Integrated Reliability Assessment of Water Distribution Networks

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ABSTRACT

Integrated Reliability Assessment of Water Distribution Networks

Azhar Uddin Mohammed

The condition of current water infrastructure in North America is alarming due to deterioration of old water mains indicating the incompetence of existing water distribution to cope with increasing demands. ASCE (2013) report card graded the drinking water networks a score of D, representing "poor condition". In contrast, the Canadian drinking water infrastructure scored better, indicating "Good: adequate for now". Despite this, 15.4% of the water distributions are graded "fair" to "very poor" with a replacement value of CAD 25.9 billion. Delaying the investment can result in degrading water service, increasing service disruptions, and increasing expenditures for emergency repairs. Taking into account the deterioration severity and investment gap, water utilities need an asset management tool that can effectively prioritize the rehabilitation works.

This research is aiming at developing an integrated reliability assessment model that can identify the crucial water main segments and prioritize their renewal at all hierarchical levels of the network. In this regard, the proposed research framework encompasses modeling aspects of mechanical and hydraulic condition of a WDN. The first model analyzes the mechanical condition of a WDN at the component, segment and network levels. This model utilizes reliability theory for assessing component and segment reliabilities, whereas minimum cut set approach is pursued for assessing mechanical reliability of a network. To facilitate this tedious process, it has been coded in MATLAB R2013b programming environment along with the utilization of Wolfram Mathematica

10.2 and Microsoft Excel 2013. The second model analyzes the hydraulic performance of a WDN in terms of hydraulic reliability. It involves the hydraulic simulation of a WDN in normal and failure conditions, which aid in obtaining the required as well as actual pressure head at demand nodes. The model is then formulated with pressure conditions to evaluate the available demand at demand nodes which in contrast to the required demand aids in predicting the hydraulic reliability of the network. Finally, an integrated reliability assessment model is presented to conclude the research methodology by determining the overall sub-network reliability.

The developed methodology is worked out on two case studies from the cities of London, Ontario and Doha, Qatar. Also, it is implemented on two different sub-networks from the City of London (north phase and south phase) for drawing comparisons, which concluded that the mechanical reliability of a network encompassed by newer components with less number of failures is greater than that of other networks. Additionally, the results of model implementation revealed that structure/configuration of the network also played an important role in affecting the overall network reliability. It was found **0.82** for the north phase sub-network and **0.84** for the south phase indicating that the south phase sub-network is more reliable. Therefore, the north phase sub-network takes the priority when scheduling the rehabilitation. The resulting reliability indices of a WDN, helps the municipalities to effectively prioritize the rehabilitation works at respective hierarchical levels. Moreover, the outcomes of this research also aid in identifying the most critical water main segments that need to be monitored constantly in order to prevent the network failure.

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CHAPTER 1

Introduction

1.1 Overview

Water distribution networks (WDNs) are the vital part of civil infrastructure whose main task is to provide consumers with a minimum acceptable level of water supply at all times under a range of operating conditions. Many developed countries spend billions of dollars every year to repair, upgrade and expand the water infrastructure to ensure its safety and the needs of a growing population and economy. According to Food and Agriculture Organization of the United States (FAO, 2013), the total water use per capita in Canada is 1,150 gal/inhab/day, whereas in United States, that number reaches 1,146 gal/inhab/day. Also, the population in North America continues to grow with Canada showing a trend of 4.6% growth, and the United States recording 3.9% (SOTWI, 2013). However, the condition of current water infrastructure in North America is alarming due to deterioration severity of age old water mains. Some of them date back to the Civil War era with many cities possessing more than 100 years old water mains (Mohamed & Zayed, 2013), indicating the incompetence of existing distribution networks to cope with increasing water demand.

ASCE (2013) graded the drinking water networks in the United States with a score of D, designating “Poor” condition. AWWA (2012) found that restoring one million miles of existing potable water pipe networks as they reach the end of their useful lives, and expanding them to serve a growing population will cost at least $1 trillion over the next 25 years. By contrast, the Environmental Protection Agency (EPA, 2013), which do not factor population growth, estimated that $384 billion will be needed to upgrade US drinking water infrastructure by 2030. In comparison, Canadian drinking water infrastructure fares better than the United States and is graded “Good: adequate for now” in the CIR (2012). Nevertheless, 15.4% of water distribution systems in Canada were ranked “fair” to “very poor” with a replacement cost of CAD 25.9 billion (CIR, 2012).

Aging infrastructure is a concern for all developed countries. The random leaks and breaks in the distribution system, resulting from deterioration, can cause flooding, service interruptions, loss of water, and water contamination and, thus, reduce the reliability of the system (Piratla & Ariaratnam, 2011). Water and wastewater infrastructure in the United States needs an investment of $126 billion by 2020 to reach a grade of B. However the estimated funding is only $42 billion indicating an investment gap of $84 billion (ASCE, 2013). Whether acknowledged or not, these costs will continue to grow as infrastructure ages and deteriorates. Delaying the investment can result in degrading water service, increasing water service disruptions, and increasing expenditures for emergency repairs.

The deterioration severity and the increasing demand of water make the task of water infrastructure maintenance a crucial public health issue, as the deteriorated pipes can get cracked making the water contaminated. Cognizant of constrained budget allocation, a comprehensive reliability assessment should be performed to identify the most critical and failure prone water mains and prioritize their renewal/rehabilitation. The evaluation of reliability should address all types of issues including hydraulic failures and not just be limited to the structural aspects of the network. Accordingly, the reliability assessment should extend to all levels of a water distribution, from components to segments, segments to sub-networks, and ultimately the entire network. Water utilities need to develop proper asset management tools in order to enhance the current performance of the network, assist in the optimum maintenance, repair and rehabilitation planning, and eliminate budget mismanagement.

1.2 Problem Statement

The need of asset management tool that can effectively prioritize the renewal/rehabilitation of deteriorating water mains under constrained budgets established the core purpose for this thesis. In pursuit of achieving this, certain limitations have been identified which require improvement. Although there were many attempts to assess reliability of WDNs, these techniques were mostly applicable to individual pipes that do not examine the condition of other components forming a water main from the perspective of a segment. Moreover, the reliability of network was evaluated ignoring the importance of crucial water main connections.

Another deficiency lies in the fact that mechanical and hydraulic failures are often studied independently even though the flow of water inside the pipe has an effect upon its condition. Also, the hydraulic performance of the network have been evaluated usually ignoring the effect of pressure on demands. And those found to be pressure driven, were analyzed manually rather than analyzing in a simulating environment. Finally, automation has rarely been employed in reliability models making the procedure tedious and calculations enormous.

1.3 Research Objectives

Appertaining to the above stated problem and the limitations identified in current approaches, the main objective of this research is to develop a comprehensive reliability assessment model that can identify the crucial water mains and prioritize their renewal. This model should examine the condition of a water distribution network at all hierarchical levels, and consider the interrelation between mechanical and hydraulic aspects. In this context, the following sub-objectives are defined:

1) Identify and study the factors that impact mechanical and hydraulic reliability of water networks at various hierarchical levels, i.e. components, segments and ultimately networks.
2) Develop mechanical and hydraulic models to assess network reliability.
3) Develop an integrated reliability assessment model for water distribution network considering mechanical and hydraulic aspects.
4) Semi-Automate the developed model using coded scripts.

1.4 Research Framework Overview

The main purpose of this research is to develop an integrated reliability assessment model that can identify the crucial water main segments and prioritize their renewal at all hierarchical levels of the network. In this context, the proposed research framework is described as depicted in figure 1-1.

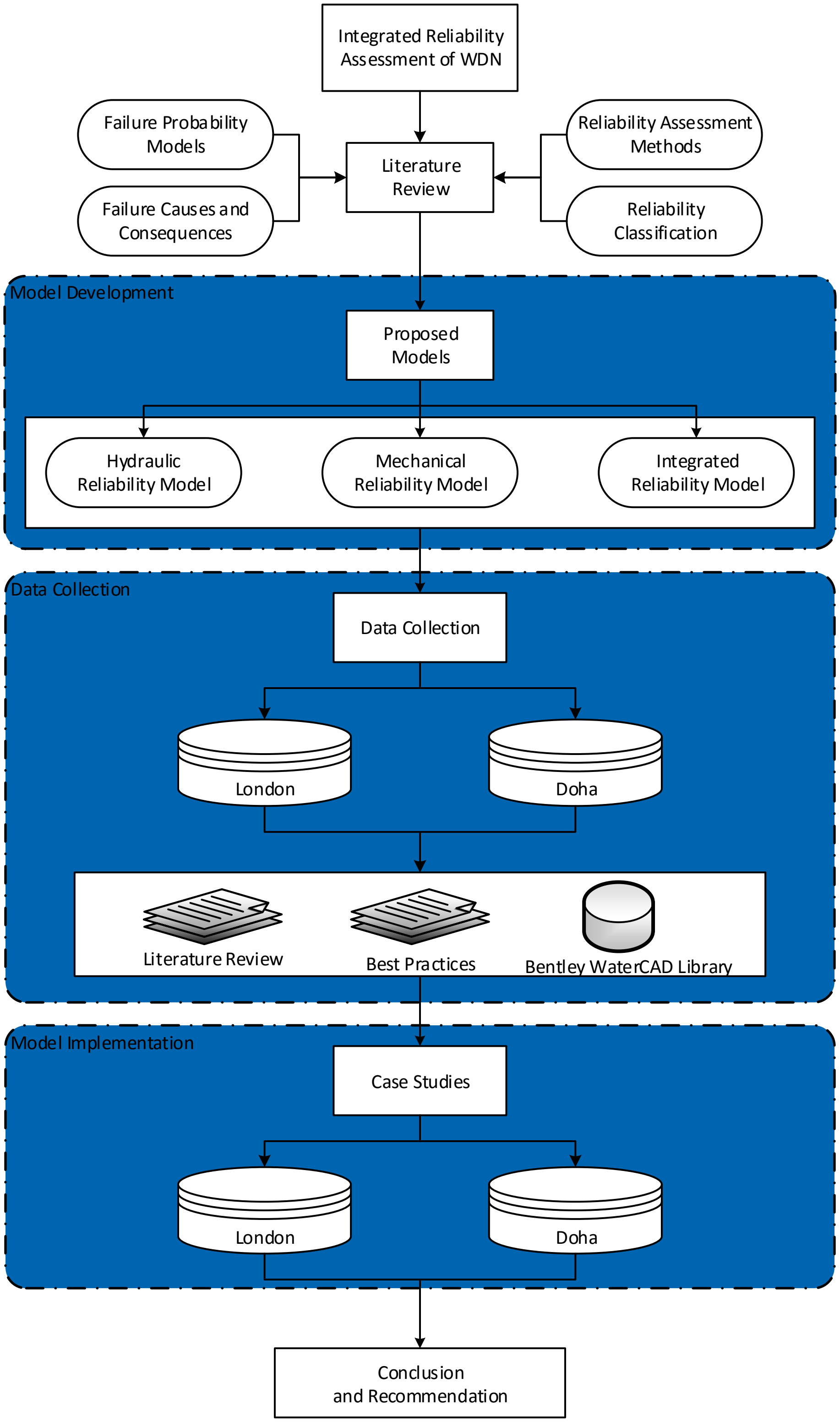


Figure 1-1: Research Framework Overview

1. Literature Review: An extensive literature review is performed primarily focusing on the current state of the art for reliability assessment modeling and identifying the limitations in the existing techniques. Concerning this, the failure rate of components, their failure probability distribution, and the causes of failure are studied. The literature also reviews the network analysis techniques to select the most suitable method for achieving the objective of identifying crucial segments.
2. Model Development: The developed methodology encompasses the modeling aspects of mechanical reliability, hydraulic reliability, and integrated reliability assessment.
    a. Mechanical Reliability Model: It deals with analyzing the structural performance of a WDN and its components. It commences by assessing the mechanical reliability at component level which consists of accessories (Valves, Hydrants etc.) and individual pipes. These component reliabilities are integrated leading to the assessment of segment reliability which is a weighted composition of components. Subsequently, network analysis is performed to finally ending the model with assessing the mechanical reliability of the network.
    b. Hydraulic Reliability Model: It deals with analyzing the hydraulic condition of a WDN. It involves the hydraulic simulation of a WDN in normal and failure conditions, which aid in obtaining the required as well as actual pressure head at demand nodes. The model is then formulated with pressure conditions to evaluate the available demand at demand nodes which in contrast to the required demand aids in predicting the hydraulic reliability of the network.

    c. Integrated Reliability Model: It addresses the main objective of developing an integrated model accounting for structural as well as hydraulic aspects of the network. The product of this model represents the overall condition of a water distribution network in terms of reliability.

3. Data Collection: Data is collected from four sources: (a) Literature, (b) Geodatabases for the City of London and Doha, (c) Best practice guides, and (d) Bentley WaterCAD library. All these four sources contribute towards the structure and development of the research framework. Literature review aids in segmentation of WDN components, whereas best practice guides reveals their failure causes and provides information about hydrant demands. Engineering library of WaterCAD possesses the industry standard protocols of nodal demand allocation, and Geodatabase contains the network attributes.

1.5 Thesis Organization

This thesis encompasses 6 chapters. The literature review is presented in chapter 2. It covers the topics of failure probability models, failure causes, reliability classification, reliability assessment methods and network analysis techniques. The listed topics are reviewed with a focus on how they reflect upon the developed models. Summary of the limitations in existing methods are presented at the end of this chapter. Chapter 3 describes the developed research methodology presenting each proposed model in detail. Chapter 4 presents the sources of data collection that are used in order to develop the proposed methodology and later aid in model implementation. In chapter 6, two case studies are worked out to demonstrate the exploitation of developed methodology in achieving stated objectives. Chapter 6 highlights the contributions and limitations of the developments made in the thesis along with suggested future enhancement and research extension.

CHAPTER 2

Literature Review

2.1 Overview

In this chapter, the literature review is primarily focusing on revealing the current state of the art for reliability assessment modeling and identifying existing limitations as well. Figure 2.1 portrays different areas of literature in an attempt to summarize the extent of this thesis.

