An-Najah National University
Faculty of Graduate Studies

COST VALUE FUNCTION OF WATER DISTRIBUTION NETWORKS

A Reliability-Based approach using MATLAB®

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Submitted in Partial Fulfillment of the Requirements for the Degree of Master in Computational Mathematics, Faculty of Graduate Studies, at An-Najah National University, Nablus, Palestine

2008

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Dedication

To the spirit of my late father, who was the source of success that was in our rough life.

To the legend of sacrifices that is totally represented in my kindhearted mother, who was the first help to my father in making us as we are now, despite of the whole challenges in our way.

To my brothers and sisters, who kept advising me to make the right decision in my work and life.

To my wife, who is continuously supporting me in my way towards the final destination, whenever and wherever it will be, having nothing except her absolute trust in me.

To my beloved kids: *Baraa*, *Ruba*, *Mohammad* and *Hasan*, hoping from Allah the almighty to help us take care of them in the right way, and to the right destiny.

To all of them

With all the love, appreciation and kindness

Khalid

ACKNOWLEDGMENTS

First, "Alhamdulillah" for helping me complete this work.

Many thanks and appreciation must be gone to my supervisors: ***Dr. Mohammad Najeeb Ass'ad*** and ***Dr. Mohammad N. Almasri***, for their continuous and great help and guidance through this study work. Great thanks also go to the defense committee.

Many special thanks must be sent to my deep friends: ***Eng. Ammar Sabha*** and ***Dr. Khalid Rabayaa***, for giving the continuous support and encouragement in all of my life and work.

Special thanks to my colleagues ***Jasem Badran*** and ***Fares Rabayaa***, for being in touch with me and for their encouragement all of the time of working in my thesis.

I cannot go without expressing the whole thanks to my family, brothers and sisters.

Thanks to all of them is a dept in my heart until the end of my life.

إقـــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Cost Value Function of Water Distribution Networks:

A Reliability-Based Approach using MATLAB.

أقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص ، باستثناء ما تمت الإشارة إليه حيثما ورد، وإن هذه الرسالة ككل ، أو أي جزء منها لم يقدم من قبل لنيل أية درجة أو لقب علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى .

DECLARATION

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name : إسم الطالب:

Signature : التوقيـع:

Date : التاريـخ:

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COST VALUE FUNCTION OF WATER DISTRIBUTION NETWORKS

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ABSTRACT

Every community on Earth ought to find the appropriate means to distribute water from different sources to a consumption centers. In general, water distribution networks (WDN) attain this. Each network is composed of arches (to deliver water) and nodes (to consume the water delivered). The ability of any WDN to satisfy the requirements at each node under normal and abnormal conditions is one of the dimensions of its ***reliability***. A method was introduced in this work to evaluate the reliability of a WDN for several combinations of diameters.

A network solver was used to find the diameter combination successively. The results obtained from the network solver were saved in a text file. This file is then read by MATLAB, in order to do the necessary calculations. The system reliability for each diameter combination was computed. The values of the system reliability of each diameter combination are recorded as a vector in the MATLAB environment. The most important objective is the maximum of the system reliability of all these combinations, which has been achieved by MATLAB.

For this maximum reliability value, we have determined the corresponding values of the cost, where each one represents a diameter combination. The minimum of these values is then determined using a computer code that was developed within the method.

MATLAB was used to develop the computer program that converts the information into matrices, which make the required outcome easy to obtain and process.

A hypothetical case study was developed to demonstrate methodology implementation. The results were composed of two important things: The computed reliability of any WDN and the way to find the least cost design with a value of reliability that is over a minimum boundary value. Another important thing is all the alternatives of reliability values that can be achieved with a specific budget that we already have.

Chapter (1)

INTRODUCTION

1.1 General

Water is one of the greatest needs for humanity, since the dawn of life, during the various stages of our living on Earth, until our present time and to the end of our lives. It was a driving reason for many of the wars that had occurred between several nations and governments all around the world, and during several periods. This is an obvious fact that put a critical importance on water and how to make it available for the people of every nation (Linsley and Franzini, 1979).

From the beginning of the life, and during the stages of our history in this planet, beginning from prehistoric times, several procedures were made and invented, in order to *supply* the water to the people, and *control* the way that brings the water to our families, houses, farms, animals and others. These two objectives were, and still are, the two main factors that affect the price and *cost* of water and its delivery to our places (Cebeci, Shao, Kafyeke and Laurendeau, 2005).

Speculation was the earliest activity in searching pure water for humans and their needs. It began in making some trenches dug in earth, and then they used a hollow log to be the first water pipe in life. May be, there were many thousands of years until humans built the first community or *city*, and made what is known now as a *Network.* The earliest archeological records of central water supply and wastewater disposal date back about 5000 years, to *Nibbur of Sumeria*, where there is an arched drain, each stone being a wedge tapering downward into place (Durant, 1997).

The first engineering report on water supply systems was at A.D 98 by Sextus Julius Frontinus, water commissioner of Rome. He describes the system as a reservoir at the head of one canal of water where the system used some pebbles catchers that were built among these canals (Viessman and Hammer, 2004).

From these ancient periods until today, the procedures continues to be improved until what we are seeing in the present time, including the complex combination of pipes, nodes, pumps, reservoirs and tanks, or simply the *Water Distribution Networks* (WDN).

Water distribution simulation and modeling is the latest technology in a process that is continually in progress and began two millennia ago when the Minoans Civilization constructed their piped water conveyance or distribution system. Today, water distribution modeling is a critical part of designing and operating water distribution systems now and in the future. The availability of increasingly sophisticated and accessible models allows these goals to be realized more fully than ever before (Walski et. al., 2003).

The complexity and size of the WDN varies from time to time, and from place to place. Despite this, the objective is still the same: to deliver water from source to costumer activities (Walski et. al., 2003).

1.2 Statement of the Problem

As mentioned earlier, the supply and control of water were an important purpose and objective to be achieved. This objective comes as this: *how to supply an adequate water **quantity** in order to cover the needed **demand** for each **node** through a highly interconnected system of **pipes**, and through using network elements such as **pumps, reservoirs** and **tanks?***

This statement is the main objective of all the water engineering science, including the supply, control, management and simulation. In this research work, the main question arises after the whole and huge work in this field to be about the ***best way***, or the ***optimum*** procedure to achieve these enormous and tremendous steps and stages in a *realistic* time interval, *suitable* cost amount, and *adequate* performance; including water *quantity* and *quality*.

This suitability or goodness must be acceptable for all the nodes and other network elements in order to arrive at the best outcomes. Apparently, *Optimization* is the wide gate to get through for optimality.

1.3 Motivations and Importance of the Study

This study is going to answer the main articulated question, which is: *How can we design a WDN with a minimum cost, and at the same time, with an acceptable performance*? *And what do we mean by acceptable performance?*

The cost of the WDN is the objective value that is to be minimized, this is obvious. The criterion that gives us a glimpse regarding the performance of the WDN is what we call *Reliability*. Throughout this thesis, reliability will be addressed in details.

Based on the above, the main question that must be addressed comes as follows:

> *What is the least-cost design of a water distribution network that can supply each node with an adequate water amount, at the* ***needed pressure****, and with a pre-specified* ***reliability****?*

1.4 The Research Objective

Having a WDN that was designed according to the above criteria and specifications, i.e. least cost and high reliability, is one of the main objectives of every network designers, every water distribution institutions, and for every decision maker in this field. During the past few decades, considerable efforts have been devoted to the development of optimization algorithms and models for the design of water distribution networks. In many cases, the primary objective of these models was *to minimize the cost* of the network (Alperovits and Shamir, 1977); (Quindry et al. 1981); (Lansey and Mays, 1989); (Eiger et al., 1994); (Simpson et al., 1994); (Savic and Walters, 1997). However, in practice, the optimal design of a water distribution network is a complex multiple objective process involving trade-offs between the cost of the network and its reliability (Alperovits and Shamir, 1977).

The main objective of this research work is to find the design of a WDN that has the minimum cost with the highest reliability.

During this work, several intermediate objectives will be achieved. Among these objectives are:

(1) Revision of the design of the network with a specific look at each of the parameters of the WDN and their importance in the design process;

(2) Calculations of Reliability of any existing WDN;

(3) The least cost design of the WDN with full supply of water for each node and with the required quantity and the minimum pressure;

(4) Implementation of this work on a hypothetical case study, getting an output that may be useful for further study to take the good decisions and procedures.

1.5 Thesis outline

The thesis comprised of five chapters, each one leads to the next, in a subsequent manner.

Water Distribution Networks and *Reliability* will be discussed in details in Chapter (2). We will define the WDN and its parameters, and the important relations in the design process. The different definitions regarding Reliability of WDNs will be considered. The summary of these studies will be reviewed and summarized in a tabular form. Chapter (3) is dedicated to the research methodology. Chapter (4) considers the implementation of the methodology and the solution procedure on a hypothetical case study. Chapter (5) provides the conclusions and recommendations.

Chapter (2)

LITERATURE REVIEW

2.1 General

In this chapter, the two main concepts in our study that include *Water Distribution Networks* and *Reliability* will be illustrated. Analysis of WDN will then be presented briefly. The design of WDN will be briefly illustrated. In addition, the Reliability concept for WDNs will be demonstrated including; history and background, definitions, computation methods of Reliability-Based optimization of WDN.

2.2 What is WDN?

A ***water distribution system*** is defined as *an interconnected collection of sources, pipes, and hydraulic control elements (e.g., pumps, valves, regulators, and tanks) aimed at delivering water to consumers in prescribed quantities and at desired pressures* (Ostfeld, 2001).

The importance of WDN arises from the importance of delivering fresh drinking water.

The behavior of the WDN is affected by different factors such as: (1) physical laws that describe and control the flow direction and distribution, (2) consumer demand, and (3) system layout (Ostfeld, 2001).

The consumption of water in urban areas is affected by other factors such as: (1) location of the demand area, (2) size of the demand area, (3) characteristics and nature of the population, e.g., agricultural, domestic or industrial, (4) cost of water and its delivery to the population, (5) technical policy of Water Department, (6) climatic conditions, and (7) standards of living (Masri, 1997).

2.3 Elements of WDN

The water distribution network consists of several nodal elements including the junction points or joints. Models use link elements to describe the pipes connecting these nodes. Table 2.1 summarizes a list of each model element, the type of element used to represent it in the model, and the primary modeling purpose in using that element (Walski et. al., 2003).

2.4 Types of WDN

As a configuration style of the WDN, two main types of configuration are usually used; *looped* and *branched* networks. Figure 2.1 shows a typical graph of both looped and branched networks. The branched network is also called *tree* or *dendritic systems* (Walski et. al., 2003).

Table 2-1 : *Common Network Elements*

Element	Type	Primary Modeling Purpose
Reservoir	Node	Provides water to the system
Tank	Node	Stores excess water within the system and releases that water at times of high usage
Junction	Node	Removes (demand) or adds (inflow) water from/to the system
Pipe	Link	Conveys water from one node to another
Pump	Node or link	Raises the hydraulic head to overcome elevation differences and friction losses
Control Valve	Node or link	Controls flow or pressure in the system based on specified criteria

The name of the two types gives us an idea about the performance and use of each type. Each type has a reason for its use, and it must have some advantages and disadvantages.

In the branched network, there is just one source, from which the water will be delivered to several dead end nodes and junctions. The main reason for using this type is the saving in the total cost of the network despite the fact that a lot of disadvantages and negativities are still present such as (Masri, 1997):

(1) Low reliability, as will be illustrated in a following example when comparing the two types;

(2) Contamination caused by parts of the network;

(3) Accumulation of sediments in the pipes because of the dead ends;

(4) Big oscillations in the pressure heads due to the variations in the demand.

In the looped network systems, water can go from more than one source to any other node through several paths, while there is just one path to take water from the source to any dead end node in the branched network.

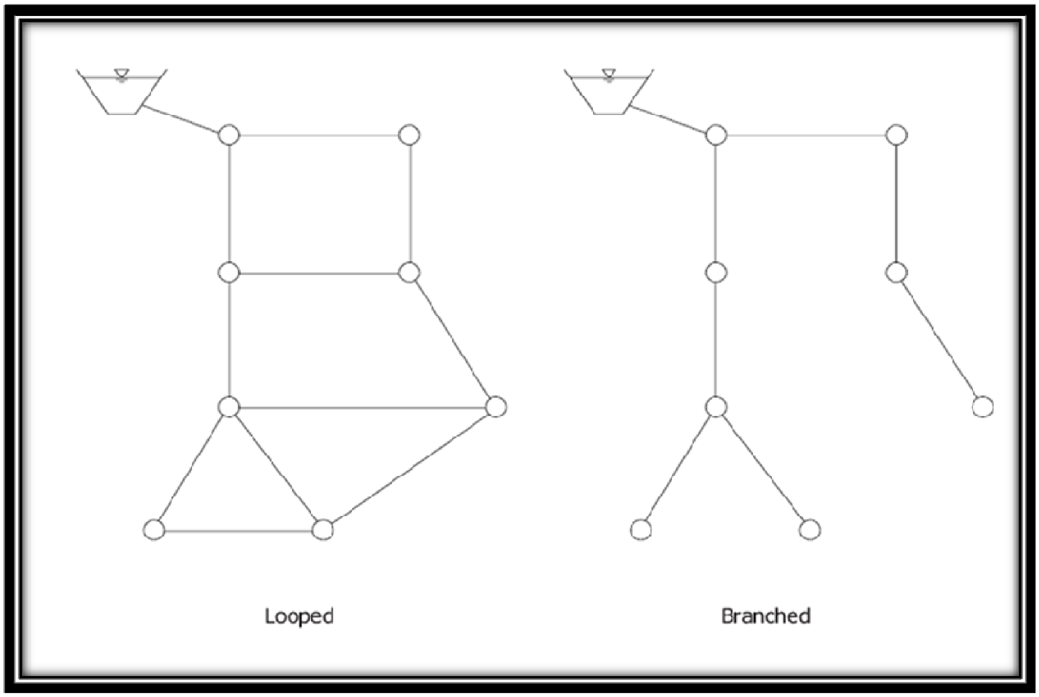


Figure 2-1 : *Looped and Branched Networks*

The looped systems are more complicated and large than the branched one. It costs much more than the branched one, but it is still more preferable in design because it gives an additional reliability level. The presence of several paths and loops in the network makes it easy to eliminate most of the disadvantages of the branched one. The water therefore can arrive at a node from more than one pipe and many directions. This is the main characteristics in the looped network.

To illustrate the mastery of the looped over the branched networks, let us assume a break occurrence in any pipe near the source in a branched network. Apparently, it will be impossible to deliver water to the nodes that are remote from the source than the pipe, which was broken, see Figure 2.2. In looped networks, the problem can be solved by getting water to the nodes from different paths or routes in the network (Walski et. al., 2003).

