and given in Figure 3.23. From Figure 3.23 calculated excavation, bedding and fill volumes are given in Table 3.14 for diameters between 100~600mm. Construction related works for steel pipes are taken same as those for HDPE pipe, but pipe related items are changed / added as follows:

- Pressure Test Before Laying
- Welding
- Inner insulation of welded ends
- Outer insulation of welded ends
- Laying
- Steel Pipe resistant to 16 Atm
- Cathodic protection (~2% of pipe price)

Unit price of inner and outer insulation items are calculated by extrapolation similar to material pipe prices. Cathodic protection item is taken as app. ~2% of pipe price after discussions with experienced engineers. No fitting or collar cost is included in the price functions. Hazen-Williams C coefficient for friction loss calculation is taken as 130. Resulting unit prices are given in Table 3.13.

Table 3.13: Unit prices for steel pipes

Diameter	Price
mm	YTL/m
100	15,84
125	20,10
150	24,82
200	34,56
250	45,29
300	57,34
350	70,59
400	82,57
450	98,27
500	114,54
600	151,39

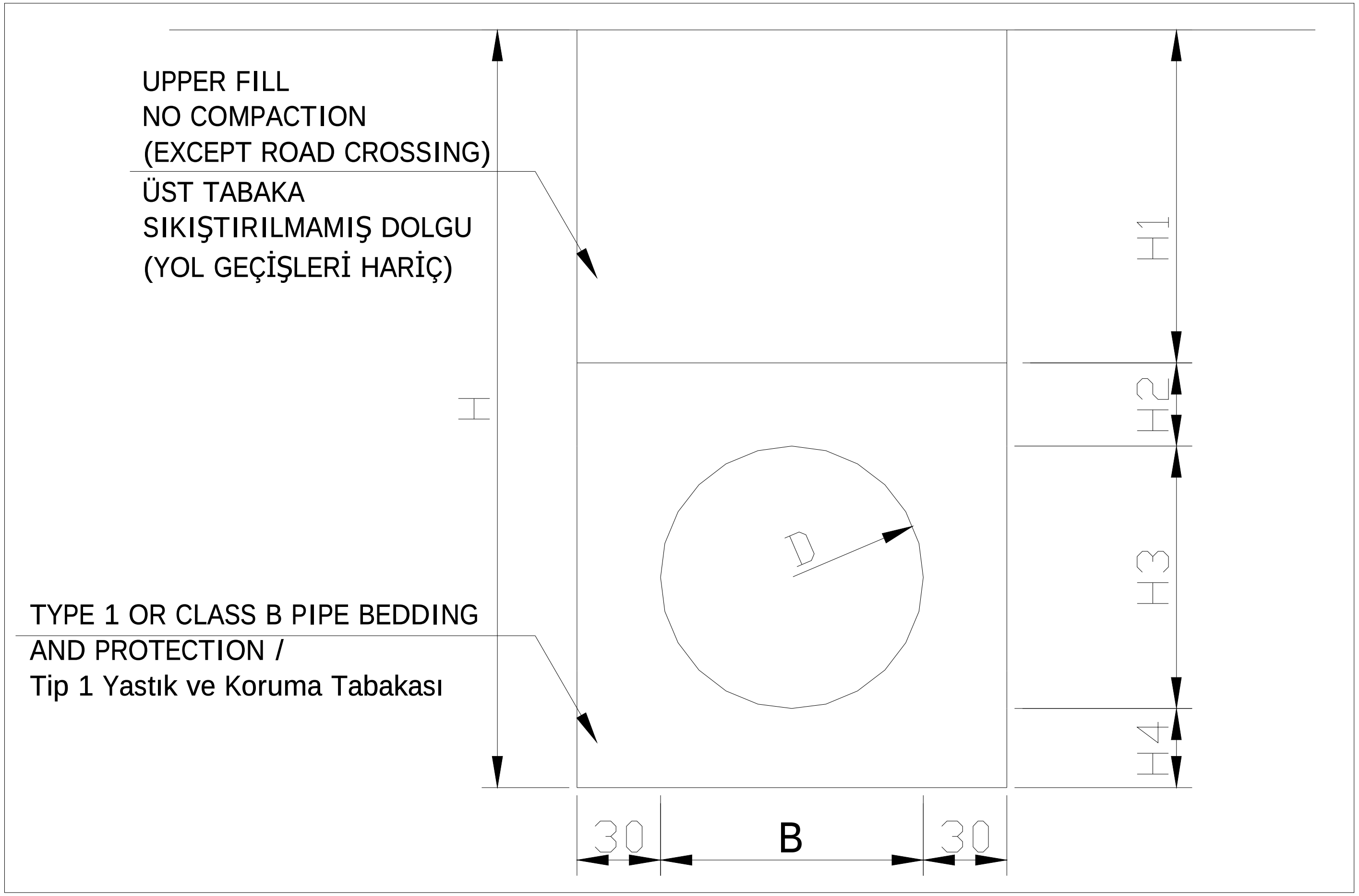

Figure 3.23: Typical trench cross-section for steel pipes (units in cm)

Table 3.14: Trench dimensions and excavation, bedding and fill volumes for Steel

DIMENSIONS						VOLUME (for 1 meter length)		
Diameter	B	H1	H2	H3	H4	EXCAVATION	BEDDING	FILL
mm	cm	cm	cm	cm	cm	m3	m3	m3
80	68	100	30	8	25	1,11	0,43	0,68
100	70	100	30	10	25	1,16	0,45	0,70
125	72,5	100	30	12,5	25	1,21	0,49	0,73
150	75	100	30	15	25	1,28	0,52	0,75
200	80	100	30	20	25	1,40	0,59	0,80
225	82,5	100	30	22,5	25	1,46	0,63	0,83
250	85	100	30	25	25	1,53	0,66	0,85
300	90	100	30	30	25	1,67	0,74	0,90
350	95	100	30	35	25	1,81	0,82	0,95
400	100	100	30	40	25	1,95	0,91	1,00
450	105	100	30	45	25	2,10	1,00	1,05
500	110	100	30	50	25	2,26	1,09	1,10
600	120	100	30	60	25	2,58	1,29	1,20

Price Functions for Ductile Iron Pipes: Ductile iron pipes has always been a primary choice of designers for water distribution networks. To perform the optimization with ductile iron pipes, price function analysis are performed using same items with the steel pipes. Unfortunately, no material unit price for ductile iron pipes is announced by either State Hydraulic Works or Bank of Provinces. Thus, a market search is conducted and material unit prices are gathered. For the pipes, using the same price items given for steel pipes, price functions for ductile iron pipes are obtained as given in Table 3.15. The unit prices include internal lining of cement (ISO4179) by centrifugal process and external coating by metallic Zinc (ISO8179), and then coverage by bituminous (asphalt) paint (BS 3416). Similar to steel pipes, Hazen-Williams C coefficient for friction loss calculation is taken as 130 also for ductile iron pipes. No fitting or collar cost is included in the price functions.

Table 3.15: Price Function for Ductile Iron Pipes

Dia	Price
mm	YTL/m
100	16,19
125	17,51
150	19,04
200	24,98
250	31,43
300	37,86
350	45,96
400	51,78
450	65,88
500	71,27
600	93,57

Price Functions of EPA (Environmental Protection Agency – USA): In 1999, the U.S. Environmental Protection Agency (EPA) conducted the second Drinking Water Infrastructure Needs Survey. The purpose of the survey is to estimate the documented 20-year capital investment needs of public water systems. The survey used questionnaires to collect infrastructure needs from medium and large water systems. EPA mailed questionnaires to all 1,111 of the nation's largest water systems serving more than 40,000 people, and to a random sample of 2,556 of the 7,759 medium systems serving over 3,300 people. As part of the survey, EPA developed cost models to assign costs to projects for which systems lacked adequate cost documentation. The data used to develop the cost models generally include materials, construction, design, administrative and legal fees, and contingencies. In addition, it was important to obtain cost data for systems of all sizes in order to minimize the extent to which costs had to be extrapolated beyond the range of the data points. (EPA, 2001). As the result of this, price functions are gathered as given in Table 3.16.

Table 3.16: Price Functions given by EPA (Transformed from US Dollar/ ft into YTL/m)

Diameter	FROST	NON-FROST
mm	YTL/m	YTL/m
150	159,43	101,80
200	156,80	107,45
250	170,25	123,59
300	183,73	139,76
350	233,46	177,49
400	283,16	215,25
450	316,30	252,74
500	349,46	290,26
600	355,74	331,62

Comparison of Price Functions: The resultant price functions based on various materials are given in Figure 3.24. As observed from Figure 3.24, for small diameters, price functions are very close to each other. However, as diameter increases, steel and ductile iron pipes are more advantageous to HDPE pipes. Thus, in this range, i.e. for diameters larger than ~250mm, the designers has to make a choice: they can install HDPE pipes with higher prices to get benefit from its advantageous properties such as low friction loss, easy installation due to low weight etc, or they can prefer ductile iron pipes which is both cheaper and has other advantages as given in Section 3.5.3. The price function announced by EPA includes transportation, contingencies, design, administrative and legal fees and many other costs that are not directly dependent on pipe diameter, but indirectly affect the project cost. These should also be included in the price function analyses performed within the context of this study, however, because very few detail information is available, it was not possible.

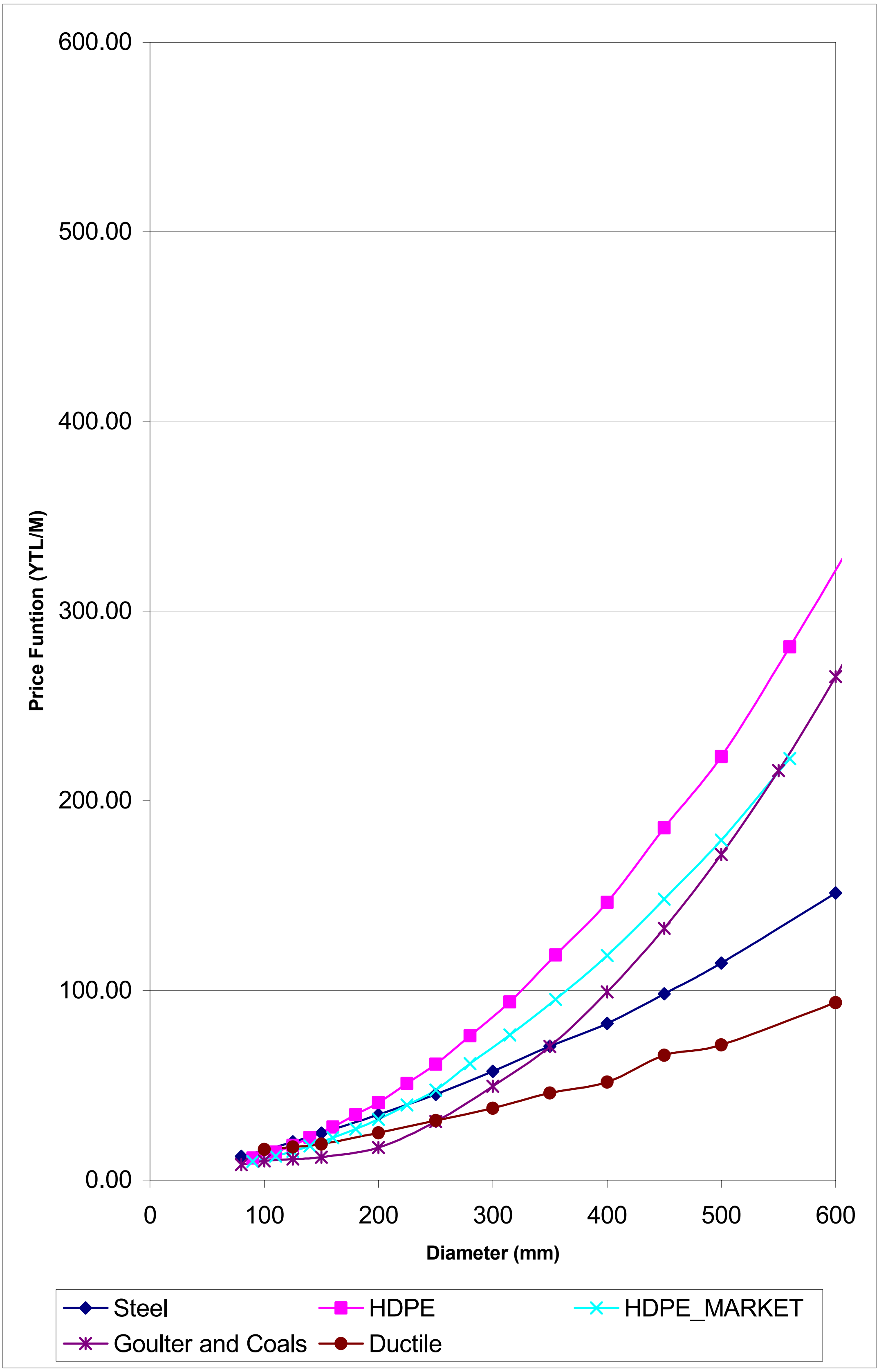

Figure 3.24: Price Functions for various materials

Thus, only items that directly affect the cost of pipe laying are included and price function of EPA is not used in optimization studies.

3.5.4 Loading Patterns and Pressure Constraints

A set of flow outputs or inputs at the nodes is defined as the loading pattern. The loading pattern that should govern the design of a water distribution system is not a definite phenomenon. Whether the system should be designed considering the most critical instant which occurs rarely during its service time or it should be designed considering average day conditions which frequently occurs is questionable. The system can be designed considering the peak hour demands. Alternatively, it can be designed considering a huge fire within the network. A system designed with these loadings will have large diameters. However, normal day demands of a system are much lower than these loadings. Having lower demands in large pipes will cause reduction of velocity, which in turns results in low quality water. As the velocity decreases, the microscopic particles within the water tend to settle and ruin the quality of water. On the other hand, if a system is designed considering average day demands, the system capacity will not be sufficient against extreme events such as fires. No one can take the responsibility of human loss due to insufficient pressures at fire hydrants during a huge fire. Consequently, a system should be designed in such a way that it should be capable of meeting all of the above criteria.

A guideline for this problem has been given by Walski (1995). He suggested using the following demand patterns in accordance with the aim of design:

Master Planning: Master planning is done to determine the size and installation date of major capital projects for a water distribution system. In this type, pipe sizing is almost completely controlled by the magnitude and location of future municipal and industrial water use. Because the sizes of larger pipes (>400mm) are generally controlled by daily demands, not fireflows, sizing has to be checked against peak-hour or peak day usage. The minimum pressure that must be met needs to be set higher than 140 kpa (20psi). The sizes selected in master planning shall not be regarded as final decisions, but rather as rough estimates of the best size if all of the assumptions made in the master planning prove to be true.

Preliminary Engineering for Transmission Mains: During master planning, routes are approximate, which should be studied in detail during preliminary design. Laying pipe in cleared land is much less expensive than in congested urban centers with many buried utilities. Piping decisions are often based on such cost differences. Additionally, during master planning, the area corresponding to a model node can be fairly large. In preliminary design, this changes because the location of water users can be refined further. More importantly, the locations of connections between large transmission lines and smaller neighborhood distribution pipes must now be precisely determined. For small distribution components, the probability of an outage occurring concurrently with the design fire demand is very low, so the system can be modeled as if all the pipes are in service. In case of large transmission mains, the probability of the peak demand occurring concurrently with the outage of a system component is much larger, and the effect of such an outage must be considered in pipe sizing.

Subdivision development: When land is subdivided for residential development, industrial parks, shopping malls, the problem is significantly different from master planning and preliminary design. The sizing is almost completely controlled by fire flow requirements and most pipes will be of minimum diameter.

In WADISO, the system design is performed considering steady state analysis. The designer can assign up to five different loading patterns. Different loading patterns can include variations in

1. Outputs at one or more nodes
2. Minimum pressure requirements at one or more nodes
3. Different specifications for pump operation, including efficiency and the percentage of time it may run under certain loading patterns.

Among the specified patterns, one may be the peak flow expected during a normal day, while another may represent the necessary flows necessary to fight a fire at specific node(s). The program will consider all specified loading patterns and will determine the pipe sizes that are capable of handling flows and minimum pressures for all patterns. In addition to flow outputs, different minimum pressure patterns can be specified for different loading patterns.

Pressure constraints are the minimum pressures defined by the designer to be met or exceeded in the final solution at as many nodes as desired, for each of the loading patterns under investigation. Pressure constraints are dependant on the aim of the loading pattern. For example, minimum pressure of 25~30m head at all nodes, which corresponds to feeding approximately to a 3-storey building without extra pumping, is the general design criteria for peak hour and maximum day demand while 30m is required at a specific node at which fire fighting takes place and only 10m head is sufficient at the remaining nodes.

3.5.5 Pump and Tank Inclusion

Optimization algorithm within WADISO allows designer to include pumping costs. As the result of the pressure distribution, the flow rates through the pump and the pump head are obtained. This permits the computation of pumping cost if the percentage of time the pump is running at this operation point is specified. As discussed, it is possible to specify several loading patterns, each with its own percentage of time. The program will then calculate and accumulate the present value of the pumping cost and add it to the pipe cost.
The pumping cost is calculated from the following equations:

$$Power(kW) = \frac{\rho g Q H}{\mu} \quad \textbf{(3.10)}$$

where ρ= mass density of liquid

g=gravitational acceleration (9,81m/s^2)

Q= pumping flow rate (m^3/s)

H= Pump head (m)

μ= Pump efficiency

The user defines the cost per kW and the program calculates the overall pumping cost considering the percentage time of running in the design life.

In the optimization routine of employed by WADISO, the cost of water storage (i.e. tanks and reservoirs) can be included in the optimization, in addition to pipe cost and energy cost. Similar to pumping cost, there exists a trade-off between pipe cost and storage cost. In general, smaller, less expensive pipe size combinations will require larger, more expensive storage tanks for balancing peaks in the water demand whereas larger diameters will increase the pipe cost and also results in low quality water.

To calculate tank cost, similar to pipe price function, user defines price function that describes the cost per unit storage with up to 25 volumes sizes. The program enumerates all of the possible combinations of tank sizes in connection with pipe combinations.

3.5.6 Pareto Optimal Solutions

The optimal solution proposed by any algorithm may be unfeasible for a number of reasons, due to political decisions, reduced reliability etc. In addition, non-optimal (but near-optimal) solutions may display attributes that make these solutions attractive. For instance, a solution may display a slightly higher than optimal cost, but it may provide significantly better pressure characteristics than the optimal solution, though both solutions meet the pressure requirement. Another solution may violate the pressure requirement by a small amount, yet it may provide for substantial cost savings. It may then be of interest to invest in a slightly more expensive solution or sacrifice somewhat on the required pressure (Walski et al., 1990)

WADISO uses partial enumeration technique, namely it tries all of the possible combinations under certain restrictions explained above. During these trials, user can give such parameters to the program that it can keep some more combinations that are not optimum, but near optimum. With the aid of this, WADISO allows one to generate such a set of alternative non-inferior solutions that have the property of being Pareto Optimal.

A Pareto optimal solution is one in which one of the measures of optimality cannot be improved without making another measure worse. For the problem of pipe network optimization specifically, there are two cases:

1. For solutions that meet pressure constraints and are within the cost tolerance, a solution is Pareto optimal (non-inferior) if there is no other solution that can give equal or greater pressure at lower cost.
2. For solutions that do not meet the pressure constraints but are within the pressure tolerance, a solution is Pareto optimal (non-inferior) if there is no other solution that can give equal or greater pressure at lower cost.

There can be many Pareto optimal solutions for a specific network problem.

CHAPTER 4

CASE STUDY

4.1 AIM OF THE STUDY

The aim of this study is to illustrate use of an optimization technique, i.e. WADISO, on an already constructed real world network and show the discrepancies between the traditional network design and design using an optimization software. The case study area is North 8 (N8) pressure zone of Ankara Municipality Water Distribution System (Merzi et al. 1998a, 1998b). Optimization software is WADISO (Water Distribution Network Analysis), which uses partial enumeration technique developed by Gessler (1985).

4.2 WATER DISTRIBUTION SYSTEM OF ANKARA

Ankara being the capital and second largest city of Turkey has a population of 3.203.362 according to year 2000 census (DİE – State Statistical Institute). Considering that its population was 2.583.963 in year 1990, there has been 21,48 % increase in the last 10 years. This great development indicates that there is a migration from rural areas to Ankara city center and in the future, this will continue. According to ASKİ (Ankara Water and Sewage Management), water consumption per capita is approximately 250 lt/day/capita as per year 2000 data. As water supply is one of the primary missions of the state institutions, Ankara has a relatively large water supply and distribution system.

Ankara water supply and distribution system is taking raw water from the following dams:

- Kurtboğazı Dam
- Çamlıdere Dam
- Akyar Dam
- Eğrekkaya Dam
- Bayındır Dam (via pumping)
- Çubuk-2 Dam

The main Water Treatment Plant is located in İvedik, which is composed of four units each having a capacity of 564.000 m^3/day. With this capacity, İvedik treatment plant is within the top ten treatment plants among European countries. Pre-stressed concrete main lines with diameters equal to 2000mm coming from Kurtboğazı Dam and Çamlıdere Dam are carrying raw water to this plant. Two other treatment plants are Bayındır Treatment Plant for Bayındır main line with 30.000-m3/day capacity and Pursaklar Treatment Plant for Çubuk main line with 75.000 m^3/day.

Water distribution system of Ankara is divided into five main pressure zones:

- Central and Western Supply Zone (e.g. Sincan, Etimesgut, Eryaman)
- Northern Supply Zone (e.g. Keçiören)
- Eastern and Southeastern Supply Zone (e.g.Mamak)
- Southern Supply Zone (e.g. Çankaya)
- Southwestern Supply Zone (e.g. Çayyolu, Ümitköy)

Each main pressure zone is composed of several pressure zones by approximately 40-50m elevation intervals. Central and Western Zone is divided into two pressure zones as C2 and W2. Northern Supply Zone is divided into eight pressure zones named N3-N10. Eastern and Southeastern Zone has seven pressure zones at east named E3-E9 and four at southeast named SE3-SE7. Southern Supply Zone has ten pressure zones named S3-S12 and South Western Supply Zone has four zones named SW3-SW6 (Figure 4.1) (YILDIZ, 2002).