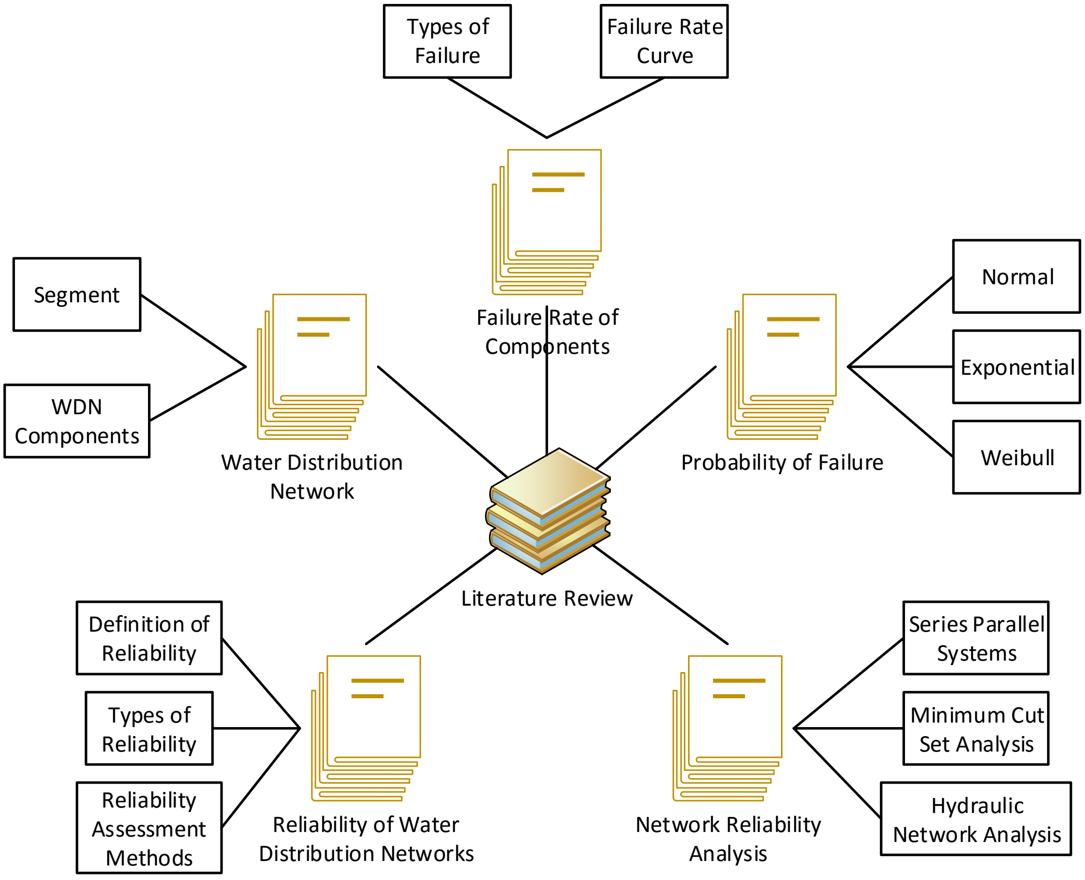


Figure 2-1: Literature Review Diagram

Chapter 2 starts with a brief description of water distribution networks (WDNs) and their components with emphasis on the segmentation of WDN and its importance in reliability assessment. Subsequently, failure patterns of WDN components are discussed along with their reported causes and consequences. The estimation of probability of failure for WDN is thoroughly examined with focus on Normal, Exponential and Weibull distribution models. The different definitions of reliability are summarized and afterwards reliability assessment methods are classified based on failure types of WDN. The impact of WDN size on performing reliability analysis is illustrated by underlining previous research efforts to circumvent the negative effect of such factor on the computational time. The chapter concludes with a summary for the reviewed literature and also identifies which limitations will be circumvented in this research.

2.2 Water Distribution Network

Water distribution networks (WDNs) are complex interconnected networks consisting of sources, pipes, and other hydraulic control elements such as pumps, valves, regulators, tanks etc., that require extensive planning and maintenance to ensure good quality water is delivered to all customers (Shinstine et al., 2002). These networks are often described in terms of a graph, with links representing the pipes, and nodes representing connections between pipes, hydraulic control elements, consumers, and sources (Ostfeld et al., 2002). They are vital part of urban infrastructure and require high investment, operation and maintenance costs.

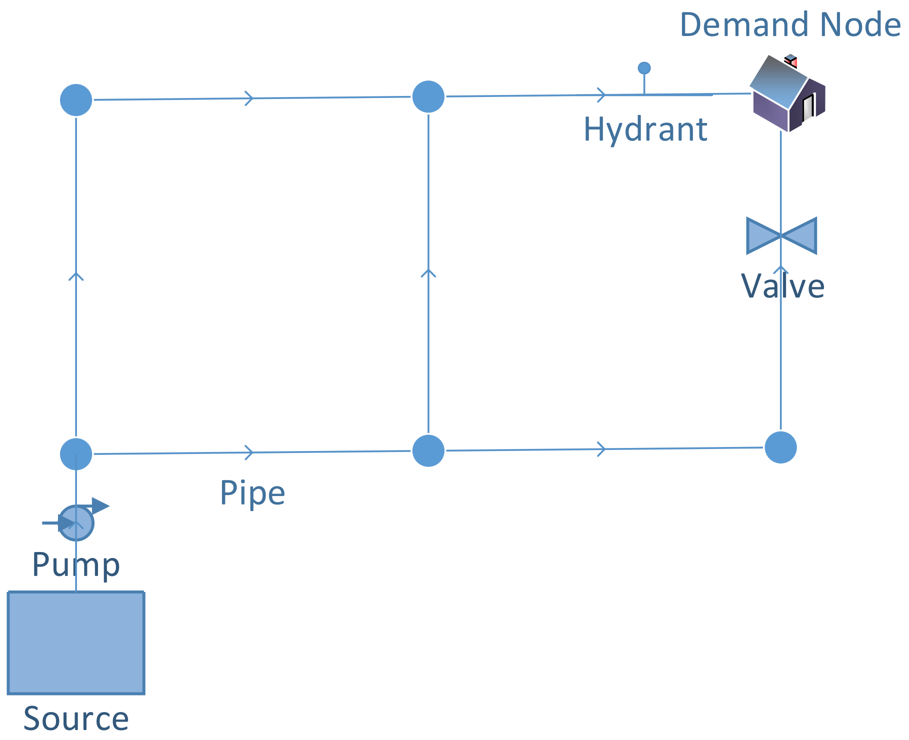


Figure 2-2: Typical Water Distribution Network

2.2.1 Water Distribution Network Components

Although there are several components, the main components which make a water distribution network are pipes, and accessories such as valves and hydrants. All network components other than pipelines are termed as accessories.

Failure of any of these components affects the performance of the network as a whole. Water utilities face unprecedented challenges because of failure of these components which results from aging infrastructure, tighter water quality and environmental regulations, and declining maintenance budgets (Rogers & Grigg, 2006). While utilities constantly monitor major components such as pumps and storage tanks, other components (pipes, joints, valves, and so on) have more chance of unplanned failure

(Perelman & Amin, 2014). Hence water utilities should monitor and maintain the condition of these components for adequate supply of water under a range of operating conditions.

2.2.2 Segmentation

The working conditions of a water distribution network are defined by taking into account the temporary unavailability of some components resulting from failures (Ciaponi et al., 2012). Researchers perform the condition assessment of a WDN by assuming that each pipe can be isolated (for maintenance and repair) by using valves located at its extremities. But in practice, this is not the case because for economic reasons, the valves are not necessarily located at the end of each pipe. For this reason, (Walski, 1993) suggested using an approach involving "segments" of a distribution system (instead of pipes), which can be isolated with valves and are considered the basic unit for assessing reliability.

According to Australian National Audit Office (2010), an Asset Portfolio should be segmented into largest groupings that allow worthwhile analysis to determine the effectiveness and efficiency of assets in supporting the delivery of specified service outcomes. (Walski, 1993) defined a segment as a pipe or a collection of pipes. Some authors (Giustolisi & Savic, 2010; Jun & Loganathan, 2007; Kao & Li, 2007) proposed methods for segmentation that will be isolated once certain valves have been closed. These authors also focused on identification of unintended isolation of a network disconnected from water source(s) as the secondary effect of segment isolation. (Salman, 2011) defined the segment as a single water main pipe or a group of connected pipes (along with all the associated components) which is located between the two nearest intersections at which isolation valves exist and the operation of these valves leads to the isolation of the segment in case of breakage or for regular maintenance of a component in the segment.

In this thesis, Salman's (2011) definition of segment have been adopted but with a slight modification. Because this work deals with analyzing a network based on connectivity, a segment is defined as a water main pipe or a group of connected pipes (along with all the associated components) which is located between two nearest intersections. Figure 2-3 attempts to visualize this segment definition.

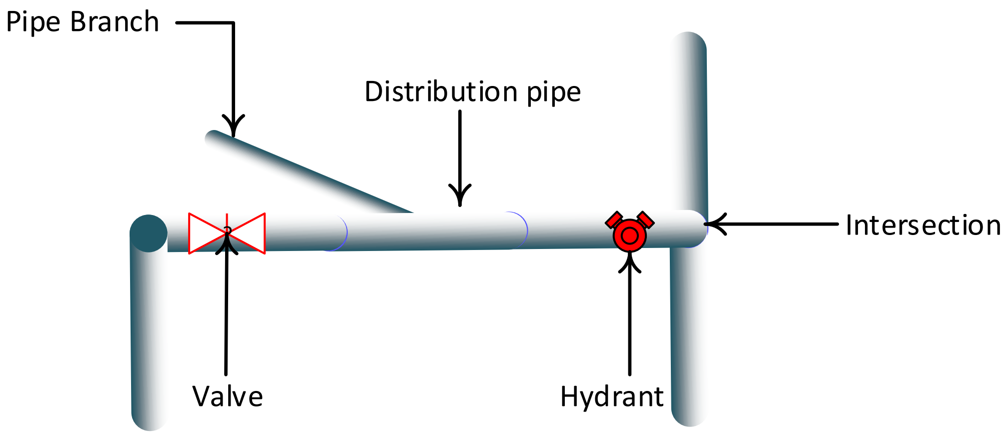


Figure 2-3: Segment

2.3 Failure Rate of Components

Failures are of a stochastic nature and are the result of unpredictable events that occur in the system itself and/or at its surrounding environment (Ostfeld, 2004). Failures of pipes and accessories in water distribution networks lead to financial and capital losses for repair and restoration of the network. They reduce the reliability of WDN due to lowering of the pressure or due to interruption of the water supply in parts of the distribution network, which ultimately leads to dissatisfaction of customers (Tabesh et al., 2009). The component failures in a WDN include pipe breaks, pump failures, valve failures, storage malfunctions, etc. (Su et al., 1987).

2.3.1 Types of Failure

According to Farmani et al. (2005), WDN deals with two types of failure. (1) Mechanical failure, which usually refers to failures of network components, such as pipe breakage or pump being out of service (2) Hydraulic failure, which refers to uncertainties, such as in nodal demand, pipe roughness, and reservoir and tank levels. More often than not, hydraulic failures are a result of mechanical failure in network components. A leakage in a pipeline due to pipe break, triggers the variation in pressure at demand nodes, and this variation highly affects the encompassing pipeline operations, and the whole network to a certain extent. Population growth and climate are known to affect water demand, but the relationship between them is uncertain (Farmani et al., 2005).

Possible causes for mechanical failure include external or internal loading, climatic conditions, natural disasters, freezing, aging process, corrosion, and permeation (Tabesh, 1998). Hydraulic failure may happen when demand exceeds the flow capacity of the system (e.g., fire-flow situations). In this instance, high demand in some nodes may undermine the hydraulic integrity of the entire system. Maintenance activities, tuberculation, and improper operational control can also threaten the hydraulic integrity of a WDN (Gheisi & Naser, 2014b). Table 2-1 summarizes few possible causes and consequences of mechanical and hydraulic failures.

Table 2-1: Causes and Consequences of Failures (NRC, 2006)

Types of failures	Causes	Consequences
Mechanical	• Corrosion • Permeation • Too high internal water pressure or surges • Shifting earth • Exposure to UV light • Stress from overburden • Temperature fluctuations, freezing • Natural disasters • Failure due to aging and weathering	• Contamination of Mains, Fittings, and Appurtenances • Contamination of Storage Facilities • Contamination Due to the Absence or Operational Failure of Backflow Prevention Devices
Hydraulic	• Pipe Deterioration • Pressure Transients and Changes in Flow Regime • Hydraulic Changes during Maintenance and Emergencies • Tuberculation and Scale • Inadequate Operational Control	• External Contamination • Sedimentation • Reduction in Hydraulic Capacity and Associated Increase in Pumping Costs • Poor Water Quality from Sediment Suspension and Removal of Scales

2.3.2 Failure Rate Curve

The shape of a failure rate curve is often referred to as a bathtub curve for self-evident reasons and can generally be divided into 3 distinct phases as shown in figure 2-4.

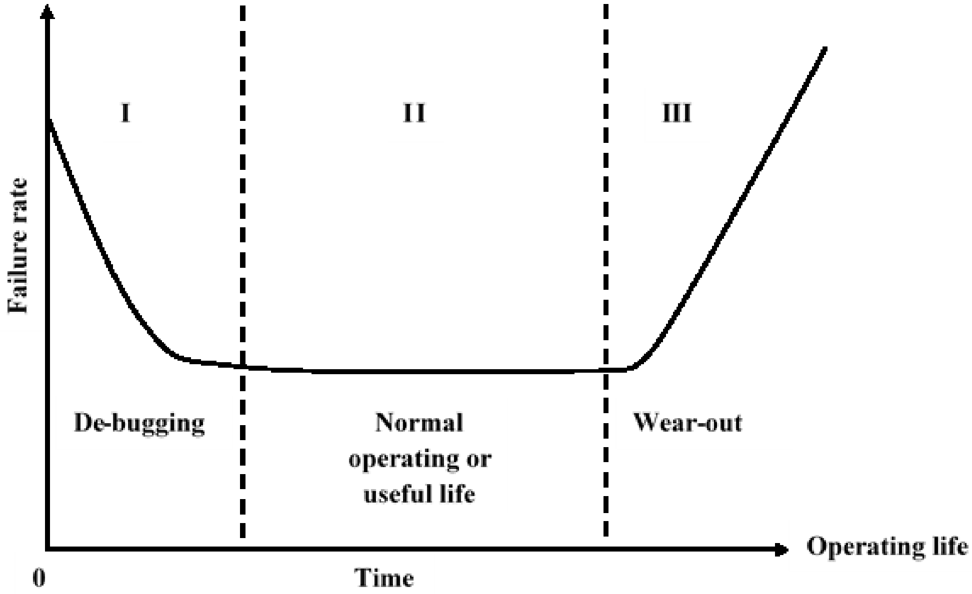


Figure 2-4: Failure Rate Curve (Billinton & Allan, 1983)

Phase (I) is known by various names, such as infant mortality or the de-bugging phase. Failure rate (λ) is very high in this region due to manufacturing errors or improper design. Phase (II) follows a constant failure rate because in this region, failures occur purely by chance. Phase (III) represents the wear-out or fatigue phase, and is characterized by a rapidly increasing failure rate with time. Phase (II) is considered as the useful life, to which the negative exponential distribution is applicable (Billinton & Allan, 1983).

Failure rate for a component in a WDN may be calculated by adopting the equation 2-1 (Chandrupatla, 2009):

$$\lambda = \frac{K}{T} \tag{2-1}$$

Where:

λ = Failure rate of a component,

K = Number of failures during the test interval,

T = Total test time

2.4 Probability of Failure

All the components of a WDN such as pipes, valves and hydrants do not fail on the same operating time but fails at random times. Consequently, these times to failure obey a probability distribution which may, or may not, be known and which describes the probability that a given component fails within a certain specified time. This probability value is a function of time that is specified or considered.

There are two main types of probability distributions – discrete and continuous. Discrete distributions represent random variables that can assume only certain discrete or countable number of values. Binomial distribution and Poisson distribution are the two most common discrete probability distributions. Continuous distributions represent random variables that can assume an infinite number of values, although within a finite range. The probability of failure of a WDN component can follow any of the following continuous distributions.

2.4.1 Normal (or Gaussian) Distribution

Normal probability distribution is probably the most important and widely used distribution in the field of statistics and probability. Although having some important applications in reliability evaluation, it is of less significance than other distributions (Billinton & Allan, 1983). The precise shape and position of the distribution function can be specified solely in terms of mean value and standard deviation. The shape of normal distribution function is often referred as ‘bell curve’ because of its curved flaring shape (Weisstein, 2002).