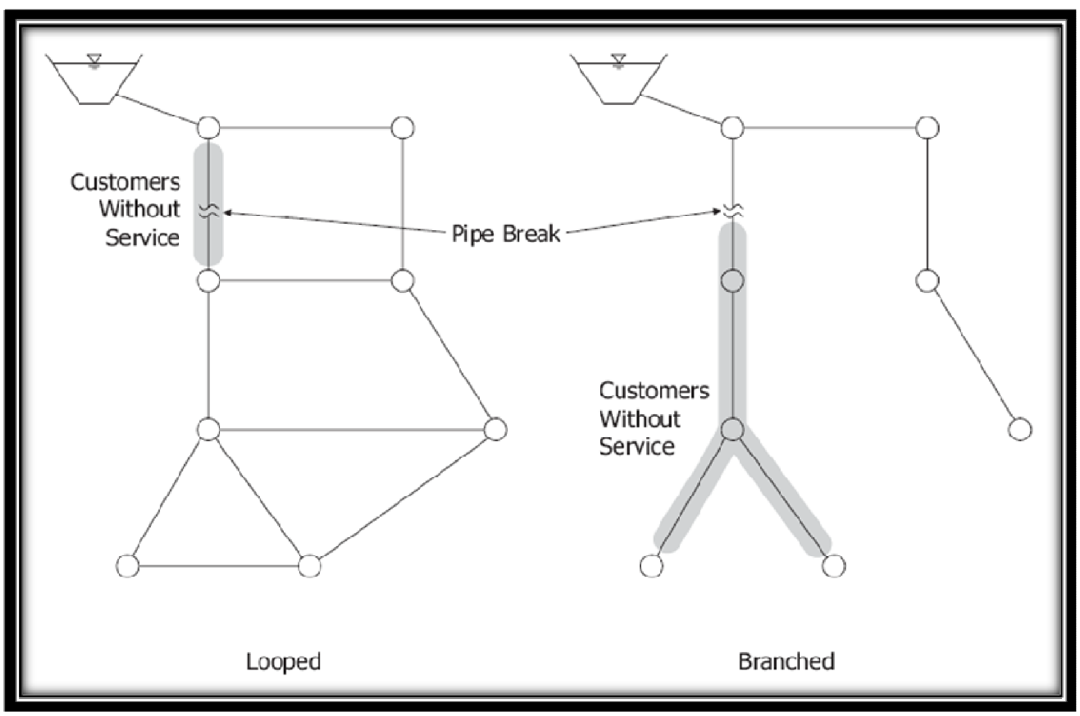


Figure 2-2: *Looped and branched network after a failure.*

In real cases, most of the water distribution systems consist of *complex combinations* of looped and branched network systems. Using looped network segments increase the redundancy or reliability of the network, while the overall cost can be decreased to a minimum level in the branched networks, because the elements that are used in the looped (such as valves, pumps, etc.) are more expensive than what we always use in the simple situation of the branched networks.

As a summary, any water distribution network consists of **three** major parts and components: *pumps, distribution storages, and distribution piping network* (Mays, 2000).

2.5 WDN Simulation

Before building a huge project or system, and before letting it in use for human beings, that system or project must be tested and examined, especially when the issue is related to a subject that affect the health of human beings.

Simulation can be defined as developing a set of equations that mimic the full system in every aspect in order to test it. This system of equations is called a *model*. This process is called *modeling* or *simulation*. Through this process, the real system can be mathematically modeled and tested. (Walski et. al., 2003).

For WDNs, simulation is used through modern and advanced software packages that use the *graphical user interface* (GUI) to facilitate data entry and for obtaining the results, as in the simulation software called EPANET. (Walski et. al., 2003).

2.6 Hydraulic principles of water distribution networks

2.6.1.Definition

Analysis of WDN is the calculation process that gives the values of the parameters of the network. These parameters include the *pressure* or *head* at nodes, *velocity* of water through pipes, *demand* at each node, etc.. There are three common procedures to analyze and solve the looped water distribution networks: *looped method*, *node method* and *element method* (Sârbu, 1987).

2.6.2.Bernoulli Equation (*Conservation of energy*)

It is known that water moves according to the principles of kinematics in one dimension. In 1750, Leonard Euler applied the Newton's Second Law of motion on water for the first time, which was the beginning of this science, and made very big advancements in fluid dynamics science and engineering. When applying these laws on a water particle or segment, the following equation will remain the same during of the trip of water, at any location, and according to the pre-specified assumptions. We can write this equation more conveniently as:

$$\frac{p}{\gamma} + \frac{v^2}{2g} + Z = H = Constant \qquad \textbf{(2.1)}$$

where,

- ❒ p : pressure at any node in the WDN (m);
- ❒ γ : specific weight of water (kg/m^3);
- ❒ v : velocity of water (m/sec);
- ❒ g : acceleration due to gravity (m/sec^2);
- ❒ Z : head at any node (m).

This is the ***Bernoulli equation*** for the dynamics of fluids. It is a good relation between the pressure at a point *p*, the velocity of that element of water *v*, and the height *z* above datum. The Benroulli constant *H* is also referred to as the *total head* (Vennard and Street, 1982).

2.6.3.Continuity Equation (*Conservation of mass*)

The quantity of the flow in the pipe network is the same at each node in the path of flow. The difference is in the velocity from one connection pipe to the other. As the pipe is small in diameter, and under the same flow rate (Volume/Area), the velocity will increase, and vice versa. Figure (2.3) shows this concept clearly.

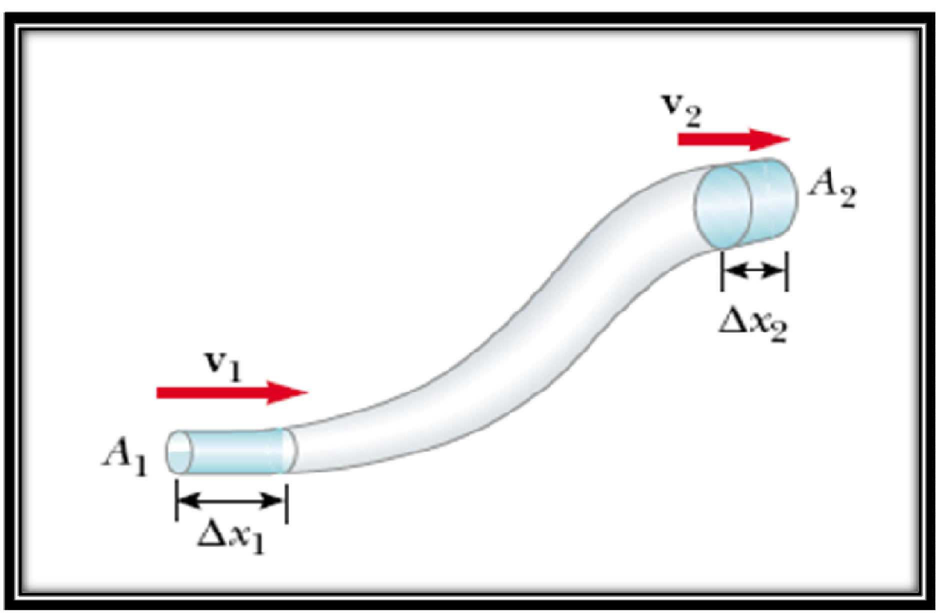


Figure 2-3: *The continuity Equation principle*

In Figure (2.4), a fluid is moving with steady flow through a pipe of varying cross-sectional area. The volume of fluid flowing through area A_1 in a time interval t must equal the volume flowing through area A_2 in the same time interval, therefore;

$$Q_1 = A_1 \times V_1 = Q_2 = A_2 \times V_2 = Constant \qquad \textbf{(2.2)}$$

This equation is known as the ***Continuity Equation***, it stated that (Halliday, 2004):

The product of the area and the fluid velocity at all points along the pipe is a constant for an incompressible fluid.

In other words, the total amount of fluid passing through any section of a pipe is fixed. This may also be thought of as the principle of *conservation of mass*. Basically, it means that liquid is neither created nor destroyed as it flows through a pipeline, (Hodges, 1996).

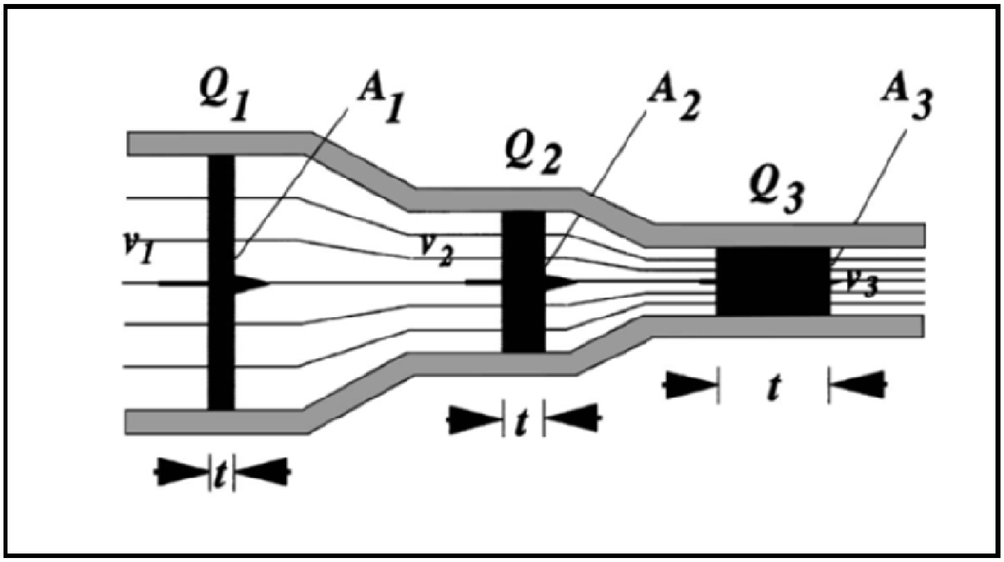


Figure 2-4 : *The principle of the continuity equation.*

The principle of conservation of mass (shown in Figure 2.5) dictates that the fluid mass entering any pipe will be equal to the mass leaving the pipe (since fluid is typically neither created nor destroyed in the hydraulic systems). In network modeling, all outflows are lumped at the nodes or junctions (Walski, et. al., 2003).

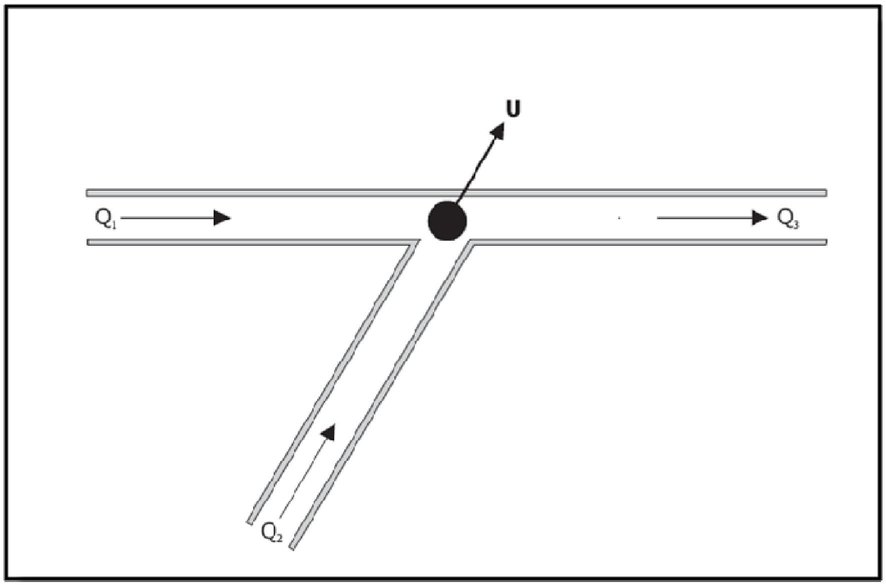


Figure 2-5: *Conservation of mass.*

In the figure, a node has an income flow from pipe (1) equals Q_1, and from pipe (2) equals Q_2, while the output from that node is to pipe (3) with a flow rate equals Q_3. The demand at that node is U. Thus, we can write the following equation:

$$\sum_{Pipes} Q_i - U - \frac{dS}{dt} = 0 \tag{2.3}$$

or;

$$Balance_f = Balance_i + \sum Deposites - \sum Withdrawals$$

2.6.4.Friction Losses

As water flows in the pipes, the energy will decrease from location to location. At any point in the pipe, the ***Hydraulic***

Grade Line (H.G.L) indicates the pressure at that point. This decrease will cause the pressure to be zero at some farther point, and the demand at a subsequent node will not be met (see Figure 2.6). Because of this, we must raise the pressure by pumps at some points in the network.

Energy losses that cause this decrease of pressure, also called head losses, are generally the result of two mechanisms, see Figure (2.6);

(1) Friction along the pipe walls;

(2) Turbulence due to changes in streamlines through fittings and appurtenances.

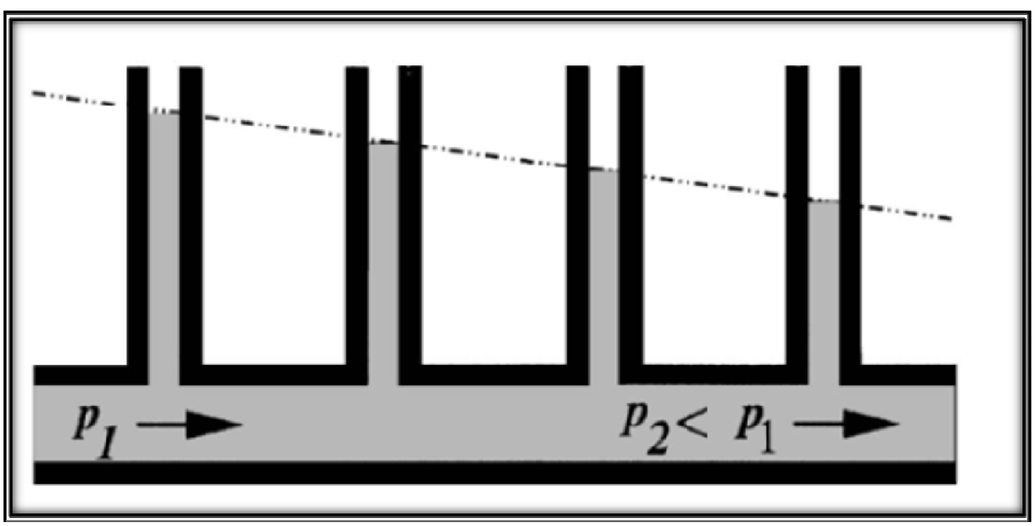


Figure 2-6: *Decrease of pressure with the flow*

Head losses along the pipe wall are called *friction losses* or *head losses* due to friction, while losses due to turbulence within the bulk fluid are called *minor losses*. So, how can we calculate these losses?

Several equations are used to calculate the friction factors. The following few lines give a quick reference for each one, (Walski, et. al., 2003).

Darcy-Weisbach Formula

This formula was developed using dimensional analysis. It uses the factors shown in Equation (2.4). The head loss, according to this formula, is:

$$\boldsymbol{h_L = f\,\frac{L}{D}\,\frac{V^2}{2g}} \qquad \textbf{(2.4)}$$

Using the flow rate instead of the velocity, and recalling that: $Q = V\,A$, and converting A to $\frac{\pi\,D^2}{4}$, the formula may be written as:

$$h_L = f\,\frac{L}{D}\,\frac{1}{2g}\left(\frac{Q}{A}\right)^2 = f\,\frac{L}{D}\,\frac{1}{2g}\,\frac{Q^2}{\left(\frac{D^2}{4}\pi\right)^2} = f\,\frac{L}{D}\,\frac{1}{2g}\,\frac{Q^2}{D^4\pi^2} \times 16$$

This expression will be:

$$\boldsymbol{h_L = 8f\,\frac{L}{g\pi^2}\,\frac{Q^2}{D^5}} \qquad \textbf{(2.5)}$$

where,

- h_L : head loss (m);
- D : diameter of the pipe (m);
- L : length of the pipe (m);
- g : acceleration of gravity (m/sec^2);
- f :Darcy-Weisbach coefficient of friction (*dimensionless*);
- Q : Flow rate of fluid (kg/m^3).