The Northern Zone, the study area is located, takes water from P1 Main Pumping Station. P1 is the main pumping station that takes water directly from İvedik Treatment Station and distributes to other sub-zones. Water from P1 main station is carried to P2, which is the main pumping station of Northern Zone. (Figure 4.2, 4.3).

4.3 STUDY AREA

4.3.1 N8 Pressure Zone

The study area, N8 Pressure Zone (Figure 4.3) is located at the end of north line of Ankara Municipal Water Supply System. In administrative terms, it is located in Yenimahalle and Keçiören counties. There are four districts fed from N8 sub-pressure zone, which are Yayla, Sancaktepe, Şehit Kubilay districts of Keçiören and Çiğdemtepe district of Yenimahalle. There are approximately 25.000 people living in these districts.

N8 pressure zone is selected for case study due to its simple network system as well as its relatively homogenous residents. The pressure zone is composed of one pumping station P23, one main line going from pump to tank, T53, and another main line feeding northern zone. This configuration is the ideal one for any research purposes. The water consumption within the zone is mostly residential type. There are almost no significant industrial or commercial activities located within the boundaries of N8. The socioeconomic level of the residents can be accepted as low income; they are distributed uniformly in the pressure zone (Eker, 1998). Additionally, with the aid of SCADA system installed in the pump station and the tank, real water consumption values are readily available. With the help of homogeneity of the system and the data from SCADA, it is possible to determine nodal demands with negligible error.

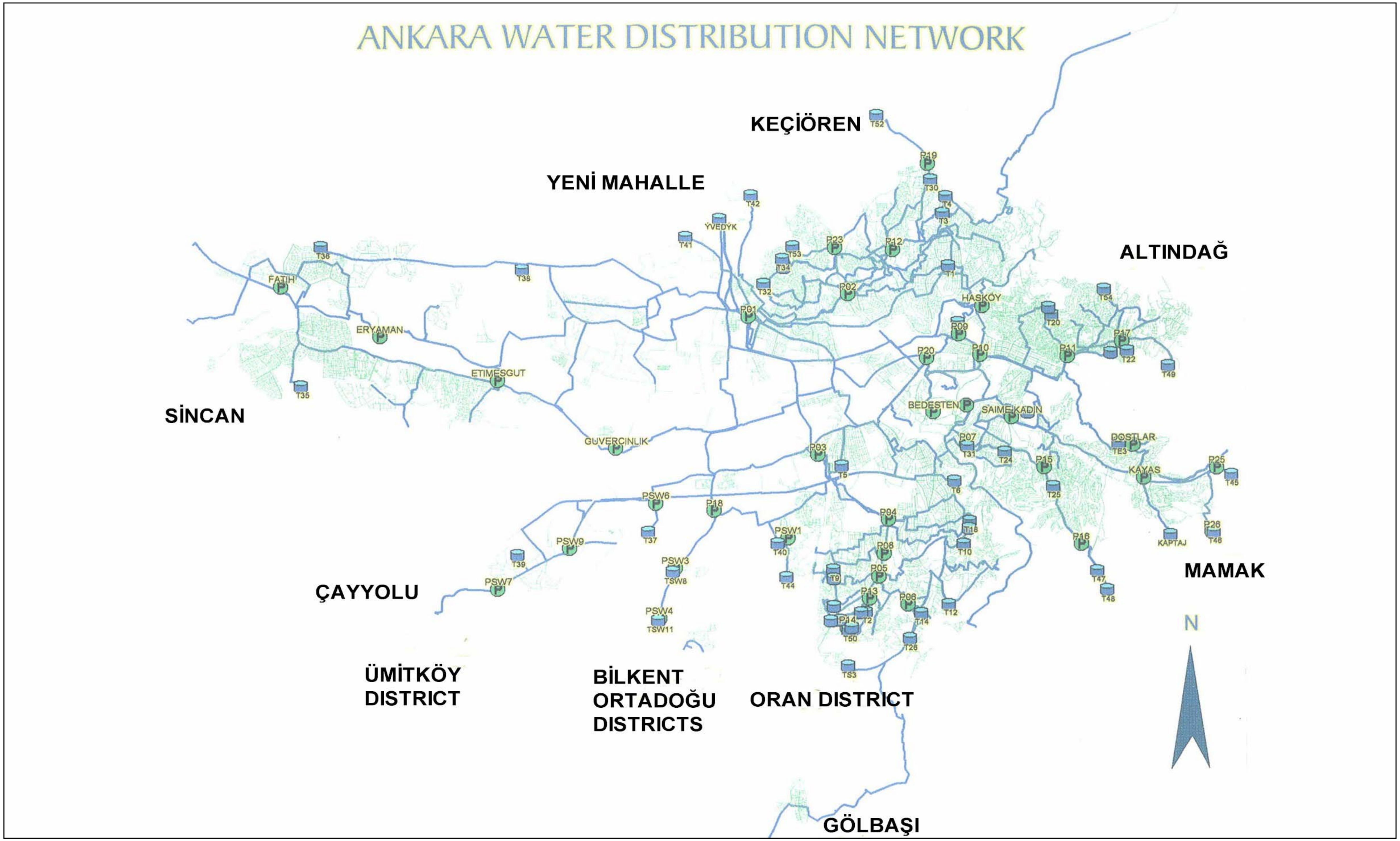

Figure 4.1: Water Distribution System of Ankara

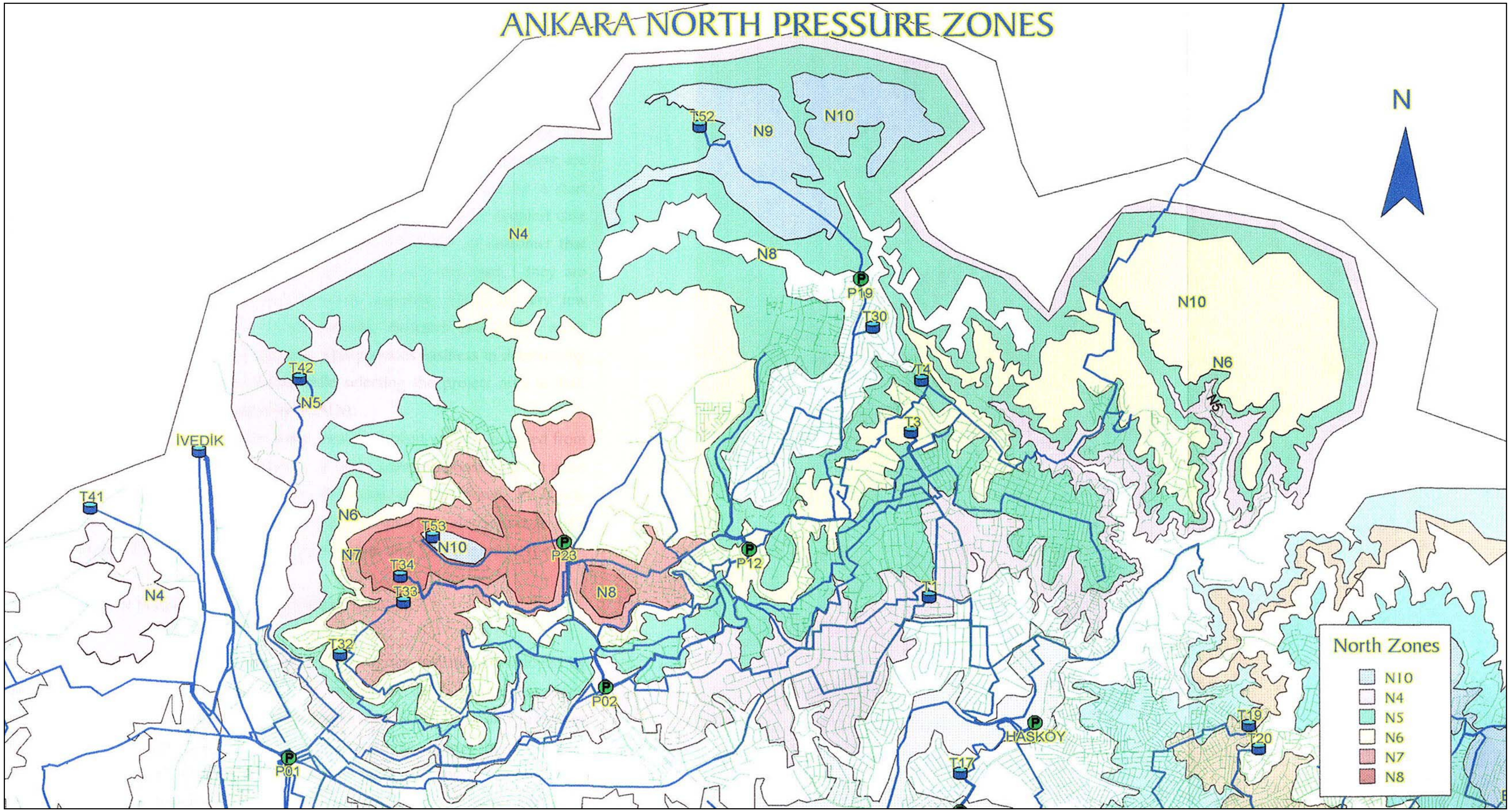

Figure 4.2: Ankara Subpressure Zones in North

Figure 4.3: N8 Pressure Zone

4.4. HYDRAULIC MODEL

4.4.1. Layout of the Pipes in N8 Pressure Zone

The layout of the existing system of N8 Pressure Zone is gathered from ASKİ, including all characteristics of the pipes, nodes, tank and the pump such as diameters, elevations, tank dimensions, pump curves etc.

4.4.2. Nodal Demands

In order to determine nodal demands to assign at the nodes of the study area, namely N8 Pressure Zone, previous studies on this area are searched and nodal demands of **August 16, 2001**, which is one of the critical months of the year due to high temperature and consequently high water usage, are selected, and nodal demands are assigned. Design load is Q_{peak}=115,75 lt/s.

4.4.3. Analysis of Existing System

All the system data are entered into WATERCAD 6.0 and the existing system is analyzed. As seen from Table 4.1 and Figure 4.4, there are some nodes (25 out of 337) with pressure values below 30m, which is the minimum design criteria as stated in Chapter 2. However, because they are not too low, i.e. around 20, it can be concluded that in the design stage, these nodes might have been sacrificed for the good of the area from cost point of view and no further improvements to increase the pressure values at the said locations were taken.

Further to above, it is observed that the main problem of existing system is not only the low pressure at specific locations, but also the low velocity in the pipes around almost the whole system. The minimum flow velocity in the pipes should not be less than 0,5 m/s to avoid poor water quality. Unfortunately, analysis revealed that the velocity in the pipes within N8 Zone is too low, where 0,07 m/s is the average velocity.

Table 4.1: Nodes with pressure values below 30m.

Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)
J-296	1,142.08	0.0699	12.339
J-289	1,136.56	0.174	17.131
J-270	1,133.79	0.5172	19.842
J-295	1,133.40	0.6408	21.001
J-271	1,132.42	0.3225	21.199
J-274	1,130.71	0.452	22.915
J-249	1,130.26	0.3675	23.357
J-250	1,129.48	0.2914	24.13
J-319	1,128.55	0.2259	25.082
J-269	1,128.46	0.3448	25.164
J-314	1,127.59	0.3537	26.018
J-315	1,127.38	0.3032	26.244
J-251	1,126.41	0.2925	27.192
J-198	1,126.76	0.2532	27.559
J-207	1,125.73	0.2155	28.645
J-291	1,125.02	0.0563	28.687
J-272	1,124.63	0.3963	28.969
J-294	1,125.31	0.0721	29.075
J-252	1,124.43	0.2913	29.166
J-256	1,124.17	0.1925	29.425
J-199	1,124.87	0.4785	29.488
J-206	1,124.78	0.2026	29.586
J-204	1,124.58	0.1991	29.781
J-205	1,124.58	0.1346	29.783
J-208	1,124.55	0.1274	29.829

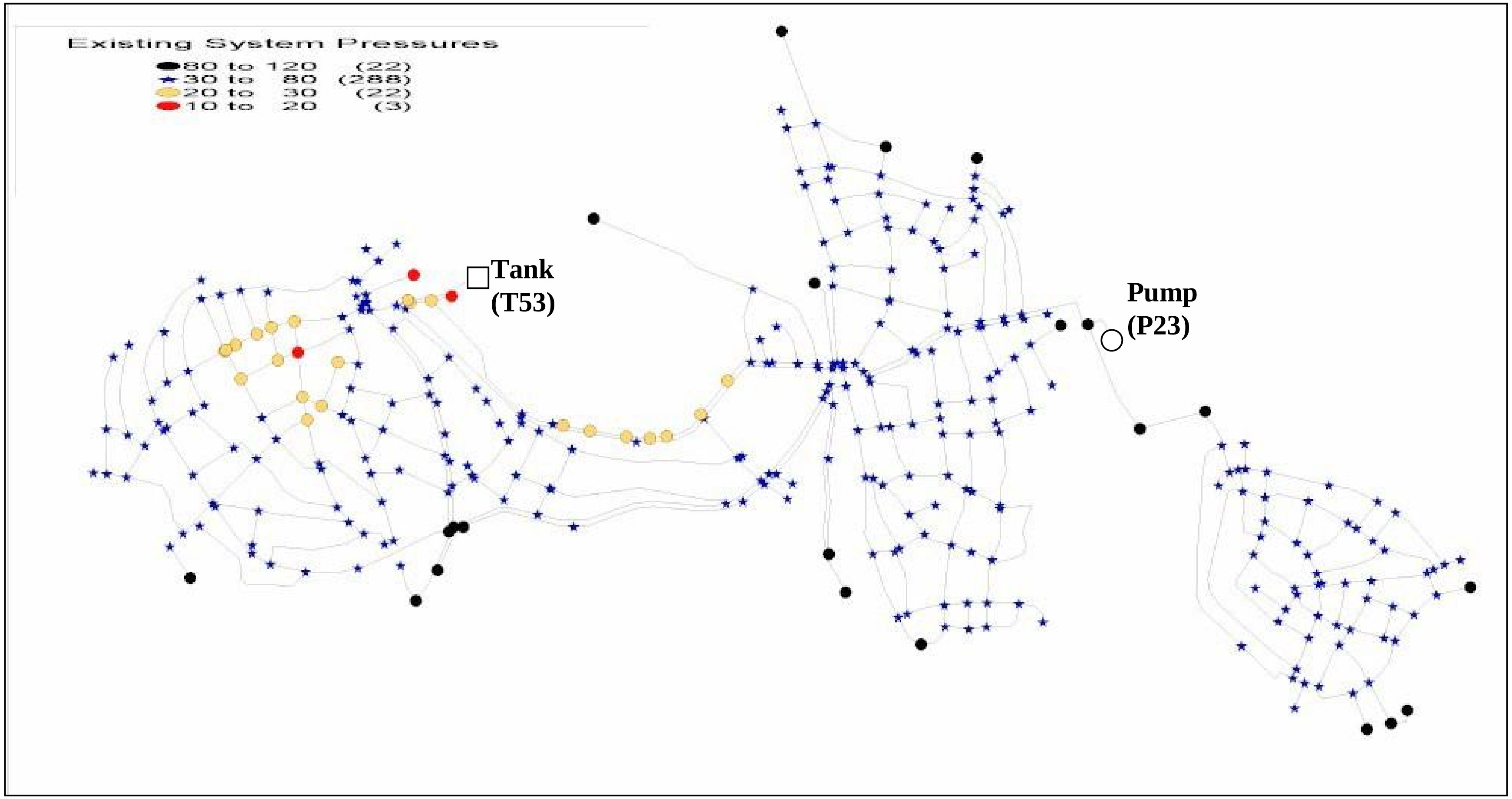

Figure 4.4: Pressure Distribution in Existing System

4.4.4. Optimization of the Existing System

4.4.4.1. Grouping of the Pipes Considering Whole System

The very first step of optimization of the system by use of WADISO is the grouping of pipes, namely, selecting similar pipes and assigning one pipe size to them. Considering the principals of grouping given in Chapter 3.5.1 (serial pipes, parallel pipes, pipes feeding same node etc), existing N8 pressure zone is analyzed. Obviously, the main line going from pump P23 to tank T53 forms Group 1 and while the other main line feeding northern area forms Group 2. Similarly, main lines within sub-pressure zones forms separate groups. After grouping of the main lines, branching lines are studied and pipes going in parallel in the same sub-pressure zone form separate groups. In short, 72 No. groups are obtained for use in the optimization.

As stated in Chapter 2, the aim of grouping pipes is to reduce computation time. However, with the aid of researchers from WADISO S.A., it is concluded that if the system would be run with 72 groups with each having 3 or more candidate pipe sizes, it would take almost 10^{30} years, almost infinity, to finish the computations with today's desktop computers. Consequently, the system has to be skeletonized in order to decrease pipe groups.

4.4.4.2 Skeletonization of the Existing System

To skeletonize a system, such as equivalent parallel pipes by changing the remaining diameters and/or friction coefficients will result in pipe diameters having values other than commercially available ones such as 113mm. Because the aim of the skeletonization in this thesis study is only to reduce number of pipe groups to allow further computations of optimization, starting computations with diameters 113mm will be not feasible.

Then, the main lines of the existing system having diameter equal to or greater than 150mm are identified and kept in the system. The resulting layout is given in Figure

4.5, yellow pipes being the pipes that should be removed (i.e. not included in optimization).

As seen from Figure 4.5, the system is not a looped network which threatens the results of optimization. In order to provide loops, some pipes with smaller diameters are also introduced (Green pipes in Figure 4.6) and finally the layout of skeletonized system is obtained as shown in Figure 4.6.

After obtaining the layout of the skeletonized system, it is time to distribute nodal demands of collapsing pipes. To perform this operation following steps are applied:

. Dead end pipes are identified and the nodal demands at the dead ends are carried to the other ends. (Figure 4.7)

. If a node is **not** on a path that is directly branching from the skeletonized system, it is transferred into the in reverse proportion of the connecting pipes. (Figure 4.8)

. If a node is on a path that is directly branching from the skeletonized system, it is transferred into the branching node. (Figure 4.9)

Completing all these steps for the entire network, skeletonized system with transferred nodal demands at each node is obtained, by which the total demand of the main system is equal to that of skeletonized system.

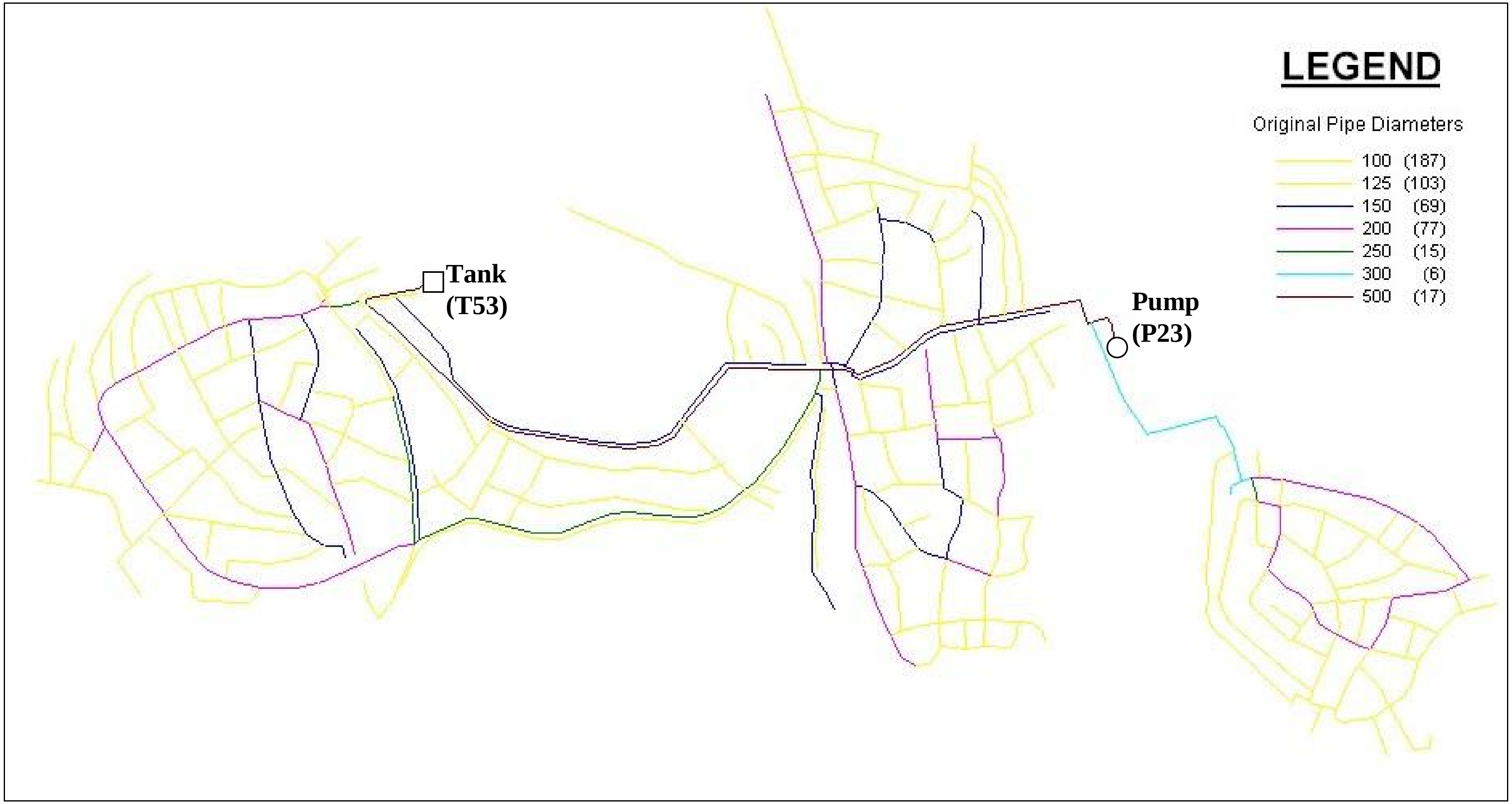

Figure 4.5: Pipes with diameter equal or greater than 150mm.