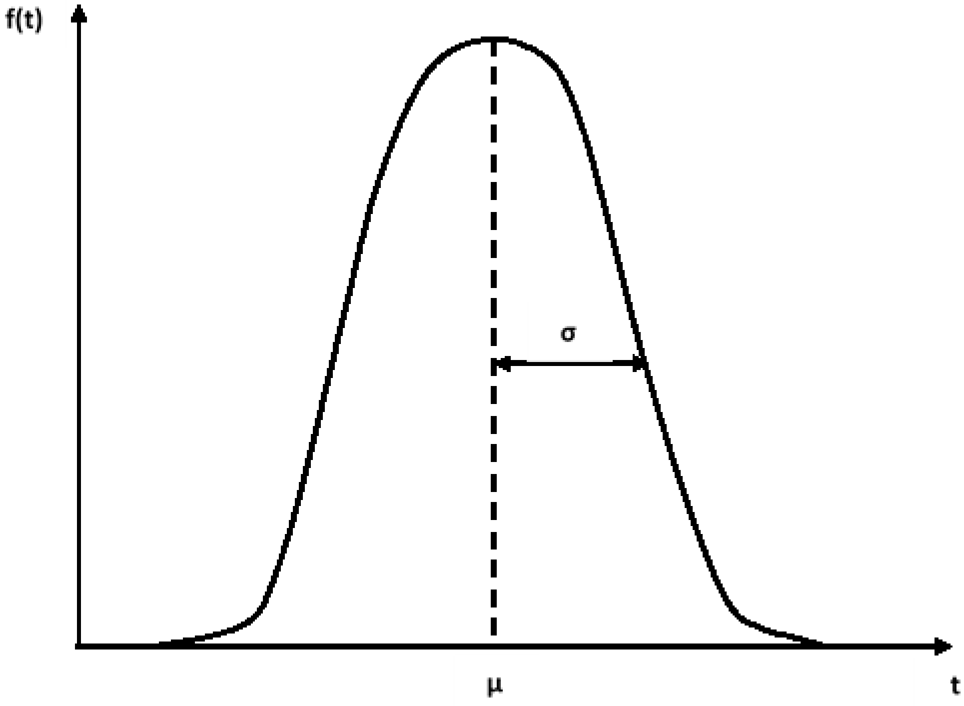


Figure 2-5: Normal Distribution Function

The normal distribution of data related to component life can be expressed by the following generic function form:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} \tag{2-2}$$

Where:

t = time,

μ = mean/location parameter,

σ = standard deviation/scale parameter

Generally, probability of failure in normal distribution is computed by using standard tables, which specify the areas under a curve for a large range of possible limits. A standard score value (*z*) which can be evaluated using equation 2-3, is required to navigate through standard tables of normal distribution and compute the probability of failure.

$$z = \frac{x-\mu}{\sigma} \tag{2-3}$$

2.4.2 Exponential Distribution

The exponential distribution is the most widely known and used distribution in reliability evaluation of systems (Shinstine et al. 2002; Salman A. 2011; Mohammed et al. 2015). It is applicable only to the useful life or normal operating period of a component, where the failure rate is constant (Billinton & Allan, 1983).

The exponential distribution function can model the data related to component life by equation 2-4:

$$f(t) = \lambda e^{-\lambda t} \tag{2-4}$$

Where:

λ = failure rate,

t = time

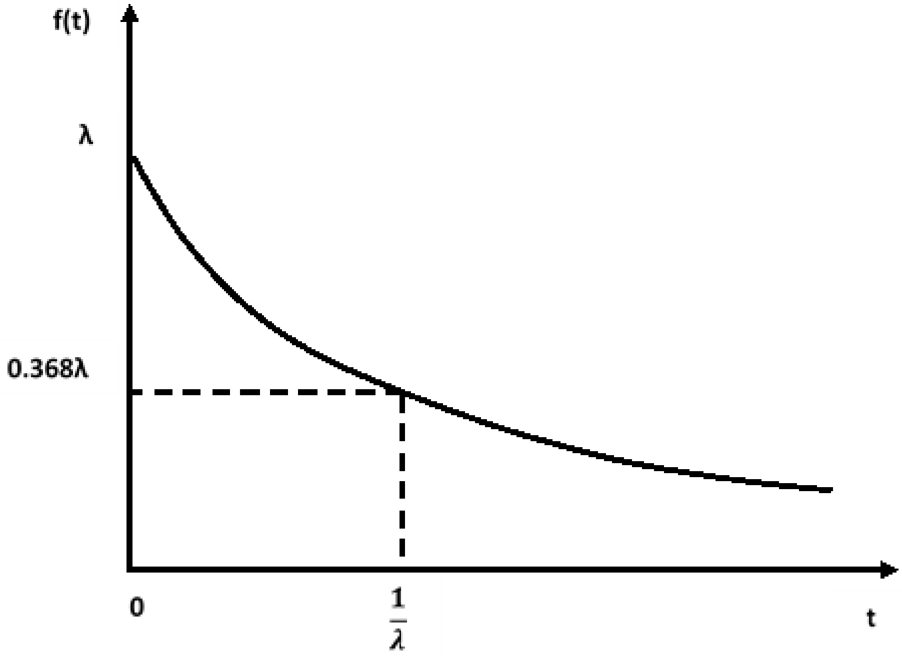


Figure 2-6: Exponential Distribution Function
(Billinton & Allan, 1983)

From this model, the cumulative distribution function i.e. the probability of failure *Q(t)* can be defined equation 2-5 as:

$$Q(t) = 1 - e^{-\lambda t} \tag{2-5}$$

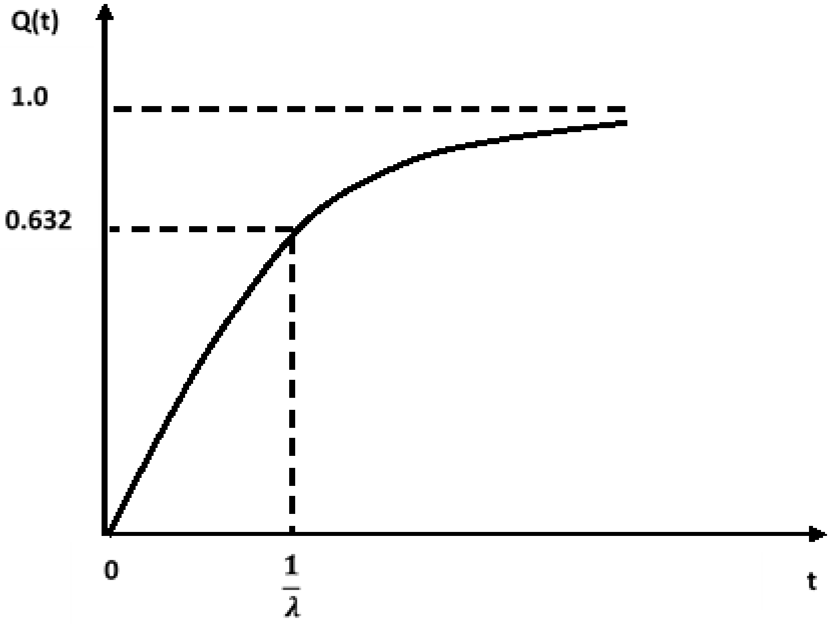


Figure 2-7: Cumulative Probability Distribution
(Billinton & Allan, 1983)

2.4.3 Weibull Distribution

The Weibull distribution is used extensively in life studies for engineering components. It was developed by a Swedish engineer Waloddi Weibull (1887-1979), who modeled the typical life of a component as described by equation 2-6 (Chandrupatla, 2009):

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \qquad (t \geq \gamma) \qquad (2\text{-}6)$$

Where:

β = shape parameter,

α = scale parameter,

γ = location parameter,

t = time

The Weibull distribution has no characteristic shape. Depending upon the values of the parameters, it can be shaped to represent many distributions (Billinton & Allan, 1983). We note that, if $\gamma = 0$ and $\beta = 1$, the Weibull distribution is precisely an exponential distribution. Exponential distribution is thus a special case of Weibull distribution.

The cumulative Weibull distribution i.e. the probability of failure *Q(t)*, deduced from the above model, can be defined by equation 2-7 as (Semaan, 2011):

$$Q(t) = 1 - e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \tag{2-7}$$

2.5 Reliability of Water Distribution Networks

The main task of a WDN is to provide consumers with a minimum acceptable level of supply (in terms of pressure, availability, and water quality) at all times under a range of operating conditions. The degree to which the network is able to achieve this, under both normal and abnormal conditions, is termed its reliability (Atkinson et al., 2014). Hence, reliability is considered as an integral part in making decisions regarding the planning, design, and operation phases of WDNs. Reliability assessment of WDN not only evaluates if the required performance will be met, but will also quantify to what extent the performance is satisfactory.

Reliability is basically the probability of survival of a component at time *t*. Hence, reliability of a component is the complement of probability of failure. Therefore, reliability and probability of failure are related by equation 2-8 (Chandrupatla, 2009):

$$\mathrm{R(t) + Q(t) = 1} \quad (2\text{-}8)$$

In this thesis, reliability is assumed to follow negative exponential distribution which would mean that reliability decreases exponentially as the failure rate increases with time. Therefore, the reliability function for exponential distribution can be described as:

$$\mathrm{R(t) = 1 - Q(t) = e^{-\lambda t}} \quad (2\text{-}9)$$

2.5.1 Definition of Reliability

Although the reliability assessment of WDNs has gained considerable attention over the last two decades, there is still no common, acceptable, reliability definition or measure (Jalal, 2008). Many researchers defined reliability based on different conditions, as found in table 2-2.

Note that the reliability of a WDN can be contemplated from two different perspectives: (1) the customer's view: the main goal of modeling is to analyze and evaluate system reliability in the case of water delivery cut-offs and the duration of these suspensions; (2) the planner's view: the main goal is to analyze and evaluate failures, examine various reliability states and undertake assessment of the system's reliability. Although efforts have generally been premised on the second perspective, customer-based evaluation is also important (Jalal, 2008).

Table 2-2: Definitions of Reliability

Authors	Definitions
Xu and Goulter (1999)	WDN capacity reliability refers to the probability that the minimum required nodal pressures are met, under the assumption that the required nodal demand flows are met, and is a function of the uncertain nodal demands and the uncertain degree to which pipe hydraulic capacities will be reduced over the design period.
Tanyimboh et al. (2001)	Reliability is defined as the time-averaged value of the ratio of the flow supplied to the flow required.
Shinstine et al. (2002)	Reliability is defined as the probability that the distribution system will function at some minimum defined pressures while satisfying the demands (hydraulic availability) given the possible failure of different components.
Kalungi and Tanyimboh (2003)	Reliability is the extent to which the network can meet customer demands at adequate pressure under normal and abnormal operating conditions.
Ostfeld (2004)	Reliability is an inherent attribute of any system, referring to its ability to perform a mission adequately under stated environmental conditions for a prescribed time interval.
Al-Zahrani and Syed (2006)	Reliability of a WDN is its ability to deliver water to individual consumers in the required quantity and quality and under a satisfactory pressure head
Ciaponi et al. (2012)	Reliability of a hydraulic system is its ability to satisfy users taking into account the various working conditions to which it may be subjected during its operative life.
Shuang et al. (2014)	The reliability is defined as the probability that the WDN meet flow and pressure requirements under the possible mechanical failure scenarios (e.g., pipe breaks).

2.5.2 Types of Reliability

Reliability assessment of WDNs is usually classified in two main categories, relating to two types of failure. (1) Mechanical Reliability and (2) Hydraulic Reliability.

2.5.2.1 Mechanical Reliability

The structural condition of urban WDN is important for the continuity and quality of the water distribution services provided by such systems. Every human-made product and system, from simple products to complex structures, has certain unreliability and they deteriorate with time until they ultimately fail (Murthy, 2010). Mechanical reliability reflects the degree to which the WDN can continue to provide adequate levels of service during unplanned events such as mechanical/structural failure (e.g., pipe bursts, pump malfunction).

2.5.2.2 Hydraulic Reliability

A component failure may undermine the hydraulic integrity of a WDN and drop the pressure at demand nodes (Gheisi & Naser, 2015). Hydraulic reliability reflects how well the network can cope with changes over time, such as deterioration of components or demand variations (Atkinson et al., 2014). It can be described as the ability of the water distribution network to satisfy the nodal demands under both normal operating conditions as well as when one or more components of the system experience failure.

On the other hand, some authors (Islam et al., 2014; Gupta et al., 2012) have also argued about water quality reliability which is assessed with respect to a predefined level or range of selected water quality parameters (e.g., residual chlorine concentration). If the water quality parameter is within the prescribed range, the WDN is considered reliable, otherwise it is considered unreliable for water quality. However, the scope of this research is limited to the evaluation of reliability considering only mechanical and hydraulic aspects of WDN and its components. Water quality measures are usually studied independently.

2.5.3 Reliability Assessment Methods

A review of the literature reveals that there is no universally acceptable measure for the reliability of water distribution networks. It gained considerable research attention over the last few decades. This research has concentrated on methodologies for reliability assessment and for reliability inclusion in optimal design and operation of WDNs. This section provides a summary of these efforts.

As reliability is not a network property that can be measured directly, it should be assessed based on other characteristics of the network that can be directly measured or calculated. Ostfeld (2004) categorized reliability assessment methods into (1) connectivity/topological, (2) hydraulic and (3) Entropy as a reliability surrogate.

2.5.3.1 Connectivity

The reliability which is based on the concept of connectivity refers to measures associated with the probability that a given network remains physically connected by taking into account the topology of the network. This type of measure mainly serves the purpose of evaluating mechanical reliability. Wagner et al. (1988) applied analytical methods and introduced the concepts of reachability and connectivity to assess the reliability of a water distribution system, where reachability is defined as the probability that a given demand node is connected to at least one source, and connectivity as the probability that all demand nodes are connected to at least one source. Shamsi (1990) and Quimpo & Shamsi (1991) incorporated the use of node pair reliability (NPR) as the network reliability measure. The NPR is defined as the probability that a specific source and demand nodes are connected. This definition corresponds to the probability that at least one path is functional between the source node and the demand node considered. Goulter (1987) noted that network reliability is, in fact, defined, or more specifically constrained, by the fundamental layout of the network. Networks with better shapes (i.e. with more redundancy in terms of interconnections, etc.) will be more reliable. Yannopoulos and Spiliotis (2013) focused on topology of network as a measure for analyzing mechanical reliability. They developed a methodology based on adjacent matrix of graph theory in order to determine connectivity among different nodes. Measures used within this category do not consider the level of service provided to the consumers during a failure. The existence of a path between a source and a consumer node in a water distribution system, in a non-failure mode or once a failure has occurred does not guarantee a sufficient service (Ostfeld et al, 2002).

2.5.3.2 Hydraulic

The second category of reliability assessment i.e., hydraulic measure is concerned with the conveyance of desired quantities and qualities of water at required pressures to the appropriate locations at the appropriate times. Cullinane (1989) introduced nodal availability which is the portion of time when the nodal pressure is higher than the required value for all demand patterns and different network component failures. Cullinane et al. (1992) examined the intermediate stage of partial pressure failure using the 'nodal availability' concept but, instead of assuming a binary index (i.e., zero when available pressure is less than required and one otherwise), they assumed a continuous fuzzy relationship. Xu and Goulter (1999) used a probabilistic hydraulic approach, based on the concept of the first-order reliability method (FORM), to determine the capacity reliability of the water distribution network, which is related to the hydraulic and demand variation failures, and is defined as 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. Shinstine et al. (2002), coupled a cut-set method with a hydraulic steady state simulation model that implicitly solves the continuity and energy equations for two large scale municipal water distribution networks in the Tucson Metropolitan Area in Arizona. The measure of reliability was defined as the probability of satisfying nodal demands and pressure heads for various possible pipe breaks in the water distribution network at any given time. Zhuang et al. (2011) presented a methodology for reliability and availability assessment of a WDN based on an adaptive pump operation. In response to a pipe break, pump operations were adapted using various sizes of pump combinations. In their method, they evaluate hydraulic reliability in terms of available water to fulfill desired demand. An accurate calculation of the hydraulic reliability of a given system requires data on its entire component reliabilities and their associated failure impacts on the consumer's demands (Ostfeld, 2004).