After substituting the values for g and π, Equation (2.5) becomes:

$$h_L - 0.0826 f\, L\, \frac{Q^2}{D^5} \qquad \textbf{(2.6)}$$

Hazen-Williams

Another head loss equation is the *Hazen-Williams Equation* (Karney, 2000) and (Williams and Hazen, 1920). This equation is:

$$Q - C_u\, C_{HW}\, D^{2.63}\, S^{0.54} \qquad \textbf{(2.7)}$$

where,

- Q : Discharge rate in pipes (m^3/sec);
- C_u : Unit factor (0.314 for British Units and 0.278 for SI Units);
- C_{HW} : Hazen-Williams roughness coefficient (*dimensionless*);
- S : Slope of Energy Line ($E.L$) $= \frac{Head\ Loss}{L}$

In SI metric units, this equation can be written as:

$$h_L = 10.654 L \frac{1}{D^{4.87}} \left[\frac{Q}{C_{HW}} \right]^{1.85185} \qquad \textbf{(2.8)}$$

The factor C_u depends on the units used in the calculations. Table (2.2) shows the values of this factor.

Table 2-2: *Typical values of the unit factor* C_u *in Hazen-Williams Equation.*

Units of Discharge, Q	Unit of diameter, D	Value of C_u
MGD	Foot	0.279
ft^3/sec.	Foot	0.432
GPM	Inch	0.285
GPD	Inch	405
m^3/sec.	Meter	0.278

About the Hazen-Williams coefficient C_{HW}, Table (2.3) shows its value for different materials (Walski et.,al., 2003).

2.6.5.Minor Losses

Because of fittings, elbows, valves, tees and bends, there is a loss of energy called *minor losses*, see Figure (2.7), (Walski, et. al., 2003). These losses can be expressed as:

$$h_m = K_L\left(\frac{V^2}{2g}\right) = K_L\left(\frac{Q^2}{2gA^2}\right) \quad \textbf{(2.9)}$$

Where,

- ❒ h_m : Minor loss (m);
- ❒ K_L : Minor loss coefficient;
- ❒ V : Velocity ($m/sec.$);
- ❒ Q : Flow rate ($m^3/sec.$);
- ❒ g : Gravitational acceleration (9.81 m/sec^2).

Table (2.3) shows the values of the minor loss coefficients for all the valves and fittings in practice (Walski, 1984).

The value of K_L is strongly dependent on the geometry of the component considered. Thus,

$$K_L = \emptyset(Re, Geometry)$$

C-factor Values for Discrete Pipe Diameters						
Type of Pipe	1.0 in. (2.5 cm)	3.0 in. (7.6 cm)	6.0 in. (15.2 cm)	12 in. (30 cm)	24 in. (61 cm)	48 in. (122 cm)
Uncoated cast iron - smooth and new		121	125	130	132	134
Coated cast iron - smooth and new		129	133	138	140	141
30 years old						
Trend 1 - slight attack		100	106	112	117	120
Trend 2 - moderate attack		83	90	97	102	107
Trend 3 - appreciable attack		59	70	78	83	89
Trend 4 - severe attack		41	50	58	66	73
60 years old						
Trend 1 - slight attack		90	97	102	107	112
Trend 2 - moderate attack		69	79	85	92	96
Trend 3 - appreciable attack		49	58	66	72	78
Trend 4 - severe attack		30	39	48	56	62
100 years old						
Trend 1 - slight attack		81	89	95	100	104
Trend 2 - moderate attack		61	70	78	83	89
Trend 3 - appreciable attack		40	49	57	64	71
Trend 4 - severe attack		21	30	39	46	54
Miscellaneous						
Newly scraped mains		109	116	121	125	127
Newly brushed mains		97	104	108	112	115
Coated spun iron - smooth and new		137	142	145	148	148
Old - take as coated cast iron of same age						
Galvanized iron - smooth and new	120	129	133			
Wrought iron - smooth and new	129	137	142			
Coated steel - smooth and new	129	137	142	145	148	148
Uncoated steel - smooth and new	134	142	145	147	150	150

Table 2-3: *Hazen-Williams coefficient* C_{HW} *for several types of materials*.

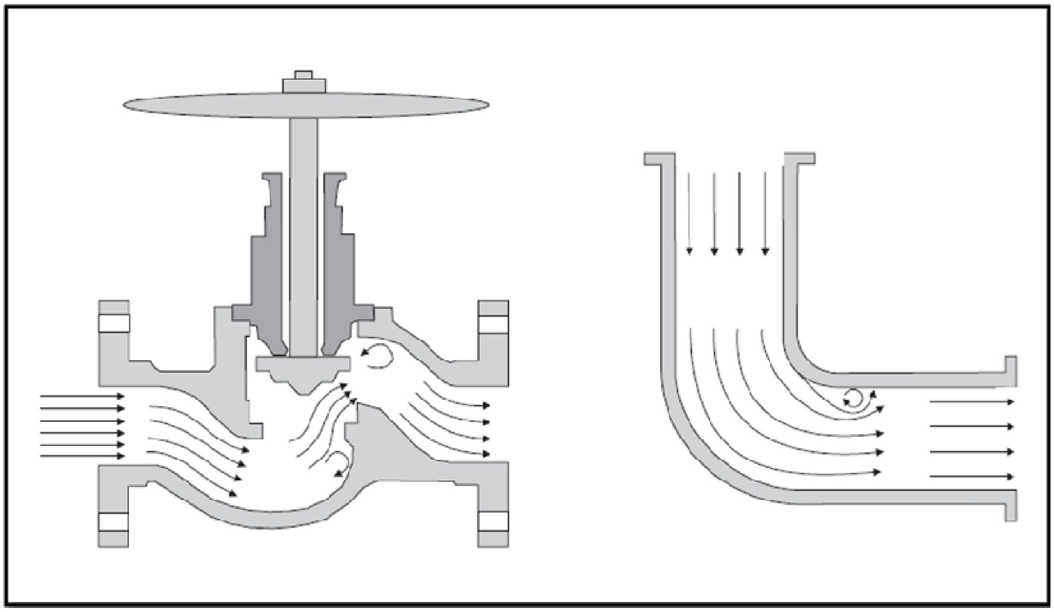


Figure 2-7: *A cross sections showing the minor loss.*

2.7 Network Hydraulic Analysis

Real water distribution systems do not consist of a single pipe and two nodes and cannot be described by a single set of *continuity* and *energy equations*. Instead, WDN are usually complex looped networks that consist of several combinations of pipes, nodes, pumps, reservoirs and tanks. Because of this, ***one continuity equation must be developed for each node in the system*** and ***one energy equation must be developed for each pipe (or loop)***, depending on the method used. For real systems, these equations can be thousands of equations. Special techniques of network analysis must be used to solve these equations. In these methods, iterative solution based on initial assumptions lead to either *balancing flows* in a system or *balancing heads* in a system. This principle preserves the mass continuity and ensures energy conservation.

Table 2--24- : *Minor loss coefficients*

Fitting	K_L	Fitting	K_L
Pipe entrance		90° smooth bend	
Bellmouth	0.03-0.05	Bend radius/D = 4	0.16-0.18
Rounded	0.12-0.25	Bend radius/D = 2	0.19-0.25
Sharp-edged	0.50	Bend radius/D = 1	0.35-0.40
Projecting	0.78	Mitered bend	
Contraction – sudden		$\theta = 15°$	0.05
D_2/D_1=0.80	0.18	$\theta = 30°$	0.10
D_2/D_1=0.50	0.37	$\theta = 45°$	0.20
D_2/D_1=0.20	0.49	$\theta = 60°$	0.35
Contraction – conical		$\theta = 90°$	0.80
D_2/D_1=0.80	0.05	Tee	
D_2/D_1=0.50	0.07	Line flow	0.30-0.40
D_2/D_1=0.20	0.08	Branch flow	0.75-1.80
Expansion – sudden		Tapping T Branch	
D_2/D_1=0.80	0.16	d = tapping hole diameter D = main line diameter	$1.97/(d/D)^4$
D_2/D_1=0.50	0.57	Cross	
D_2/D_1=0.20	0.92	Line flow	0.50
Expansion – conical		Branch flow	0.75
D_2/D_1=0.80	0.03	45° Wye	
D_2/D_1=0.50	0.08	Line flow	0.30
D_2/D_1=0.20	0.13	Branch flow	0.50
Gate valve – open	0.39	Check valve – conventional	4.0
3/4 open	1.10	Check valve – clearway	1.5
1/2 open	4.8	Check valve – ball	4.5
1/4 open	27	Cock – straight through	0.5
Globe valve – open	10	Foot valve – hinged	2.2
Angle valve – open	4.3	Foot valve – poppet	12.5
Butterfly valve – open	1.2		

In any looped network, the following equation holds:

$$P = J + L + F - 1 \tag{2.10}$$

where:

- ❒ P : number of pipes;
- ❒ J : number of junction nodes;
- ❒ L : number of loops;
- ❒ F : number of fixed-grade nodes.

As an example of this, see Figure (2.8). In the figure, L = 3, F = 2 and J = 8. According to Equation (2.10), the number of pipes must be: $P = 8 + 3 + 2 - 1 = 12$ and this number is the same as in the figure.

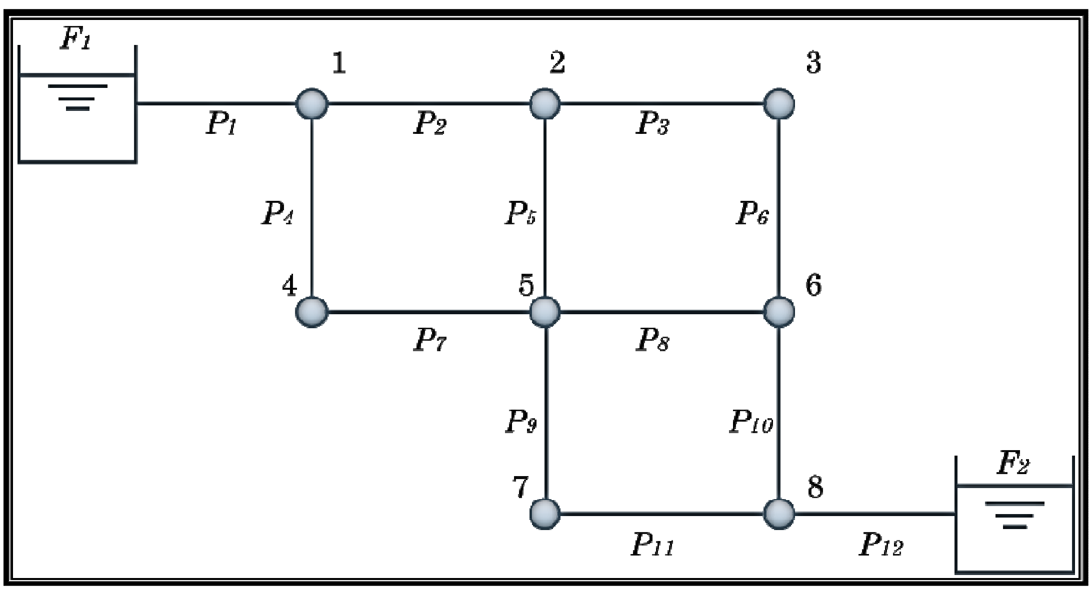


Figure 2-8: *Pipe network that shows pipes and nodes.*

Equation (2.10) is the basis of the analysis of WDN. Using the unknown information about the flows in the pipes in each loop, the mass continuity and energy conservation equations can be written for the pipes and nodes. These two sets of equations are the *loop equations* and *node equations.*

For each loop, an energy conservation equation can be written. In this equation, the total sum of energy in the loop must equal zero. The sum in this energy means that the inflow energy constructed by pumps (***E_p***) must equal *in magnitude* the total head loss (***h_L***) during the loop including the minor losses (***h_M***) . The amount of these equations must equal the number of loops in the whole WDN. Thus,

$$\sum h_L + \sum h_M = \sum E_p \qquad (L \text{ equations}) \qquad \mathbf{(2.11)}$$

where,

- ❒ h_L : head losses in the loop;
- ❒ h_M : minor losses in the loop;
- ❒ E_p : energy exerted by pumps in the loop.

For each node on the other hand, the mass conservation yields that the total *inflow* in the node must equal exactly the total *outflow* from the same node, see Figure (2.5). We repeat Equation (2.3) here in a different form to illustrate the method,

$$\sum Q_{in} - \sum Q_{out} = Q_e \qquad (J \text{ equations}) \qquad \textbf{(2.12)}$$

where,

- ❒ Q_{in} : total inflow to the node;
- ❒ Q_{out} : total out flow from the node;
- ❒ Q_e : the external flow (+) or withdrawal (-) from the system.

For the fixed-grade nodes, the same thing can be said. The number of paths from the first fixed-grade node to the last one in the WDN is F-1 paths. The difference in energy during any path will equal the difference in elevation (*grade*) for these two fixed-grade nodes, denoted by ΔE. In mathematical form, this can be written as follows:

$$\Delta E = \sum h_L - \sum E_p \qquad \textbf{(}F - 1 \text{ equations}\textbf{)} \qquad \textbf{(2.13)}$$

The first systematic approach for solving these equations was developed by **Hardy Cross** (1936). The invention of digital computers, however, allowed more powerful numerical techniques to be developed. These techniques set up and solve the system of equations describing the hydraulics of the network in ***matrix form***. Because *the energy equations are nonlinear* in terms of flow and head, they cannot be solved directly. Instead, these techniques estimate a solution and then *iteratively* improve it until the difference between two successive solutions falls within a specified tolerance. At this point, the hydraulic equations are considered solved.

Some of the methods used in network analysis are described in Todini and Pilati (1987); Bhave (1991); Larock, Jeppson, and Watters (1999); and Lansey and Mays (2000);

Two methods are commonly used in solving that set of nonlinear equations; **Hardy Cross** Method and **Newton-Raphson** Method. In our study, we have used a computer program for the *Gradient Method* to analyze the WDN. Salgado, Todini and O'Connell (1988) developed it.

2.8 RELIABILITY: Background and Definitions

After talking about WDN and its analysis and calculations, it is important to present a brief history of the other main concept of our study; *Reliability*.

2.8.1 General Background

The history of *engineering reliability* may be traced back to World War II, when the Germans first introduced the reliability concept to improve the reliability of their *V1* and *V2* rockets. In 1950 the U.S. Department of Defense established an ad hoc committee on reliability, and in 1952 it was transformed to a permanent group called the Advisory Committee on the Reliability of Electronic Equipment (Dhillon, 2006).