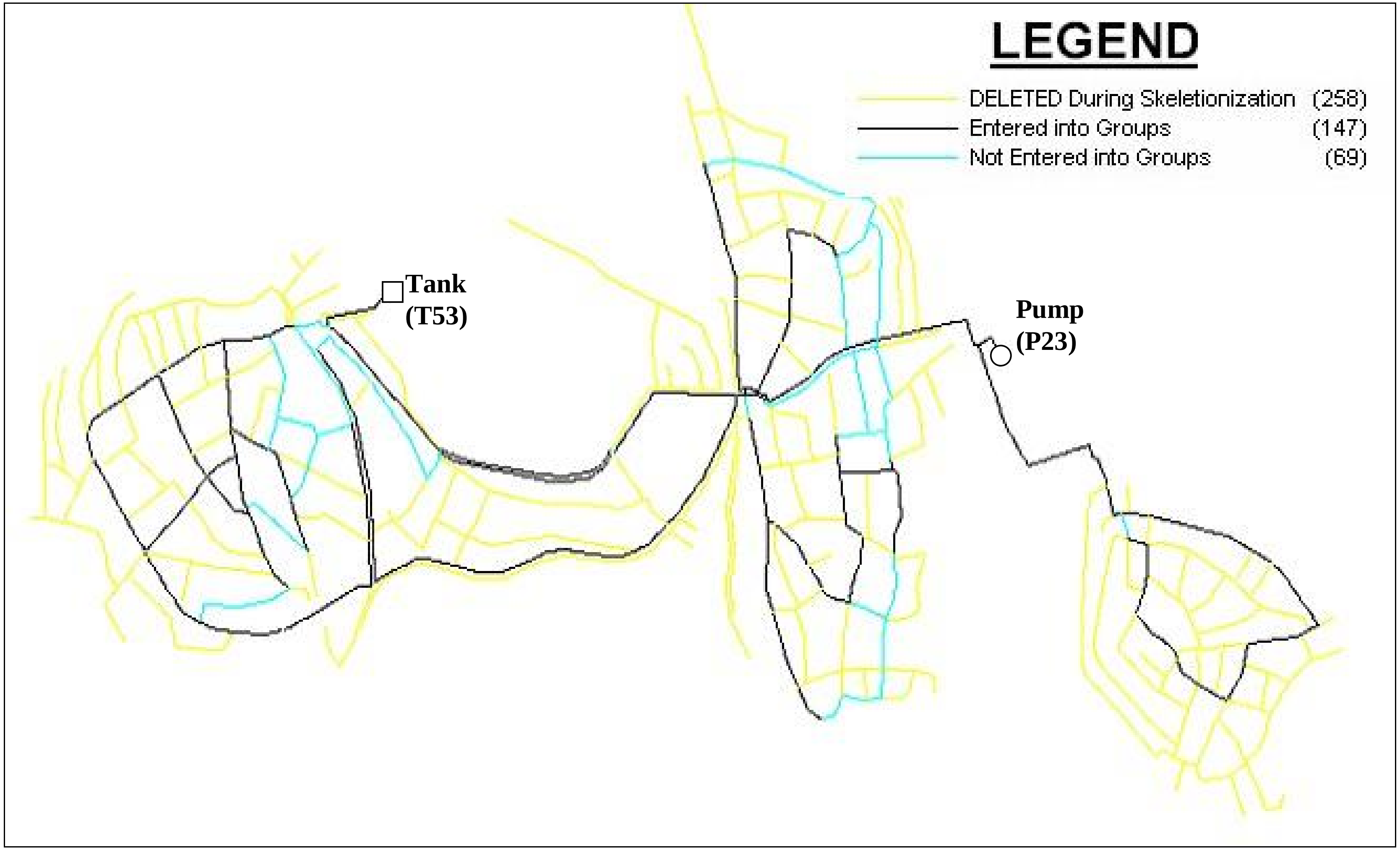

Figure 4.6: Skeletonized Layout of N8 Pressure Zone

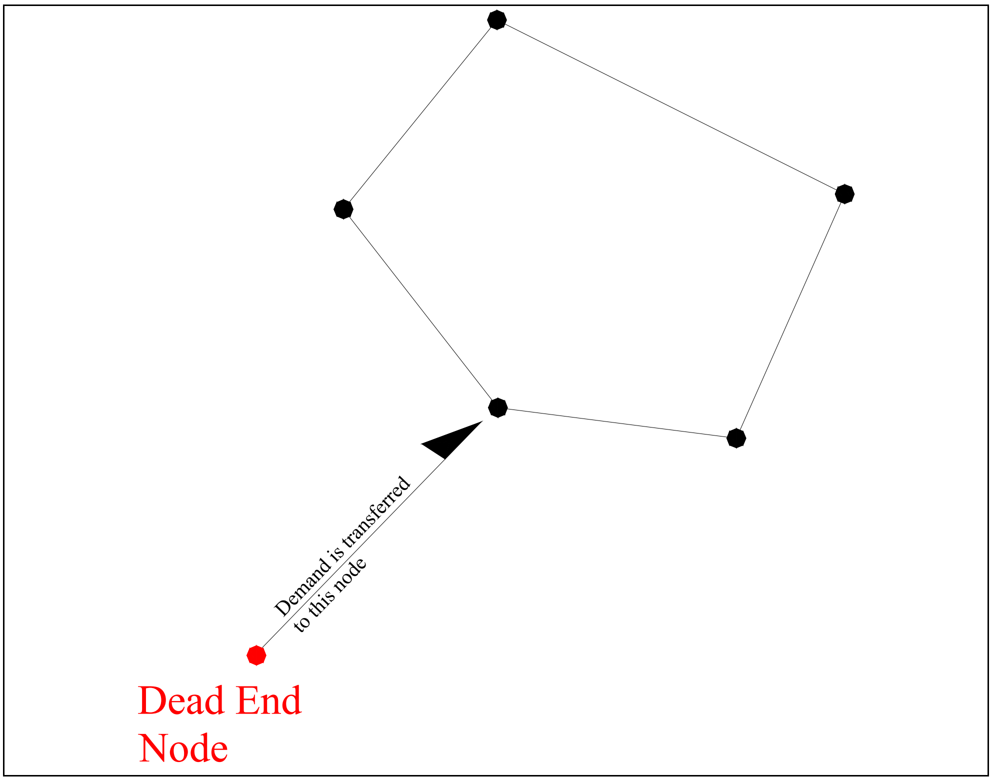

Figure 4.7: Demand Transfer of a Dead End Node

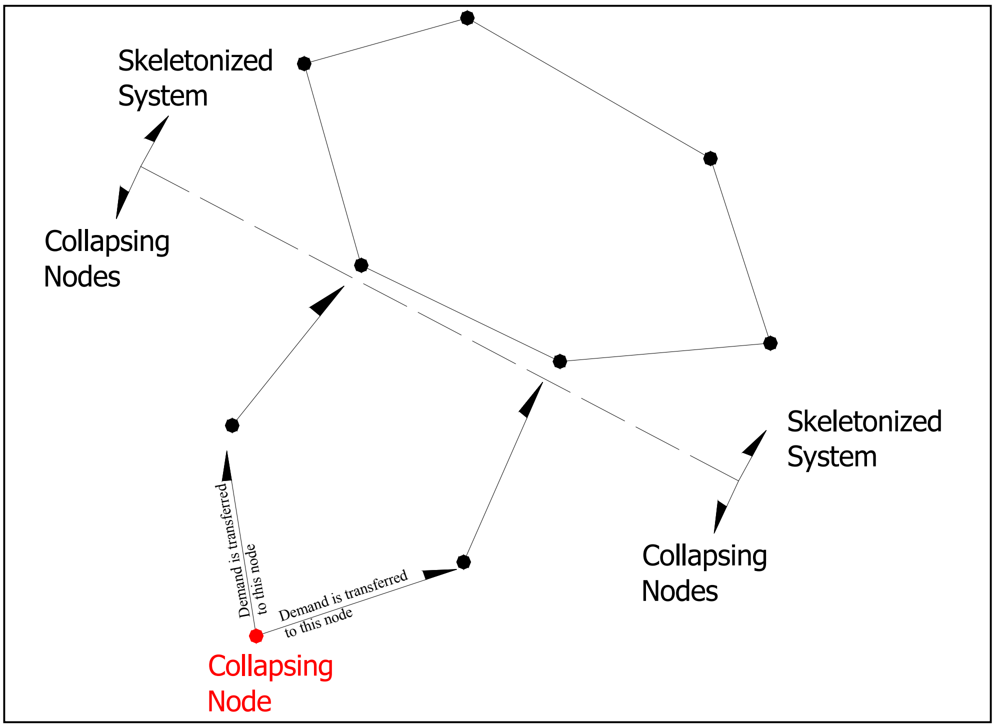

Figure 4.8: Demand Transfer of a Node That is NOT ON THE PATH

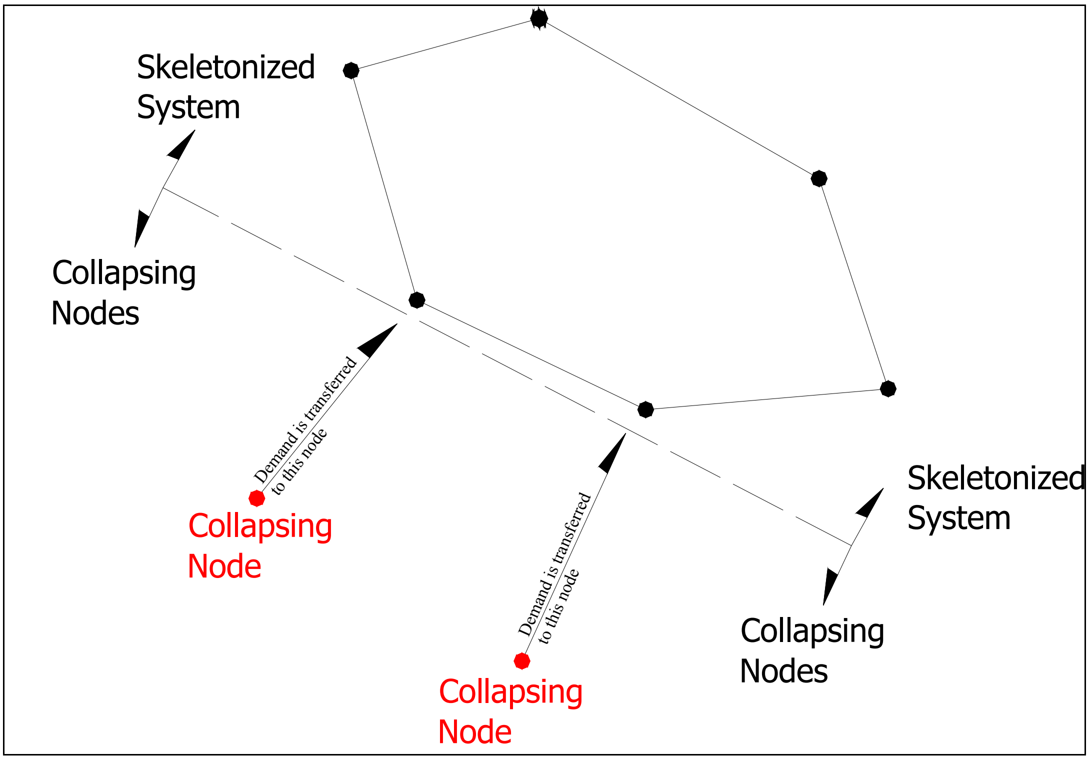

Figure 4.9: Demand Transfer of a Node That is ON THE PATH

4.4.4.3 Grouping of Pipes for the Skeletonized Network

The grouping of pipes within skeletonized network is initiated by grouping of the main lines forming individual groups. The result is seven groups. As discussed previously, in order to reduce computation time, number of pipe groups should not exceed 15, which is a constraint resulting from WADISO. Thus, remaining pipes, i.e. pipes with diameters equal to either 125mm or 100mm, are studied very carefully in order to find the most critical ones. After this, remaining eight Groups are formed and first step of optimization is completed (Figure 4.10, Table 4.2). As can be noted from Figure 4.10, there are some pipes that are not introduced in the optimization process (yellow ones, mostly with diameter equal to 125mm or 100mm); they are not contained in any group and their diameters remain unchanged. However, since those remaining pipes have already smaller diameters, this does not have a significant effect on the results.

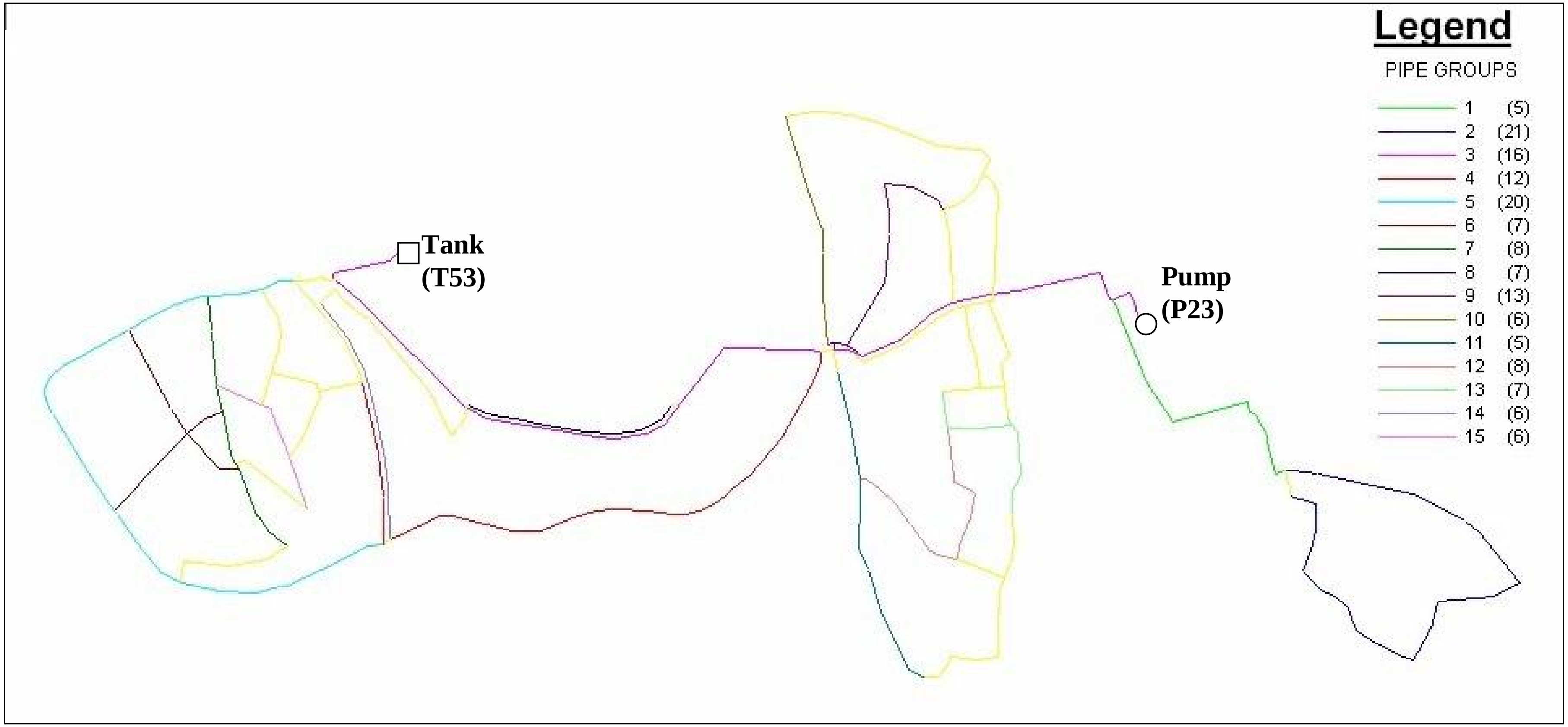

Figure 4.10: Pipe Groups of Skeletonized Network

Table 4.2: Pipe Groups of Skeletonized Network

	GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6	GROUP 7	GROUP 8	GROUP 9	GROUP 10	GROUP 11	GROUP 12	GROUP 13	GROUP 14	GROUP 15
PIPES IN THE GROUP	2	12	1	251	348	377	379	301	111	102	237	201	192	462	442
	3	15	125	272	349	382	384	302	149	103	240	202	193	463	443
	4	17	126	273	354	391	424	303	152	104	249	212	194	464	453
	10	30	127	274	358	435	431	304	153	105	263	215	195	465	454
	11	31	128	279	367	436	432	305	154	137	266	216	196	466	460
		42	158	299	368	439	433	306	156	166		261	205	470	461
		43	172	318	371	440	438	307	157			262	206		
		46	174	321	372		441		159			265			
		50	177	326	376				160						
		55	291	457	387				161						
		56	292	467	388				162						
		59	308	469	392				171						
		61	309		396				173						
		65	412		399										
		66	480		416										
		74	481		418										
		75	998		419										
		82			420										
		88			427										
		92			428										
		93													

4.4.4.4. Candidate Pipe Sizes

After grouping of pipes, it is time to assign candidate pipe sizes for every individual group. Similar to number of groups, number of candidate pipe size for a group has also significant effect on the computation time, the more the candidate sizes the more computation time. Thus, every group has to be studied very carefully and unnecessary candidate sizes should be eliminated at the beginning.

For the first run, it is decided to give three candidate pipe sizes for each group, one being the existing diameter, one size higher and one size smaller. As an example, the main line going from pump to tank with existing diameter equal to 500mm that also forms Group No 3, is assigned candidate pipes sizes of 400mm, 500mm, and 600mm. The aim of this procedure is to determine whether the system is over-designed or under-designed. After determination of this, more pipe sizes are assigned in order to find the optimum pipe size for each group (Refer to Section 3.5.2).

Table 4.3 shows candidate pipe sizes for each group for the first run to determine if the system is over-designed or under-designed. Table 4.4 shows the candidate pipe sizes for the final run.

4.4.4.5. Price Functions

The main objective of optimization is being to assign the most economical diameters for every pipe; one of the crucial points of the whole process is to assign correct price functions to each diameter. A small error on this step may ruin the whole result. As an example, if the price function of 200mm pipe is assigned very close to 100mm pipe, the software will assign 200mm. Then, the result will be most probably an over-designed system with pipes having 200mm diameter where 100mm would be sufficient. As a summary, the price functions should reflect the real world situation as much as possible.

Table 4.3: Candidate Pipe Sizes to determine if the system is over-designed or under-designed.

	GR 1	GR 2	GR 3	GR 4	GR 5	GR 6	GR 7	GR 8	GR 9	GR 10	GR 11	GR 12	GR 13	GR 14	GR 15
CANDIDATE PIPE SIZES	250	150	400	200	150	100	125	125	125	150	150	125	150	125	150
	300	200	500	250	200	125	150	150	150	200	200	150	200	150	200
	350	250	600	300	250	150	200	200	200	250	250	200	250	200	250
EXISTING PIPE SIZES	300	200	500	250	200	125	150	150	150	200	200	150	200	150	200

Table 4.4: Candidate Pipe Sizes for the final run

	GR 1	GR 2	GR 3	GR 4	GR 5	GR 6	GR 7	GR 8	GR 9	GR 10	GR 11	GR 12	GR 13	GR 14	GR 15
CANDIDATE PIPE SIZES	200	125	200	125	100	100	125	125	125	150	150	100	150	125	150
	150	100	250	150	125	125	150	150	150	200	200	125	200	150	200
	125		300	200	150		100	100	100	100	100	150	100	100	100
	100		400	250											
EXISTING PIPE SIZES	300	200	500	250	200	125	150	150	150	200	200	150	200	150	200

In this section of case study, price functions determined by **Goulter and Coals** (1986) has been used. The price functions that are not given are obtained by simple interpolation (Table 4.5 and Figure 4.11)

Table 4.5: Price Function given by Goulter and Coals

Diameter (mm)	80	100	125	150	200	250	300	350
Price Function ($/m)	11,44	14,30	15,60	16,90	24,10	43,20	69,20	98,60

Diameter (mm)	400	450	500	600
Price Function ($/m)	139,00	185,96	240,39	371,66

4.4.4.6. Optimization Results With August Demands

Following the completion of the previous steps, optimization process by use of WADISO has been done. Minimum pressure constraint as 30m at every node are assigned with 1m tolerance to find pareto optimal results, except the nodes which are located significantly at higher elevations than the tank. The first run is made by using the demands of August given in Section 4.4.2, i.e. **peak demand of day August 16, 2001 and the** price function given by **Goulter and Coals** (1986).