2.5.3.3 Entropy as a Reliability Surrogate

Entropy, as a surrogate measure for reliability is the third category which has been used by several researchers for reliability assessment during recent years (Shannon, 1948; Ostfeld, 2004; Setiadi et al. 2005; Prasad & Tanyimboh, 2009; Tanyimboh et al. 2011; Gheisi & Naser, 2014). The fundamental idea is to use Shannon’s (1948) entropy measure of uncertainty that quantifies the amount of information contained in a finite probability distribution, to measure the inherent redundancy of a network. In this regard, entropy is more related to the category of connectivity/topological analysis than to that of hydraulic reliability. It is assumed that distribution networks, which are designed to carry maximum entropy flows, are generally reliable (Ostfeld, 2004). A WDN with higher entropy is expected to cope better with simultaneous multi-pipe failure (Gheisi & Naser, 2014a). Prasad and Tanyimboh (2009) used flow Entropy, a statistical entropy measure for WDNs to show that surrogate reliability measure can be used effectively to improve reliability of multi-source networks. Tanyimboh et al. (2011) used statistical entropy and other surrogate measures such as network resilience, resilience index and modified resilience index, for the reliability assessment of WDN to assess the effectiveness of surrogate reliability measures in relation to more rigorous and accurate hydraulic reliability measures. Shibu and Janga Reddy (2012) presented a methodology based on cross-entropy for optimal design of WDN by considering the uncertainty in nodal demands and applied the methodology on two case studies, two-loop WDN and Hanoi WDN design under uncertain nodal demands, and compared the solutions with deterministic model solutions. Although more than a decade of research has passed, it is still an open question of what a given level of entropy means in terms of reliability for a particular system. Setiadi et al. (2005)

performed a comparative study between entropy and mechanical reliability (operation of the network after pipe failure), concluding that the two have a strong correlation despite having different methods of calculation.

In this thesis, the concept of connectivity has been incorporated, and integrated with the hydraulic performance of a WDN for assessing network reliability.

2.6 Network Reliability Analysis

The evaluation of network reliability is a very broad concept. It has been observed in the examined literature that researchers have applied this concept for various engineering applications; subway networks (Gkountis, 2014; Semaan, 2011), pipeline networks (El Chanati, 2014; Salman, 2011) and bridges (Ghodoosi et al. 2013). They evaluated the network reliability based on series-parallel systems.

2.6.1 Series Parallel Systems

If the success of every component in the system results in the success of the system, then it is said to represent a series connection. The system is said to fail if any one of the components fails. The links in a bicycle chain may be considered components in series (Chandrupatla, 2009). A block diagram of a system with *n* components connected in series is shown in figure 2-8.

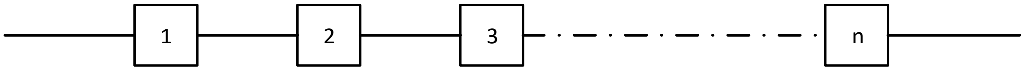


Figure 2-8: Components in Series

The system reliability of components connected in series can be represented by equation 2-10:

$$R_S = R_1 R_2 R_3 \ldots\ldots\ldots . R_n = \prod_{i=1}^{n} R_i \qquad (2\text{-}10)$$

Where:

R_S = System Reliability,

R_i = Component Reliability

If the success of any one of the components in the system results in the success of the system, then it is said to represent a parallel connection. The system fails only if all the components fail, but if at least one component is functioning then the system does not fail. If a twin engine turbojet can land safely with only one engine, this is because the engines are connected in parallel (Chandrupatla, 2009). A block diagram of a system with *n* components connected in parallel is shown in figure 2-9.

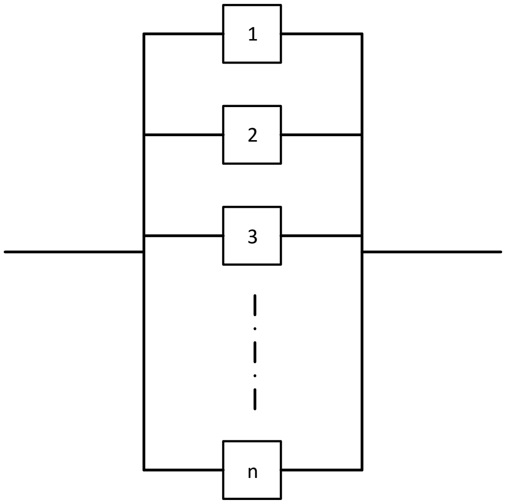


Figure 2-9: Components in Parallel

The system reliability of components connected in parallel can be represented by equation 2-11:

$$R_S = 1 - Q_1 Q_2 Q_3 \ldots\ldots\ldots Q_n = 1 - \prod_{i=1}^{n} Q_i \qquad (2\text{-}11)$$

Where:

Q_i = Probability of failure of a component

In a water distribution network, the components i.e. segments form a combined series parallel system. For example, the network reliability for the system shown in Figure 2-10 can be calculated by the series of equations 2-12 to 2-16:

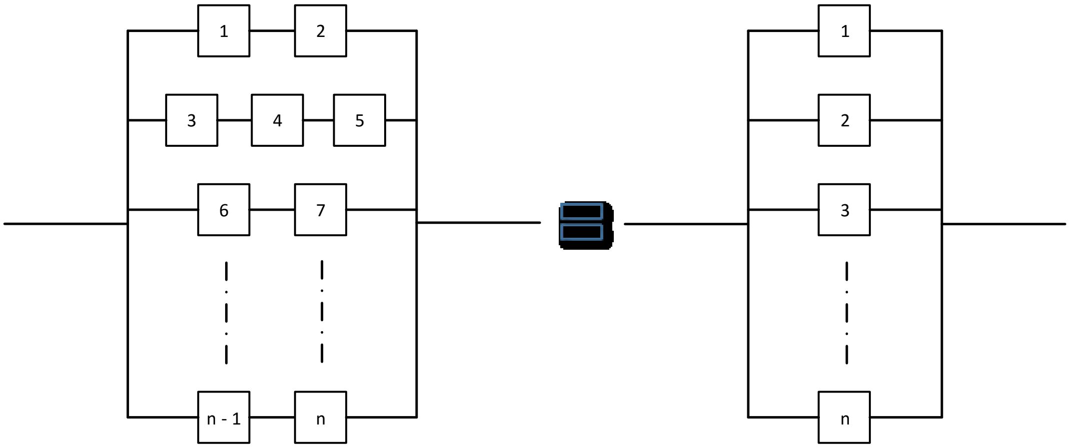


Figure 2-10: Series Parallel Network

$$R_{S1} = R_1 R_2 \qquad (2\text{-}12)$$

$$R_{S2} = R_3 R_4 R_5 \qquad (2\text{-}13)$$

$$R_{S3} = R_6 R_7 \qquad (2\text{-}14)$$

$$R_{S_n} = R_{n-1}R_n \tag{2-15}$$

$$R_N = 1 - Q_{S_1}Q_{S_2}Q_{S_3} \ldots\ldots\ldots Q_{S_n} = 1 - \prod_{i=1}^{n} Q_{S_i} \tag{2-16}$$

Where:

R_N = Network reliability

This method of assessing the network reliability has been employed by many researchers albeit for small sections of network. It is not convenient to be applied on large and complex networks, where there are large number of segments and bridge connections apart from series and parallel systems as shown in figure 2-11. For large and complex networks, Cut Set and Path Set techniques prove to be appropriate (Quimpo, 1996).

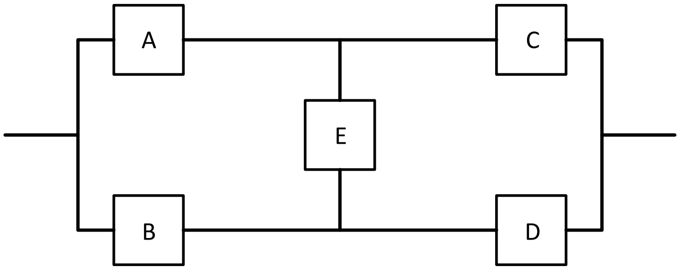


Figure 2-11: Bridge-type Network (Billinton & Allan, 1983)

2.6.2 Minimum Cut Set Analysis

Among the most well-defined processes to determine the topological/ mechanical reliability of a network is the process of minimum cut-set (Yannopoulos & Spiliotis, 2013). Tung (1985) discussed six techniques for WDN reliability evaluation and concluded that the cut-set method is the most efficient technique in evaluating the network reliability. Unlike other generic methods or techniques such as series-parallel systems, which can only be applied for analyzing small networks, minimum cut set approach can be employed to effectively analyze complex and larger networks.

A ‘cut set’ or a ‘minimum cut set’ can be defined as a minimum set of network segments which, when failed, causes failure of the network; but if just one segment of the set has not failed, no failure of network occurs. For instance, in Figure 2-12 the set of segments {a, c, h} is a cut set. There are many other cut sets, such as {a, b, g}, {d, h, f}, {b, c, e, d} and so on. The segment {i} alone is also a cut set because its failure would disconnect the whole network and prevents the flow of water.

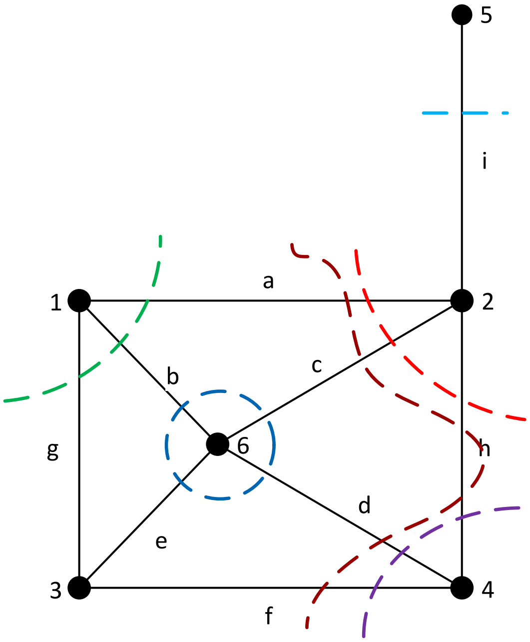


Figure 2-12: Network with Minimum Cut Sets

Note that, if a cut set contains only a single segment, then it is termed as first order cut set; and if a cut set contains two segments, then it is termed as a second order cut set. Thus if a cut set contains n segments, it would be termed as nth order cut set. It should also be noted that, if a set of segments causing failure contains a cut set as a subset, then that set of segments should not be recorded as a cut set. For example, the set of segments {a, c, h, d} causes the failure of network; but it has a cut set {a, c, h} as a subset; therefore {a, c, h, d} is not a cut set. This is because {a, c, h} is the minimum set of network segments to cause the network failure. Hence to emphasize this property, a cut set is referred as a minimum cut set in this thesis.

Billinton and Allan (1983) enumerated the minimum cut sets for the bridge type network shown in figure 2-11, and quantified the network reliability using a set of equations 2-17 to 2-23:

$$\mathrm{Q_N} = \mathrm{P}(\mathrm{C_1} \cup \mathrm{C_2} \cup \mathrm{C_3} \cup \mathrm{C_4}) \tag{2-17}$$

$$= \mathrm{P}(\mathrm{C_1}) + \mathrm{P}(\mathrm{C_2}) + \mathrm{P}(\mathrm{C_3}) + \mathrm{P}(\mathrm{C_4}) \tag{2-18}$$

Where:

$$\mathrm{P}(\mathrm{C_1}) = \mathrm{Q_A Q_B} \tag{2-19}$$

$$\mathrm{P}(\mathrm{C_2}) = \mathrm{Q_C Q_D} \tag{2-20}$$

$$\mathrm{P}(\mathrm{C_3}) = \mathrm{Q_A Q_D Q_E} \tag{2-21}$$

$$\mathrm{P}(\mathrm{C_4}) = \mathrm{Q_B Q_C Q_E} \tag{2-22}$$

$$\mathrm{R_N} = 1 - \mathrm{Q_N} \tag{2-23}$$

Where:

$\mathrm{R_N}$ = Network reliability

Q_N = Probability of failure of network

$P(C_i)$ = Probability of failure of a minimum cut set i

Q_A, Q_B, Q_C, Q_D, Q_E are probability of failure of segments A, B, C, D and E respectively.

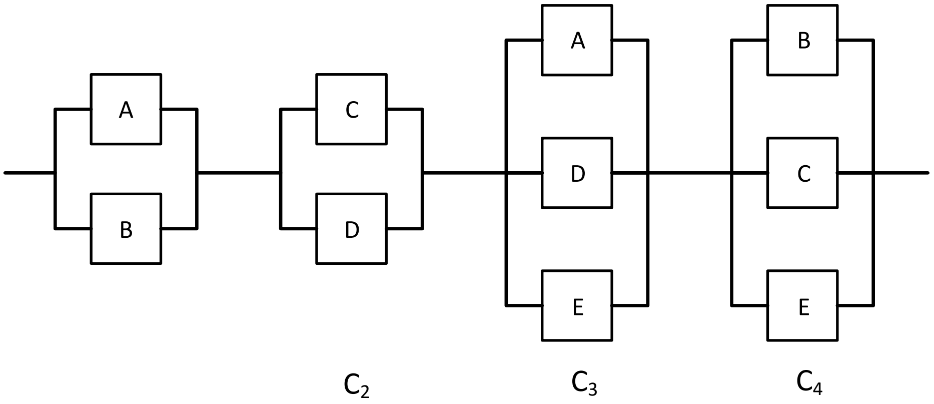


Figure 2-13: Minimum Cut Sets of Figure 2-11

The minimum cut set approach has been adopted by researchers in diverse fields for the study of networks. Zhou et al. (2012) applied this method to compute the reliability of a power distribution network while Alhomidi and Reed (2013) identified minimum cut sets of attack graphs to aid in decision making using genetic algorithm. Yannopoulos and Spiliotis (2013) studied the reliability of WDN and enumerated minimum cut sets using adjacent matrix theory. Shinstine et al. (2002) analyzed four possible measures of reliability and availability of water distribution network using minimum cut set method with steady state simulation.

The minimum cut-set approach is usually used in order to investigate the topology of a water distribution network and the detection of its critical elements, the failure of which will affect the network operation. Thus this approach employs the concept of connectivity, and serves the purpose of evaluating mechanical reliability.

2.6.3 Hydraulic Network Analysis

A WDN is a large scale network with complex topological structure designed to convey volumes of water to consumers at required demands and under adequate pressure. But this course of transporting water to consumers involves much more complex hydraulic analysis. The hydraulic analysis of a WDN is required to be performed for monitoring the safe movement of water as it reaches consumers. Therefore, the primary purpose of this kind of network analysis is to ensure the conveyance of water at satisfactory pressure. And to serve this purpose, mainly two methods of network analysis are found to be extensively used in literature – Demand Driven Analysis (DDA) and Pressure Driven Analysis (PDA).