During the previous decades, several works had been done in dealing with reliability, the most earlier one was done by Damelin which was an attempt to analyze the reliability of water supply (Damelin, 1972). After that, Shamir and Howard did two papers where they had constructed a probability distribution function of system capacity (Shamir and Howard, 1982, 1985). As an application, a work was done by Hobbs when he presented some *analytical methods* to calculate and find the reliability of water system capacity (Hobbs, 1985). In 1987, Shamir suggested several methods to measure reliability, which lead to a number of studies in this field (Shamir, 1987). Goulter (1992) pointed out that the reliability cannot be incorporated into the network design because of the lack in the universally accepted measure of it. Wagner et al. (1988) found two algorithms to analyze the *reachability* or *connectivity* of WDN. Additional research was developed concerning the reliability; including the work of Tung (1986) who created a model for optimal-risk-based water distribution network design. Another work was carried out by Jacobs and Goulter (1988) where an evaluation of some methods for decomposition of water distribution networks for reliability analysis were performed. Another attempt was made by Mays et al. (1989) in modeling reliability in water distribution systems (Mays, 1989) and (Mays, Duan and Su, 1989).

A good work was done in two attempts, one was by Yang et al. (1996) for the determination of WDN reliability as a connectivity analysis. In addition, the other work was developed by (Guercio and Xu, 1997) where they developed a *Linearized* optimization model for reliability-based design of water systems.

All these papers and researches were for the WDN and reliability in several aspects; ranging from its definition and introduction, to the assessment of it in a WDN in a Linear Programming approach (Guercio and Xu, 1997), or in a probabilistic approach, (Xu and Goulter, 1999) in their work titled by: *Reliability-Based Optimal Design of WDN's.*

As a summary, Table (2.5) summarizes the different approaches to study the reliability (Misirdali, 2003; Mays, 2000).

Table 2-5: *Summary of Major Simulation and Analytical Approaches to the Assessment of Reliability of WDN, (Mays, 2000)*

Study	Year	Approach
Rowel and Barnes	1982	Minimum Cost branched network with cross connections
Morgan and Goulter	1985	Minimum-Cost design model for looped systems
Kettler and Goulter	1983	Minimum-Cost design model with constraints on the probability of pipe failing
Goulter and Goals	1986	Minimum-Cost design model with constraints on the probability of node isolation
Su et al.	1987	Minimum-Cost design model with constraints on the probability of “minimum cut sets”
Germanopoulos	1986	Assessing reliability of supply and

et al.		level of service
Wagner et al	1988a	Reliability analysis-analytical approach
Wagner et al	1988b	Reliability analysis-simulation approach
Lansey et al	1990	Minimum-Cost design model chance constrained on probability of meeting demands
Bao and Mays	1990	Reliability of water distribution systems
Goulter and Bouchart	1990	Minimum-cost design model with reliability constraints on node performance
Duan and Mays	1990	Reliability analysis of pumping systems, Frequency/duration analysis
Duan et al.	1990	Optimal reliability-based design of pumping and distribution systems
Kessler et al.	1990	Least Cost improvements in network reliability
Fujiwara and De Silva	1990	Reliability-based optimal design of water distribution systems
Awumah et al.	1990	Entropy-based measures of network redundancy
Bouchart and Goulter	1990, 1991	Improving reliability through valve location

Quimpo and Shamsi	1991	Estimation of network reliability-cut set approaches
Jacobs and Goulter	1991	Estimation of network reliability-cut set approaches
Cullinine et al.	1992	Minimum cost model with availability constraints
Wu et al.	1993	Capacity weighted reliability
Park and Liebman	1993	Redundancy Constrained minimum cost model
Juwitt and Xu	1993	Predicting pipe failure effects on service
Gupta and Bhave	1994	Reliability analysis considering nodal demands and heads simultaneously

2.8.2 Definition of Reliability

For a WDN, reliability is a very important concept that enables us to prevent leakage and sunderance of water to any node in the WDN. This concept must be taken into consideration when designing the network. Reliability must be calculated in order to have a precise value of it and not to depend on approximate expectation of whether the WDN will be reliable or not. Several definitions have been used to identify this concept during the past years, but the most understandable definition as stated in several papers is that of Goulter (1995) in his work to improve the efficiency and reliability in water distribution systems, which states that the reliability is:

The ability of the network to provide an adequate supply of water to the consumers under both normal and abnormal operating conditions

The term "*Adequate*" in the definition means both *Quality* and *Quantity*. The *quantity* means that the water that has been sent to a node is above a minimum red line value and above a minimum pressure restriction (Goulter, 1995). By *quality*, we mean that the water has a specified minimum concentration of some disinfectant (Mays, 1996).

This definition of reliability must not lead to an idea that it is simple and straightforward to evaluate. On the contrary, it is a complex parameter since it must take into consideration several factors including:

- Failure of the network: This may happen due to many reasons and may cause the reliability to collapse and become very low. Mechanical failure of any WDN is of two types: *Component* and *Hydraulic*. The component failure is a result of main bursts, blockage of valves, etc. The hydraulic failure is the failure that results from the inability of the system to handle the flow because of the decrease of the pipe diameters due to corrosion and deposition, etc. and due to the complete breakage in a pipe in a WDN (Shinstine et. al., 2002).

- ▷ The variability of demand at each node. This may be a main reason for the failure of the WDN. The problem is in the *increase of the demand*, which is commonly a reason of two factors: *increase in population and economic activity and increase in the return period* beyond the design one for the WDN.
- ▷ Uncertainty in the capacity of the pipes to achieve the service to the customer at the specified level.

2.8.3 Assessment of Reliability

Several methods were used to calculate or evaluate a quantitative value of reliability.

As mentioned above in introducing the reliability concept, reliability implies that the WDN not to collapse and fail. This might be considered *probabilistic*. The previous studies about reliability attempted to incorporate reliability through cost and traditional approaches. The early models concentrated on assuring a satisfactory quantity of water to any node, which necessitates the availability of two things (Rowell and Barnes, 1982):

❶ Ensuring a new or *redundant supply way* in case of a component failure,

❷ Ensuring *adequate capa*city through these new path ways in order to meet the demand under extreme conditions and unexpected circumstances.

Probability was considered in the reliability for the first time by both Ketler and Goulter (1982). Thereafter, Goulter and Coals (1986) and Goulter and Bouchart (1990) considered the probabilistic reliability. Each approach of the above used different concept from the others.

This research work deals with what is called ***capacity reliability***, which is defined as (Xu and Goulter, 1999):

The probability that the nodal demand is met at or over the prescribed minimum pressure for a fixed network configuration under random nodal demands and random pipe roughnesses.

The method that will be used throughout this thesis is the method developed by Gupta and Bhave (1994) in their reliability analysis of WDNs and the details used for implementing it are provided by Misirdali (2003). This method is also called the *Pressure Dependent Demand Theory* (Misirdali, 2003).

Chapter (3)

METHODOLOGY AND RELIABILITY CONCEPTS

3.1 Introduction

In order to illustrate the computations carried out in the next chapter, it is essential to demonstrate the research methodology. The methodology is summarized in the following and depicted in Figure (3.1):

(1) Full review of the hydraulic principles of water distribution networks, energy conservation, continuity equation, head losses and analysis methods of WDN.

(2) A hydraulic simulator (a network solver) was dapted and used in order to perform the necessary calculations. The output from the simulator was obtained in a tabular form where it was read by another application to calculate the reliability.

(3) Full review of reliability concepts was done including reliability history, definitions, and assessment methods. These methods and procedures were put in a tabular form for ease of comprehension and understanding.

(4) A method was chosen to calculate reliability and is illustrated in this chapter in detail. This explanation includes the steps of calculating reliability, and the post processing of the results to enhance the analysis.

(5) To find out the optimal solution with the minimum cost and the maximum reliability, a code was developed using MATLAB and presented in this chapter.

(6) A hypothetical case study from the literature was considered for the illustration and implementation of the methodology.

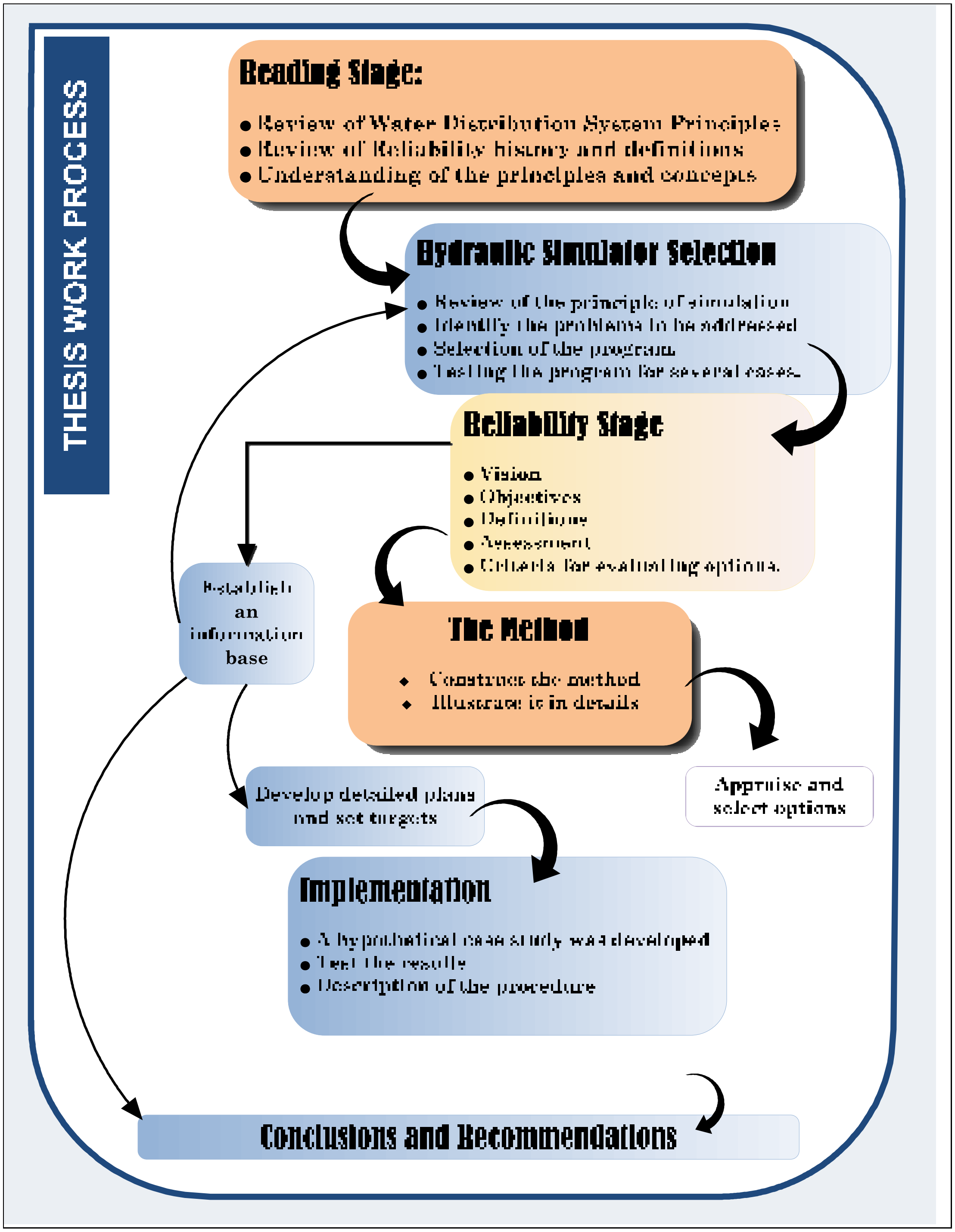


Figure 3-1 : *The Flow Chart of the methodology*.

3.2 Evaluation of Reliability

As we mentioned earlier in Chapter (2), the procedure to calculate the reliability is that of Gupta and Bhave (1994). In this work, the procedure will be illustrated in detail. There are several causes in real life where the operation of the WDN deteriorates over time (Misirdali, 2003). The reasons about this can be attributed to the *accelerated growth*, *increase in demand, and aging and mechanical malfunctioning of network elements.* These factors cause the pressure at some locations to go below the required value.

The simulation approaches described earlier are based on the traditional network analysis in solving the system of non-linear equations (*Hardy Cross, Newton-Raphson, or linear theory method*) that presumes that the demands at all nodes of a WDS are satisfied and determines the available heads. It is termed "***node head analysis***," (NHA) (Bhave, 1991). When the obtained nodal heads are less than the minimum required, the network is improved by *changing the pipe sizes* until the obtained nodal heads are at least equal to the required minimum value.

However, during a pump failure or a pipe break, or during an excessive demand at a node as in fire-flow conditions, the network may become deficient and unable to supply water with minimum required heads at all nodes.

Since the deficiency in nodal heads is temporary, the question of network modification does not arise. The behavior of the WDS in such a temporary deficient condition must be considered and the reliability has to be estimated. Therefore, a network analysis that *considers the nodal heads and nodal flows* simultaneously is required for the reliability estimation of WDNs (Gupta and Bhave, 1994).

At any point, the following inequalities are valid (Gupta and Bhave, 1994) which is known as the "***Node Flow Analysis***" (NFA):

When $H_j^{avl} > H_j^{\min}$ (Supercritical Node), $Q_j^{avl} = Q_j^{req}$ (Adequate flow node);

When $H_j^{avl} = H_j^{\min}$ (Critical Node), $0 < Q_j^{avl} < Q_j^{req}$ (Partial flow node);

When $H_j^{avl} < H_j^{\min}$ (Subcritical Node), $Q_j^{avl} = 0$ (No flow node).

Several studies considered the shortfall in demand relative to the desired demand to calculate the reliability as in Shamir and Howard (1981), Fujiwara and De Silva (1990), and Bao and Mays (1990). Their approach is used herein but the available nodal flow is obtained from NFA. The situation where the available nodal flow is less than or equal to the required flow is a *function of the demand pattern and the condition of the distribution network* (pipes, pumps, and valves in working conditions). A time interval during which the nodal demands and condition of the network remain constant is termed a "***state***". The number of states during the period of analysis depends on the number of demand patterns and the number of different combinations of pipes and pumps in working or failure conditions.

In order to calculate the reliability for the whole network, three values must be determined. These are the ***Node-Reliability Factor***, ***Volume-Reliability Factor*** and ***Network-Reliability Factor***.

▶ Node-Reliability Factor

It is defined as the *ratio of the total available outflow volume at a node to the desired outflow volume at that node for all states during the period of analysis*, thus,

$$R_{nj} = \frac{\sum_s V_{js}^{avl}}{\sum_s V_{js}^{req}} = \frac{\sum_s Q_{js}^{avl} t_s}{\sum_s Q_{js}^{req} t_s} \tag{3.1}$$

where,

- ❒ $\boldsymbol{V^{avl}}$: available volume;
- ❒ $\boldsymbol{V^{req}}$ **:** required volume;
- ❒ $\boldsymbol{Q^{avl}}$: available discharge rate;
- ❒ $\boldsymbol{Q^{req}}$ **:** required discharge rate;
- ❒ $\boldsymbol{t_s}$: time duration of a state;
- ❒ $\boldsymbol{j}$: subscript denoting demand node;
- ❒ $\boldsymbol{s}$: subscript denoting the state.