After getting the optimization results from WADISO for the skeletonized network, found diameters are assigned to the whole network and hydraulic analysis performed. As can be noted from previous tables, there are pipes that has diameters greater than 100mm in the system that are also not included in the optimization process, because they are dead or due to the 15 available group limitation. Thus, after having optimization results, the system is analyzed and those remaining pipes are assigned smaller diameters manually in order to complete the optimization process. After all,

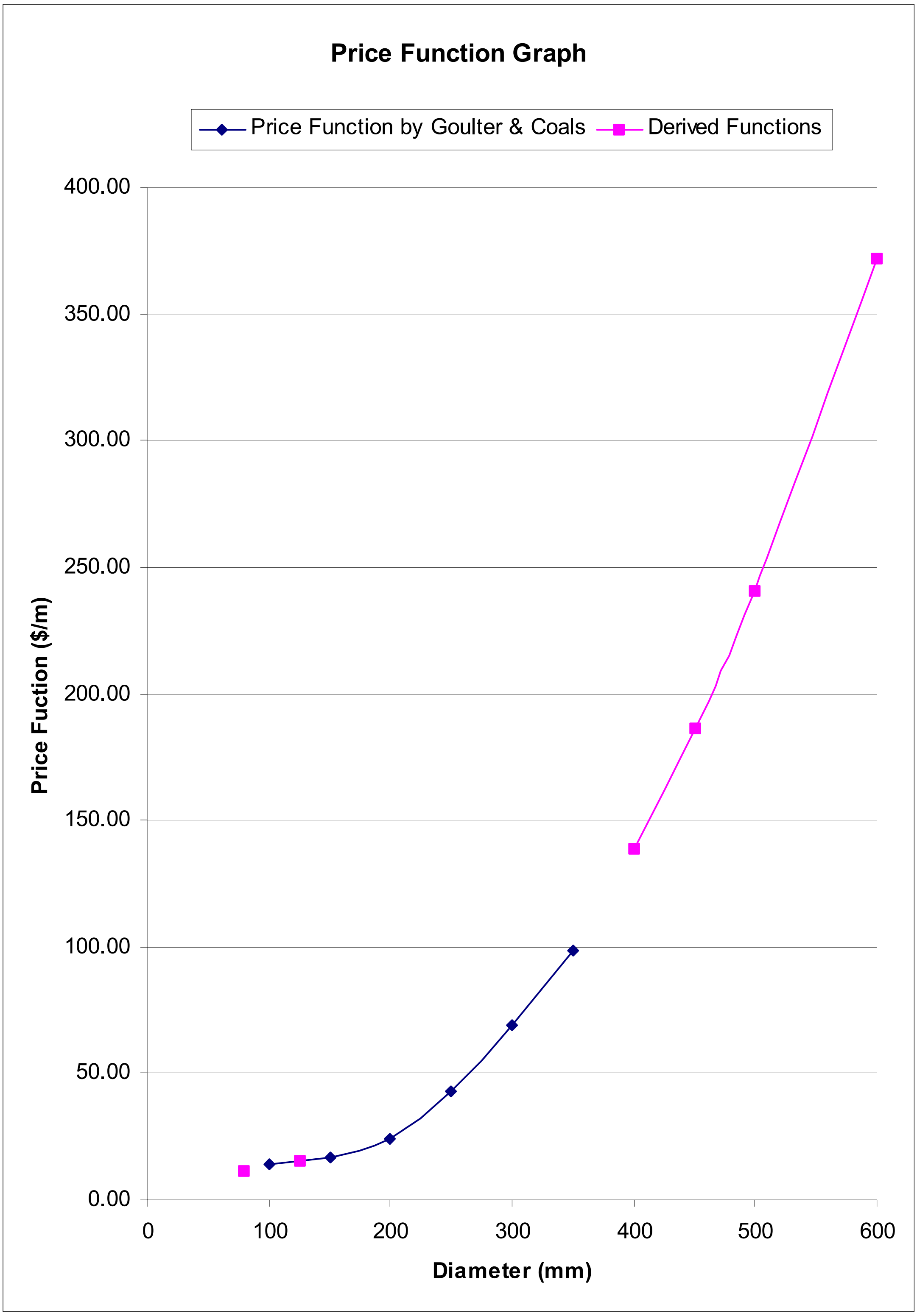

Figure 4.11: Graphical Interpretation of Price Function

optimized system is obtained with the pressure values below 30m as tabulated in Table 4.6. As can be observed, there are some nodes that have pressure values above 30m in the existing system but have less than 30m in the optimized system. The reason for this is that, in order to obtain the most economical system, pressure constraint is relaxed for this small number of nodes. Nodes designated as “N/A” in Table 4.6 are the ones that are not included in optimization process.

The results show that the system is over-designed with the demands of August. The cost of existing system is **939.630,13 YTL (with ductile price function)** while the pressure constraints can be satisfied with a system having total cost of **542.297,52YTL (with price function given by Goulter and Coals)**. The diameters of main lines are reduced to almost half of the existing ones. Most of the diameters of pipes are assigned as 100mm, which is the smallest diameter pipe that is allowed by the Municipality. Optimum pipe diameters for every group is given is Table 4.7.

Because the pipe diameters are decreased, some improvement on velocity also gained. The result found by optimization is not a surprise since the demands are very low due to the socio-economical nature of the pressure zone.

4.4.4.7. Optimization Results with Demands Including Pipe Leakages and Year 2020

Today’s N8 pressure zone design was completed and implemented in 1990s. However, in 1998, thesis study of İlker EKER (1998) showed that there were leakages in N8 zone and further studies done with cooperation of METU and ASKİ revealed the leakage causes (Merzi et al 1998a, 1998b). Consequently, it was revealed that the real demands of N8 zone are lower than the ones used in the previous design stage. Daily demand curve of N8 before the said studies is given in Figure 4.12.

Furthermore, as discussed in Chapter 2, the system designs are made considering future demands, normally considering 20~25 years later. Considering this situation, the demands are further increased according to forecasted total demand of year 2020.

Table 4.6: Nodes of Optimized System with pressure values less than 30m

Label	Pressure Head (m)		Assigned minimum pressure
	Existing System	Optimized System	
J-296	12.339	11.791	N/A
J-289	17.131	14.806	N/A
J-270	19.842	17.097	20
J-295	21.001	20.454	N/A
J-271	21.199	18.424	N/A
J-274	22.915	20.143	20
J-249	23.357	20.581	20
J-250	24.13	21.333	20
J-319	25.082	22.468	N/A
J-269	25.164	22.437	20
J-314	26.018	23.208	25
J-315	26.244	23.599	25
J-251	27.192	24.378	25
J-198	27.559	26.703	N/A
J-207	28.645	28.086	30
J-291	28.687	28.322	N/A
J-272	28.969	26.179	25
J-294	29.075	28.527	N/A
J-252	29.166	26.342	25
J-256	29.425	26.602	25
J-199	29.488	28.897	30
J-206	29.586	29.009	30
J-204	29.781	29.193	30
J-205	29.783	29.199	30
J-208	29.829	29.29	30
J-318	30.157	27.56	30
J-275	30.445	27.842	30
J-197	30.913	30.329	30
J-211	30.926	30.376	30
J-209	31.329	30.799	30
J-317	31.432	28.865	30
J-276	32.051	29.506	30
J-273	32.452	29.662	30
J-313	32.727	29.9	30

Table 4.7: Optimum Diameters with August Demands

	GR 1	GR 2	GR 3	GR 4	GR 5	GR 6	GR 7	GR 8	GR 9	GR 10	GR 11	GR 12	GR 13	GR 14	GR 15
EXISTING DIAMETERS	300,00	200,00	500,00	250,00	200,00	125,00	150,00	150,00	150,00	200,00	200,00	150,00	200,00	150,00	200,00
CANDIDATE DIAMETERS (mm)	200	125	200	125	100	100	125	125	125	150	150	100	150	125	150
	150	100	250	150	125	125	150	150	150	200	200	125	200	150	200
	125		300	200	150		100	100	100	100	100	150	100	100	100
	100		400	250											
OPTIMUM DIAMETERS (mm)	150	100	300	200	125	100	100	100	100	100	100	100	100	125	100

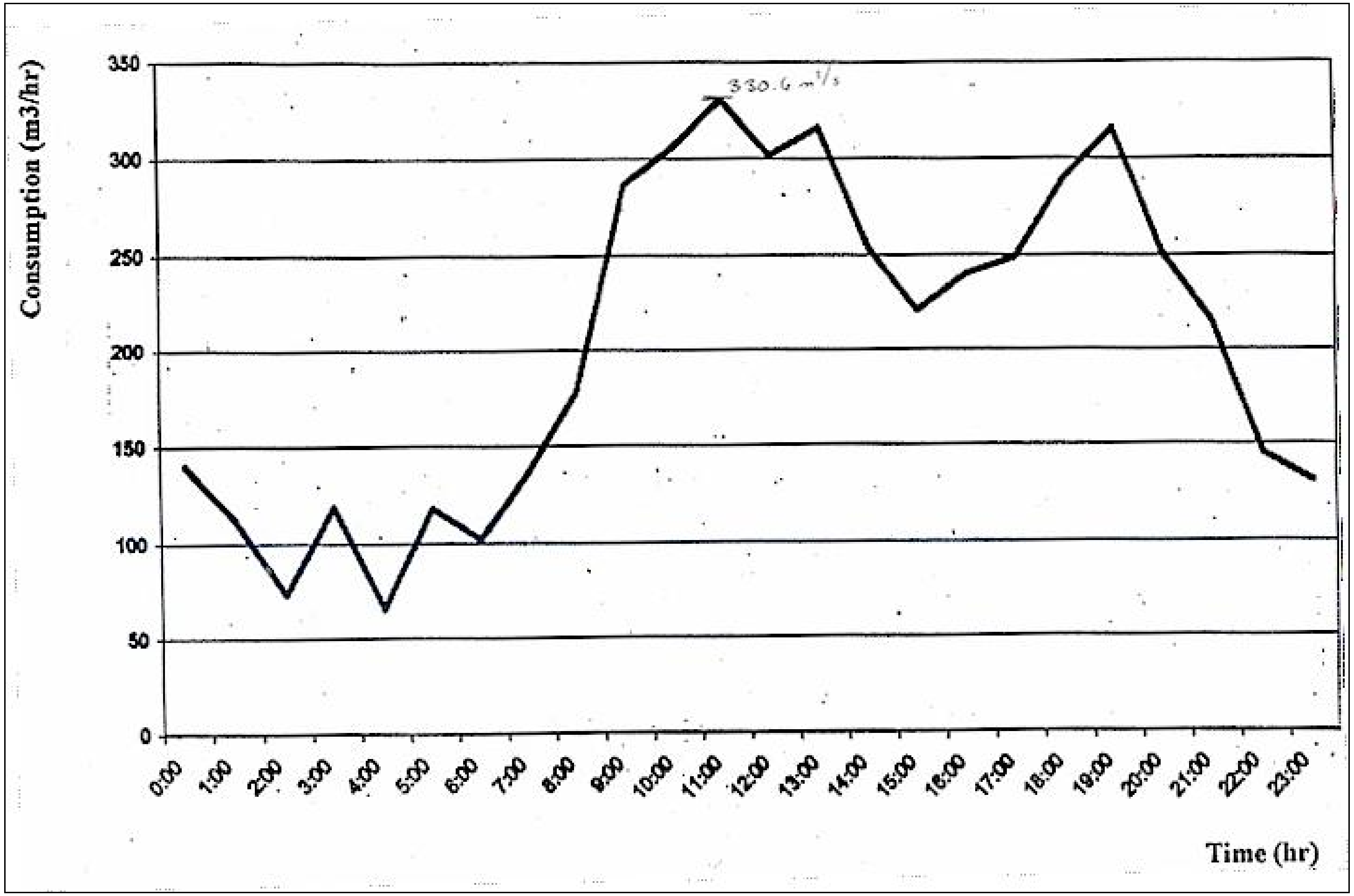

Figure 4.12: Daily Demand Curve of N8 Including Leakages

From Figure 4.12, peak loading is read as Q_{peak}=330,4 m^3/h (91,77 lt/s) and night loading as 64,6 m^3/h (17,94 lt/s).

Demand Forecast for Year 2020

Demand projection for year 2020 is performed by use of the following formula (İller Bankası, 1998):

$$F_{2020} = F_{know} * \sqrt{1 + k/100}^{\,2020-Year_{known}} \qquad \textbf{(4.1)}$$

where F is the total demand, k is a coefficient.

In this equation, maximum value of k can only be 3.
In order to find the maximum available design in year 2020, it is decided to take k as maximum, i.e. k=3.

Consequently for **peak loading**, Q_{peak} ,

$$F_{2020} = 91{,}77 * \sqrt{1 + 3/100}^{\,2020-1997} \Rightarrow Q_{peak} = 181{,}13 lt/s$$

Similarly for **night loading**, Q_{night},

$$F_{2020} = 17{,}94 * \sqrt{1 + 3/100}^{\,2020-1997} \Rightarrow Q_{night} = 35{,}417 lt/s$$

For **fire loading**, , Q_{fire} , 15lt/s fire flow need is assigned to two neighboring critical nodes, i.e. nodes with pressure values below 30m, during Q_{peak}. These nodes are selected as Node 270 and Node 271.

Additionally, as discussed in Section 3.5.3, the price function can also be very significant. To demonstrate this in this section, the same system is optimized using various price functions with three loading cases of Year 2020, but keeping all the other variables unchanged, i.e. groups. At every optimization trial, Peak Loading (Q_{peak}), Fire Loading (Q_{fire}) and Night Loading (Q_{night}) are assigned simultaneously to the software so that it can decide the critical one. As pressure constraints, following are assigned for every loading case as given in Table 4.8.

Table 4.8: Pressure Constraints for Optimization

Loading	Pressure Constraint
Peak loading	30m minimum head at every node, except the ones located at significantly higher elevations than the tank
Fire Loading	15m minimum head at every node
Night Loading	30m minimum head at every node, except the ones located at significantly higher elevations than the tank

<u>Optimization With Various Price Functions:</u> Using built price functions in Section 3.5.3.1 and Hazen-Williams coefficient based on material type; series of optimization studies are performed for three loading cases (Peak, fire and night loading). Total cost of N8 pressure zone with the optimum diameters, which are found based on various price functions, are given in Table 4.9. As it is observed from Table 4.9, the cost of the same system varies based on the material used. As the result of these studies, optimum pipe diameters depending on price functions are tabulated in Table 4.10. However, on the contrary to expectations, there are no significant development in pressures regardless of the pipe material used and the cost of total system, namely, pressures almost remain same whatever material is used and the problematic nodes remain almost same with all the system configurations (Figures 4.13~4.27, APPENDIX A).

Table 4.9: Total System Cost Optimized With Various Price Functions

PRICE FUNCTION	TOTAL COST (YTL)
HDPE Price Function with DSI Prices	920.425,91
HDPE Price Function with Market Prices	758.148,59
Steel Price Function with DSI Prices	935.841,50
Ductile Price Function with Market Prices	832.375,39
COST OF EXISTING SYSTEM (with ductile price function)	939.630,13

Table 4.10: Optimum pipe diameters depending on price functions

OPTIMUM DIAMETERS (mm)	GR 1	GR 2	GR 3	GR 4	GR 5	GR 6	GR 7	GR 8	GR 9	GR 10	GR 11	GR 12	GR 13	GR 14	GR 15
STEEL	200	100	400	300	200	100	125	100	100	100	100	100	100	100	100
DUCTILE	200	100	400	300	200	100	125	100	100	100	100	100	100	100	100
HDPE_MARKET	160	110	400	250	160	90	110	90	90	90	90	90	90	125	180
HDPE_DSI	160	110	400	250	160	90	110	90	90	90	90	90	90	125	180
EXISTING PIPE DIAMETERS	300	200	500	250	200	125	150	150	150	200	200	150	200	150	200