The DDA approach is a traditional network analysis which has been widely used in the water industry for many years. This method assumes that consumer demands are always satisfied regardless of the pressures throughout the system and formulates the constitutive equations of flow accordingly to solve for the unknown nodal heads (Barun, 2009). The model gives acceptable results when WDNs are subject to normal operating conditions. However, WDNs are subject to component failures or very large demands, which may result in a reduction of the pressure in the system. In consequence, when the pressure drops below the required level, network analysts would have no information on how much water would be delivered by the system under the available pressure regime. In this situation some customers would receive reduced supplies and, in the worst scenario, they might not receive any supply at all. When this happens, demand-driven analysis (DDA) often gives results that indicate that the system is still supplying the full demand at lower, and sometimes, negative pressures (Setiadi et al., 2005).

Pressure Driven Analysis, also known as Head Dependent Analysis (HDA) has long been suggested to surpass demand driven analysis, particularly for networks under abnormal operating conditions. It is well known that outflows from a WDN are dependent upon the pressure within that system and, therefore, the DDA assumption that demands are always satisfied regardless of the pressure in the system is often inappropriate (Barun, 2009). PDA takes into consideration the pressure dependency of nodal outflows, and in consequence, the results are more realistic. Although some researchers (Setiadi et al. 2005; Giustolisi et al. 2008; Pathirana 2011) have considered this issue in the past, computer programs for analyzing large systems with insufficient pressure in a routine manner were not commercially available in the recent past. But now, water industries have taken an initiative to include pressure dependent demand analysis in their hydraulic simulation software. One such example is WaterCad by Bentley. The objective of PDA is to establish the actual supply quantity and pressure at each node in a WDN (Kalungi & Tanyimboh, 2003). A minor reduction in the network reliability which is caused due to consideration of nodal pressures yields noticeable cost savings in the design of WDN (Ghajarnia et al., 2009).

The analysis of flow conditions of this type of networks is customarily described by a set of equations expressing the relationship between three basic determinants, namely the flow, the diameter of the branches and the hydraulic head at each node (Tsakiris & Spiliotis, 2014). Distant computational methods such as Hardy Cross Method, Linear

Theory Method, Newton–Raphson Method and Gradient Algorithm are capable of solving the flow relationships in a WDN (Barun, 2009). And hence these methods are employed for the application of DDA or PDA in analyzing a hydraulic network. Yannopoulos and Spiliotis (2013) used the Newton Raphson Method for analyzing a WDN based on PDA for assessing the hydraulic reliability. Giustolisi and Laucelli (2011) presented a pressure-driven analysis method, using the Enhanced Global Gradient Algorithm. Tsakiris and Spiliotis (2014) categorized the various methods proposed so far for the hydraulic network analysis into 5 generations as displayed in table 2-3.

Table 2-3: Various Methods of Hydraulic Network Analysis

Category	Method
First Generation	Hardy Cross Method
Second Generation	Linear Method, Newton Raphson Method
Third Generation	Gradient Algorithm
Fourth Generation	Enhanced Global Gradient Algorithm
Fifth Generation	First Order Reliability, Fuzzy Sets and Systems

Before the emergence of computers, the hydraulic network analysis were used to be done by means of manual calculation which was very tedious and time consuming. Nowadays modelling software are being used to simulate a hydraulic network and solve the flow equations. Different software like Epanet 2, Mike Net, AquaNet, H2ONet, WaterCAD, KYPipe etc. are available to perform hydraulic network analysis. Figure 2-14 and figure 2-15 illustrates a screen grab of Epanet 2 and WaterCAD respectively. These software implements the algorithm based on computational methods as mentioned earlier. For example, Epanet 2 employs Gradient Algorithm for solving flow equations (Tsakiris and Spiliotis, 2014). For this research, WaterCAD has been used to simulate a WDN and solve flow equations by employing Pressure Dependent Demand Analysis.

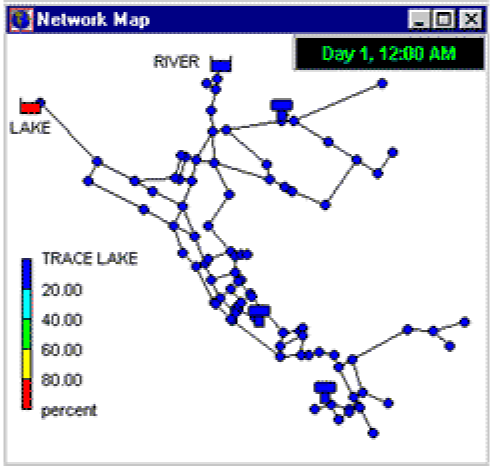
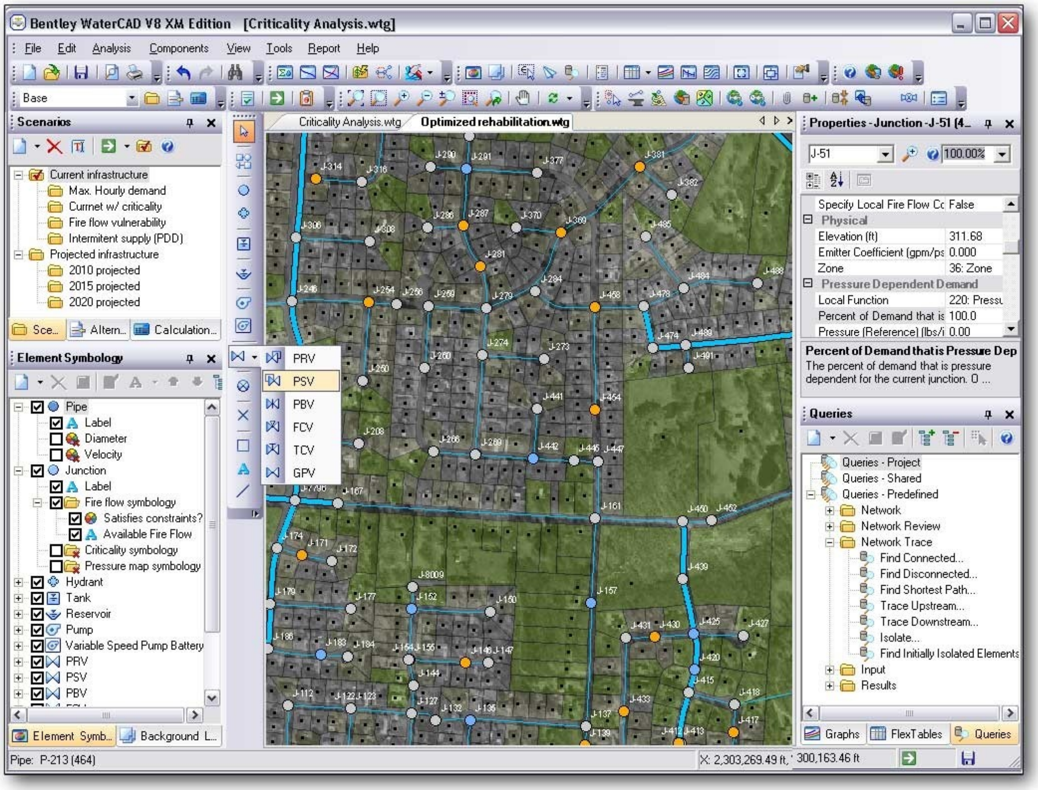


Figure 2-14: Epanet Simulation Example (USEPA website)



Specify Local Fire Flow Cc False
Physical
Elevation (ft) 311.68
Emitter Coefficient (gpm/ps 0.000
Zone 36: Zone
Pressure Dependent Demand
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Percent of Demand that is 100.0
Pressure (Reference) (lbs/i 0.00

Percent of Demand that is Pressure Dep
The percent of demand that is pressure dependent for the current junction. 0 ...

Figure 2-15: WaterCAD Simulation Example

Wagner et al. (1988) proposed the formulation as depicted in equation 2-24, for computing the available demand at a node:

$$Q_{j_{avl}} = \begin{cases} 0 & H_j < H_{j_{min}} \\ Q_{j_{req}} \sqrt{\frac{H_j - H_{j_{min}}}{H_{j_{req}} - H_{j_{min}}}} & H_{j_{min}} \leq H_j \leq H_{j_{req}} \\ Q_{j_{req}} & H_{j_{req}} < H_j \leq H_{j_{max}} \\ 0 & H_j > H_{j_{max}} \end{cases} \tag{2-24}$$

The network reliability for hydraulic analysis can be worked out by the equation 2-25 (Zhuang et al., 2013):

$$R_N = \frac{\sum_{j=1}^{N_{Node}} Q_{j_{avl}}}{\sum_{j=1}^{N_{Node}} Q_{j_{req}}} \tag{2-25}$$

Where:

R_N = Hydraulic Network Reliability

Q_{javl} = Available demand at node j

Q_{jreq} = Required demand at node j

H_j = Actual pressure head at node j

H_{jmin}, H_{jmax} = Minimum and maximum pressure head at node j respectively

H_{jreq} = Required pressure head at node j

2.7 Summary and Limitations

This chapter provided a thorough insight on WDN and its components by attempting to define it and providing extensive literature about their reliability evaluation. Firstly, the different types of failures, causes and consequences for WDNs were discussed. Then, three probability distribution functions, frequently used in literature, were reviewed to estimate the probability of failure for WDNs based on collected historical data from operation and maintenance reports. Two types of reliability assessment models were identified from literature; mechanical reliability and hydraulic reliability. These models were reviewed to reveal the current state of the art for reliability assessment modeling and recognize current research gaps and limitations. The main limitations are the following:

1) A failure of a component can occur due to one or more factors, and it is not easy to know the cause behind a failure. Relation among various factors have not been studied comprehensively.
2) Water utilities usually ignore and do not record the causes which would help them identify the primary type of failure and relation among them.
3) Although there were many attempts to assess reliability of WDNs and identify which pipes control flow inside such networks, these techniques were either applied to small scale networks or assessed mechanical and hydraulic reliability independently. An integrated reliability model would endeavor to accurately assess the network reliability.
4) Although there were few models which attempted to analyze network for hydraulic properties based on pressure, many were found to be relying only on demands

without considering the effect of pressure. And those found to be pressure driven, were analyzed manually rather than analyzing in a simulating environment.

5) Many models were found to be developed and implemented based on assumptions which may not produce desired results.

Considering all the above limitations observed in the literature, there is a need for integrated reliability assessment models for WDNs considering simultaneously their structural and hydraulic properties. To make such integrated approach viable on real applications, the scalability and suitability of any developed models should be tested on large scale WDNs. Also, integrating reliability assessment models within available hydraulic simulation environments (i.e. WaterCad) can facilitate the computational time for integrated reliability assessment of WDNs and decrease chances for inadvertent errors.

CHAPTER 3

Research Methodology

3.1 Introduction

This chapter describes the methodology adapted in the course of model development. The methodology encompasses the modeling aspects of mechanical reliability, hydraulic reliability, and integrated reliability assessment. Figure 3-1 depicts the steps of the proposed approach.

The first model is the mechanical reliability model which deals with analyzing the structural performance of a WDN and its components. The model initiates by assessing the mechanical reliability at component level which consists of accessories (Valves, Hydrants etc.) and individual pipes. These component reliabilities leads to the assessment of segment reliability which is a weighted composition of components. Then minimum cut set analysis is performed to aid in network analysis, finally ending the model with assessing the mechanical reliability of the selected sub-networks.

For analyzing the hydraulic performance of a WDN, a hydraulic reliability model is developed. It involves the hydraulic simulation of a WDN in normal and failure conditions, which aid in obtaining the required as well as actual pressure head at demand nodes. The model is then formulated with pressure conditions to evaluate the available demand at demand nodes which in contrast to the required demand aids in predicting the hydraulic reliability of the selected sub network. An integrated reliability assessment model concludes the research methodology by determining the overall sub network reliability.

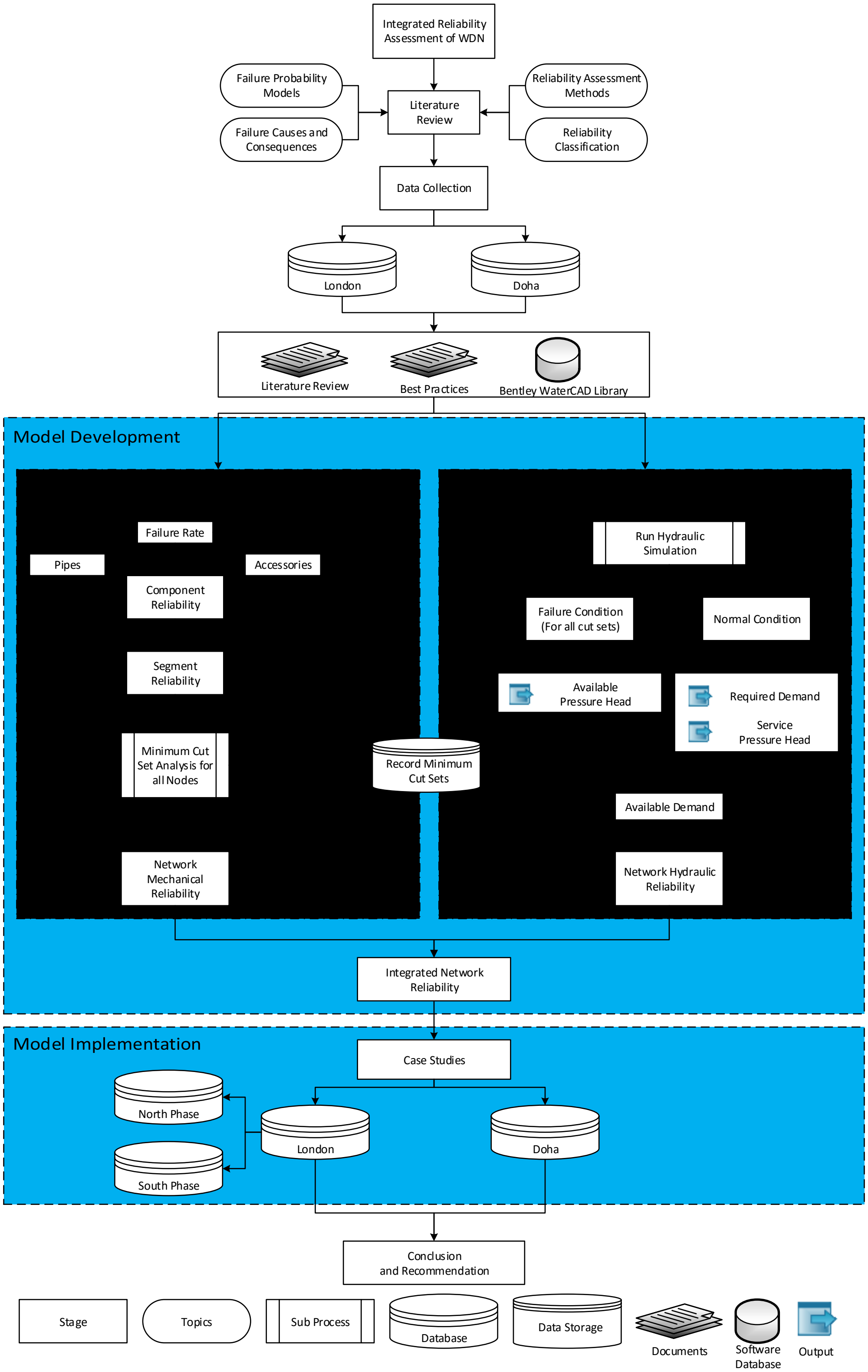


Figure 3-1: Detailed Methodology Flowchart

3.2 Literature Review

An extensive literature review was performed to get acquainted with previous reliability assessment methods, identify their limitations and develop a new model by improving upon those shortcomings. It is thoroughly discussed in chapter 2, the summary of which is presented herein.