▶ Volume-Reliability Factor

It is defined as *the ratio of the* ***total*** *available outflow volume to the required outflow volume for the* ***entire network***, thus,

$$R_v = \frac{\sum_s \sum_j V_{js}^{avl}}{\sum_s \sum_j V_{js}^{req}} = \frac{\sum_s \sum_j Q_{js}^{avl} t_s}{\sum_s \sum_j Q_{js}^{req} t_s} \tag{3.2}$$

▶ Network-Reliability Factor

The two preceding factors do not give a precise indication of the reliability of the network. To understand this concept, let us take the following three cases (Gupta and Bhave, 1994):

(1) 90% of demand is satisfied for 100% of time at 100% nodes, i.e. there is a ***uniform shortfall of 10% supply at each node during the entire period of analysis***. This is tolerable in spite of being not desirable.

(2) 100% of demand is satisfied for 90% of time at 100% nodes, i.e. there are ***no supply at all the nodes during 10% of time*** of the period of analysis. If this time duration is not concentrated but is distributed throughout the period of analysis, this situation is also tolerable, though less acceptable than situation (1).

(3) 100% of demand is satisfied for 100% of time at 90% of nodes, i.e. ***there is no supply at all at 10% of nodes during the entire period*** of analysis. This situation is the worst and is unacceptable.

For all the three preceding situations, R_v = 0.9. For situations (1) and (2) R_n = 0.9 at all nodes, while for situation (3), R_n = 1 for 90% nodes and R_n = 0 for 10% nodes. The R_v and R_n values are the same for situations (1) and (2), even though their performances are not the same. The value of R_v is also the same for situation (3), however, the values of R_n are different. Therefore, R_v and R_n values together can indicate the reliability of the network for situation (3). However, it is preferable to have a single reliability factor that can describe situation (3) and can also properly distinguish between situations (1) and (2). It is therefore useful to consider the network reliability factor, R_{nw} as in the following equation:

$$\boldsymbol{R_{nw} = R_v \times F_t \times F_n} \quad \textbf{(3.3)}$$

where,

- F_t : Time factor;

- F_n : Node factor.

The time factor F_t is calculated from the following equation:

$$F_t = \frac{\sum_s \sum_j a_{js} \times t_{js}}{JT} \tag{3.4}$$

where,

- J : the total number of the nodes;
- T : overall period of analysis $= \sum t_s$;
- a_{js} : a factor depending on the discharge ratio $\left(\frac{Q_j^{avl}}{Q_j^{req}}\right)$ and it equals 1 if the ratio is more than an acceptable specified value and zero otherwise.

The node factor, F_n, is the *geometric mean* of the node-reliability factors and it can be calculated from the following equation:

$$F_n = \left[\prod_{j=1}^{J} R_{nj}\right]^{1/J} \tag{3.5}$$

3.3 Research Methodology

The following subsections summarize and illustrate the methodology

3.3.1 Classification of the problem

The procedure relies on a sort of exhaustive search where all the potential combinations between all the pipes are considered.

So each pipe will have a list of candidate diameters (potential alternatives) and for each potential combination across all the pipes the reliability is evaluated with the aid of the network solver. Each combination of pipe diameters were considered as a stage.

This procedure utilizes the concept of the nested loops where the very inner loop represents the very last pipe where all the candidate diameters are altered consequently and so on. This procedure is illustrated in Table (3.1) for a 6-pipe network with 5 candidate diameters.

Table 3-1: *Diameter data for the first 10 stages of calculations for a 5-pipe network*

Stage	P (1)	P (2)	P (3)	P(4)	P (5)
1	6	6	6	6	6
2	6	6	6	6	8
3	6	6	6	6	10
4	6	6	6	6	12
5	6	6	6	6	14
6	6	6	6	8	6
7	6	6	6	8	8
8	6	6	6	8	10
9	6	6	6	8	12
10	6	6	6	8	14

This procedure is illustrated below:

For D1 = 6 to 14 STEP 2

For D2 = 6 to 14 STEP 2

For D3 = 6 to 14 STEP 2

For D4 = 6 to 14 STEP 2

For D5 = 6 to 14 STEP 2

Execute the network solver and perform the calculations for the cost and reliability

Next D5

Next D4

Next D3

Next D2

Next D1

The number of iterations for that 5-pipe network example, with the stages from 6 inches to 14 inches, will be $5^5 = 3125$ iterations. For 10 pipes, it will be $5^{10} = 9'765'625$ iterations!!

This will be obvious in the input stage of the problem.

3.3.2 Input Data

We used the program developed to simulate the water distribution network. In this program, we need to provide the following information related to the network:

(1) Number of nodes and their identification numbers including the reservoir and demand nodes. In addition, necessary information such as the demand and elevation are also provided.

(2) Number of pipes in the network and their connection information; for instance, initial and final nodes. In addition,

the friction coefficient (Hazen-Williams), the length of each pipe and the initial diameter are provided.

(3) The nested loops are implemented as depicted in section 3.3.1. The candidate diameters for each pipe are determined in each iteration.

By this, the input data is complete. The output is obtained as a text file in a format that allows the quick processing to calculate the cost and reliability.

3.3.3 Output Data

For any iteration, the output that we get among other output is the pressure head (in *meters*) at each node and the flow rate in each pipe (in m^3/sec) or the velocity of water in (*m*/*sec*).

The head that the program gives at each node is the *simulated head, which is not the required head* at that node. The important thing for each node is the ability of the system to produce a head (or pressure) to maintain the required demand at that node. Therefore, we need to calculate the **available demand** at each node (based on the simulated head) from which the reliability can be estimated.

3.3.4 Available Demand at Nodes

In any WDN, several procedures have been used to calculate the available demand or flow at each node. Currently, there are several hydraulic simulation models and most of them are based on ***demand driven analysis*** (**DDA**) (Cheung et al., 2005). Recently, a number of studies have highlighted some of the limitations of demand driven analysis leading to remarks that such models may be inadequate when abnormal conditions are encountered. In fact, demand flow rates are not only function of time, since the node outflows occur via orifices (e.g. open taps or valves) and are thus dependent on the pressure in the system. Analysis that incorporates the relationship between demand and pressure are called ***pressure driven analysis*** (**PDA**), (Cheung et al., 2005).

Currently, several approaches such as: Rossman (2000), Wagner et al. (1988b), Chandapillai (1991), Fujiwara (1998), Tucciarelli (1999), Tabesh (2000) and Tanyimboh (2001) based on PDA can be used to <u>*model the pressure-demand relation on water distribution systems*</u>. It assumes the Node Flow Analysis (NFA) considered by Gupta and Bhave (1994), which assumes fixed flow above a given critical pressure, zero flow below a given minimum pressure and *some proportional flow for intermediate pressures*. The model that was used is the *modified Chandapillai* model (Misirdali, 2003) and will be summarized in the following section. For the other mentioned models that we talked about in the previous paragraph, the following are the corresponding relationships:

- **Rossman (2000);**

$$Q^{avl} = S \times (H^{avl} - H^{\min})^{\alpha} \tag{3.6}$$

- **Wagner (1988b);**

$$Q^{avl} = Q^{req}\left[\frac{H^{avl} - H^{\min}}{H^{des} - H^{\min}}\right]^{1/\alpha} \tag{3.7}$$

- **Tucciarelli (1999);**

$$Q^{avl} = Q^{req} \times \sin^2\left[\pi \frac{H^{avl}}{2H^{des}}\right] \tag{3.8}$$

❒ **Fujiwara (1998);**

$$Q^{avl} = Q^{req}\left[\frac{\left(H^{avl} - H^{\min}\right)^2 \times \left(3H^{des} - 2H^{avl} - H^{\min}\right)}{\left[H^{des} - H^{\min}\right]^3}\right] \qquad \textbf{(3.9)}$$

where,

❒ S : Node constant that depends on consumer characteristics.

❒ H^{avl} : Available nodal pressure;

❒ H^{min}: Minimum nodal pressure below which no flow can occur;

❒ H^{des} : Desired nodal pressure to satisfy full demand at node;

❒ Q^{avl} : Available calculated demand flow at node;

❒ Q^{req} : Required demand flow at node;

❒ n : Number of nodes in the network;

❒ α : constant, Wagner (1988) suggests $\alpha = 2$.

3.3.5 Chandapillai Method

The most satisfying model is the one suggested by Chandapillai (1991) and later developed by Tanyimboh et. al. (2001). In this study, this model was used with the name modified Chandapillai model (Nohutçu, 2002).

The method begins with the assumption that the true consumption of each node depends on the pressure at all nodes of the system. When the pressure at each node is below the required pressure, then a case of low-supply situation exists. Here, the consumer collects the water at an overhead tank (OHT). The water from the supply main to the tank can be delivered only if the pressure is over the minimum pressure h_1, which is the level difference between distribution main and OHT. Figure 3.2 shows that relation (Chandapillai, 1991).

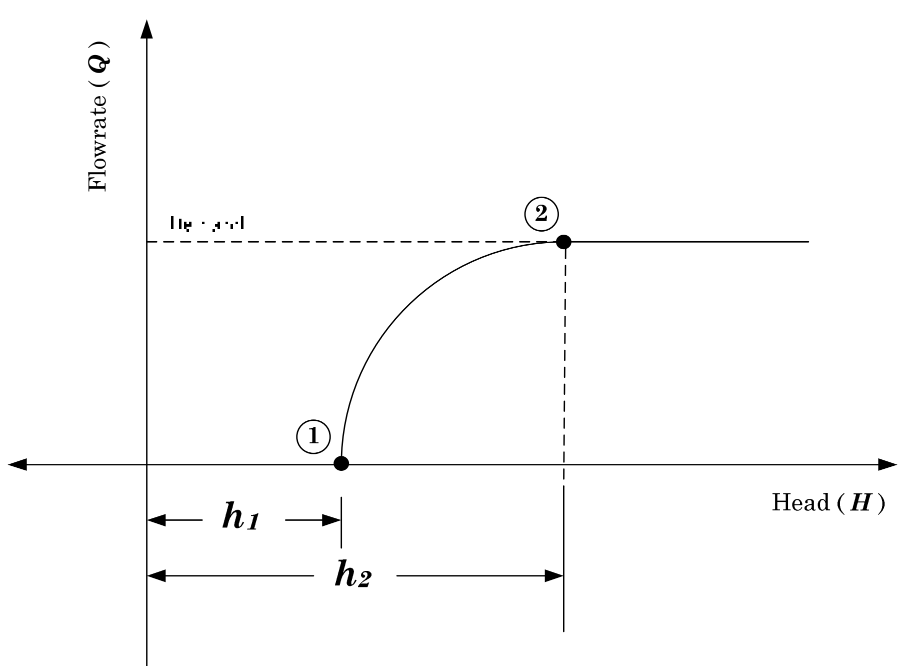


Figure 3--32- : *Relationship between head and flowrate*

When the pressure is below h_1, there is no supply at all. When the pressure is over the required value h_2, full supply occurs and consumer demand is acheived. The value of h_1 is the minimum pressure, and we are going to denote it as H_{min} in the following paragraphs and discussion. The case when the pressure is in between h_1 and h_2 is the case where the relation between the head and the flowrate Q is not linear, and can be represented by the following equation (Misirdali, 2003):

$$\boldsymbol{H = H_{min} + KQ^n} \qquad \textbf{(3.10)}$$

In this equation, K and n are constants. If we replace Q by the consumption of the flow, C, and arrange the equation, we can get:

$$C = \left[\frac{H - H_{\min}}{K}\right]^{1/n} \qquad \textbf{(3.11)}$$

If the demand is fully achieved, $C = Q_{req}$, with the required head at that node, H_{req}, then the case will be as follows:

$$Q^{req} = \left[\frac{H_{req} - H_{\min}}{K}\right]^{1/n} = \frac{\left(H_{req} - H_{\min}\right)^{1/n}}{K^{1/n}} \qquad \textbf{(3.12)}$$

And then,

$$\frac{1}{K^{1/n}} = \frac{Q^{req}}{(H_{req} - H_{\min})^{1/n}} \tag{3.13}$$

Using this relation in Equation (3.12) yields:

$$C = \left[\frac{H - H_{\min}}{H_{req} - H_{\min}} \right]^{1/n} \tag{3.14}$$

Which is the same equation used by Wagner et al. (1988b). By taking the minimum pressure to be zero, the final modified Chandapillai model will be:

$$Q^{avl} = Q^{req} \left[\frac{H^{avl}}{H^{des}} \right]^{1/n} \tag{3.15}$$

3.3.6 Reliability Calculations

At this point, everything is ready for the calculations of the reliability according to section 3.2.

Example (3.1):

As an example, I did these steps for a WDN composed of six pipes and five nodes, see Figure (3.3).

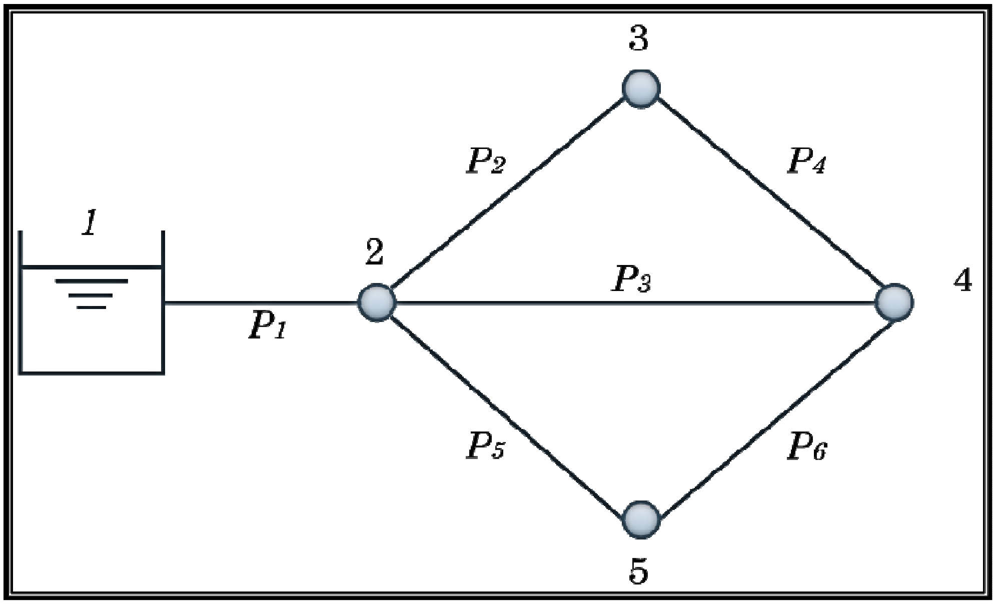


Figure 3-3: *The Network of Example 3.1*

To do the required calculations in order to find the available flow rate at nodes, Equation (3.6) to Equation (3.9) depend on several factors according to the consumer characteristics, which will lead to several steps and long calculations. Instead, I used the Chandapillai method in Equation (3.15) because it gives the available flow rate directly, depending only on the number of nodes, available pressure, required demand and the required pressure. The required head at each node was set to be 21 m. Node no. (1) was a reservoir. Table (3.2) shows the first stage of calculations for all the nodes using Equation (3.15).