<u>**EXISTING SYSTEM ANALYSIS**</u>

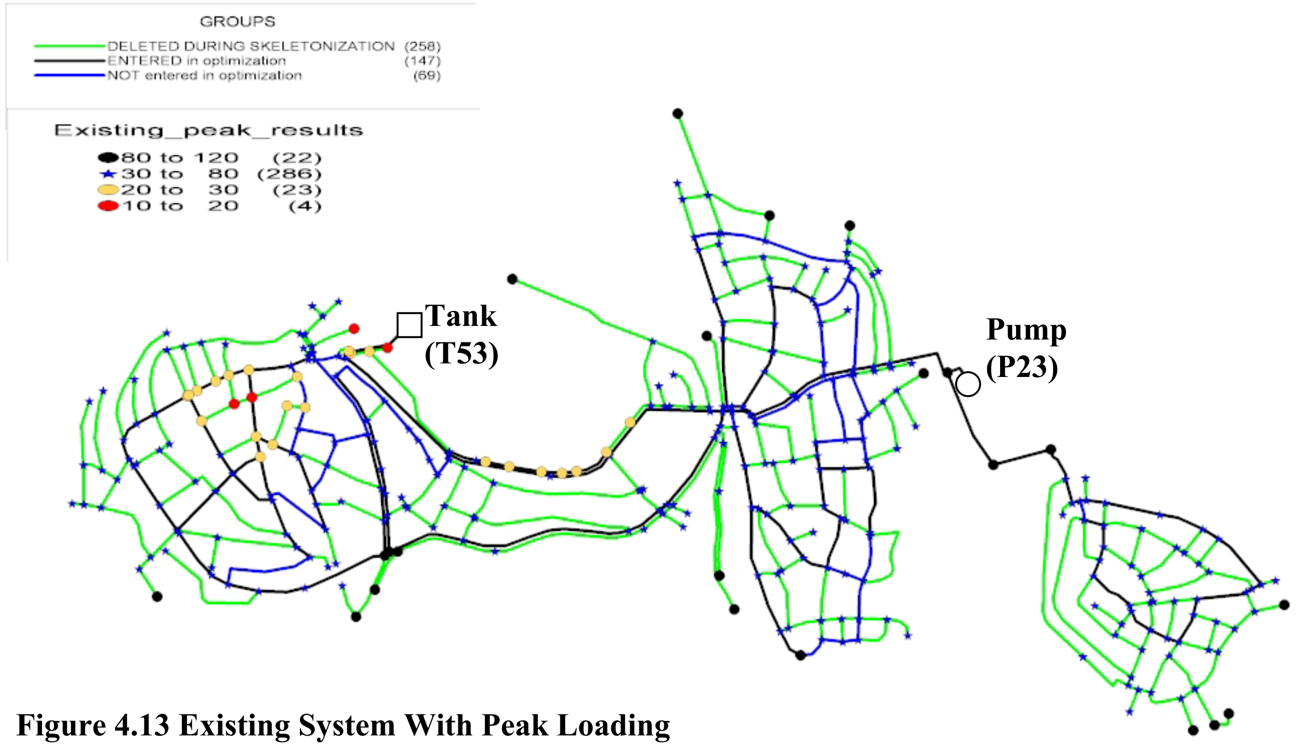

Figure 4.13 Existing System With Peak Loading

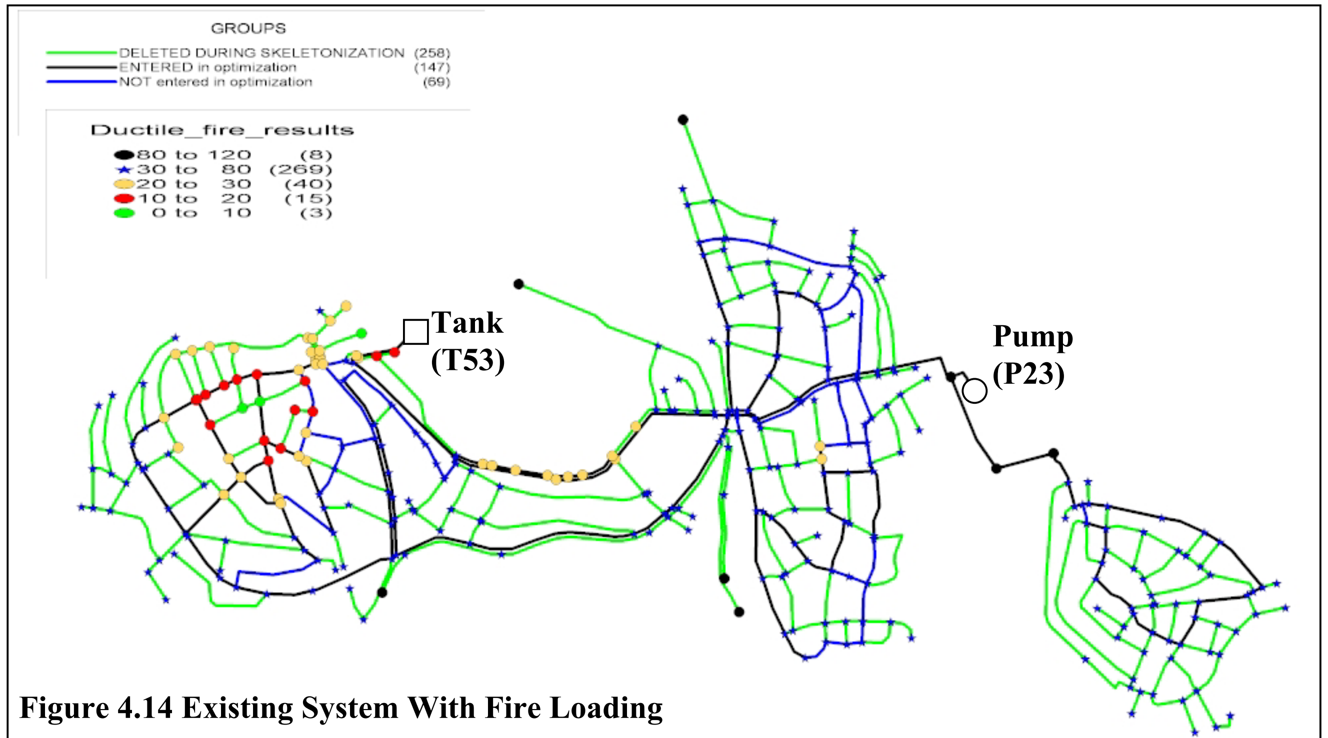

Figure 4.14 Existing System With Fire Loading

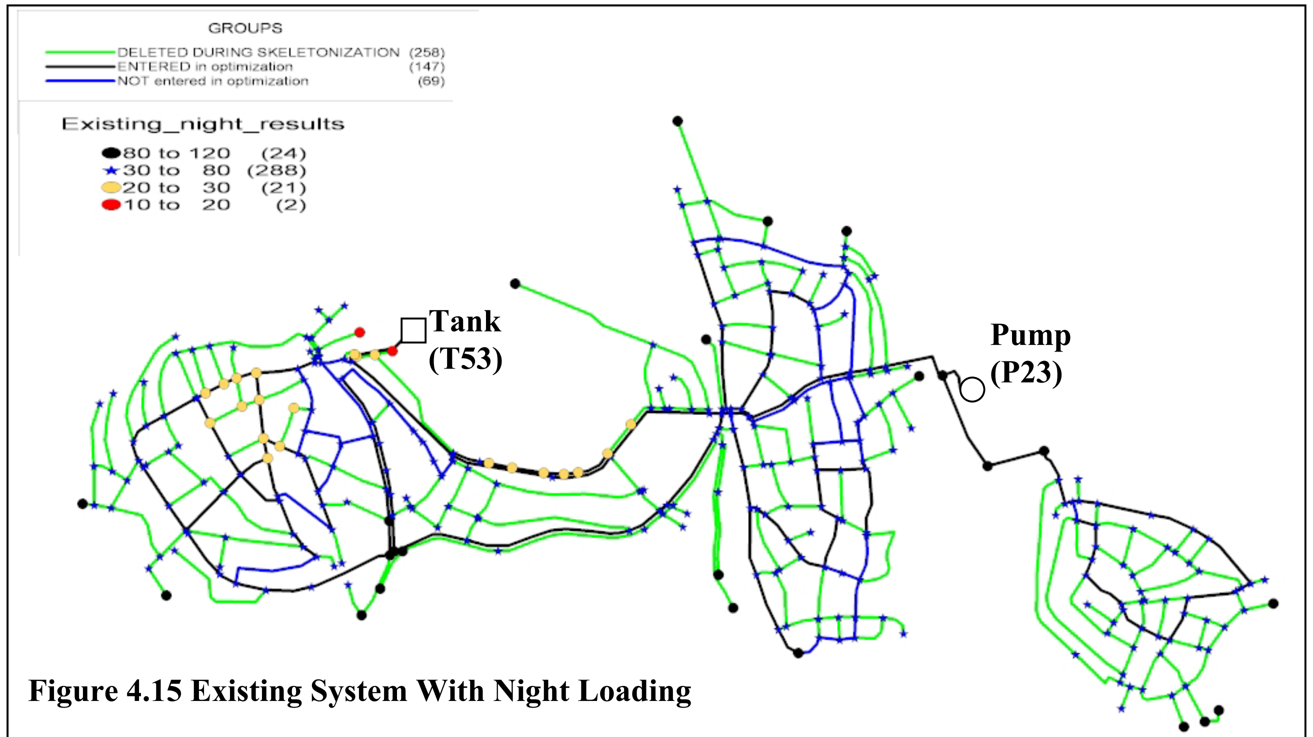

Figure 4.15 Existing System With Night Loading

RESULTS WITH PEAK DEMANDS

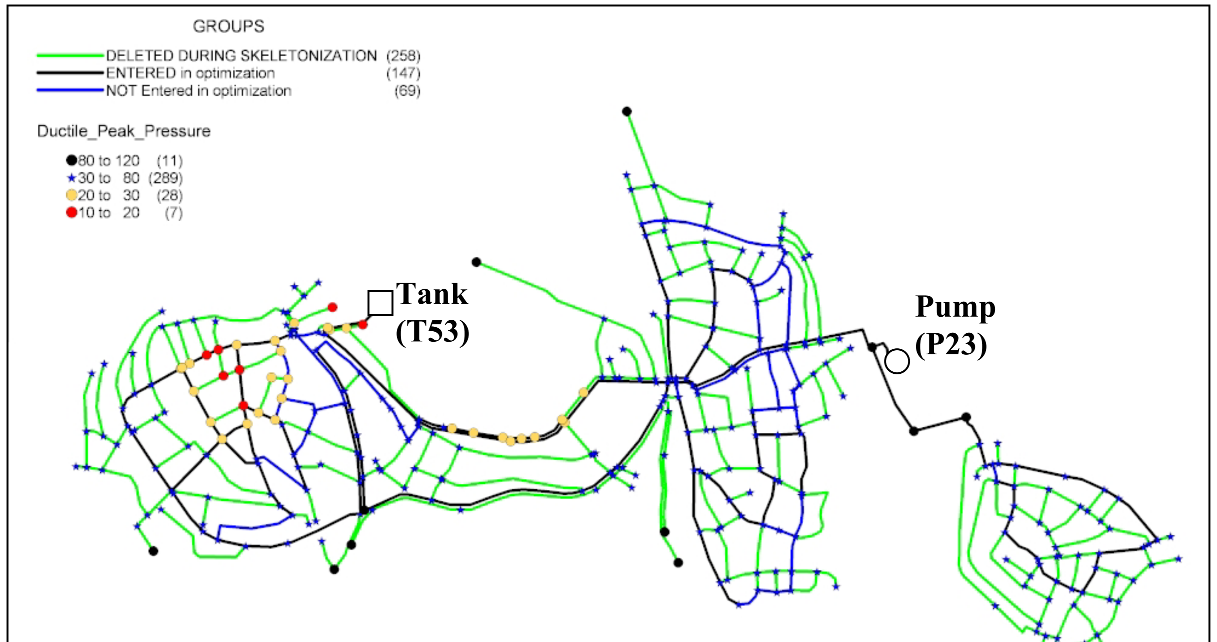

Figure 4.16: System with Ductile (or Steel) Pipes Under Peak Loading

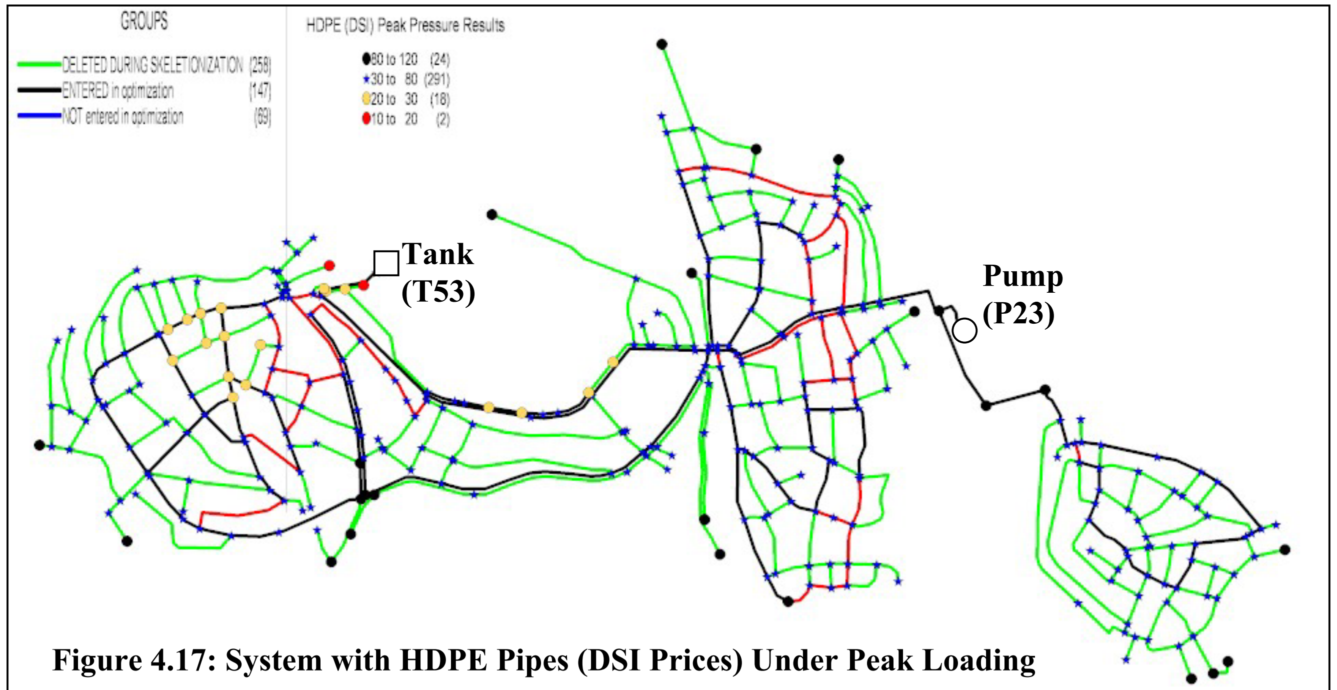

Figure 4.17: System with HDPE Pipes (DSI Prices) Under Peak Loading

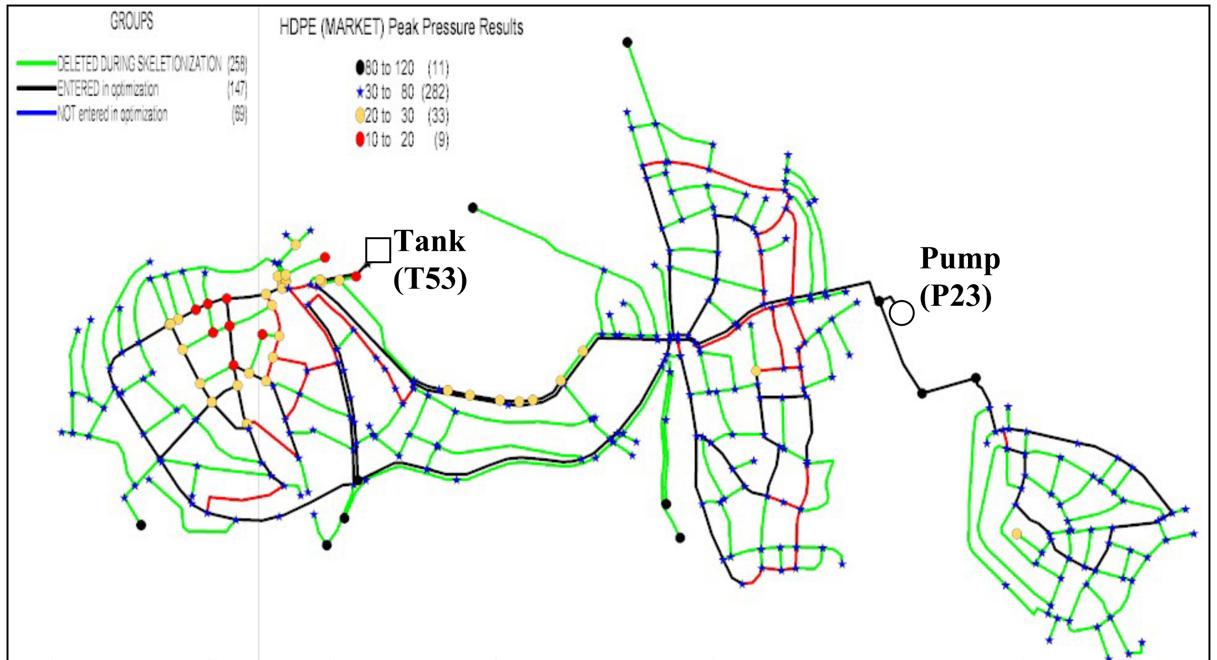

Figure 4.18: System with HDPE Pipes (Market Prices) Under Peak Loading

RESULTS WITH FIRE DEMANDS

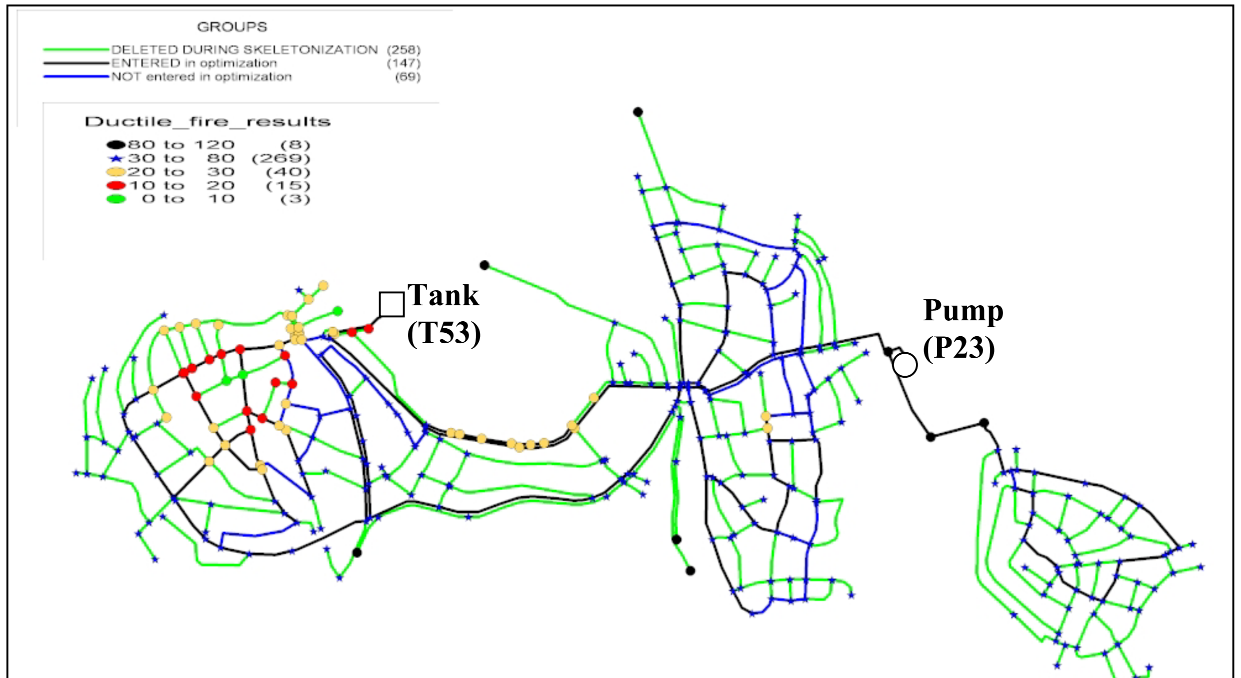

Figure 4.19: System with Ductile (or Steel) Pipes Under Fire Loading

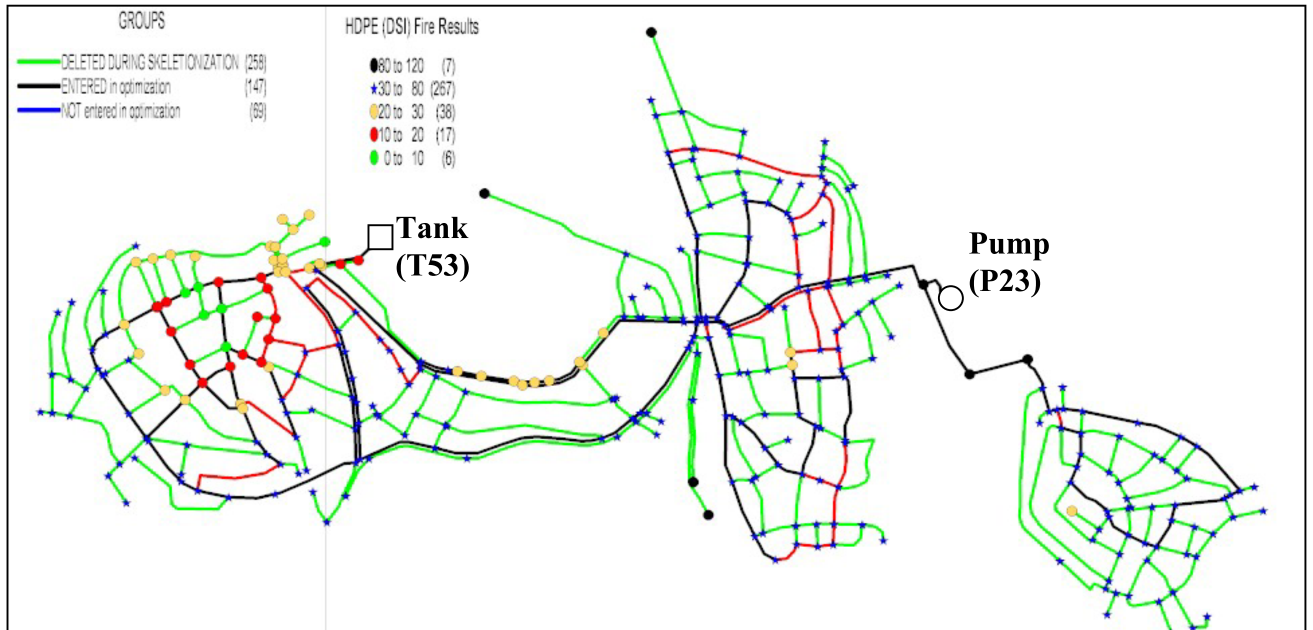

Figure 4.20: System with HDPE Pipes (DSI Prices) Under Fire Loading

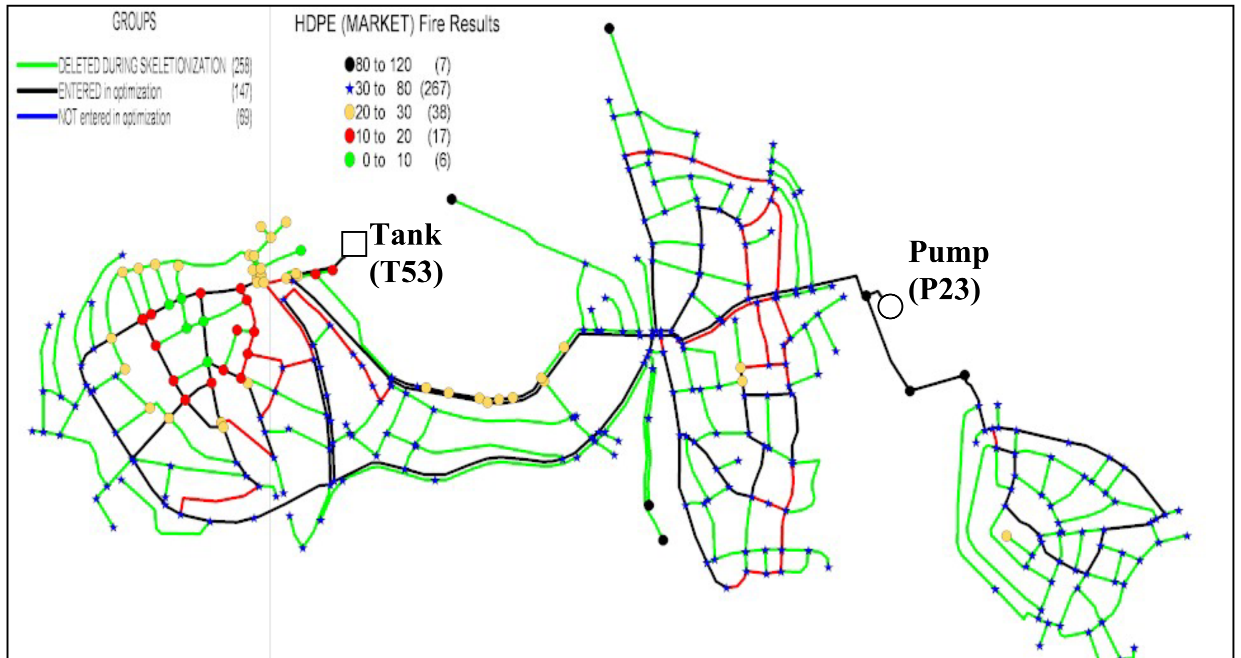

Figure 4.21: System with HDPE Pipes (Market Prices) Under Fire Loading

RESULTS WITH NIGHT DEMANDS

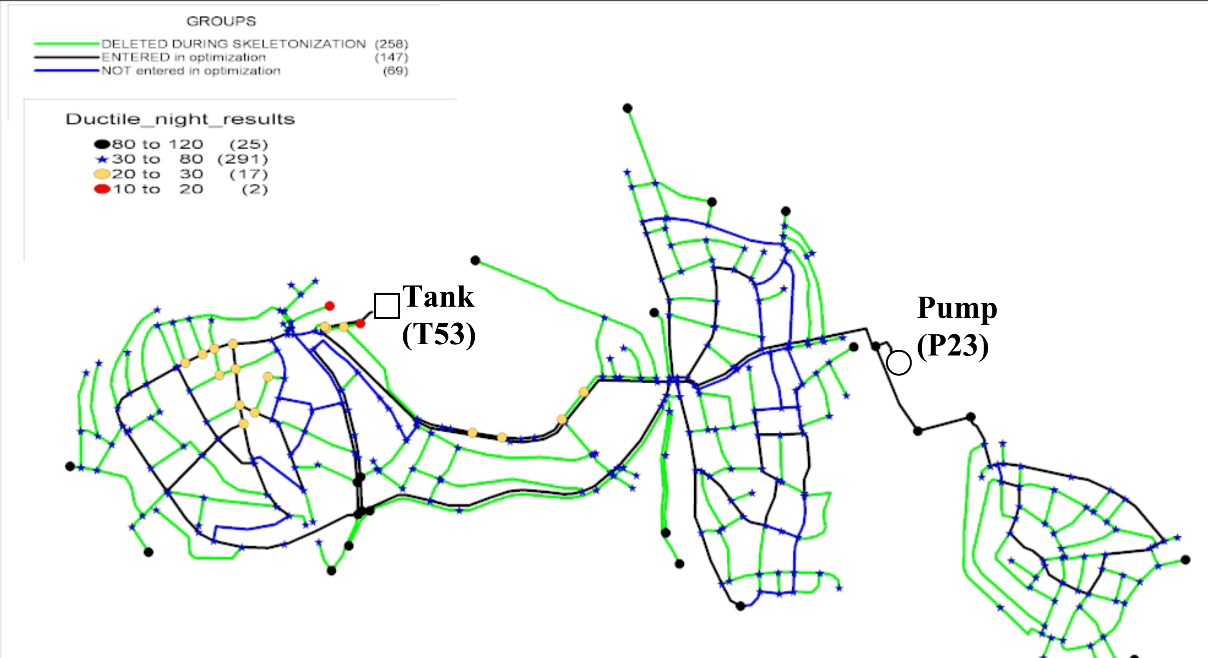

Figure 4.22: System with Ductile (or Steel) Pipes Under Night Loading

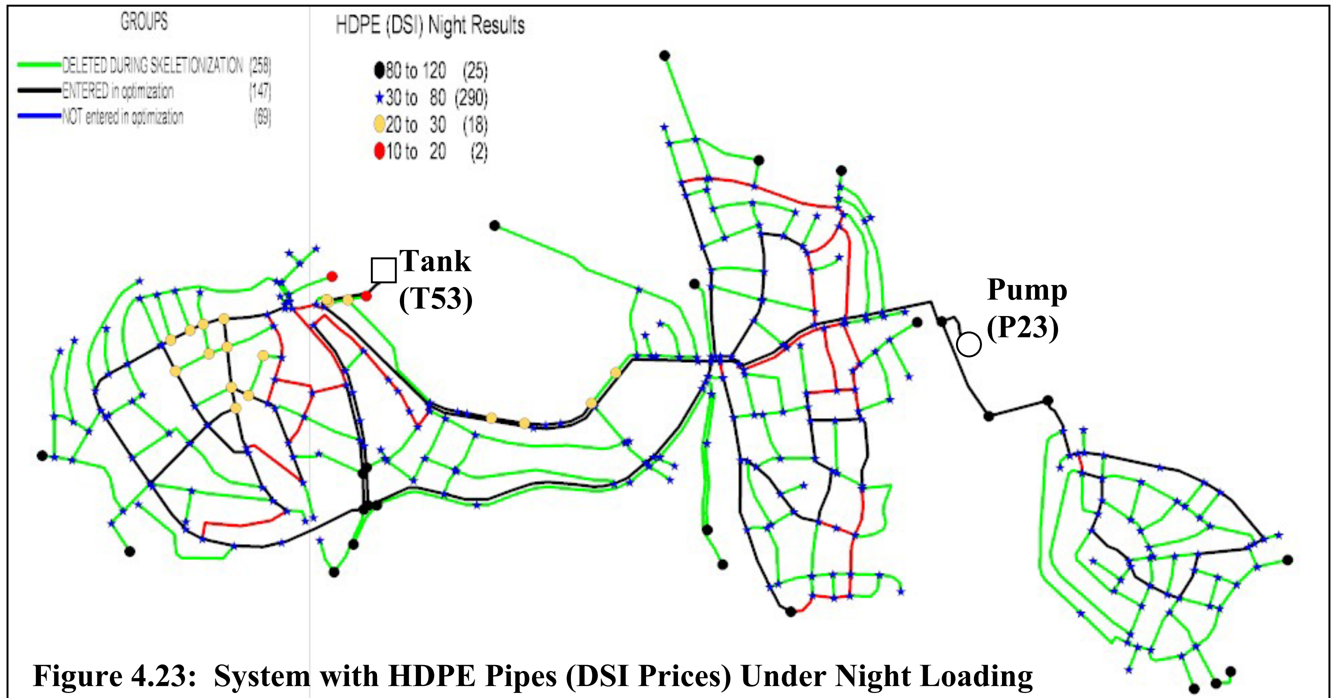

Figure 4.23: System with HDPE Pipes (DSI Prices) Under Night Loading

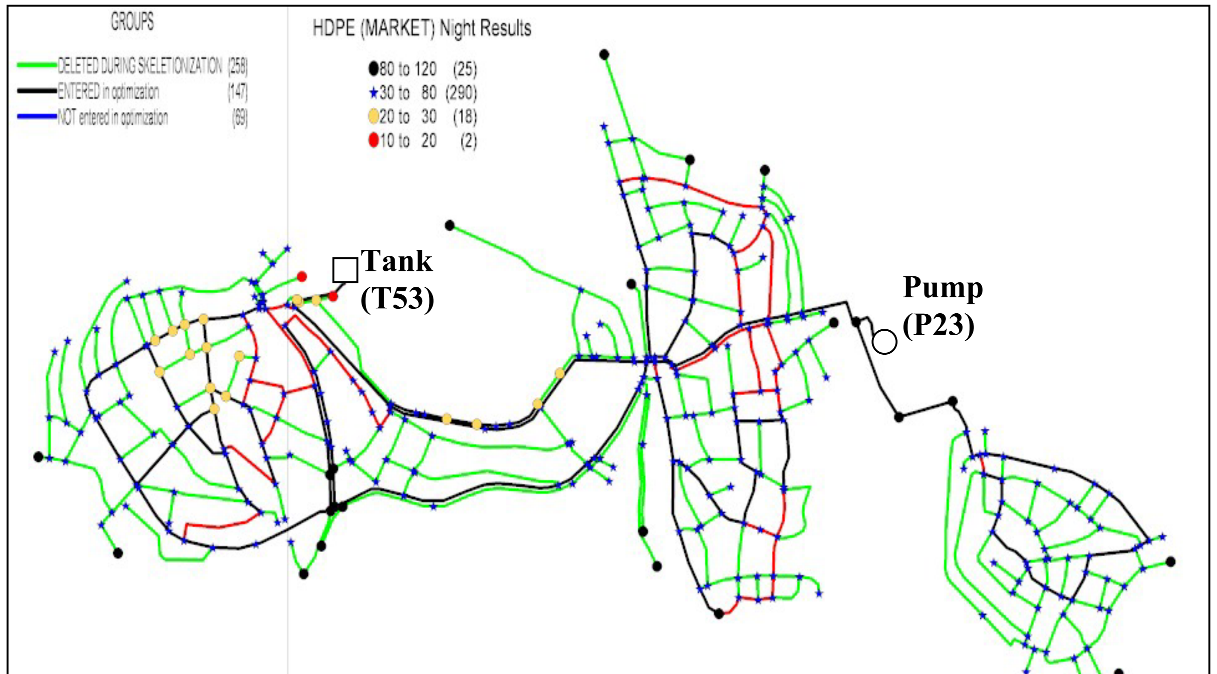

Figure 4.24: System with HDPE Pipes (Market Prices) Under Night Loading

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The design of water distribution networks is generally being performed with traditional (trial-and-error) techniques. This is because most of the techniques are automatic techniques which do not allow designer to control the steps of process. However, partial enumeration technique developed by Gessler (1985) is a useful tool to the designers in which they can control all the steps of the process.

In this study, in order to demonstrate this, a water distribution network is designed by using Gessler's (1985) partial enumeration technique with software, WADISO. As the result of this study, the following conclusions are drawn:

- Partial enumeration technique is a powerful tool that assists designers. With this technique, designers can select the pipes that should be optimized, the pipes that should have the same diameters, and the pipes that can be eliminated or should not be eliminated to secure reliability. Moreover, the technique provides pareto optimal solutions that offers a different design which is close to the optimal. The only disadvantage of it is the required computation time depending on the scale of the design.

- Since partial enumeration technique is based on trial of all possible combinations one by one considering some rules defined by user, it is guaranteed that the solution is close to the global minimum, if not itself.

- The price function is very significant in any of the optimization technique. Correct price functions have to be formed considering special characteristics of the subject area and the selected pipe materials. There are various pipe materials that can be used in distribution networks such as ductile iron, HDPE or steel, each having different price functions. However, since each of these materials has advantageous properties over the others, not only the price function should be considered, but also factors other than price function should also be considered.

- It is shown that the cost of pipe fittings can have a significant effect on the global cost, especially if the system is composed of densely located junctions. However, no guideline is available to include the cost of pipe fittings in the price functions.

- Water distribution network of N8 pressure zone is over-designed. Either smaller diameter pipes should have been installed or staged development should have been planned.

- Velocities within N8 zone is far below desired values. Because low velocities in the pipes cause low quality water, aging of pipes occur. In order to satisfy water quality objective, periodical flushing (extracting water from pipe hydrants to increase velocities and clean the pipes) should be performed. Another solution for increasing water quality is to divide N8 pressure zone further sub-pressure zones.

Furthermore, during the study, conventional pipe laying techniques are considered. More detailed study can be performed considering other construction techniques such as pipe jacking, trenchless construction etc.

Although the network designed by use of partial enumeration technique satisfies the minimum pressure constraints, there is no possibility to control maximum pressures. Thus, pipe material has to be selected considering pressures. Additionally, there is no way to satisfy both velocity constraints and pressure constraints with WADISO. The software does not take velocities into consideration. Future studies on these subjects will definitely improve the capacities of the technique. Finally, with the advances in the computer technology and development of much more rapid processors in the future, there will not be any need to follow the steps, which are explained in this study to reduce computation time, and the software will be capable of enumerating all possible combinations resulting in the global minimum.

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APPENDIX - A

Pressure values of Optimum System with various price functions and under three loadings (Peak, Fire and Night Demands of Year 2020)

Table A - Pressure values of Optimum System with various price functions and under three loadings (Peak, Fire and Night Demands of Year 2020)

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-1	1.061,750	1,173	91,218	1,173	90,513	0,116	93,614	93,392	90,994	93,408	91,524	90,990	93,408	92,160	91,955	92,937
J-2	1.051,770	0,970	99,590	0,970	98,885	0,096	103,552	103,302	97,341	103,318	97,870	97,336	103,318	101,900	101,694	102,894
J-3	1.061,250	0,560	89,267	0,560	88,562	0,055	94,079	93,814	85,919	93,830	86,449	85,915	93,830	92,319	92,114	93,431
J-4	1.076,440	1,560	73,623	1,560	72,918	0,155	78,913	78,639	69,658	78,655	70,187	69,653	78,656	77,093	76,887	78,271
J-5	1.076,650	1,571	70,993	1,571	70,289	0,156	78,670	78,403	66,962	78,411	67,492	66,958	78,412	76,639	76,434	78,058
J-6	1.090,980	0,483	56,359	0,483	55,654	0,048	64,364	64,098	52,360	64,106	52,890	52,356	64,106	62,328	62,123	63,757
J-7	1.090,590	0,286	56,701	0,286	55,996	0,028	64,753	64,487	52,711	64,495	53,241	52,707	64,495	62,716	62,510	64,146
J-8	1.078,420	0,142	68,846	0,142	68,141	0,014	76,898	76,633	64,856	76,640	65,386	64,852	76,641	74,861	74,655	76,291
J-9	1.085,450	0,100	64,398	0,100	63,694	0,010	69,918	69,640	60,116	69,656	60,646	60,112	69,656	68,063	67,857	69,278
J-10	1.087,530	0,298	62,323	0,298	61,618	0,029	67,842	67,564	58,041	67,580	58,570	58,036	67,580	65,987	65,782	67,203
J-11	1.086,610	0,316	63,168	0,316	62,463	0,031	68,759	68,480	58,786	68,496	59,316	58,782	68,496	66,893	66,688	68,121
J-12	1.086,120	0,133	63,255	0,133	62,550	0,013	69,243	68,966	58,982	68,981	59,511	58,977	68,981	67,371	67,165	68,609
J-13	1.077,120	0,133	72,236	0,133	71,531	0,013	78,225	77,948	67,963	77,963	68,493	67,959	77,963	76,352	76,146	77,591
J-14	1.093,900	1,776	54,342	1,776	53,637	0,176	61,463	61,191	50,150	61,202	50,680	50,146	61,202	59,592	59,386	60,845
J-15	1.086,610	0,618	61,589	0,618	60,884	0,061	68,738	68,468	57,626	68,480	58,156	57,622	68,480	66,847	66,641	68,120
J-16	1.094,240	0,612	53,821	0,612	53,117	0,061	61,121	60,851	49,744	60,861	50,274	49,740	60,862	59,209	59,003	60,505
J-17	1.093,570	1,457	53,774	1,457	53,069	0,144	61,780	61,514	49,775	61,521	50,305	49,771	61,522	59,745	59,539	61,172
J-18	1.090,200	0,557	57,050	0,557	56,345	0,055	65,142	64,876	53,072	64,883	53,602	53,068	64,884	63,105	62,899	64,535
J-19	1.086,180	0,540	61,035	0,540	60,330	0,053	69,153	68,888	57,061	68,895	57,591	57,057	68,896	67,113	66,907	68,547