In the course of performing the literature review, firstly, the different types of failures, their causes and consequences for WDNs were discussed. Then, three probability distribution functions, frequently used in literature, were reviewed to estimate the probability of failure for WDNs based on collected historical data from operation and maintenance reports. Two types of reliability assessment models were identified from literature; mechanical reliability and hydraulic reliability. These models were reviewed to reveal the current state of the art for reliability assessment modeling and recognize current research gaps and limitations.

3.3 Mechanical Reliability Model

This model commences by evaluating the failure rate of WDN components, followed by the assessment of component and segment reliabilities, and ultimately determines the sub-network mechanical reliability. Figure 3-2 depicts the detailed flowchart of the mechanical reliability model for water networks. The developed model utilizes reliability theory for assessing component and segment reliabilities, whereas minimum cut set approach is pursued for assessing mechanical reliability for the selected sub networks. This section attempts to describe each stage in the development of this model.

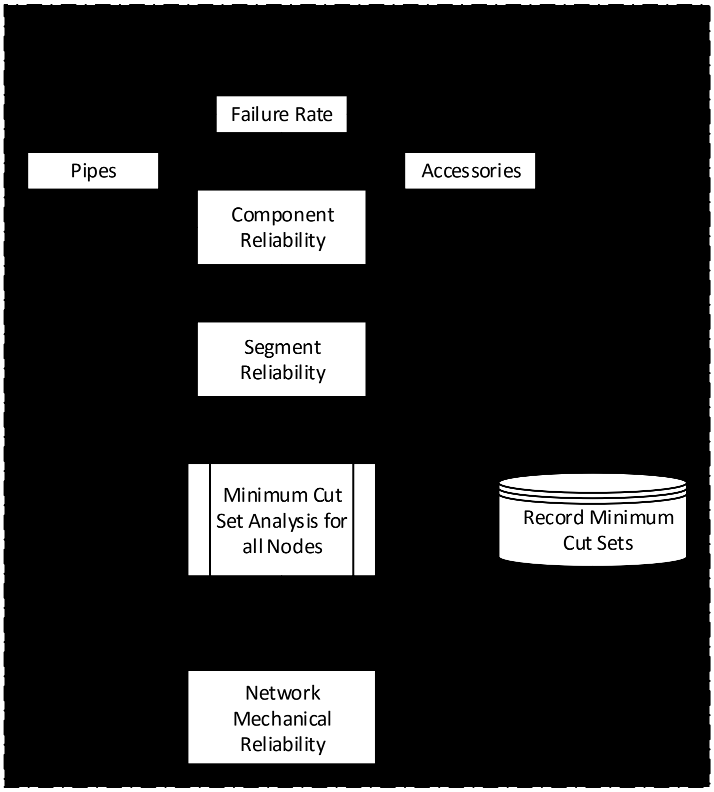


Figure 3-2: Mechanical Reliability Model Flowchart

3.3.1 Network Breakdown

Water distribution networks are very large and complex interconnected networks that consist of an extremely high number of different components. This reality can bring about numerous difficulties when attempting to depict the entire network in a single scheme. In order to compute the mechanical reliability, a better understanding of WDN composition is required. Figure 3-3 illustrates the composition of water distribution networks. The mechanical reliability model breaks the network into zones which are in terms of sub-network based on the source of water supply. Each sub-network is also divided into pipe segments. At this level, each segment consists of a series of pipe sections along with their accessories (i.e. hydrants and valves).

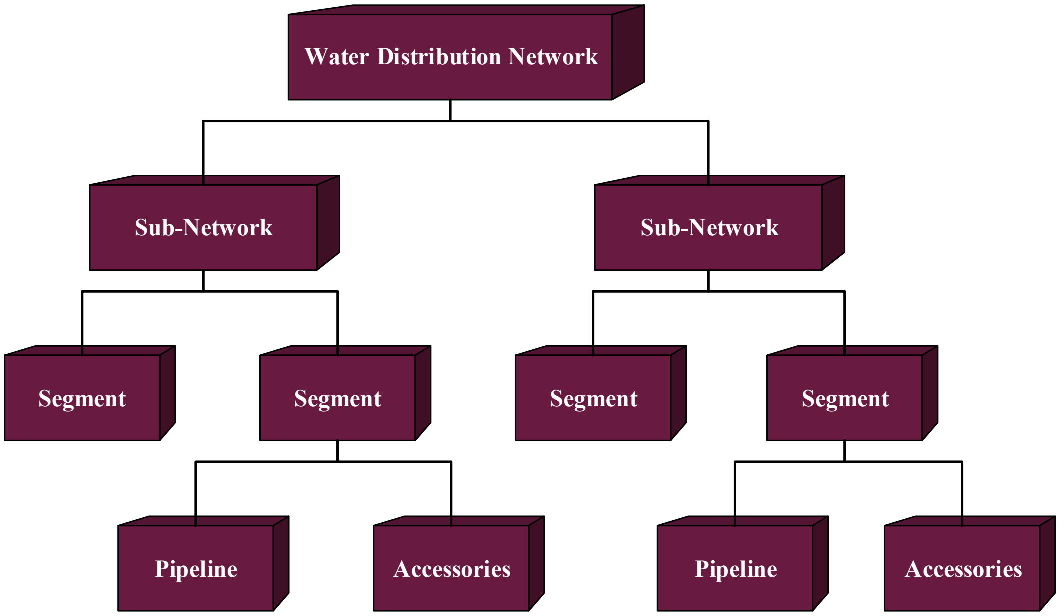


Figure 3-3: Water Distribution Network Composition (El Chanati, 2014)

The process of breaking down a WDN depends on several factors such as population density, zoning type (i.e. residential, commercial, industrial, park, undeveloped, etc.), tax rate, limitation supporting of major infrastructure such as pumps etc. (Salman, 2011). In this thesis, the network is clustered into zones according to their water supply source. The main idea behind this selection emerges from the fact that different sources of water possess different characteristics which may differ in terms of elevation, pumping stations set up and amount of water supplied. These characteristics of a water source may regulate the pressure at demand nodes and hence affecting the functionality of a WDN.

3.3.2 Failure Rate

Many researchers (Shinstine et al., 2002; Salman, 2011; Yannopoulos and Spiliotis, 2013) have chosen failure rate as the primary indicator of reliability. Quantitatively, it is defined as the number of breaks per year per unit length. Breaks are considered one of the significant factors contributing to water losses and require substantial human effort and cost to repair such failures. As the number of breaks increases, the reliability of a WDN decreases. The most often applied formulae for estimating the pipe failure rate have been obtained using simple regression models on the available pipe failure data from a limited time period. In this thesis, the pipe failure rate or breakage rate is computed using a regression model based on age of pipe. According to this model, the failure rate of a pipe can be expressed as given by equation 3-1 (Karimian et al., 2015):

$$\lambda_{\text{pipe}} = 6 \times 10^{-6} X^2 + 0.0004X + 0.0026 \qquad (3\text{-}1)$$

Where:

X is the age of pipe in years

λ_{pipe} is the failure rate of pipe expressed in number of breaks per unit length of pipe.

The failure rate of other components (hydrants, valves, controls) can be expressed as given by equation 3-2:

$$\lambda_{\text{accessory}} = \frac{\mathrm{N_f}}{\text{Length of Segment}} \qquad (3\text{-}2)$$

Where:

N_f is the number of failures

$\lambda_{accessory}$ is the failure rate of component expressed in number of failures per unit length of segment.

3.3.3 Component Reliability

After determining the failure rates of pipes and other components, the reliability of the component can be found. The reliability is assumed to follow negative exponential distribution which would mean that reliability decreases exponentially as the failure rate increases with time. This can be computed using equation 3-3:

$$R_c = e^{-\lambda t} \tag{3-3}$$

Where:

R_c = reliability of a component

λ = failure rate of a pipe or accessory

t = time

3.3.4 Segment Reliability

As discussed earlier in chapter 2, a segment is defined as a water main pipe or a group of connected pipes in series (along with all the associated components) which is located between two nearest intersections. Figure 2-3 portrays a typical segment which has hydrant, valve, and branch pipe attached to it. According to the definition, the segment reliability can be expressed by equation 3-4:

$$R_{Seg} = \sum R_C \tag{3-4}$$

The above equation represents segment reliability where components have the same weight which is not true. Each component has its relative importance in a segment. To be more specific in determining segment reliability, a relative weight component (w_i) is included in equation 3-4 to adjust it.

$$R_{Seg} = \sum_{i=1}^{n} R_{C_i} w_i \tag{3-5}$$

Where:

i = water main component

n = total number of water main components

w_i = relative weight of component

The relative weight of component (w_i) characterize the relative importance of each component in the composition of a segment. Mathematically, it is the ratio of weight of component under consideration to the total weight of components in that particular segment as shown in equation 3-6. The weights of components are obtained from Salman (2011) which will be detailed in chapter 4.

$$\text{Relative Weight}\ (\mathrm{w_i}) = \frac{\text{Weight of component}}{\text{Sum of weights of all components}} \tag{3-6}$$

3.3.5 Network/Sub-Network Reliability

The network has to be analyzed for the study of its configuration prior to assessing the network reliability, because it consists of several segments connected in various ways. The reliability of a small and simple network, where its segments are connected in series and/or parallel can be determined by using equations 2-10 to 2-16. But, if a network is large and complex with several bridge connections as in most cases, its configuration needs to be studied extensively. For this purpose, the network is analyzed using minimum cut set approach as it can be employed to effectively analyze complex and larger networks as discussed in literature.

The procedure for determining the network reliability of a WDN based on the minimum cut-set method is as follows.

1. Probability of failure of segments

Minimum cut set analysis of a network requires the probability of failure of its segments to later formulate the network reliability assessment. Quantitatively, the probability of failure of a segment is the complement of its reliability (Chandrupatla, 2009) and can be determined by equation 3-7 as:

$$Q_{Seg} = 1 - R_{Seg} \tag{3-7}$$

Where:

Q_{seg} = probability of failure of a segment

2. Identification of minimum cut sets

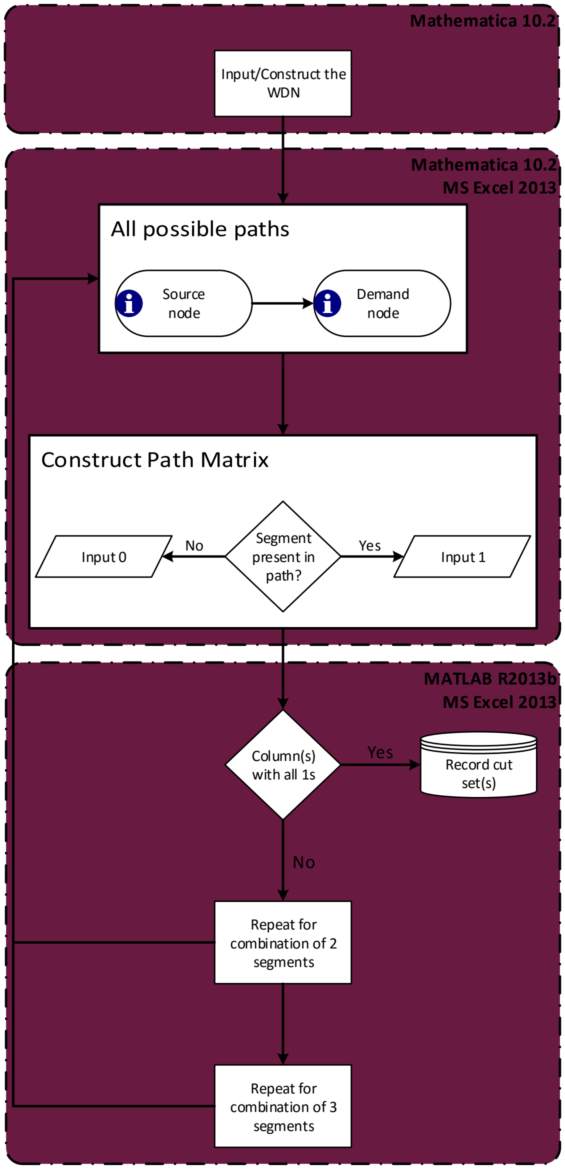


Figure 3-4: Minimum Cut Set Analysis

To identify the minimum cut sets of a network in a reduced computational time, a method generally used in power transmission networks for the same purpose has been adopted (Zhou et al., 2012). It involves 1) finding all possible paths from the source node to the demand node, 2) constructing a path matrix and 3) getting minimum cut sets from the path matrix. While the method for power transmission networks involves finding minimum cut sets for a single demand node, the developed model in this thesis expands upon to include and implement the adopted method to all demand nodes as it is the primary objective of a WDN design to successfully supply water to all demand nodes. Figure 3-4 illustrates the detailed procedure for minimum cut set analysis. Note that the procedure has to be repeated for each and every demand node in the network. To facilitate this tedious process, it has been coded in MATLAB R2013b programming environment along with the utilization of Wolfram Mathematica 10.2 and Microsoft Excel 2013.

The process of minimum cut sets identification commences by inputting the WDN and enumerating all possible paths from a source node to a demand node under consideration (Mathematica 10.2). A path is a connection between a source node and a demand node. This model considers a node to be adequately supplied as long as there is at least one link connecting it to the rest of the network which means that the network is not considered as failed even if there is a single path from the source node to the demand node. After finding all possible paths, a path matrix is constructed in which, number of rows is equivalent to the number of paths from source node to demand node under consideration, and number of columns is equivalent to the number of segments (or combinations of segments) in a network (Mathematica 10.2). This matrix is a zero-one matrix with 1 as its (i, j)th entry if the segment is present in the path to the demand node, and 0 as its (i, j)th entry if it is not. In other words, if the path matrix is $\mathbf{P} = [\mathrm{p_{ij}}]$, then:

$$\begin{aligned} \mathrm{p_{ij}} &= 1 \qquad \text{if segment is part of the path to demand node} \\ &= 0 \qquad \text{if segment is not a part of the path to demand node} \end{aligned}$$

For example, there are 3 segments A, B and C in a network and the possible paths from the source node to the demand node are AB and AC. Then the path matrix is expressed as

Table 3-1: Path Matrix Example

	A	B	C
AB	1	1	0
AC	1	0	1

Once the path matrix is constructed for the demand node under consideration, the network is analyzed for minimum cut sets. First order cut set is a single segment which when fails, causes the failure of entire network. Similarly, second order cut set is the combination of two segments, the combined failure of which causes the failure of entire network. If any column in a path matrix contains all elements as 1, then the segment corresponding to that column is recorded as a first order cut set. For example, all the elements of the first column in the matrix table 3-1 are 1. Hence segment {A} is recorded as a first order cut set. To find the second order cut sets, create all combinations of 2 segments and construct a new path matrix by merging the elements as per the combinations. For example, combination of 2 segments for the above example network are {A, B}, {B, C} and {C, A}. New path matrix would be

Table 3-2: Modified Path Matrix Example

	A + B	B + C	C + A
AB	1	1	1
AC	1	1	1

From the matrix table 3-2, combination of B and C results in a column with all elements as 1. Hence {B, C} is recorded as second order cut set. Note that, any combination with A is neglected here because A is already a minimum cut set (as discussed in chapter 2). The same procedure is followed for finding third and higher order cut sets with combinations of corresponding segments. All the identified cut sets are recorded in Excel spreadsheets for further calculations.