Table 3-2: *Calculations for iteration (1) in Example (3.1).*

Node ID	Required Demand **(Q^{req})**	Pressure **(H^{avl})**	Available Demand **(Q^{avl})**	Nodal Reliability **(R_n)**
2	5	12.87	4.4	**0.8800**
3	7.5	12.16	6.5	**0.8667**
4	10	6.2	7.4	**0.7400**
5	12.5	9.61	10.3	**0.8240**

Example calculations for node (2) are as follows:

$$Q_2^{avl} = Q_2^{req}\left[\frac{H_2^{avl}}{H_2^{des}}\right]^{1/4}$$

$$= 5 \times \left[\frac{12.87}{21}\right]^{1/4}$$

$$= 5 \times 0.885$$

$$= 4.4$$

The nodal reliability is calculated from Equation (3.1):

$$R_{nj} = \frac{\sum_s V_{js}^{avl}}{\sum_s V_{js}^{req}} = \frac{\sum_s Q_{js}^{avl} t_s}{\sum_s Q_{js}^{req} t_s}$$

So, for node (2) we have:

$$R_{n2} = \frac{\sum_s V_{2s}^{avl}}{\sum_s V_{2s}^{req}} = \frac{\sum_s Q_{2s}^{avl} t_s}{\sum_s Q_{2s}^{req} t_s} = \frac{Q_2^{avl}}{Q_2^{req}} = \frac{4.4}{5.0} = 0.8800$$

This is under the assumption that the time for each stage is the same.

The volume reliability is calculated from Equation 3.2:

$$R_v = \frac{\sum_s \sum_j V_{js}^{avl}}{\sum_s \sum_j V_{js}^{req}} = \frac{\sum_s \sum_j Q_{js}^{avl} t_s}{\sum_s \sum_j Q_{js}^{req} t_s}$$

From Table (3.2) and for the first iteration, the volume reliability is:

$$\begin{aligned} R_v &= \frac{\sum_j Q_{js}^{avl} t_s}{\sum_j Q_{js}^{req} t_s} = \frac{\sum_j Q_j^{avl}}{\sum_j Q_s^{req}} \\ &= \frac{4.4 + 6.5 + 7.4 + 10.3}{5 + 7.5 + 10 + 12.5} \\ &= \frac{28.6}{35} \\ &= 0.8171 \end{aligned}$$

Equation (3.5) is used to calculate the node factor:

$$F_n = \left[\prod_{j=1}^{J} R_{nj} \right]^{1/J}$$

$$F_n = \left[0.88 \times 0.87 \times 0.74 \times 0.82\right]^{1/4} = \left[0.4646\right]^{1/4} = 0.8256$$

The network reliability is now obtained from Equation (3.3) to be:

$R_{nw} = R_v \times F_t \times F_n$

$R_{nw} = 0.8171 \times 1 \times 0.8256 = 0.6746 = 67.46\%$

3.3.7 Cost Calculations

The cost of the WDN here is only the cost of the pipes of the network, as the cost of the other components and fittings are constant, and were neglected. Let the number of the pipes in the network be *np*. The cost of the whole network can be defined as:

$$C = \sum_{i=1}^{np} L_i c_i \qquad \textbf{(3.16)}$$

where,

- ❒ L_i : The length of pipe i in meters;
- ❒ c_i : Cost of one meter of the pipe i.

3.3.8 Cost / Reliability Chart

The Cost-Reliability relationship for the first 20 stages in the above example is shown in the following Figure (**3.4**). Based on this, we notice the following:

(1) The relation is repeating itself from iteration to the other, which means that this relation consistent in nature.

(2) As the reliability increases from one iteration to another, the cost increases, also.

(3) As an overall progress, the shape for any iteration is increasing in its cost value from iteration to the other. This means that the maximum cost and the maximum reliability in any iteration will increase in the iteration that follows it.

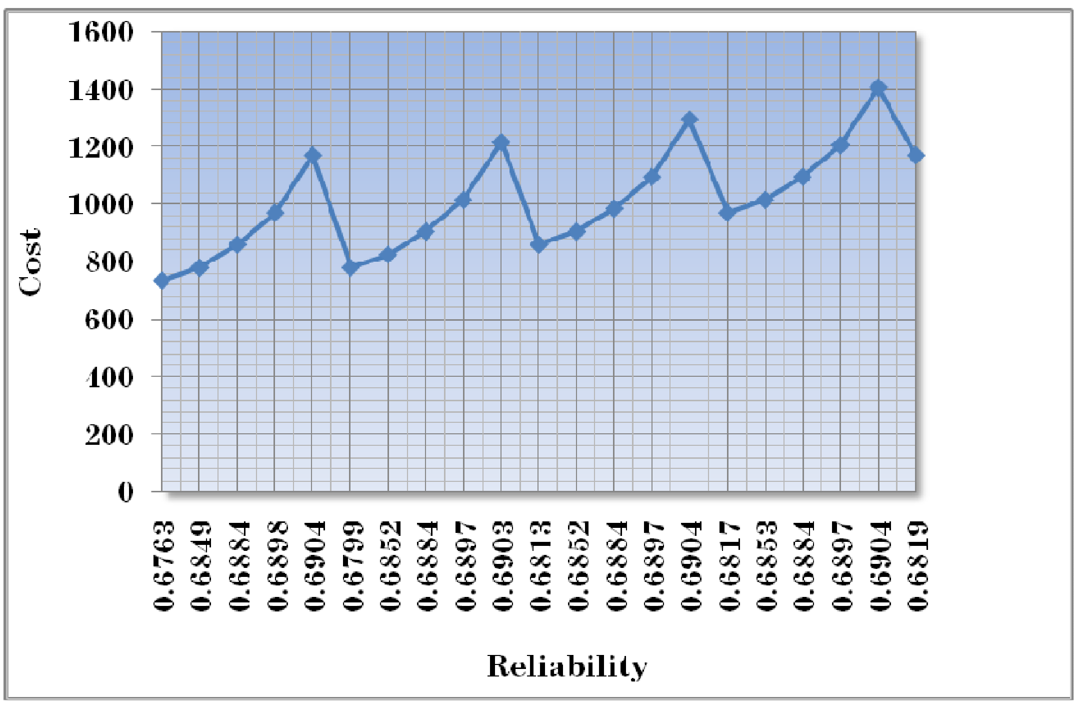


Figure 3-4: *Cost/Reliability relationship for 20 iterations*

3.4 Optimization Algorithm using MATLAB®

MATLAB® is a powerful mathematical program that was originally developed to deal with matrices. Its name came from the beginning of the two words: MATrix LABoratory. In order to solve the problem of our study, a code program was written in MATLAB programming language (m file). The problem of our study is solved after converting it into matrices, as will be illustrated in the following steps:

(1) The WDN simulator that was used in the design process to calculate the heads and flow rates into the pipes gives the results as a text file. The values were arranged in a manner that is readable by MATLAB.

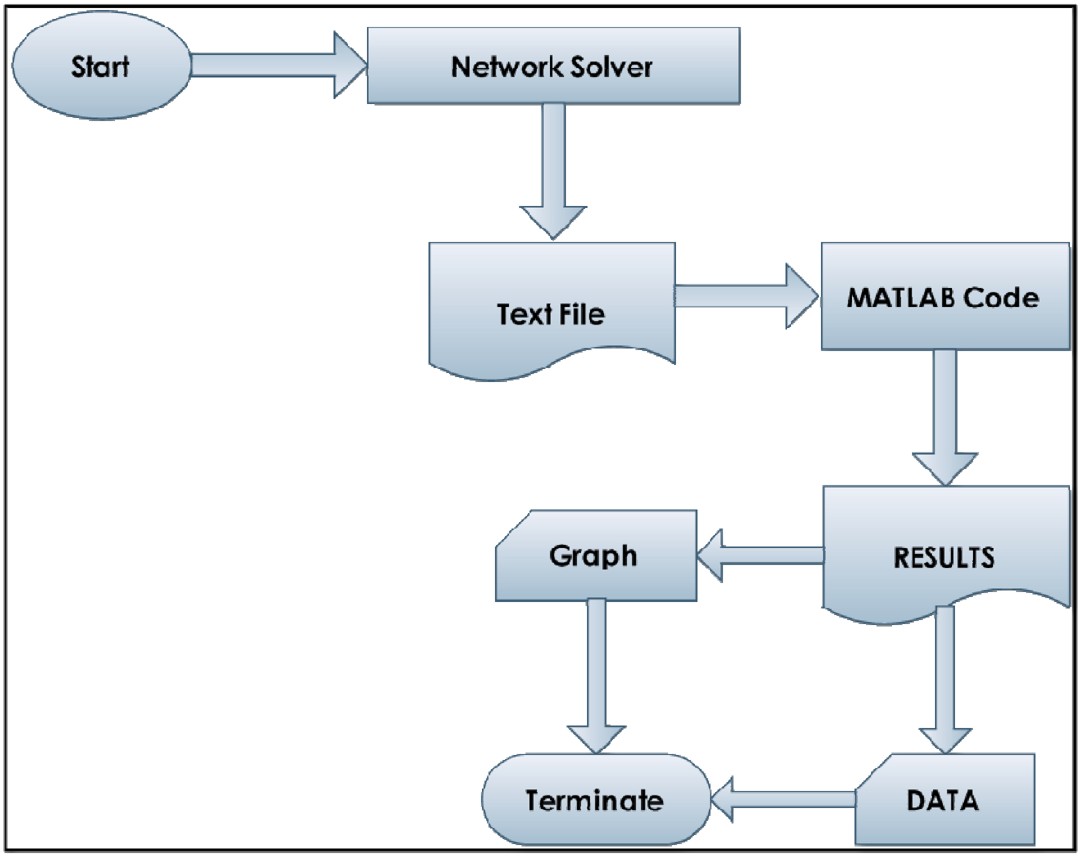


Figure 3-5: *The Flow Chart of the method*

(2) MATLAB reads these values and converts them into a huge matrix that contains the number of iteration in the first column, the diameters of the pipes in the next columns (equals the number of pipes in the WDN), and the pressures at each node in the last columns (equals the total number of supply nodes in the WDN). The dimension of that matrix is ***(number of iterations)* × *(1 + number of pipes + number***

of nodes including the reservoir node). The general form of that matrix is the following:

$$M = \left[t \;\; D \;\; P\right]$$

$$M = \begin{bmatrix} 1 & D_{11} & D_{12} & D_{13} & \cdots & D_{1p} & P_{11} & P_{12} & P_{13} & \cdots & P_{1n} \\ 2 & D_{21} & D_{22} & D_{23} & \cdots & D_{2p} & P_{21} & P_{22} & P_{23} & \cdots & P_{2n} \\ 3 & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ t & D_{t1} & D_{t2} & D_{t3} & \cdots & D_{tp} & P_{t1} & P_{t2} & P_{t3} & \cdots & P_{tn} \end{bmatrix}$$

(3) The matrix is, then, split into two sub-matrices; the diameter matrix and the pressure matrix. The general form of each of them is:

$$\text{Diameter Matrix} = \boldsymbol{D} = \begin{bmatrix} D_{11} & D_{12} & \cdots & \cdots & D_{1p} \\ D_{21} & D_{22} & \cdots & \cdots & D_{2p} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ D_{t1} & D_{t2} & \cdots & \cdots & D_{tp} \end{bmatrix}$$

$$\text{Pressure Matrix} = \boldsymbol{P} = \begin{bmatrix} P_{11} & P_{12} & \cdots & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & \cdots & P_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ P_{t1} & P_{t2} & \cdots & \cdots & P_{tn} \end{bmatrix}$$

where

- ❒ D_{ij} : the diameter of the j^{th} pipe in the i^{th} iteration;
- ❒ P_{ik} : the pressure at the k^{th} node at the i^{th} iteration;
- ❒ p : total number of pipes in the network;
- ❒ n : total number of nodes;
- ❒ t : total number of iterations.

(4) Calculations of the cost for each row of the main matrix are now accomplished using Equation (3.16). The resulting values are arranged in a *vector* to be utilized by MATLAB later.

(5) The node reliability factor for each node and the volume reliability factor for the network are now calculated using Equations (3.1) and (3.2).

(6) These values are used to find the system reliability for the whole WDN in each iteration using Equation (3.3).

(7) So far, two vectors are produced: ***cost vector*** (***C***) and ***reliability vector*** (***R***).

(8) The values of the reliability are not ranked in a descending or ascending order. They are just the values of R for each stage as obtained from the WDN solver and specific values may be the same for different stages and different diameter combinations (network configuration).

(9) On the other hand, the cost vector is randomly ranked according to the number of iteration and not according to ascending or descending order.

(10) The problem here is that there are several cost alternatives for specific reliability values and several reliability alternatives for specific cost values.

(11) In order to solve this, reliability values were put in a *discrete form*, beginning from the *minimum* value up to the *maximum* value, with all the cost alternatives for each reliability value shown. This is a very complex process, and needs a lot of time using a personal computer, even if it is INTEL® Pentium® 4 or higher, but for a CORE Due 2 Processor, these calculations can be faster.

(12) These steps were performed using MATLAB and the corresponding vectors were produced.

(13) We have now a reliability vector, starting from the minimum value up to the maximum one. For each value, we have also a vector for the cost; each cost value can be achieved by following the corresponding diameter combinations to produce the cost value and the reliability for this combination.

(14) A graph was constructed between the reliability (on the ***x***-axis) and the cost (on the ***y***-axis) as shown in Figure (3.4).

(15) From the graph, we can get the cost alternatives for a reliability value, and at a specific cost value we can get the reliability alternatives.

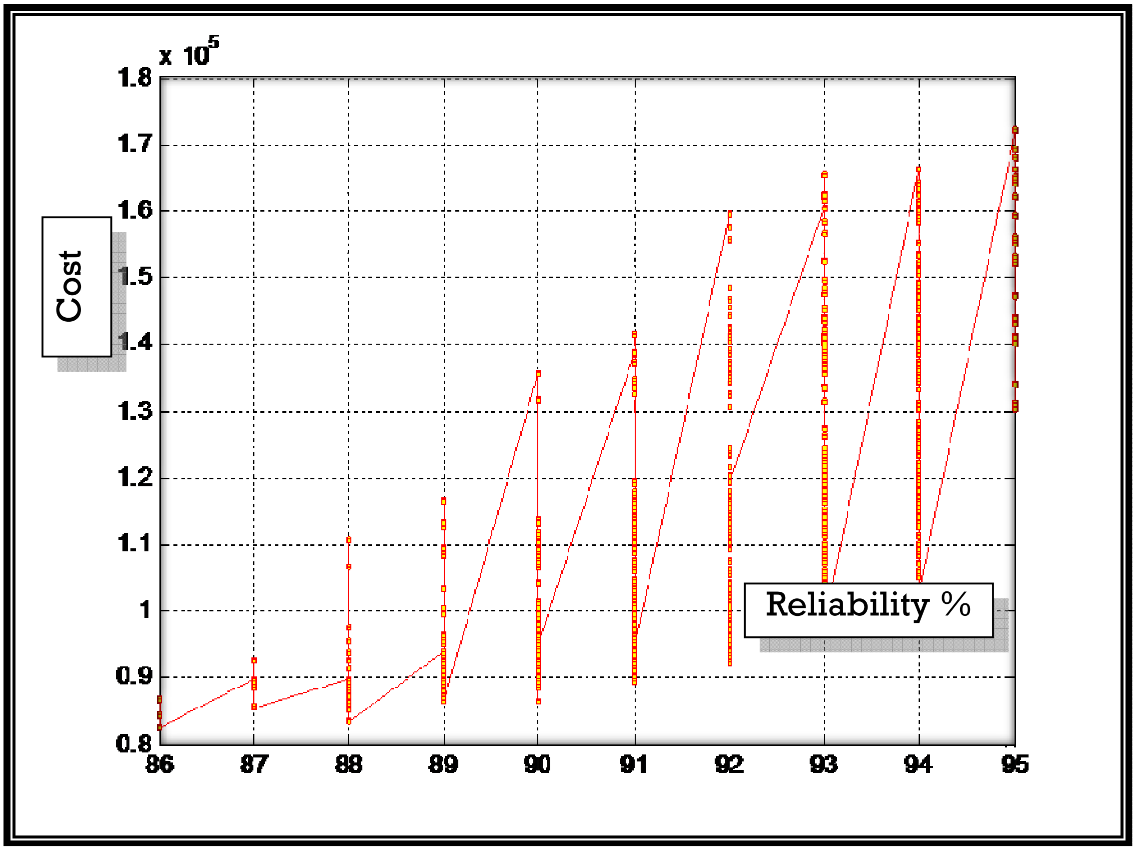


Figure 3-6: *Reliability/Cost relationship- Example (1)*

(16) As an example of the cost, the minimum reliability for this example is 86 % while the maximum value is 95 %. The cost range for the 90 % reliability is from 0.87×10^{5} to 1.36×10^{5}.