J-20	1.067,720	0,205	79,457	0,205	78,752	0,020	87,576	87,310	75,482	87,318	76,012	75,478	87,318	85,534	85,329	86,970
J-21	1.086,710	0,869	60,506	0,869	59,801	0,086	68,624	68,359	56,532	68,366	57,062	56,528	68,367	66,584	66,378	68,018
J-22	1.069,860	0,388	77,312	0,388	76,608	0,038	85,440	85,175	73,336	85,182	73,866	73,332	85,182	83,391	83,185	84,834
J-23	1.068,020	0,141	79,148	0,141	78,443	0,014	87,276	87,011	75,172	87,018	75,702	75,167	87,019	85,227	85,021	86,670
J-24	1.102,870	0,598	44,393	0,598	43,688	0,059	52,497	52,231	40,425	52,239	40,954	40,420	52,239	50,468	50,262	51,891
J-25	1.109,490	0,607	37,847	0,607	37,142	0,060	45,891	45,625	33,870	45,633	34,400	33,866	45,634	43,880	43,674	45,284
J-26	1.108,300	0,485	39,050	0,485	38,346	0,048	47,079	46,813	35,067	46,821	35,597	35,063	46,821	45,058	44,852	46,472
J-27	1.104,580	0,410	42,727	0,410	42,022	0,041	50,791	50,525	38,758	50,533	39,288	38,754	50,533	48,779	48,573	50,184
J-28	1.101,650	0,542	45,615	0,542	44,910	0,054	53,715	53,449	41,658	53,457	42,188	41,654	53,457	51,701	51,495	53,108
J-29	1.089,790	0,416	57,444	0,416	56,740	0,041	65,551	65,285	53,484	65,293	54,014	53,480	65,293	63,525	63,320	64,944
J-30	1.084,780	0,498	62,441	0,498	61,736	0,049	70,550	70,285	58,478	70,293	59,008	58,474	70,293	68,520	68,315	69,944
J-31	1.081,740	0,448	65,478	0,448	64,773	0,044	73,584	73,319	61,517	73,326	62,047	61,513	73,327	71,557	71,352	72,978
J-32	1.097,530	0,425	49,727	0,425	49,022	0,042	57,826	57,561	45,771	57,568	46,300	45,766	57,569	55,813	55,608	57,220
J-33	1.088,550	0,435	58,682	0,435	57,977	0,043	66,788	66,523	54,722	66,530	55,251	54,717	66,531	64,762	64,557	66,182
J-34	1.096,820	0,528	50,450	0,528	49,746	0,052	58,535	58,269	46,489	58,277	47,019	46,485	58,278	56,524	56,318	57,929
J-35	1.102,950	0,498	44,354	0,498	43,649	0,049	52,418	52,152	40,386	52,160	40,915	40,381	52,160	50,407	50,202	51,811
J-36	1.106,980	0,338	40,376	0,338	39,671	0,034	48,396	48,130	36,405	48,138	36,934	36,400	48,139	46,393	46,187	47,789
J-37	1.107,610	0,168	39,747	0,168	39,042	0,017	47,768	47,502	35,775	47,510	36,305	35,771	47,510	45,764	45,558	47,161
J-38	1.112,350	0,098	35,013	0,098	34,308	0,010	43,037	42,771	31,041	42,779	31,571	31,037	42,780	41,034	40,828	42,430
J-39	1.112,630	0,367	34,733	0,367	34,029	0,036	42,758	42,492	30,758	42,500	31,288	30,754	42,500	40,743	40,538	42,151
J-40	1.109,620	0,746	37,738	0,746	37,033	0,074	45,762	45,496	33,762	45,504	34,292	33,758	45,504	43,747	43,541	45,154
J-41	1.075,320	0,088	71,949	0,088	71,244	0,009	79,992	79,727	67,993	79,734	68,523	67,989	79,735	77,992	77,786	79,386

Table A - CONTINUED

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-42	1.078,880	0,564	68,396	0,564	67,691	0,056	76,440	76,174	64,440	76,182	64,970	64,436	76,182	74,439	74,234	75,833
J-43	1.082,460	0,294	64,815	0,294	64,110	0,029	72,867	72,601	60,856	72,609	61,386	60,852	72,609	70,864	70,658	72,260
J-44	1.084,300	0,526	62,956	0,526	62,251	0,052	71,030	70,764	59,003	70,772	59,533	58,999	70,773	69,025	68,819	70,424
J-45	1.079,860	0,465	67,362	0,465	66,658	0,046	75,461	75,195	63,404	75,203	63,934	63,399	75,203	73,435	73,230	74,854
J-46	1.072,560	0,181	74,647	0,181	73,942	0,018	82,746	82,480	70,688	82,488	71,218	70,683	82,489	80,720	80,515	82,140
J-47	1.080,210	0,561	67,236	0,561	66,531	0,056	75,115	74,848	63,290	74,857	63,820	63,286	74,857	73,144	72,939	74,506
J-48	1.078,590	0,676	68,806	0,676	68,101	0,067	76,731	76,464	64,851	76,473	65,380	64,846	76,473	74,751	74,545	76,122
J-49	1.091,650	0,378	55,777	0,378	55,073	0,037	63,697	63,431	51,817	63,439	52,347	51,813	63,440	61,712	61,507	63,089
J-50	1.094,280	0,341	53,185	0,341	52,480	0,034	61,073	60,806	49,221	60,815	49,751	49,217	60,815	59,092	58,886	60,464
J-51	1.088,450	0,604	59,287	0,604	58,582	0,060	66,895	66,627	55,353	66,637	55,882	55,348	66,638	64,957	64,752	66,283
J-52	1.094,740	0,697	52,874	0,697	52,169	0,069	60,616	60,348	48,875	60,357	49,404	48,870	60,358	58,650	58,444	60,005
J-53	1.094,770	0,567	52,744	0,567	52,039	0,056	60,584	60,317	48,763	60,326	49,293	48,759	60,327	58,607	58,401	59,975
J-54	1.089,880	0,753	57,494	0,753	56,789	0,075	65,463	65,196	53,525	65,205	54,055	53,521	65,205	63,469	63,263	64,855
J-55	1.100,700	0,410	47,021	0,410	46,316	0,041	54,669	54,401	43,022	54,411	43,551	43,017	54,411	52,724	52,519	54,058
J-56	1.103,280	0,519	44,352	0,519	43,647	0,051	52,093	51,826	40,354	51,834	40,884	40,350	51,835	50,130	49,924	51,482
J-57	1.104,590	0,473	42,938	0,473	42,233	0,047	50,784	50,517	38,953	50,526	39,483	38,949	50,526	48,804	48,599	50,175
J-58	1.104,850	0,492	42,870	0,492	42,165	0,049	50,527	50,259	38,840	50,268	39,369	38,835	50,269	48,572	48,366	49,916
J-59	1.106,220	0,547	41,186	0,547	40,481	0,054	49,156	48,889	37,213	48,898	37,743	37,209	48,898	47,159	46,953	48,548
J-60	1.112,160	0,628	35,208	0,628	34,504	0,062	43,227	42,961	31,240	42,969	31,769	31,235	42,969	41,226	41,020	42,620
J-61	1.110,990	0,874	36,522	0,874	35,817	0,087	44,397	44,130	32,560	44,139	33,090	32,555	44,139	42,425	42,220	43,788
J-62	1.114,310	0,195	33,056	0,195	32,351	0,019	41,081	40,815	29,080	40,823	29,610	29,076	40,824	39,065	38,860	40,474
J-63	1.072,950	0,092	77,691	0,092	76,982	0,009	81,998	81,879	76,853	81,873	77,389	76,849	81,874	80,499	80,286	81,604
J-64	1.080,260	0,421	70,396	0,421	69,686	0,042	74,702	74,584	69,558	74,578	70,094	69,554	74,579	73,204	72,991	74,309
J-65	1.080,630	0,261	70,024	0,261	69,315	0,026	74,333	74,214	69,186	74,209	69,722	69,181	74,209	72,832	72,619	73,939
J-66	1.059,650	0,517	91,046	0,517	90,338	0,051	95,274	95,154	90,233	95,150	90,768	90,229	95,150	93,903	93,695	94,877
J-67	1.086,770	1,305	63,999	1,305	63,291	0,129	68,209	68,089	63,192	68,085	63,726	63,187	68,085	66,856	66,648	67,812
J-68	1.080,940	0,492	69,841	0,492	69,133	0,049	74,028	73,908	69,040	73,903	69,575	69,036	73,904	72,730	72,523	73,631
J-69	1.078,200	0,100	72,575	0,100	71,867	0,010	76,762	76,642	71,774	76,638	72,309	71,770	76,638	75,465	75,258	76,366
J-70	1.082,900	0,484	67,964	0,484	67,256	0,048	72,073	71,953	67,186	71,949	67,720	67,181	71,949	70,779	70,572	71,675
J-71	1.081,360	0,517	69,525	0,517	68,817	0,051	73,611	73,490	68,753	73,486	69,288	68,749	73,487	72,318	72,111	73,212
J-72	1.079,270	0,593	71,935	0,593	71,227	0,059	75,701	75,580	71,255	75,578	71,789	71,251	75,578	74,442	74,235	75,298
J-73	1.075,610	0,546	76,014	0,546	75,306	0,054	79,355	79,235	75,456	79,233	75,989	75,451	79,234	78,122	77,915	78,950
J-74	1.076,980	0,810	74,949	0,810	74,242	0,080	77,987	77,868	74,477	77,866	75,009	74,473	77,867	76,775	76,569	77,583
J-75	1.087,400	0,330	63,275	0,330	62,566	0,033	67,577	67,458	62,439	67,453	62,975	62,435	67,453	66,080	65,867	67,183
J-76	1.094,340	0,609	56,367	0,609	55,658	0,060	60,651	60,533	55,536	60,527	56,072	55,531	60,528	59,158	58,946	60,257
J-77	1.099,170	0,790	51,558	0,790	50,849	0,078	55,831	55,713	50,731	55,707	51,267	50,726	55,708	54,342	54,130	55,437
J-78	1.103,630	0,912	47,161	0,912	46,452	0,090	51,382	51,263	46,348	51,258	46,884	46,344	51,259	49,908	49,696	50,987
J-79	1.117,260	0,405	34,028	0,405	33,320	0,040	37,799	37,677	33,350	37,673	33,883	33,345	37,674	36,511	36,304	37,393
J-80	1.115,520	0,370	35,756	0,370	35,048	0,037	39,533	39,411	35,076	39,408	35,609	35,071	39,409	38,248	38,040	39,129
J-81	1.101,100	0,196	50,146	0,196	49,438	0,019	53,924	53,802	49,465	53,799	49,999	49,461	53,799	52,637	52,430	53,520
J-82	1.084,980	0,778	65,681	0,778	64,971	0,077	69,991	69,872	64,842	69,867	65,378	64,837	69,867	68,491	68,279	69,598
J-83	1.088,610	0,796	62,061	0,796	61,351	0,079	66,367	66,249	61,222	66,244	61,759	61,218	66,244	64,882	64,669	65,976
J-84	1.078,120	0,125	72,529	0,125	71,820	0,012	76,836	76,717	71,691	76,713	72,227	71,686	76,713	75,351	75,138	76,445
J-85	1.112,010	0,179	39,362	0,179	38,654	0,018	43,045	42,921	38,710	42,919	39,244	38,706	42,919	41,760	41,553	42,635
J-86	1.117,910	0,522	33,475	0,522	32,767	0,052	37,157	37,033	32,823	37,031	33,357	32,819	37,031	35,873	35,666	36,747