3. Mechanical reliability of WDN based on Minimum Cut Set

According to Shinstine et al. (2002), for n components (segments) in the ith minimum cut set of a WDN, the failure probability of the jth component (segment) is Qj, which can be obtained by equation 3-7. The failure probability of the ith minimum cut set is

$$Q(MC_i) = \prod_{j=1}^{n} Q_j \quad (3\text{-}8)$$

Where n is the number of segments in corresponding minimum cut set.

Assuming that the occurrence of the failure of the components within a minimum cut set are statistically independent. For example, if a water distribution network has four minimum cut sets, MC_1, MC_2, MC_3, and MC_4, for the network reliability, the failure probability of the network Q_N, is then defined as follows (Billinton and Allan 1983):

$$Q_N = Q(MC_1 \cup MC_2 \cup MC_3 \cup MC_4) \quad (3\text{-}9)$$

By applying the principle of inclusion and exclusion, equation 3-9 can be reduced to:

$$Q_N = Q(MC_1) + Q(MC_2) + Q(MC_3) + Q(MC_4) \quad (3\text{-}10)$$

$$Q_N = \sum_{i=1}^{M} Q(MC_i) \quad (3\text{-}11)$$

Where M is the number of minimum cut-sets in the network.

Finally, the mechanical reliability of the network can be obtained by equation 3-12 as:

$$R_{NM} = 1 - Q_N = 1 - \sum_{i=1}^{M} Q(MC_i) \quad (3\text{-}12)$$

Where: R_{NM} = Mechanical reliability of network/sub-network

Q_N = Failure probability of network/sub-network

3.4 Hydraulic Reliability Model

This model deals with analyzing the hydraulic performance of a WDN in the form of hydraulic reliability. It commences with importing the shape files of the selected sub network along with its attributes to Bentley WaterCAD (ArcMap 10.3.1; WaterCAD V8i) for the hydraulic simulation of a WDN in normal and failure conditions. The simulation results from both conditions respectively aid in obtaining the required as well as actual pressure head at demand nodes. The model is then formulated with pressure conditions in spreadsheets to evaluate the available demand at demand nodes which is then compared to the required demand for assessing the hydraulic reliability of the selected sub network. Figure 3-5 illustrates the detailed flowchart of the hydraulic reliability model for water networks.

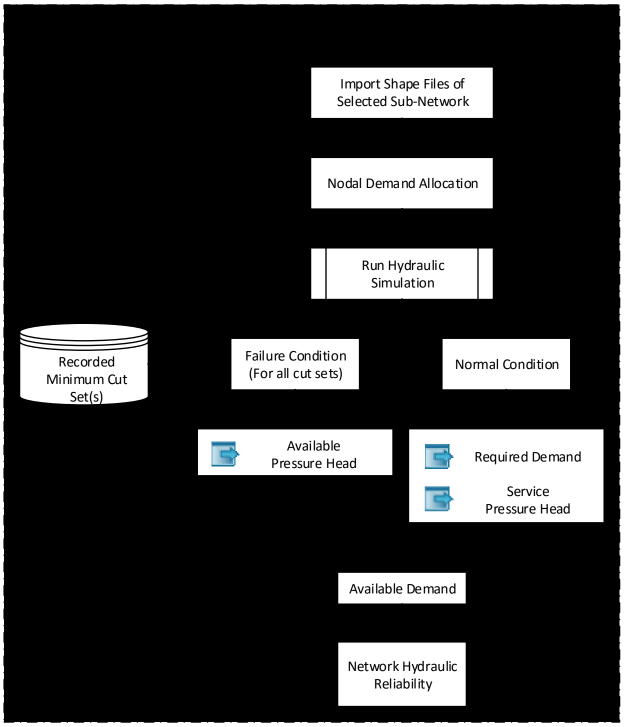


Figure 3-5: Hydraulic Reliability Model

3.4.1 Import Shape File of Network/Sub-Network

The shape files of entire water distribution network are accessible through geodatabases of cities under consideration. Each water asset, feature class, is designed to have its physical and functional attributes stored in a separate table. The table is located inside the ArcGIS geodatabase and it is called feature attribute table. Any feature class can have only one geographic location and therefore each feature attribute table is connected to one geographic table (Youssef, 2015). Figure 3-6 shows the geodatabase configuration design. Note that the figure 3-6 depicts the required attributes for a feature class in this model. A geodatabase for a city may contain more or less attributes in actual.

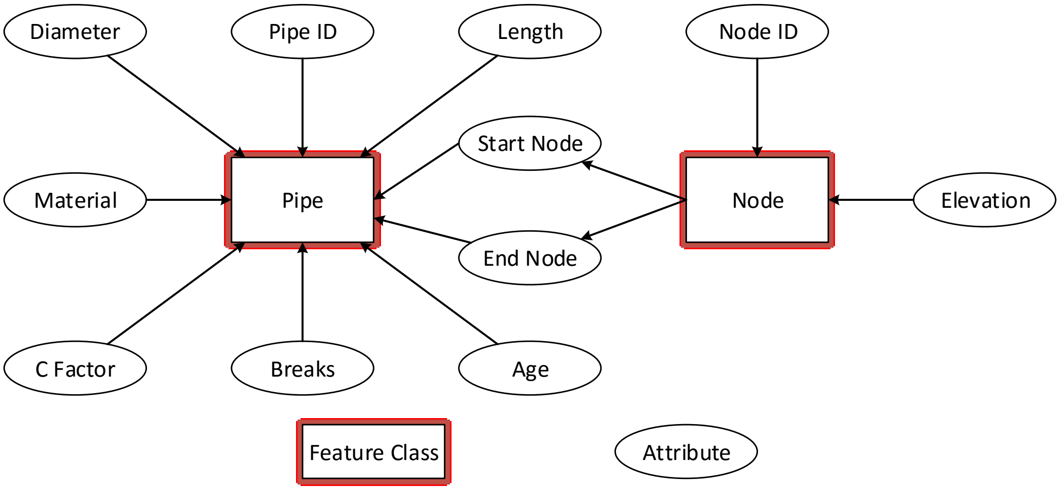
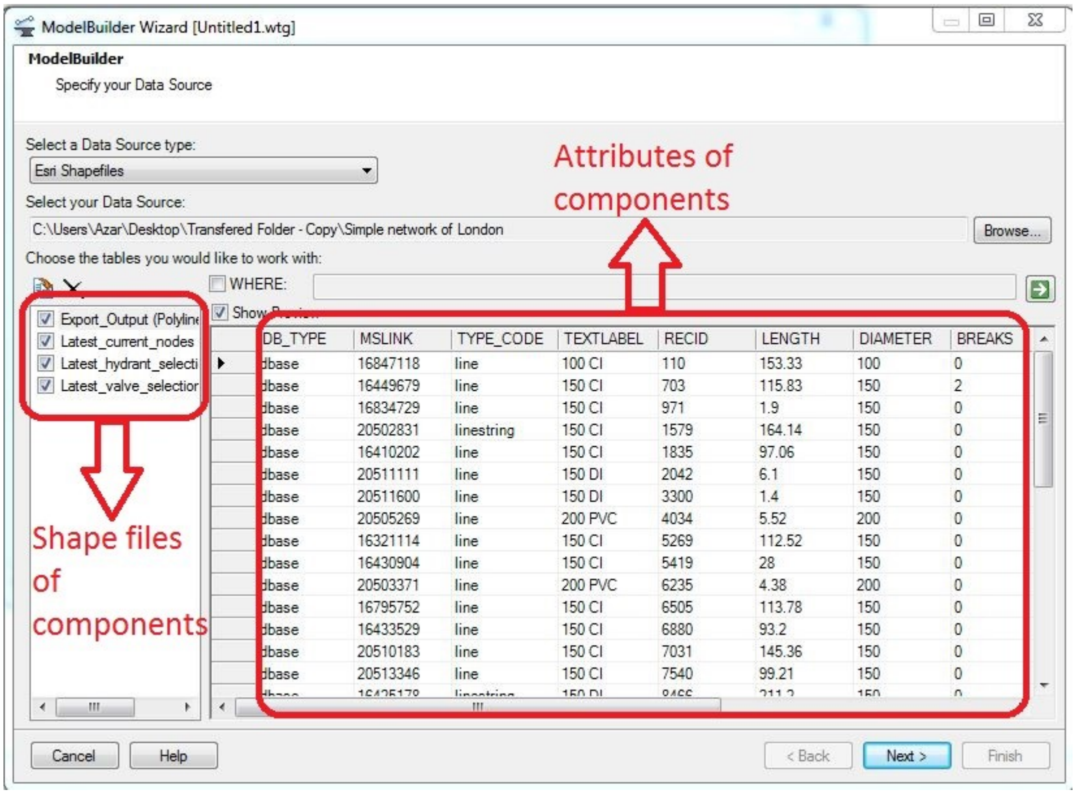


Figure 3-6: Geodatabase Configuration

WaterCAD V8i simulation engine contains a distinctive tool named ModelBuilder. Using ModelBuilder, a hydraulic model of the selected sub-network is created by importing the shape files of required feature classes/assets/components to WaterCAD V8i simulation engine. The created hydraulic model inherits the attributes of all components from the imported shape files, thus curtailing the tedious task of inputting them manually. This is significant in a way as it allows to simulate and analyze as much larger and complex networks. Figure 3-7 displays a screen grab of ModelBuilder tool.



Select a Data Source type: Esri Shapefiles

Select your Data Source: C:\Users\Azar\Desktop\Transfered Folder - Copy\Simple network of London

Choose the tables you would like to work with:

☑ Export_Output (Polyline
☑ Latest_current_nodes
☑ Latest_hydrant_selecti
☑ Latest_valve_selectior

☐ WHERE:

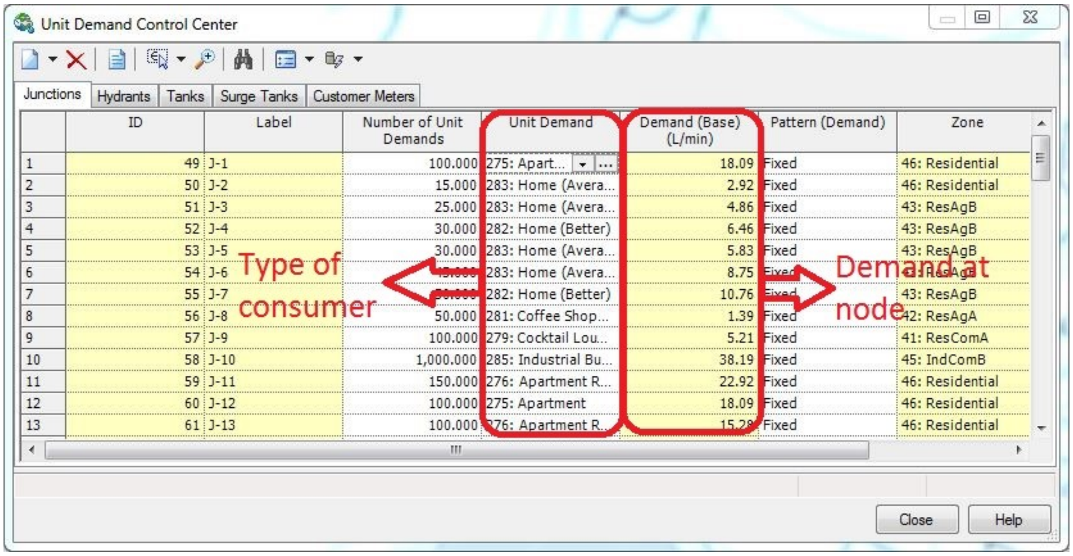
☑ Show

DB_TYPE	MSLINK	TYPE_CODE	TEXTLABEL	RECID	LENGTH	DIAMETER	BREAKS
dbase	16847118	line	100 CI	110	153.33	100	0
dbase	16449679	line	150 CI	703	115.83	150	2
dbase	16834729	line	150 CI	971	1.9	150	0
dbase	20502831	linestring	150 CI	1579	164.14	150	0
dbase	16410202	line	150 CI	1835	97.06	150	0
dbase	20511111	line	150 DI	2042	6.1	150	0
dbase	20511600	line	150 DI	3300	1.4	150	0
dbase	20505269	line	200 PVC	4034	5.52	200	0
dbase	16321114	line	150 CI	5269	112.52	150	0
dbase	16430904	line	150 CI	5419	28	150	0
dbase	20503371	line	200 PVC	6235	4.38	200	0
dbase	16795752	line	150 CI	6505	113.78	150	0
dbase	16433529	line	150 CI	6880	93.2	150	0
dbase	20510183	line	150 CI	7031	145.36	150	0
dbase	20513346	line	150 CI	7540	99.21	150	0

Figure 3-7: Screen Grab of ModelBuilder

3.4.2 Nodal Demand Allocation

The hydraulic performance of a WDN is analyzed based on its ability to meet the demands placed on it. The data availability of nodal demands will make the simulation more accurate and realistic in analyzing the hydraulic reliability. However, this data is not easily available and the absence of such crucial information would limit the ability for testing the developed hydraulic component of the reliability assessment model. Therefore in a case of data unavailability of nodal demands, the hydraulic reliability model utilizes the unit demand control center tool which draws the demand data from engineering library developed by Bentley. This library contains industry used protocols for assuming demands based on the type of supplied consumers (home, café, restaurant, school, hospital…etc.). In an attempt to improve the accuracy of demand allocation, Google Earth Pro is used to view the geospatial position of the sub-network and determine the number and types of consumers at each node. Figure 3-8 displays the partial screen grab of unit demand control center tool. These allocated demands are thus the required customer demands to be met at nodes.



	ID	Label	Number of Unit Demands	Unit Demand	Demand (Base) (L/min)	Pattern (Demand)	Zone
1	49	J-1	100.000	275: Apart...	18.09	Fixed	46: Residential
2	50	J-2	15.000	283: Home (Avera...	2.92	Fixed	46: Residential
3	51	J-3	25.000	283: Home (Avera...	4.86	Fixed	43: ResAgB
4	52	J-4	30.000	282: Home (Better)	6.46	Fixed	43: ResAgB
5	53	J-5	30.000	283: Home (Avera...	5.83	Fixed	43: ResAgB
6	54	J-6	[illegible]	283: Home (Avera...	8.75	Fixed	43: ResAgB
7	55	J-7	[illegible]	282: Home (Better)	10.76	Fixed	43: ResAgB
8	56	J-8	50.000	281: Coffee Shop...	1.39	Fixed	42: ResAgA
9	57	J-9	100.000	279: Cocktail Lou...	5.21	Fixed	41: ResComA
10	58	J-10	1,000.000	285: Industrial Bu...	38.19	Fixed	45: IndComB
11	59	J-11	150.000	276: Apartment R...	22.92	Fixed	46: Residential
12	60	J-12	100.000	275: Apartment	18.09	Fixed	46: Residential
13	61	J-13	100.000	276: Apartment R...	15.28	Fixed	46: Residential

Figure 3-8: Screen Grab of Unit Demand Control Center

3.4.3 Hydraulic Simulation

Once the demand allocation is completed, the hydraulic model of the WDN is configured for simulation. The accuracy of simulation results depends on how well the model is equipped. Utmost care should be taken to verify the imported data, as sometimes the shape files contain incomplete data for some parts.