(17) On the other hand, for a cost of 1.0×10^{5}, there are just 5 reliability values; which are: 89 %, 90 %, 91 %, 92 %, and 93%.

In the following chapter, I will apply this model to a hypothetical case study to further illustrate this procedure.

Chapter (4)

THE HYPOTHETICAL CASE STUDY

4.1 Introduction

The methodology that was developed and presented in Chapter (3) will be utilized now in detail. A case study from the literature is adopted to implement the suggested method. Before this, the problem will be illustrated and the components will be analyzed. The diameters of the pipes and the connection information between nodes will also be provided.

4.2 Description of the hypothetical case

The water distribution network that we are going to solve is shown in Figure (4.1). It was adopted from the paper of Alperovits and Shamir (1977), and the same network was used in the work done by Liong and Atiquzzaman (2004). Additionally, Masri (1997) used the same network in finding the optimum design in his work.

The link data for this network is summarized in Table (4.1). The node data is summarized in Table (4.2). The cost for each pipe diameter is summarized in Table (4.3) below.

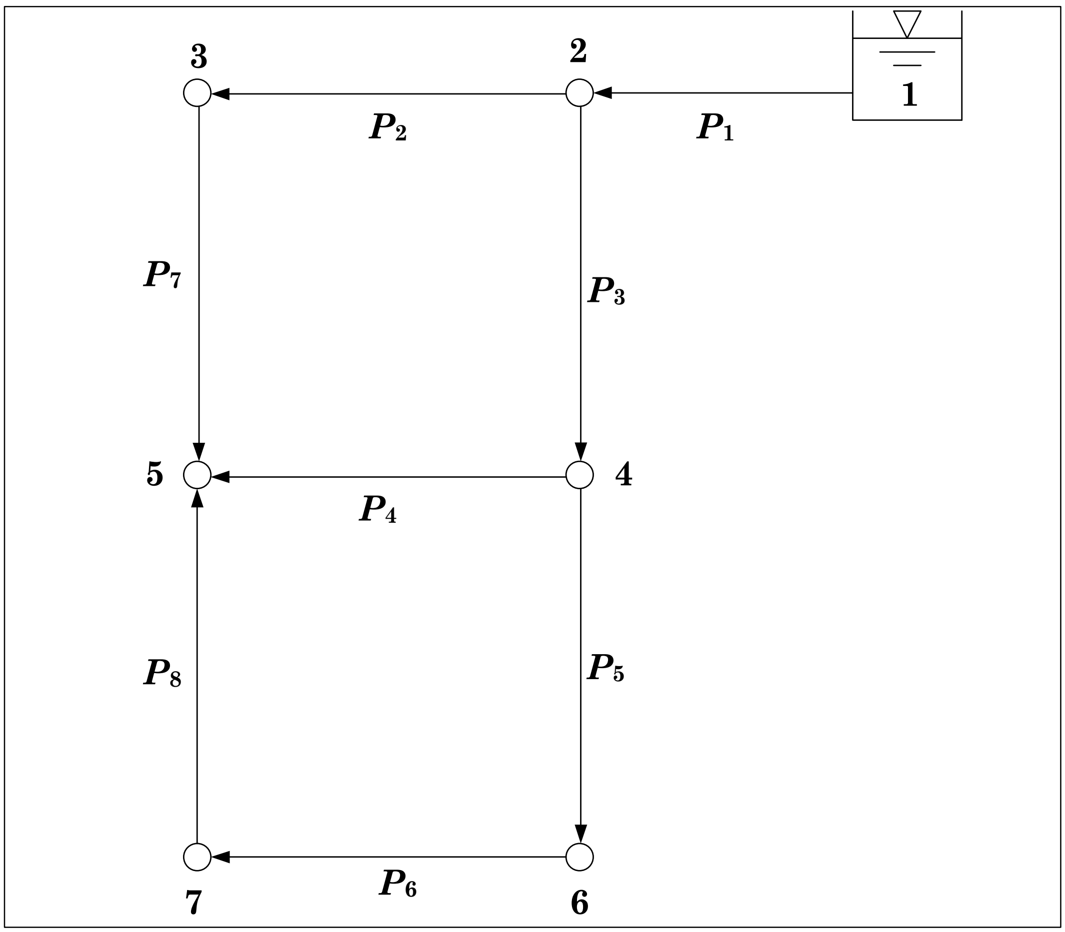


Figure 4-1-: *The Two-Loop Network (Alperovits & Shamir (1977)).*

Table 4-1 : *Link (Pipe) Data for the hypothetical case study.*

Link (Pipe)	Initial Node	Final Node	Length (m)
P_1	1	2	1000
P_2	2	3	1000
P_3	2	4	1000
P_4	4	5	1000
P_5	4	6	1000
P_6	6	7	1000
P_7	3	5	1000
P_8	5	7	1000

Table 4-2 : *Node Data for the hypothetical case study.*

Node No.	Demand (m^3/hr)	Elevation (m)	Min. Allowable Pressure (m)
1	– 1120	210	00.0
2	100	150	30.0
3	100	160	30.0
4	120	155	30.0
5	270	150	30.0
6	330	165	30.0
7	200	160	30.0

Table 4-3 : *Basic Unit Cost Data for the Pipes (Masri, 1997).*

Diameter (*Inch*)	**Unit Cost (per meter)**	**Diameter (*Inch*)**	**Unit Cost (per meter)**
1	2	**12**	50
2	5	**14**	60
3	8	**16**	90
4	11	**18**	130
6	16	**20**	170
8	23	**22**	300
10	32	**24**	550

4.3 Solution of the problem

The steps of the solution are the same as in Chapter (3), and these steps are summarized in the following points:

(1) The diameter distributions here was not distributed as mentioned earlier, because the number of choices may be very large. Instead, engineering judgment regarding the flow velocity was used here to determine the range of diameters (candidate diameters) for each pipe. Table (4.4) summarizes the candidate diameters for each link of the WDN.

Table 4-4: *Diameter distribution (candidate diameters*

Pipe No.	Candidate Diameter	Number of Choices
P_1	24, 22, 20, 18	**4**
P_2	18, 16, 14, 12, 10	**5**
P_3	24, 22, 20, 18, 16, 14	**6**
P_4	3, 2	**2**
P_5	22, 20, 18, 16, 14	**5**
P_6	16, 14, 12, 10, 8	**5**
P_7	16, 14, 12, 10	**4**
P_8	2	**1**

(2) The number of iterations transpired from these choices equals: $[4 \times 5 \times 6 \times 2 \times 5 \times 5 \times 4 \times 1 = 24{,}000]$, for each iteration, the network solver was executed and the outcomes were written in an output text file to be read later by MATLAB.

(3) MATLAB read the file and made the comprehensive matrix. This matrix is composed of two matrices; one for the diameters and the other for the pressure at nodes. The dimension of this matrix is 24,000 × (1 + 8 pipes + 7 nodes) = **24,000** *(Rows)* **× 16** *(Columns).*

(4) The cost for any iteration is calculated according to Equation (3.16). MATLAB stored the resulting values in a vector, whose entries will be used later in plotting the results and their relation with reliability. The minimum cost value was **34,700** and it occurs at iteration 24,000, where the reliability was **77** %, and the diameter combination is {18, 10, 14, 2, 14, 8, 10, 2}.

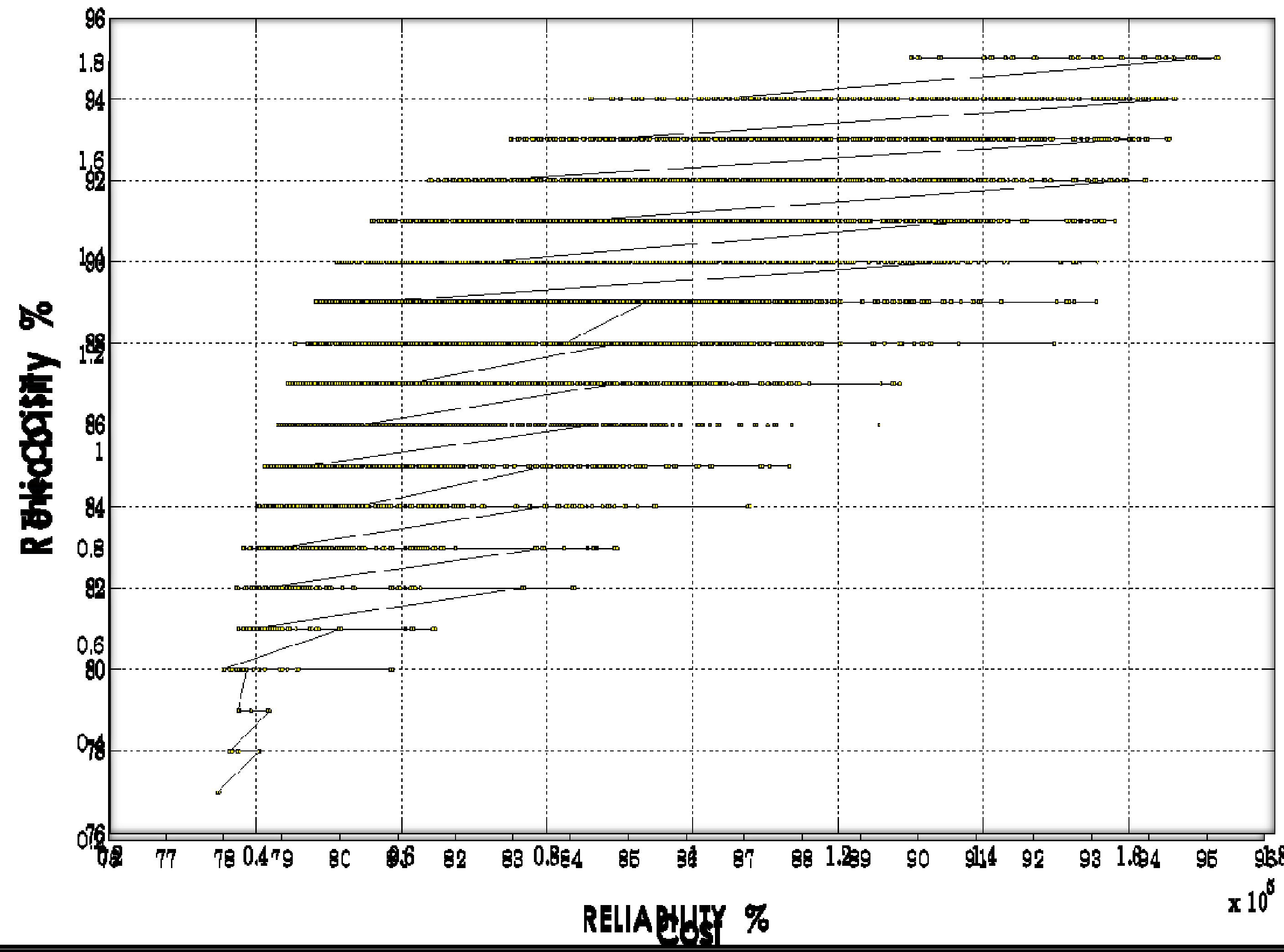
(5) The reliability of the network for any iteration is found by utilizing the equations in section (3.3.6). First, and for any iteration in the process, the node reliability factor is calculated and written in one vector. Then, the volume reliability factor is found. We need now the node factor, which is calculated also. By using these three values, the final value for the reliability of the network is calculated and put in a vector for the whole network and the complete number of iterations. According to our case study, the maximum reliability was **94.89** %, where the cost was a combination of values as we will see in the following section.

(6) Now, we have three important set of information; the reliability values, the corresponding cost values, and the

combination of diameters for these values. These numbers will be arranged by MATLAB into a new whole matrix in order to make the required sorting.

(7) After this point, the new big matrix will be re-arranged and sorted in a descending or ascending order according to the reliability values.

(8) The graph between the reliability and cost will be constructed now and any combination of the cost will be found for any value of reliability. Figure (4.2) shows the relationship between the cost and the reliability for our case study.



Figu **Figure 4-3** : **(B)** *Cost vs. Reliability for the hypothetical case*

4.4 Analysis and discussion

The graph depicted in Figure (4.2) is interesting. Several notes can be drawn out as illustrated below:

(1) The overall relation between the reliability and the cost is directly proportional; as the reliability increases, the cost will also increase.

(2) The minimum and the maximum reliability values are obvious and meaningful. Their respective values are 77 % and 95 %.

(3) The minimum value occurs at the unreliable network configuration, where the diameters are very low, and the pressure correspondingly will also be very low, but the water may not be supplied completely at some locations. At this low reliability, the cost will be low and optimum, because the diameters are low and they are low in cost.

(4) On the other hand, the maximum reliability will surely occurs at the high diameters, and the network will therefore

be at the highest reliability, because every node in the network will be supplied with sufficient quantities of water. However, the cost will be very high since the diameters.

(5) At a specific value of reliability, there are several corresponding values of costs, and therefore different configurations, which all get similar value of reliability. For instance and from the figure, several combinations of diameters produce 90 % reliability. When inquiring about this reliability value, the program provides us with the following information:

```
The Reliability = 0.9000
This Occurs for 3578 iterations with a unit
cost
The minimum Cost for this value is 51200
This Minimum Cost occurs at the following
Diameters:
20   14   16   2   16   10   14   2
```

(6) The previous point states that if we use the given arrangement of pipes, the reliability we would get will be

90% and the cost for this arrangement will be a minimum with a value of 51,200 units cost.

(7) From Figure (4.2), the cost combinations for each value of reliability have a minimum cost value. These values are shown as a column over each value of reliability, and may be consisting of many points of cost values depending on the calculations. They can be traced by **MATLAB** to form a vector of minimum cost values. Table (4.5) shows these values with their corresponding reliability values.

Table 4-5 : *The values of reliability and their corresponding minimum cost values.*

R	C_{min}	R	C_{min}	R	C_{min}	R	C_{min}
77	34700	82	37400	87	44400	92	64000
78	36500	83	38400	88	45400	93	75000
79	37700	84	40200	89	48400	94	86000
80	35600	85	41400	90	51200	95	130000
81	37700	86	43200	91	56000		

(8) By using the vector of these minimum cost values with the corresponding reliability values, we can make a graph, which has the reliability values at one axis, and the corresponding

minimum cost at the other axis. The graph of the hypothetical case study is shown in Figure (4.3).