Table A - CONTINUED

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-87	1.115,340	0,630	37,017	0,630	36,311	0,062	39,783	39,644	36,642	39,650	37,174	36,638	39,651	38,564	38,358	39,338
J-88	1.107,460	0,587	43,296	0,587	42,586	0,058	47,555	47,436	42,470	47,432	43,007	42,466	47,432	46,084	45,871	47,164
J-89	1.097,260	0,908	53,443	0,908	52,733	0,090	57,734	57,616	52,609	57,611	53,145	52,604	57,612	56,253	56,040	57,343
J-90	1.108,720	0,508	42,042	0,508	41,332	0,050	46,297	46,179	41,218	46,174	41,755	41,213	46,175	44,828	44,615	45,907
J-91	1.089,160	0,532	63,811	0,532	63,106	0,053	66,109	65,922	63,599	65,937	64,129	63,595	65,938	64,788	64,582	65,531
J-92	1.097,020	0,221	55,956	0,221	55,250	0,022	58,232	58,052	55,746	58,068	56,277	55,742	58,068	56,940	56,735	57,676
J-93	1.108,000	0,300	44,983	0,300	44,278	0,030	47,231	47,061	44,777	47,077	45,308	44,773	47,077	45,978	45,772	46,703
J-95	1.115,220	0,467	37,758	0,467	37,052	0,046	39,965	39,809	37,557	39,825	38,087	37,552	39,826	38,766	38,560	39,477
J-96	1.100,980	0,608	51,152	0,608	50,445	0,060	54,055	53,933	50,723	53,933	51,255	50,719	53,933	52,840	52,634	53,637
J-97	1.073,410	0,544	77,307	0,544	76,598	0,054	81,542	81,422	76,492	81,417	77,027	76,487	81,418	80,141	79,932	81,145
J-98	1.093,760	0,915	56,997	0,915	56,289	0,091	61,233	61,113	56,182	61,108	56,717	56,178	61,109	59,827	59,619	60,836
J-99	1.087,420	0,668	63,406	0,668	62,697	0,066	67,562	67,441	62,614	67,437	63,148	62,609	67,438	66,238	66,031	67,164
J-100	1.087,670	0,064	63,184	0,064	62,475	0,006	67,312	67,192	62,399	67,188	62,934	62,395	67,189	65,996	65,789	66,915
J-101	1.086,910	0,306	63,992	0,306	63,284	0,030	68,072	67,951	63,222	67,948	63,757	63,218	67,948	66,769	66,562	67,673
J-102	1.086,560	0,530	64,497	0,530	63,789	0,052	68,424	68,304	63,771	68,301	64,306	63,767	68,301	67,131	66,924	68,025
J-103	1.086,720	0,534	64,446	0,534	63,739	0,053	68,266	68,145	63,752	68,143	64,286	63,747	68,143	66,988	66,781	67,865
J-104	1.100,900	0,625	50,271	0,625	49,563	0,062	54,116	53,994	49,569	53,992	50,103	49,565	53,992	52,831	52,624	53,716
J-105	1.103,510	0,401	47,698	0,401	46,990	0,040	51,511	51,390	47,006	51,388	47,539	47,001	51,388	50,233	50,026	51,111
J-106	1.103,880	0,405	47,372	0,405	46,664	0,040	51,144	51,022	46,692	51,020	47,225	46,687	51,021	49,866	49,659	50,742
J-107	1.111,190	0,414	40,070	0,414	39,362	0,041	43,849	43,727	39,388	43,725	39,922	39,384	43,726	42,569	42,362	43,448
J-108	1.106,090	0,412	45,123	0,412	44,415	0,041	48,938	48,816	44,431	48,814	44,965	44,427	48,814	47,652	47,445	48,537
J-109	1.100,850	0,690	50,830	0,690	50,123	0,068	54,172	54,050	50,274	54,049	50,806	50,269	54,050	52,932	52,725	53,766
J-110	1.101,010	0,306	51,136	0,306	50,429	0,030	54,025	53,903	50,712	53,903	51,244	50,708	53,903	52,812	52,606	53,607
J-111	1.111,630	0,507	41,327	0,507	40,621	0,050	43,479	43,339	41,129	43,354	41,659	41,124	43,355	42,342	42,137	43,037
J-112	1.099,930	0,632	52,671	0,632	51,964	0,063	55,104	54,983	52,378	54,984	52,909	52,374	54,984	53,934	53,728	54,685
J-113	1.099,080	0,494	53,753	0,494	53,047	0,049	55,921	55,800	53,529	55,811	54,059	53,524	55,812	54,836	54,630	55,531
J-114	1.096,820	0,127	56,009	0,127	55,302	0,013	58,161	58,043	55,784	58,054	56,315	55,780	58,055	57,090	56,885	57,782
J-115	1.096,280	0,408	56,454	0,408	55,748	0,040	58,701	58,583	56,203	58,593	56,734	56,199	58,594	57,597	57,391	58,321
J-116	1.096,320	0,561	56,412	0,561	55,705	0,056	58,661	58,543	56,160	58,553	56,690	56,155	58,554	57,556	57,350	58,281
J-117	1.073,570	0,444	79,104	0,444	78,397	0,044	81,365	81,247	78,848	81,257	79,379	78,844	81,258	80,249	80,043	80,985
J-118	1.112,820	0,778	39,840	0,778	39,133	0,077	42,270	42,135	39,556	42,147	40,088	39,552	42,148	41,047	40,839	41,827
J-119	1.102,150	0,680	50,322	0,680	49,614	0,067	52,859	52,737	49,990	52,749	50,523	49,985	52,749	51,738	51,531	52,469
J-120	1.101,000	0,401	51,932	0,401	51,226	0,040	54,007	53,885	51,735	53,898	52,265	51,730	53,898	52,947	52,741	53,617
J-121	1.097,380	0,166	55,545	0,166	54,839	0,016	57,589	57,474	55,348	57,487	55,878	55,343	57,487	56,560	56,354	57,220
J-122	1.096,900	0,255	56,025	0,255	55,319	0,025	58,053	57,941	55,827	57,954	56,358	55,823	57,954	57,039	56,833	57,697
J-123	1.114,450	0,732	36,607	0,732	35,897	0,073	40,586	40,466	35,863	40,464	36,399	35,858	40,464	39,163	38,950	40,190
J-124	1.073,370	0,189	77,185	0,189	76,474	0,019	81,565	81,449	76,320	81,444	76,858	76,315	81,445	80,049	79,833	81,181
J-125	1.090,820	0,538	59,771	0,538	59,060	0,053	64,150	64,035	58,906	64,030	59,445	58,902	64,030	62,635	62,420	63,766
J-126	1.093,380	0,243	57,216	0,243	56,505	0,024	61,596	61,480	56,351	61,475	56,889	56,346	61,475	60,080	59,864	61,211
J-127	1.102,460	0,517	48,167	0,517	47,456	0,051	52,534	52,418	47,306	52,413	47,844	47,301	52,414	51,031	50,815	52,150
J-128	1.106,700	0,489	43,929	0,489	43,218	0,048	48,300	48,184	43,065	48,180	43,604	43,061	48,180	46,800	46,584	47,918

Table A - CONTINUED

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-129	1.115,620	0,372	35,027	0,372	34,316	0,037	39,396	39,281	34,164	39,277	34,702	34,159	39,278	37,902	37,686	39,016
J-130	1.114,720	0,343	35,963	0,343	35,252	0,034	40,296	40,181	35,111	40,177	35,649	35,106	40,177	38,805	38,589	39,914
J-131	1.111,170	0,428	39,520	0,428	38,810	0,042	43,844	43,728	38,673	43,723	39,211	38,668	43,724	42,362	42,148	43,459
J-132	1.113,610	0,166	37,079	0,166	36,369	0,016	41,407	41,291	36,230	41,287	36,768	36,225	41,287	39,917	39,702	41,023
J-133	1.115,470	0,282	35,313	0,282	34,601	0,028	39,544	39,429	34,487	39,427	35,026	34,482	39,427	38,060	37,843	39,165
J-134	1.120,580	0,535	30,216	0,535	29,505	0,053	34,444	34,329	29,391	34,327	29,931	29,387	34,327	32,960	32,744	34,066
J-135	1.120,180	0,308	30,637	0,308	29,926	0,031	34,842	34,727	29,818	34,726	30,358	29,814	34,726	33,359	33,143	34,465
J-136	1.118,950	0,446	31,727	0,446	31,016	0,044	36,068	35,952	30,869	35,951	31,409	30,865	35,951	34,583	34,366	35,692
J-137	1.119,360	0,602	31,252	0,602	30,541	0,060	35,659	35,543	30,376	35,541	30,916	30,372	35,542	34,170	33,953	35,283
J-138	1.115,750	0,605	34,856	0,605	34,145	0,060	39,263	39,147	33,980	39,144	34,520	33,976	39,145	37,772	37,556	38,886
J-139	1.118,850	0,654	31,930	0,654	31,219	0,065	36,175	36,059	31,102	36,056	31,640	31,097	36,056	34,689	34,474	35,793
J-140	1.117,830	0,549	32,778	0,549	32,066	0,054	37,182	37,066	31,900	37,065	32,441	31,896	37,065	35,699	35,482	36,809
J-141	1.119,170	0,631	31,327	0,631	30,615	0,063	35,844	35,728	30,417	35,726	30,957	30,412	35,727	34,354	34,138	35,472
J-142	1.118,980	0,305	31,515	0,305	30,803	0,030	36,033	35,918	30,605	35,916	31,145	30,600	35,916	34,544	34,328	35,662
J-143	1.116,090	0,893	34,377	0,893	33,665	0,089	38,917	38,801	33,460	38,799	34,000	33,456	38,800	37,428	37,211	38,546
J-144	1.116,450	0,612	34,001	0,612	33,290	0,061	38,557	38,442	33,080	38,440	33,620	33,076	38,440	37,068	36,851	38,187
J-145	1.107,260	1,254	43,106	1,254	42,394	0,124	47,727	47,611	42,165	47,609	42,706	42,161	47,610	46,233	46,016	47,358
J-146	1.108,680	0,894	41,690	0,894	40,979	0,089	46,309	46,194	40,751	46,192	41,291	40,746	46,192	44,817	44,599	45,940
J-147	1.107,610	0,227	42,757	0,227	42,045	0,022	47,377	47,262	41,817	47,260	42,357	41,812	47,260	45,884	45,667	47,008
J-148	1.108,110	0,437	42,280	0,437	41,568	0,043	46,878	46,763	41,346	46,761	41,886	41,341	46,761	45,397	45,179	46,509
J-149	1.107,650	0,485	42,786	0,485	42,074	0,048	47,337	47,222	41,864	47,220	42,405	41,860	47,221	45,864	45,646	46,968
J-150	1.114,450	0,144	35,999	0,144	35,287	0,014	40,551	40,436	35,078	40,434	35,618	35,073	40,434	39,077	38,859	40,182
J-151	1.080,520	0,182	69,727	0,182	69,015	0,018	74,411	74,296	68,769	74,294	69,309	68,764	74,294	72,891	72,673	74,043
J-152	1.090,050	0,613	60,217	0,613	59,505	0,061	64,901	64,785	59,259	64,783	59,800	59,254	64,783	63,381	63,164	64,532
J-153	1.090,060	0,623	60,210	0,623	59,498	0,062	64,891	64,775	59,253	64,773	59,793	59,248	64,773	63,373	63,156	64,522
J-154	1.078,720	0,481	71,525	0,481	70,813	0,048	76,208	76,093	70,567	76,090	71,108	70,562	76,091	74,690	74,472	75,839
J-155	1.079,490	0,357	70,757	0,357	70,045	0,035	75,439	75,324	69,799	75,322	70,340	69,794	75,322	73,923	73,705	75,071
J-156	1.090,580	0,364	59,691	0,364	58,979	0,036	64,372	64,257	58,734	64,254	59,274	58,729	64,255	62,857	62,639	64,003
J-157	1.081,490	0,415	68,763	0,415	68,051	0,041	73,443	73,328	67,805	73,326	68,346	67,801	73,326	71,933	71,716	73,075
J-158	1.090,650	0,753	59,624	0,753	58,912	0,075	64,302	64,187	58,667	64,184	59,208	58,663	64,185	62,791	62,574	63,933
J-159	1.071,850	0,371	78,386	0,371	77,674	0,037	83,064	82,949	77,429	82,946	77,970	77,425	82,947	81,583	81,365	82,696
J-160	1.083,880	0,606	66,392	0,606	65,680	0,060	71,058	70,943	65,439	70,941	65,979	65,434	70,941	69,579	69,361	70,690
J-161	1.086,410	0,588	63,867	0,588	63,155	0,058	68,533	68,418	62,914	68,416	63,455	62,909	68,416	67,047	66,829	68,165
J-162	1.090,490	0,919	59,863	0,919	59,151	0,091	64,462	64,347	58,928	64,345	59,469	58,923	64,345	62,995	62,777	64,094
J-163	1.098,160	0,337	52,208	0,337	51,496	0,033	56,808	56,692	51,273	56,690	51,814	51,269	56,691	55,332	55,114	56,439
J-164	1.099,830	0,701	50,541	0,701	49,829	0,069	55,141	55,026	49,606	55,024	50,147	49,601	55,024	53,663	53,445	54,772
J-165	1.113,510	0,658	37,799	0,658	37,086	0,065	41,499	41,383	37,120	41,384	37,661	37,115	41,385	40,110	39,892	41,121
J-166	1.107,070	0,444	44,237	0,444	43,525	0,044	47,926	47,810	43,561	47,811	44,103	43,556	47,811	46,545	46,327	47,549
J-167	1.103,830	0,440	47,534	0,440	46,821	0,044	51,159	51,043	46,874	51,044	47,417	46,870	51,045	49,789	49,571	50,782
J-168	1.095,100	0,609	56,278	0,609	55,564	0,060	59,864	59,750	55,624	59,752	56,169	55,619	59,753	58,528	58,307	59,493
J-169	1.096,400	0,454	56,328	0,454	55,600	0,045	58,560	58,445	56,018	58,454	56,588	56,013	58,455	57,369	57,144	58,196
J-170	1.096,120	0,090	56,743	0,090	55,994	0,009	58,825	58,711	56,423	58,724	57,024	56,417	58,725	57,716	57,451	58,469
J-171	1.102,340	0,392	49,854	0,392	49,145	0,039	52,664	52,543	49,440	52,553	49,975	49,435	52,553	51,476	51,267	52,277
J-172	1.109,480	0,630	41,189	0,630	40,477	0,062	45,515	45,399	40,332	45,398	40,873	40,328	45,399	44,055	43,837	45,142
J-173	1.101,790	0,466	48,768	0,466	48,056	0,046	53,186	53,071	47,884	53,070	48,426	47,880	53,070	51,733	51,515	52,817

Table A - CONTINUED

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-174	1.098,800	0,401	51,754	0,401	51,042	0,040	56,170	56,055	50,871	56,054	51,412	50,866	56,054	54,729	54,511	55,801
J-175	1.097,230	0,764	53,356	0,764	52,643	0,076	57,737	57,622	52,482	57,621	53,023	52,477	57,621	56,310	56,091	57,367
J-176	1.057,800	1,025	94,717	1,025	93,965	0,102	97,064	96,950	94,310	96,961	94,920	94,304	96,962	95,912	95,640	96,710
J-177	1.092,830	1,421	59,889	1,421	59,136	0,141	62,106	61,992	59,519	62,004	60,129	59,513	62,005	60,971	60,699	61,751
J-178	1.065,460	0,505	87,125	0,505	86,372	0,050	89,420	89,306	86,733	89,318	87,342	86,726	89,318	88,207	87,934	89,065
J-179	1.083,150	0,809	69,488	0,809	68,735	0,080	71,766	71,651	69,100	71,663	69,710	69,094	71,664	70,570	70,297	71,411
J-180	1.095,870	0,257	56,986	0,257	56,233	0,025	59,074	58,959	56,653	58,973	57,263	56,647	58,973	57,955	57,683	58,717
J-181	1.095,420	1,023	57,416	1,023	56,646	0,101	59,520	59,404	57,036	59,418	57,675	57,029	59,418	58,372	58,073	59,163
J-182	1.091,820	0,576	59,908	0,576	59,138	0,057	63,097	62,985	59,218	62,991	59,858	59,211	62,992	60,864	60,566	62,741
J-183	1.079,680	0,145	71,876	0,145	71,106	0,014	75,211	75,099	71,145	75,104	71,784	71,138	75,105	72,832	72,534	74,854
J-184	1.091,730	0,374	59,851	0,374	59,081	0,037	63,185	63,073	59,120	63,078	59,759	59,113	63,079	60,807	60,509	62,829
J-185	1.084,050	0,132	68,587	0,132	67,631	0,013	70,832	70,699	67,737	70,721	68,697	67,722	70,722	69,452	68,880	70,474
J-186	1.094,050	0,677	58,607	0,677	57,651	0,067	60,852	60,720	57,758	60,741	58,717	57,743	60,742	59,473	58,901	60,495
J-187	1.063,990	0,916	87,569	0,916	86,988	0,091	90,723	90,645	86,967	90,639	87,405	86,964	90,639	89,521	89,350	90,459
J-188	1.084,180	1,878	67,514	1,878	66,934	0,186	70,575	70,497	66,939	70,491	67,377	66,937	70,492	69,467	69,296	70,311
J-189	1.100,050	0,669	51,710	0,669	51,129	0,066	54,737	54,659	51,144	54,654	51,582	51,142	54,654	53,718	53,547	54,474
J-190	1.105,870	0,481	45,923	0,481	45,343	0,048	48,929	48,851	45,364	48,846	45,802	45,361	48,846	47,915	47,744	48,666
J-191	1.115,120	0,126	36,771	0,126	36,191	0,012	39,699	39,621	36,234	39,616	36,672	36,232	39,616	38,700	38,528	39,435
J-192	1.120,730	0,678	31,231	0,678	30,651	0,067	34,101	34,023	30,710	34,018	31,149	30,708	34,019	33,112	32,941	33,836
J-193	1.112,840	0,126	39,046	0,126	38,466	0,012	41,974	41,896	38,509	41,892	38,947	38,507	41,892	40,975	40,803	41,710
J-194	1.102,770	0,243	49,015	0,243	48,434	0,024	52,023	51,945	48,455	51,940	48,893	48,452	51,940	51,007	50,835	51,760
J-195	1.113,310	0,246	38,562	0,246	37,981	0,024	41,505	41,427	38,020	41,422	38,458	38,018	41,422	40,503	40,332	41,241
J-196	1.099,750	0,804	53,201	0,804	52,506	0,080	55,195	55,086	53,007	55,098	53,530	53,002	55,099	54,200	53,997	54,847
J-197	1.123,470	1,129	29,737	1,129	29,147	0,112	31,393	31,307	29,569	31,315	30,016	29,567	31,315	30,584	30,405	31,122
J-198	1.126,760	0,396	25,681	0,396	25,100	0,039	28,090	28,010	25,291	28,009	25,730	25,289	28,009	27,159	26,988	27,820
J-199	1.124,870	0,749	28,270	0,749	27,690	0,074	29,986	29,904	28,079	29,908	28,518	28,077	29,908	29,143	28,972	29,707
J-200	1.105,050	0,299	47,658	0,299	46,748	0,030	49,806	49,698	46,833	49,712	47,755	46,826	49,712	48,494	47,940	49,497
J-201	1.104,960	0,167	47,747	0,167	46,836	0,017	49,896	49,788	46,920	49,802	47,842	46,914	49,802	48,584	48,029	49,587
J-202	1.105,000	0,909	47,705	0,909	46,795	0,090	49,856	49,748	46,879	49,762	47,800	46,872	49,762	48,543	47,988	49,547
J-203	1.093,440	0,444	59,197	0,444	58,221	0,044	61,457	61,323	58,296	61,345	59,291	58,280	61,346	60,053	59,451	61,099
J-204	1.124,580	0,311	28,598	0,311	28,044	0,031	30,234	30,158	28,409	30,161	28,830	28,407	30,161	29,451	29,286	29,985
J-205	1.124,580	0,211	28,621	0,211	28,079	0,021	30,218	30,144	28,434	30,148	28,847	28,432	30,148	29,461	29,298	29,980
J-206	1.124,780	0,317	28,462	0,317	27,939	0,031	29,998	29,927	28,280	29,931	28,680	28,279	29,931	29,276	29,118	29,774
J-207	1.125,730	0,337	27,603	0,337	27,114	0,033	29,018	28,953	27,433	28,956	27,808	27,432	28,956	28,357	28,205	28,817
J-208	1.124,550	0,199	28,867	0,199	28,407	0,020	30,174	30,113	28,711	30,116	29,065	28,711	30,115	29,560	29,414	29,987
J-209	1.123,050	0,225	30,404	0,225	29,955	0,022	31,662	31,603	30,254	31,606	30,599	30,254	31,606	31,068	30,924	31,482
J-210	1.119,120	1,010	34,464	1,010	34,054	0,100	35,560	35,505	34,339	35,508	34,655	34,340	35,508	35,027	34,890	35,396
J-211	1.123,460	1,025	29,900	1,025	29,380	0,102	31,335	31,261	29,750	31,267	30,146	29,749	31,267	30,635	30,473	31,105
J-212	1.117,100	1,455	36,492	1,455	36,083	0,144	37,576	37,521	36,370	37,524	36,684	36,370	37,524	37,048	36,913	37,412
J-213	1.114,900	1,346	37,671	1,346	36,640	0,133	39,920	39,803	36,396	39,823	37,603	36,428	39,821	38,571	37,924	39,621
J-214	1.116,370	0,561	36,327	0,561	35,368	0,056	38,410	38,308	35,143	38,325	36,273	35,187	38,321	37,191	36,603	38,145
J-215	1.114,550	0,276	38,477	0,276	37,724	0,027	40,175	40,095	37,653	40,107	38,504	37,703	40,102	39,225	38,797	39,957
J-216	1.089,730	1,377	62,656	1,377	61,476	0,136	65,058	64,929	61,089	64,952	62,522	61,119	64,951	63,566	62,786	64,740
J-217	1.090,590	2,183	61,960	2,183	60,893	0,216	64,289	64,149	60,836	64,174	61,987	60,815	64,176	62,778	62,042	63,931
J-218	1.089,530	0,153	62,851	0,153	61,661	0,015	65,264	65,131	61,272	65,156	62,716	61,298	65,155	63,747	62,941	64,941

Table A - CONTINUED

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-219	1.089,680	1,057	61,696	1,057	60,926	0,105	65,228	65,117	60,908	65,121	61,548	60,901	65,121	62,652	62,354	64,872
J-220	1.075,920	1,516	74,750	1,516	73,980	0,150	78,951	78,842	73,771	78,841	74,411	73,764	78,842	75,706	75,408	78,595
J-221	1.076,610	1,662	75,613	1,662	74,175	0,165	78,194	78,037	73,632	78,068	75,401	73,588	78,071	76,304	75,027	77,835
J-222	1.090,220	0,592	62,186	0,592	61,039	0,059	64,531	64,416	60,628	64,438	62,049	60,686	64,432	63,126	62,393	64,243
J-223	1.078,770	0,336	73,577	0,336	72,409	0,033	75,954	75,840	71,911	75,863	73,415	72,014	75,855	74,527	73,764	75,668
J-224	1.081,570	0,537	70,753	0,537	69,561	0,053	73,156	73,042	68,965	73,066	70,567	69,121	73,057	71,656	70,790	72,870
J-225	1.071,280	0,219	80,782	0,219	79,138	0,022	83,498	83,333	78,327	83,367	80,445	78,262	83,371	81,370	79,741	83,134
J-226	1.071,310	1,633	78,291	1,633	72,981	0,162	83,305	83,199	70,446	83,190	77,236	70,392	83,191	81,314	79,646	83,103
J-227	1.071,510	0,871	79,058	0,871	78,288	0,086	83,351	83,242	78,053	83,240	78,692	78,046	83,241	80,014	79,716	82,995
J-228	1.069,740	0,267	80,821	0,267	80,051	0,026	85,118	85,008	79,815	85,007	80,455	79,809	85,007	81,777	81,479	84,761
J-229	1.101,750	0,484	50,835	0,484	49,820	0,048	52,976	52,883	49,403	52,901	50,721	49,533	52,891	51,719	51,045	52,730
J-230	1.081,590	0,120	70,710	0,120	69,496	0,012	73,137	73,022	68,860	73,047	70,512	69,032	73,037	71,567	70,618	72,849
J-231	1.081,580	0,076	70,720	0,076	69,506	0,008	73,147	73,032	68,870	73,057	70,522	69,042	73,047	71,577	70,628	72,859
J-232	1.074,610	0,468	77,550	0,468	76,207	0,046	80,113	79,991	75,344	80,021	77,287	75,605	80,008	78,135	76,699	79,811
J-233	1.068,160	0,613	81,400	0,613	76,091	0,061	86,449	86,342	73,546	86,333	80,336	73,491	86,334	84,424	82,756	86,246
J-234	1.078,690	0,206	70,890	0,206	65,581	0,020	75,940	75,834	63,035	75,825	69,825	62,981	75,825	73,914	72,246	75,737
J-235	1.088,620	0,482	60,176	0,482	53,554	0,048	65,972	65,872	49,973	65,858	58,869	50,342	65,864	63,527	61,001	65,797
J-236	1.087,700	0,706	61,109	0,706	54,488	0,070	66,891	66,790	50,911	66,776	59,806	51,279	66,782	64,461	61,935	66,716
J-237	1.078,660	0,742	70,126	0,742	63,505	0,074	75,912	75,812	59,928	75,798	68,822	60,296	75,804	73,478	70,955	75,737
J-238	1.081,420	0,387	67,363	0,387	60,743	0,038	73,158	73,057	57,163	73,043	66,057	57,531	73,049	70,721	68,198	72,983
J-239	1.074,000	0,070	74,786	0,070	68,168	0,007	80,563	80,463	64,594	80,449	73,485	64,963	80,454	78,133	75,612	80,388
J-240	1.078,840	0,411	69,956	0,411	63,338	0,041	75,733	75,632	59,764	75,618	68,655	60,132	75,624	73,303	70,782	75,558
J-241	1.091,840	0,491	57,013	0,491	50,390	0,049	62,759	62,659	46,822	62,645	55,721	47,191	62,651	60,363	57,829	62,584
J-242	1.084,050	0,766	64,770	0,766	58,154	0,076	70,534	70,433	54,585	70,419	63,473	54,953	70,425	68,109	65,590	70,358
J-243	1.099,070	0,122	49,938	0,122	43,290	0,012	55,545	55,444	39,749	55,431	48,684	40,123	55,437	53,153	50,618	55,369
J-244	1.105,610	0,268	43,412	0,268	36,750	0,027	49,017	48,916	33,208	48,904	42,160	33,579	48,909	46,630	44,084	48,842
J-245	1.106,860	0,519	42,168	0,519	35,505	0,051	47,769	47,669	31,964	47,656	40,916	32,335	47,662	45,385	42,840	47,594
J-246	1.101,650	0,995	47,363	0,995	40,708	0,099	52,969	52,869	37,166	52,856	46,110	37,539	52,862	50,579	48,040	52,794
J-247	1.097,750	0,746	51,203	0,746	44,547	0,074	56,861	56,760	40,990	56,747	49,935	41,363	56,753	54,419	51,879	56,685
J-248	1.116,170	0,192	32,933	0,192	26,233	0,019	38,476	38,377	22,705	38,365	31,696	23,068	38,370	36,143	33,561	38,303
J-249	1.130,260	0,575	18,872	0,575	12,172	0,057	24,414	24,316	8,645	24,303	17,636	9,008	24,308	22,083	19,500	24,241
J-250	1.129,480	0,456	19,636	0,456	12,942	0,045	25,193	25,094	9,411	25,081	18,395	9,776	25,087	22,850	20,273	25,020
J-251	1.126,410	0,458	22,687	0,458	15,997	0,045	28,257	28,158	12,460	28,145	21,443	12,828	28,151	25,909	23,334	28,083
J-252	1.124,430	0,456	24,657	0,456	17,969	0,045	30,233	30,134	14,429	30,121	23,412	14,799	30,127	27,879	25,306	30,059
J-253	1.112,890	0,825	36,168	0,825	29,486	0,082	41,749	41,650	25,947	41,638	34,920	26,315	41,643	39,391	36,824	41,576
J-254	1.112,470	0,485	36,590	0,485	29,907	0,048	42,169	42,070	26,371	42,057	35,343	26,738	42,062	39,814	37,248	41,995
J-255	1.112,650	0,971	36,421	0,971	29,743	0,096	41,988	41,890	26,224	41,877	35,177	26,577	41,882	39,649	37,113	41,815
J-256	1.124,170	0,301	24,916	0,301	18,228	0,030	30,493	30,393	14,689	30,381	23,670	15,058	30,386	28,139	25,565	30,319
J-257	1.113,560	0,972	35,487	0,972	28,817	0,096	41,082	40,982	25,277	40,970	34,236	25,647	40,975	38,706	36,153	40,908
J-258	1.112,810	0,268	36,222	0,268	29,554	0,027	41,831	41,731	26,031	41,719	34,967	26,381	41,724	39,442	36,901	41,656
J-259	1.108,820	0,514	40,201	0,514	33,535	0,051	45,814	45,714	30,018	45,701	38,946	30,361	45,706	43,423	40,884	45,638
J-260	1.099,680	0,159	49,322	0,159	42,656	0,016	54,935	54,835	39,139	54,822	48,067	39,482	54,828	52,544	50,005	54,760
J-261	1.110,450	0,708	38,576	0,708	31,911	0,070	44,190	44,089	28,465	44,076	37,322	28,739	44,081	41,798	39,282	44,013
J-262	1.096,150	0,719	52,859	0,719	46,263	0,071	58,462	58,361	42,757	58,348	51,608	43,114	58,353	56,073	53,570	58,284
J-263	1.098,740	0,472	50,268	0,472	43,628	0,047	55,875	55,774	40,091	55,761	49,015	40,464	55,767	53,483	50,952	55,698

Table A - CONTINUED

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-264	1.086,580	0,791	62,298	0,791	55,716	0,078	68,012	67,910	52,180	67,897	61,016	52,540	67,903	65,595	63,097	67,835
J-265	1.066,910	0,197	81,924	0,197	75,342	0,020	87,642	87,541	71,805	87,527	80,640	72,164	87,533	85,224	82,726	87,465
J-266	1.081,040	0,296	67,823	0,296	61,241	0,029	73,540	73,439	57,705	73,426	66,540	58,064	73,431	71,123	68,625	73,363
J-267	1.096,150	1,066	52,868	1,066	46,318	0,106	58,464	58,362	42,833	58,350	51,620	43,185	58,355	56,079	53,601	58,285
J-268	1.113,280	1,158	35,755	1,158	29,078	0,115	41,366	41,267	25,685	41,254	34,500	25,902	41,257	38,984	36,473	41,189
J-269	1.128,460	0,540	20,700	0,540	14,019	0,053	26,210	26,112	10,531	26,099	19,472	10,870	26,104	23,903	21,330	26,038
J-270	1.133,790	0,809	15,355	15,809	8,292	0,080	20,893	20,794	4,765	20,782	14,119	4,991	20,786	18,578	15,854	20,719
J-271	1.132,420	0,505	16,703	15,505	9,499	0,050	22,260	22,161	5,909	22,148	15,463	6,171	22,153	19,922	17,008	22,086
J-272	1.124,630	0,620	24,463	0,620	17,485	0,061	30,034	29,935	13,974	29,923	23,219	14,225	29,927	27,684	25,029	29,860
J-273	1.121,140	0,603	27,942	0,603	21,142	0,060	33,521	33,424	17,844	33,410	26,696	17,935	33,413	31,168	28,615	33,344
J-274	1.130,710	0,707	18,405	0,707	11,611	0,070	23,971	23,875	8,399	23,861	17,162	8,409	23,863	21,649	19,112	23,794
J-275	1.123,190	0,568	26,016	0,568	19,497	0,056	31,471	31,373	16,070	31,360	24,803	16,400	31,365	29,214	26,787	31,297
J-276	1.121,590	0,438	27,657	0,438	21,187	0,043	33,065	32,967	17,940	32,955	26,455	18,123	32,960	30,834	28,432	32,894
J-277	1.116,020	0,799	33,179	0,799	26,760	0,079	38,622	38,525	23,628	38,513	31,967	23,701	38,518	36,410	34,098	38,452
J-278	1.118,470	0,079	30,835	0,079	24,485	0,008	36,177	36,080	21,448	36,068	29,650	21,472	36,073	34,017	31,741	36,007
J-279	1.118,980	0,027	30,326	0,027	23,976	0,003	35,668	35,571	20,939	35,559	29,141	20,963	35,564	33,508	31,233	35,498
J-280	1.118,770	0,231	30,535	0,231	24,185	0,023	35,878	35,780	21,148	35,769	29,350	21,173	35,774	33,718	31,442	35,707
J-281	1.119,130	0,047	30,141	0,047	23,799	0,005	35,518	35,421	20,783	35,409	28,946	20,779	35,414	33,354	31,101	35,348
J-282	1.117,720	0,914	31,609	0,914	25,306	0,091	36,925	36,828	22,353	36,816	30,431	22,314	36,822	34,794	32,568	36,755
J-283	1.117,770	0,234	31,479	0,234	25,137	0,023	36,875	36,778	22,115	36,766	30,279	22,112	36,771	34,692	32,439	36,705
J-284	1.119,350	0,403	29,909	0,403	23,567	0,040	35,298	35,201	20,548	35,189	28,711	20,544	35,195	33,122	30,869	35,128
J-285	1.118,880	0,027	30,425	0,027	24,076	0,003	35,768	35,671	21,038	35,659	29,240	21,063	35,664	33,608	31,332	35,598
J-286	1.117,000	0,129	32,240	0,129	25,899	0,013	37,643	37,546	22,875	37,534	31,038	22,871	37,540	35,453	33,201	37,473
J-287	1.118,300	0,367	30,943	0,367	24,602	0,036	36,346	36,249	21,578	36,237	29,741	21,574	36,242	34,156	31,904	36,176
J-288	1.111,160	0,088	38,069	0,088	31,727	0,009	43,472	43,374	28,703	43,363	36,867	28,700	43,368	41,282	39,029	43,302
J-289	1.136,560	0,272	12,731	0,272	6,389	0,027	18,123	18,026	3,368	18,014	11,532	3,365	18,019	15,944	13,691	17,953
J-290	1.120,610	0,290	32,033	0,290	30,010	0,029	33,945	33,903	29,197	33,899	31,725	29,186	33,901	31,956	29,786	33,870
J-291	1.125,020	0,088	27,632	0,088	25,609	0,009	29,544	29,502	24,796	29,498	27,324	24,784	29,500	27,555	25,385	29,469
J-292	1.121,110	1,273	32,994	1,273	32,811	0,126	33,407	33,387	32,929	33,387	33,071	32,929	33,387	33,211	33,149	33,351
J-294	1.125,310	0,113	28,148	0,113	27,737	0,011	29,381	29,326	27,984	29,328	28,299	27,984	29,328	28,830	28,693	29,218
J-295	1.133,400	1,003	20,075	1,003	19,664	0,099	21,307	21,253	19,911	21,255	20,226	19,911	21,254	20,756	20,620	21,145
J-296	1.142,080	0,109	11,412	0,109	11,001	0,011	12,645	12,590	11,248	12,592	11,563	11,248	12,592	12,093	11,957	12,482
J-297	1.095,650	0,233	53,371	0,233	46,831	0,023	58,964	58,862	43,353	58,849	52,124	43,702	58,855	56,581	54,109	58,784
J-298	1.090,150	0,762	58,983	0,762	52,879	0,076	64,470	64,364	49,641	64,353	57,776	49,914	64,358	62,169	59,978	64,282
J-299	1.082,720	1,230	66,455	1,230	60,351	0,122	71,886	71,780	57,128	71,769	65,264	57,401	71,774	69,603	67,412	71,697
J-300	1.083,920	0,890	65,183	0,890	58,911	0,088	70,681	70,576	55,572	70,565	63,969	55,891	70,571	68,355	66,057	70,496
J-301	1.087,060	0,447	62,019	0,447	55,675	0,044	67,545	67,440	52,297	67,429	60,796	52,626	67,434	65,202	62,857	67,361
J-302	1.101,960	0,893	47,049	0,893	40,437	0,088	52,665	52,564	37,025	52,552	45,794	37,282	52,556	50,270	47,780	52,486
J-303	1.090,490	0,184	58,495	0,184	51,883	0,018	64,112	64,011	48,471	63,998	57,240	48,727	64,003	61,716	59,225	63,933
J-304	1.099,510	0,676	49,496	0,676	42,839	0,067	55,110	55,010	39,473	54,997	48,241	39,671	55,001	52,727	50,225	54,931
J-305	1.094,010	0,835	54,986	0,835	48,341	0,083	60,599	60,500	44,976	60,486	53,731	45,179	60,490	58,216	55,715	60,420
J-306	1.086,880	0,146	62,101	0,146	55,456	0,015	67,715	67,615	52,091	67,602	60,846	52,294	67,606	65,331	62,831	67,536
J-307	1.083,260	0,796	66,062	0,796	60,229	0,079	71,358	71,252	57,232	71,242	64,916	57,401	71,245	69,168	67,155	71,165
J-308	1.086,450	0,212	62,653	0,212	56,373	0,021	68,157	68,050	52,792	68,035	61,432	53,334	68,046	65,847	63,435	67,967
J-309	1.096,680	0,774	52,445	0,774	46,165	0,077	57,948	57,841	42,585	57,826	51,225	43,127	57,837	55,637	53,226	57,758

Table A - CONTINUED

		DUCTILE / STEEL						HDPE/DSI			HDPE/MARKET			EXISTING SYSTEM		
		Qpeak		Qfire		Qnight		Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight	Qpeak	Qfire	Qnight
Label	Elevation (m)	Base Flow (l/s)	Pressure (m H2O)	Base Flow (l/s)	Pressure (m)	Base Flow (l/s)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)	Pressure (m H2O)
J-310	1.118,850	0,670	30,213	0,670	23,513	0,066	35,808	35,710	20,186	35,696	28,963	20,336	35,699	33,445	30,928	35,630
J-311	1.117,360	0,550	31,696	0,550	25,000	0,055	37,295	37,197	21,665	37,183	30,445	21,822	37,187	34,930	32,413	37,117
J-312	1.104,330	0,836	44,687	0,836	38,013	0,083	50,299	50,200	34,660	50,186	43,432	34,838	50,190	47,919	45,414	50,121
J-313	1.120,860	0,775	28,204	0,775	21,464	0,077	33,801	33,703	18,134	33,689	26,953	18,272	33,693	31,437	28,908	33,624
J-314	1.127,590	0,553	21,498	0,553	14,745	0,055	27,085	26,988	11,471	26,974	20,250	11,551	26,976	24,737	22,210	26,908
J-315	1.127,380	0,474	21,800	0,474	15,294	0,047	27,300	27,199	11,802	27,185	20,577	12,190	27,191	24,985	22,499	27,118
J-316	1.120,890	0,323	28,338	0,323	22,058	0,032	33,785	33,678	18,358	33,663	27,133	19,032	33,675	31,475	29,036	33,595
J-317	1.122,190	0,531	27,041	0,531	20,761	0,053	32,488	32,380	17,101	32,366	25,836	17,735	32,377	30,185	27,757	32,298
J-318	1.123,470	0,434	25,735	0,434	19,284	0,043	31,202	31,100	15,783	31,086	24,522	16,204	31,093	28,912	26,482	31,019
J-319	1.128,550	0,353	20,650	0,353	14,179	0,035	26,133	26,030	10,680	26,016	19,432	11,089	26,023	23,830	21,379	25,950
J-320	1.107,800	0,860	41,503	0,860	35,532	0,085	46,862	46,750	31,939	46,736	40,326	32,617	46,749	44,582	42,270	46,663
J-321	1.117,680	0,453	31,574	0,453	25,424	0,045	36,994	36,882	21,589	36,867	30,378	22,442	36,883	34,680	32,251	36,799
J-322	1.091,420	1,080	58,185	1,080	52,817	0,107	63,233	63,123	50,144	63,116	57,099	50,147	63,118	61,144	59,282	63,025
J-323	1.107,720	0,603	41,607	0,603	35,672	0,060	46,943	46,832	32,220	46,819	40,437	32,771	46,830	44,687	42,429	46,745
J-324	1.105,680	0,475	43,570	0,475	37,509	0,047	48,974	48,859	33,607	48,844	42,380	34,559	48,862	46,658	44,248	48,776
J-325	1.074,290	0,684	75,298	0,684	69,961	0,068	80,330	80,222	67,353	80,214	74,228	67,331	80,215	78,293	76,539	80,125
J-326	1.093,360	0,436	55,982	0,436	50,163	0,043	61,279	61,166	46,696	61,153	54,828	47,315	61,166	59,041	56,848	61,078
J-327	1.102,470	0,399	46,773	0,399	40,712	0,040	52,178	52,062	36,814	52,047	45,583	37,762	52,065	49,862	47,452	51,979
J-328	1.079,210	0,277	72,949	0,277	71,616	0,027	75,513	75,397	70,755	75,426	72,686	71,015	75,411	73,544	72,114	75,221
J-329	1.083,600	0,315	68,562	0,315	67,238	0,031	71,123	71,012	66,380	71,040	68,300	66,641	71,023	69,163	67,741	70,840
J-330	1.089,590	0,302	62,583	0,302	61,269	0,030	65,135	65,030	60,415	65,058	62,322	60,682	65,038	63,186	61,776	64,862
J-331	1.095,680	0,615	56,505	0,615	55,206	0,061	59,050	58,949	54,352	58,977	56,245	54,631	58,956	57,111	55,711	58,784
J-332	1.079,910	0,877	69,679	0,877	64,325	0,087	74,721	74,612	61,680	74,604	68,600	61,673	74,606	72,657	70,848	74,514
J-333	1.111,980	0,719	40,237	0,719	38,940	0,071	42,781	42,681	38,087	42,709	39,977	38,367	42,687	40,844	39,447	42,517
J-334	1.110,540	0,772	41,690	0,772	40,413	0,076	44,217	44,118	39,590	44,144	41,437	39,857	44,124	42,317	40,979	43,954
J-335	1.104,440	0,238	48,057	0,238	46,986	0,024	50,294	50,199	46,481	50,219	47,910	46,639	50,207	48,887	48,076	50,045
J-336	1.108,230	0,221	44,168	0,221	43,028	0,022	46,514	46,418	42,413	46,440	43,981	42,607	46,426	44,929	43,946	46,261
J-337	1.108,860	0,305	43,483	0,305	42,302	0,030	45,887	45,791	41,624	45,813	43,275	41,840	45,798	44,204	43,118	45,632