(9) At each point of reliability, and for those combinations of cost values, we also have a maximum value for each combination. These maximum values do not make any importance for us, because we are searching for the minimum cost. The maximum values are not important for us.

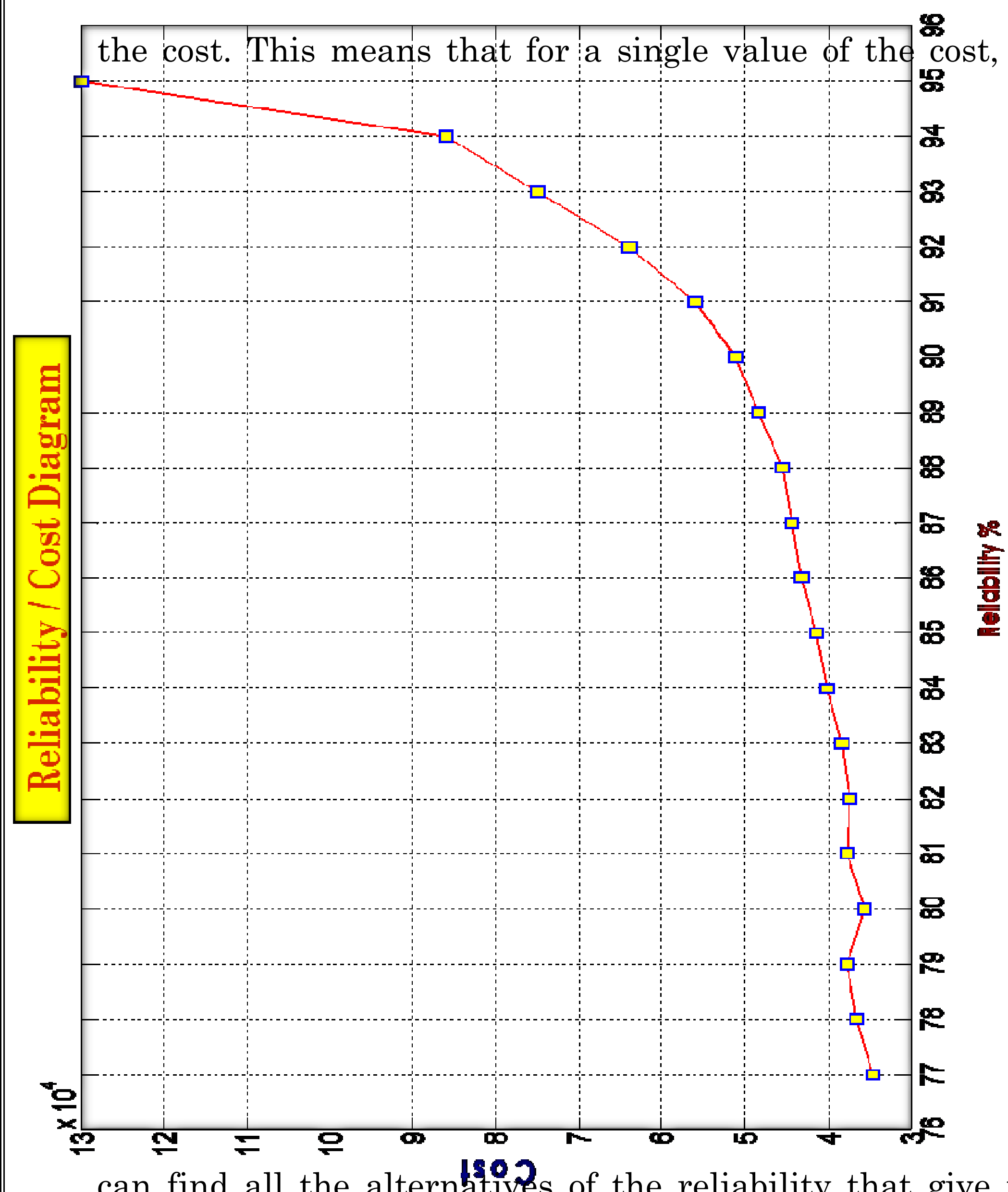


Figure 4-4: *The Minimum cost of the various values of reliability.*

(10) As we did for the reliability, one can find the same thing for the cost. This means that for a single value of the cost, we can find all the alternatives of the reliability that give the same cost value. This seems to be as if we draw a *horizontal line* from any point on the cost axis. The points of

intersection between that line and the reliability columns in the graph of Figure (4.2) are what we need. These points have two coordinates, one for the cost that we have, and the other is the value of reliability that we can get at this point.

(11) As an example of the previous point, let us take a cost of 0.6 $\times 10^5$. The corresponding values of reliability that can give this cost value are different diameter combinations up to 101 combinations. The minimum of these values is 86% and the maximum is 91%.

(12) Mathematically, the program, using **MATLAB**, can give the corresponding diameter combinations for each value. Each point of intersection has two coordinates, the abscissa is the reliability value and the ordinate is the cost value. From the big matrix ***M***, we can find these diameter combinations. For the minimum value, the diameter combination is {18, 12, 14, 2, 20, 16, 16, and 2}. Several diameter combinations produce the same maximum reliability value of 91%. One of these combinations is {20, 16, 18, 2, 16, 14, 12, and 2}.

(13) One may ask, what is the benefit of having several combinations of diameters that produce the same combination of reliability and cost? The point here is that we can use different types of diameter combination, according to the availability in the market, and it will produce the same results that we want. Sometimes there is unavailability of some types of diameters in the market; this point covers this problem absolutely.

(14) Let us take the maximum value of the cost. The maximum cost for the whole design is 130,000 as seen in Table (4.5). If we want to find the reliability values that may have the same cost of 130,000, we can find the following results:

- ▷ Number of combinations = 16 (Only!)
- ▷ The maximum reliability value = 95%
- ▷ The diameter combination for this maximum value is {24, 16, 22, 2, 20, 16, 16, and 2}.
- ▷ The minimum reliability value = 91 %
- ▷ The diameter combination for this maximum value is {18, 18, 24, 2, 22, 16, 16, and 2}.

(15) If we take the reliability value of 94%, we can see that there are several corresponding cost values, which can give the same reliability of 94%. From Figure (4.3), we can see that the minimum of these cost values is 86,000 units cost. Looking at the successive reliability value of 95%, which is just one percent more than 94%, the minimum cost for this reliability value jumped a very large amount to be 130,000 units cost. As a decision maker, one may hesitate most when he is going to have one percent increase in the system reliability and pay an additional cost of 130,000 - 86,000 = 44,000 units cost!!

Chapter (5)

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions of the study

The following are the main research conclusions:

(1) Water Distribution Networks (WDNs) are the principal technique to deliver water to the consumers and consumption centers. It is important to arrive at the minimum cost of the WDN while maintaining a sound design from the hydraulic perspective. In addition, it is so important to maximize the WDN reliability while maintaining a minimum cost.

(2) The reliability of any WDN depends on different factors and can be computed using several formulas. Its value is a probability value and is recorded as a percentage. The WDN is usually said to be unreliable or weak in reliability

if its reliability value is about or below 65%. If the cost is not important and we can use large diameter pipes in the WDN, the reliability value can be large up to 90% and 95% depending on the diameters combinations used in the design.

(3) There are several techniques to find the least cost design using mathematical programming. Howerver, the exhaustive full numeration technique was utilized in this work and was found to achieve a global minimum cost and accordingly the global optimum design.

(4) For different WDN configurations, it is possible to obtain similar reliability values. However, optimal WDN design implies the determination of the network least cost.

(5) Improving the reliability of a WDN implies the increase in the overall network cost due to the increase in the pipe diameters.

(6) **MATLAB** was used in this work to perform most of the calculations. **MATLAB** proves to be a versatile with practical flexibility.

5.2 Recommendations

As was mentioned in the previous section, additional work needs to be carried out to determine the minimum cost and the maximum reliability for any water distribution network. The following are the research recommendations:

(1) Full numeration technique is important to be taken into consideration in any future work, since it yields the global optimum design of the WDN. However, to avoid time-intensive runs, smart algorithms ought to be developed and utilized.

(2) Since intermittent pumping is the common pattern of water supply in the developing countries, it is important to consider this practice when designing WDNs optimally based on reliability.

According to the previous point, it is important to take many other network components such as pumps in calculations of reliability, and thus the optimum design of that WDN.

Appendix
The MATLAB Code

A **MATLAB** Program to find the Least Cost Design

of Water Distribution Networks (**W D N**)

A RELIABILITY Based Approach

Programmed By

K H A L I D   A s - S A D I Q

```
clear all
clc
ns=3
nn=6
np=8
PMIN=55;
LP=[100 100 100 100 100 100 100 100];
%for i =1:np
%    LP(i)=input('Enter the Length of Pipes, one
by one = ');
```

```
%end
CS=[2 5 8 11 0 16 0 23 0 32 0 50 0 60 0 90 0 130 0
170 0 300 0 550];
QREQ=[100 100 120 270 330 200];
%it=(ns-1)*(ns^(np-1))
it=24000
fid = fopen('Output_new.dat');
A =
textscan(fid,'%n%n%n%n%n%n%n%n%n%n%n%n%n%n%n%n%n%n
%n%n%n%n%n%n%n%n%n%n%n%n%n%n%n%n%n');
fclose(fid);
for i=1:np
    D(:,i)=A{i+1};
end
for j=1:nn
    P(:,j)=A{j+np+2};
end
%break
%D=[A{2} A{3} A{4} A{5} A{6} A{7}];
%P=[A{15} A{16} A{17} A{18}];
for i=1 : it
```

```
    for j=1 : nn
    QAV(i,j)=QREQ(j)*((P(i,j)/PMIN)^(1/nn));
    NR(i,j)=QAV(i,j)/QREQ(j);
    end
    VR(i)=sum(QAV(i,:))/sum(QREQ);
    NF(i)=(prod(NR(i,:)))^(1/nn);
    SR(i)=VR(i)*NF(i);
end
[SRMAX,K]=max(SR);
for i=1:it
    for j=1:np
        CST(i,j)=LP(j)*CS(D(i,j));
        COST(i)=sum(CST(i,:));
    end
end
[CMIN,N]=min(COST)
fprintf (' The Maximum Network Reliability is :
'), SRMAX
fprintf (' This Maximum Network reliability occurs
at iteration No. :'), K
R=round(100*SR');
```

```
C=COST';

M=[R C D];

FM=sortrows(M,1);

grid on

plot(FM(:,1),FM(:,2),'-rs','LineWidth',1,...

                'MarkerEdgeColor','r',...

                'MarkerFaceColor','y',...

                'MarkerSize',2)

grid on

answer='y'

while answer=='y'

RR=input('Enter the value of Reliability you want

= ');

s=1;

for i=1:it

    if FM(i,1)==RR

        cc(s)=FM(i,2);

        DD(s,1:np)=FM(i,3:2+np);

        J(s)=i;

        s=s+1;

    end
```

```
end
s
cc'
[minc, I]=min(cc');
fprintf (' The Minimum Value of the cost for this
choice is ( '), minc
fprintf (' The Diameter Combination for this
choice is [ '), DD(I,:)



answer=input('Do you want to know the cost for
another Reliability value (y/n)? ', 's');
clc
end

% To find the minimum COST for the different
values of
% RELIABILITY from the minimum to the maximum

clear s
clear j
```

```
clear CC
clear MC
s=1
for j=1:z
    for i=1:it

        if RC(i,1)==DR(j)
            CC(s)=RC(i,2);
            s=s+1;
        end
    end
    MC(j)=min(CC);
    clear CC
    clear s
    s=1;
end
fprintf('The Reliability values and their minimum
costs are : '),MC

% To plot these values :
grid on
```

```
plot(MC(1,:),MC(2,:),'-rs','LineWidth',2,...
                'MarkerEdgeColor','b',...
                'MarkerFaceColor','y',...
                'MarkerSize',4)
grid on
% To find the reliability values for a specific
cost value
% Let us say that we want these values for a cost
of 70000
nd=find(C==70000)
for i=1:size(nd)
    r(i)=R(nd(i));
end
[minr, I]=min(r);
[maxr, J]=max(r);
fprintf ('The Minimum is at the diameter
combination of : '), D(nd(I),:);
fprintf ('The Maximum is at the diameter
combination of : '), D(nd(J),:);
```

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جامعة النجاح الوطنية

كلية الدراسات العليـــا

إقـــتران قيـــمة التكلفة لشبكات تـــوزيع المياه من خلال دراسة تعتمد مفهوم المعـّـوليّـــة وباستخدام برنامج MATLAB

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قدمت هذه الأطروحة استكمالا لمتطلبات نيل درجة الماجستير في الرياضيات المحوسبة بكلية الدراسات العليا في جامعة النجاح الوطنية في نابلس ، فلسطين

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الملخص

يسعى كل مجتمع لإيجاد الوسيلة المناسبة لتوزيع المياه من عدة مصادر، ويتم هذا من خلال **شبكات توزيع المياه** . تتكون كل شبكة من أنابيب (لتوصيل المياه) ونقاط توزيع (لاستهلاك المياه) . إن قدرة أي شبكة لتزويد جميع النقاط بالكميات المطلوبة من المياه وتحت جميع الظروف هو أحد عناصر ما يسمى **بالمعــوّلية** أو **الوثوقية** لهذه الشبكة . لقد تم في هذه الدراسة تقديم طريقة لحساب المعولية لأي شبكة مياه وذلك لعدد كبير من التراكيب المختلفة لأقطار أنابيب الشبكة. لقد تم استخدام برنامج جاهز لتحليل الشبكات لإيجاد قيم الضغط عند كل نقطة لجميع الحالات، وتم تخزين النتائج في ملف نصي تمت قراءته باستخدام MATLAB الذي خزنها على شكل مصفوفة .

لقد تم بناء برنامج خلال هذه الطريقة وذلك باستخدام MATLAB لإجراء كافة الحسابات المطلوبة. تم حساب قيمة المعولية والتكلفة للشبكة وذلك لجميع التراكيب المختلفة للأقطـــار. القيم الناتجة للمعولية والتكلفة تم تخزينها في متجهات منفصلة .

إن الهدف الرئيس للدراسة هو إيجاد أكبر قيمة للمعولية ، وفي نفس الوقت ، إيجاد أقل قيمة للتكلفة. لقد تم هذا من خلال حصر جميع الحالات التي تحقق أكبر معولية ، ومن بينها تم إيجاد أقل تكلفة ممكنة . وقد تم تحقيق هذا من خلال البرنامج الذي تم إنجازه في بيئة MATLAB .

من أجل تطبيق هذه الطريقة ، تم اختيار حالة دراسية افتراضية ، وتم تطبيق هذه الطريقة عليها بشكل كامل. النتائج اشتملت على شيئين مهمين : حساب المعولية لأي شبكة ، وإيجاد تصميم لشبكة بأقم تكلفة لمعولية معروفة ، أو إيجاد تصميم لشبكة بأعلى معولية ممكنة إذا كان لدينا ميزانية (تكلفة) معروفة .