In order to meet the customers' daily needs, each component of the WDN must be able to provide required water demand and pressure head under both normal and failure conditions. Therefore, the developed research framework requires the hydraulic model to be simulated in normal as well as failure condition to assess the overall hydraulic performance of the network.

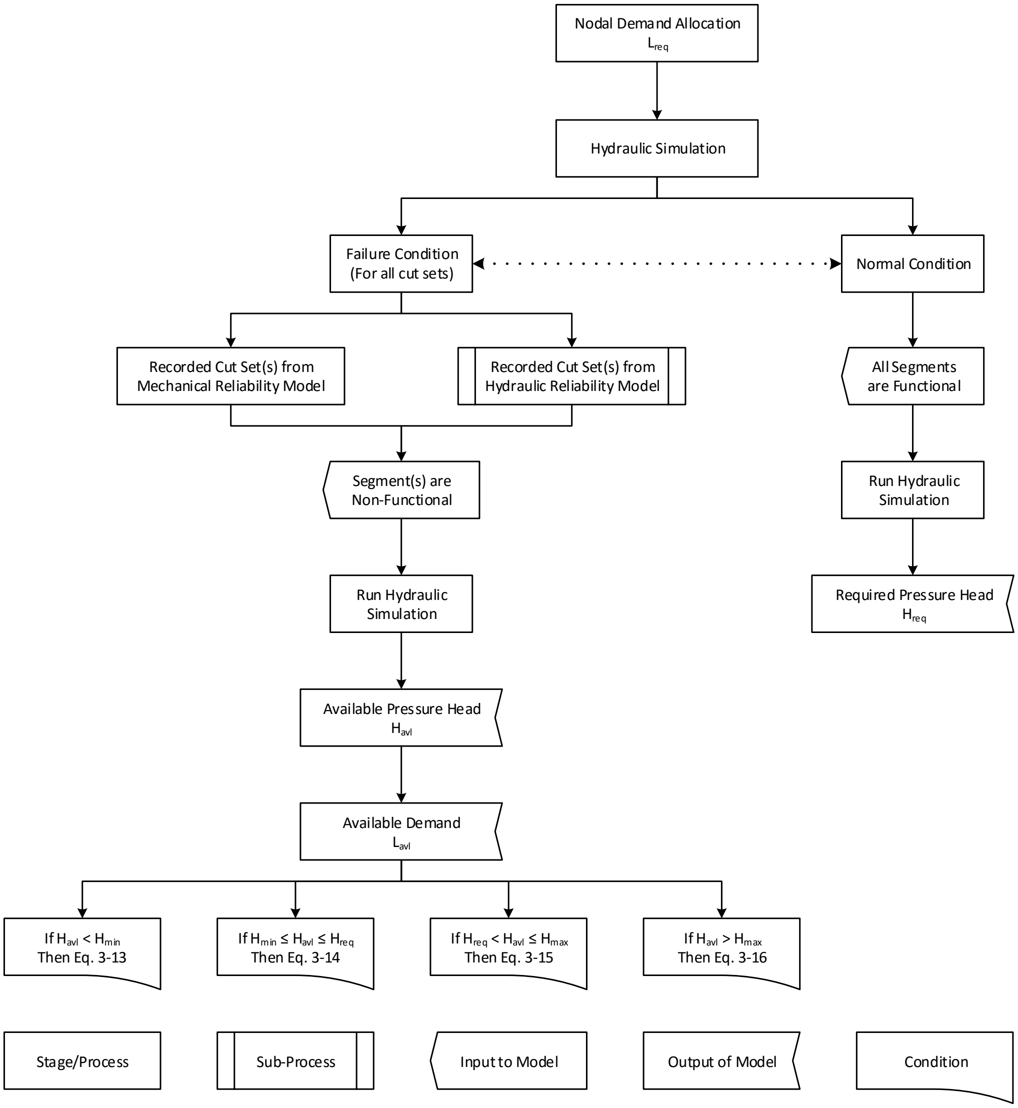


Figure 3-9: Hydraulic Simulation Detailed Flowchart

The hydraulic model of a WDN is said to in normal condition when all the segments are functional and satisfy the nodal demands at required pressure. In the course of preparing the hydraulic model for simulation in normal condition, initial setting of segments are configured to remain in 'open' status to allow the flow of water through them. The required demands have already been allocated by now using the unit demand control center as mentioned in section 3.4.2. The hydraulic model is now set to be run for simulation as it has been constructed to meet the conditions of functional segments as well as required demands (allocated) at nodes. Finally, the constructed hydraulic model is simulated and the required pressure head at nodes to meet the customers' demands are obtained as shown in figure 3-9. These nodal pressure heads are recorded as service pressure heads (H_{req}) which need to be satisfied for supplying water at required demands.

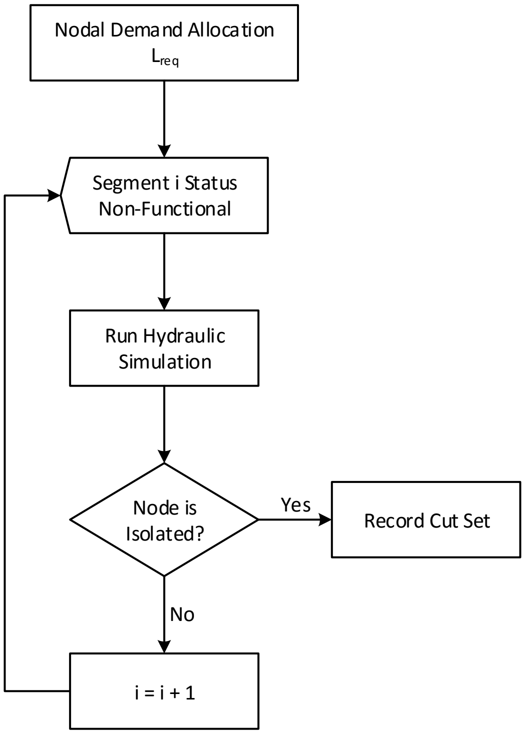


Figure 3-10: Hydraulic Reliability Model Cut Set(s) Analysis Flowchart

If at-least one of the segments is non-functional and halts the flow of water through it, then the hydraulic model of a WDN is said to be in failure condition. Note that, this does not imply the failure of a WDN as there may be other segments through which the water can propagate to reach the nodes. However, this unavailability of a segment may lead to reduced level of water supply at nodes, partially fulfilling the customers' demands. The hydraulic model is constructed for failure condition by configuring the initial setting of segments to 'closed' status. As illustrated in figure 3-10, the simulations are run by considering the failure of each individual segment to scrutinize the hydraulic performance of WDN in each failure condition and this makes the task tedious. However, WaterCAD V8i allows to create a scenario for each failure condition and batch run the simulation of all scenarios at once reducing the task tediousness. The hydraulic model is also simulated for failure condition by considering the closure of minimum cut sets identified in mechanical reliability model because these segment(s) causes the isolation/disconnection of a node. The simulations of the hydraulic model in failure conditions results in the available pressure head (H_{avl}) at nodes as depicted in figure 3-9.

The developed hydraulic reliability model is then formulated with pressure conditions which aid in achieving the actual/available demand at nodes by comparing the simulation results with that of service pressure head (H_{req}), minimum pressure head (H_{min}) and maximum pressure head (H_{max}). The designed minimum and maximum pressure heads for a WDN will be detailed in chapter 4. As illustrated in figure 3-9, the evaluation of available demand at nodes is based on the formulation of pressure conditions proposed by Wagner et al. (1988) and modified by Shuang et al. (2012) and can be summarized in equations 3-13 to 3-16 as follows:

$$L_{avl} = 0 \qquad H_{avl} < H_{min} \tag{3-13}$$

$$L_{avl} = L_{req}\sqrt{\frac{H_{avl}-H_{min}}{H_{req}-H_{min}}} \qquad H_{min} \leq H_{avl} \leq H_{req} \tag{3-14}$$

$$L_{avl} = L_{req} \qquad H_{req} < H_{avl} \leq H_{max} \tag{3-15}$$

$$L_{avl} = 0 \qquad H_{avl} > H_{max} \tag{3-16}$$

Where:

H_{req} = Required pressure head at a node (m)

H_{avl} = Available pressure head at a node (m)

H_{min} & H_{max} = Minimum and maximum pressure head at a node respectively (m)

Lreq = Required demand at a node (m^3/day)

Lavl = Available demand at a node (m^3/day)

The developed hydraulic reliability model is flexible in that it allows to accommodate the data about as many types of components that are available. For instance, if the data about valves, pumps, tanks etc. is available, then these components can be easily included in the model for hydraulic simulation. As mentioned earlier in this section, the quality and amount of data improves the accuracy of simulation results.

3.4.4 Network Hydraulic Reliability

The final step in the development of hydraulic reliability model is the reliability assessment of selected network/sub-network. For this purpose, the definition of reliability as suggested by Zhuang et al. (2013) has been adopted. Mathematically, the hydraulic reliability of a WDN can be expressed as the ratio of the available demand to the require demand and can be worked out by the equation 3-17 as:

$$R_{H(x)} = \frac{\sum_{j=1}^{N_{Node}} L_{j_{avl}}}{\sum_{j=1}^{N_{Node}} L_{j_{req}}} \tag{3-17}$$

Where:

$R_{H(x)}$ = Hydraulic reliability of a network/sub-network in failure condition x

L_{jreq} = Required demand at node j

L_{javl} = Available demand at node j

Equation 3-17 aids in evaluating the hydraulic reliability of a WDN in failure condition ‘x’. The actual hydraulic reliability of a WDN can be assessed by equation 3-18 as the average of hydraulic reliability in all failure conditions.

$$R_{NH} = \frac{\sum R_{H(x)}}{\text{Number of Minimum Cut Sets}} \tag{3-18}$$

Where:

R_{NH} = Hydraulic reliability of a network/sub-network

3.5 Integrated Network Reliability

The need for integrated reliability assessment was identified from the literature. It is evaluated based on the list of causes of failures as proposed in NRC (2006) best practice guide for assessing and reducing risks in drinking water distribution systems. It lists the most possible causes of failures accordingly categorizing them into mechanical and hydraulic types as will be elaborated in chapter 4. The integrated reliability of the selected network/sub-network is assessed by the equation 3-18 as follows:

$$R_N = \frac{\text{No.of structural failures} \times R_{NM} + \text{No.of hydraulic failures} \times R_{NH}}{\text{Total number of failures}} \qquad (3\text{-}19)$$

Where:

R_N = Integrated mechanical and hydraulic network reliability

R_{NM} = Mechanical reliability of the network

R_{NH} = Hydraulic reliability of the network

The information about the condition of a WDN component is found from the operation and maintenance reports of the WDN. These reports contains the detailed information about the cause of a failure as recorded by the water utility.

3.6 Summary

In this chapter, two models of reliability were described which are later integrated for assessing the overall reliability of a WDN. The first model was the mechanical reliability model which deals with analyzing the structural performance of a WDN at the component, segment and network levels. This model utilizes reliability theory for assessing component and segment reliabilities, whereas minimum cut set approach is pursued for assessing mechanical reliability for the selected sub networks. To facilitate this tedious process, it has been coded in MATLAB R2013b programming environment along with the utilization of Wolfram Mathematica 10.2 and Microsoft Excel 2013. The second model analyzes the hydraulic performance of a WDN in terms of hydraulic reliability. It commences by importing the shape files of selected sub-network to WaterCAD V8i simulation engine. The imported hydraulic model is then equipped with required demands and any other available data about valves, hydrants, pumps etc. for the hydraulic simulation of a WDN in normal and failure conditions. The simulation results aid in obtaining the required as well as actual pressure head at demand nodes. The model is then formulated with pressure conditions to evaluate the available demand at demand nodes which in contrast to the required demand aids in predicting the hydraulic reliability of the selected sub network. An integrated reliability assessment model was presented to conclude the research methodology by determining the overall sub network reliability.

CHAPTER 4

Data Collection

4.1 Introduction

In this chapter, the process of data collection is discussed. Data is collected from four sources: (a) Literature, (b) Database (ArcGIS) for the city of London and Doha, (c) Best practice guides, and (d) Bentley WaterCAD library. All these four sources contribute towards the structure and development of the research framework.

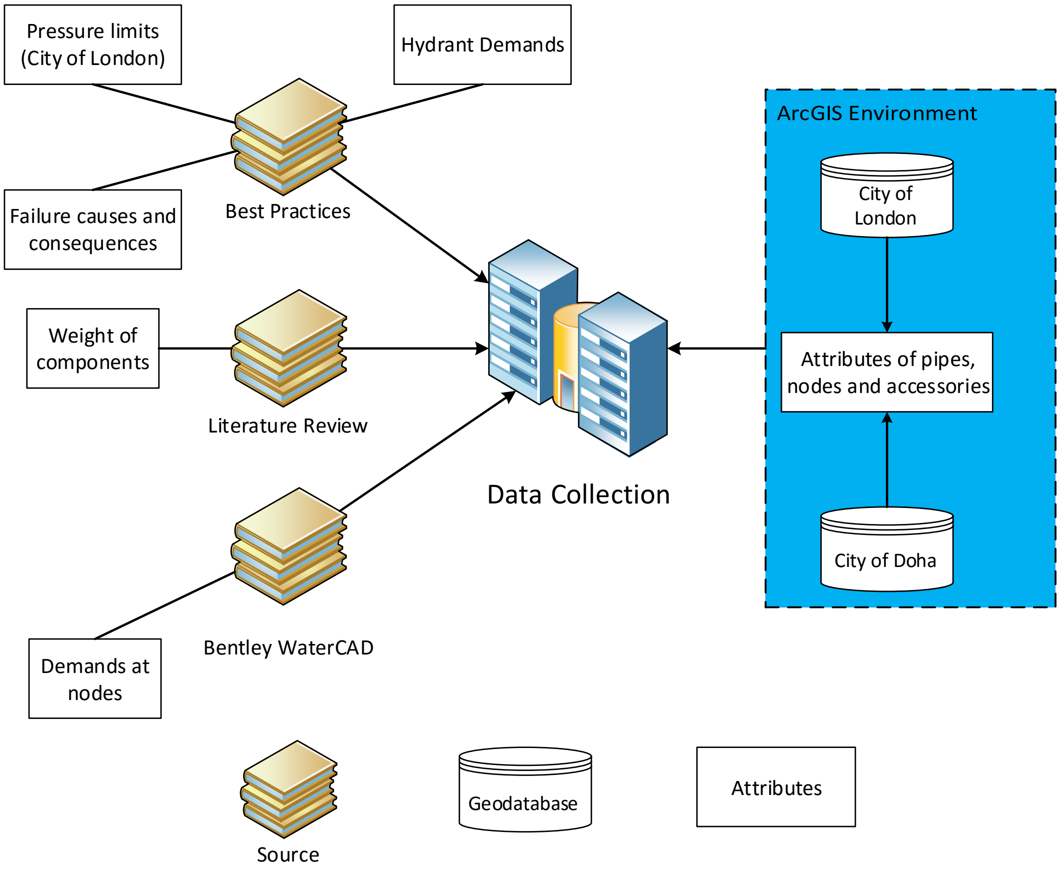


Figure 4-1: Data Collection Sources

In the next sections, each source of data is discussed in detail to explain their contribution in structuring the research framework. Mutual observations among the two analyzed datasets will also be covered as well.

4.2 Literature Review

Salman (2011) attended meetings with the asset management team for the City of Hamilton and two consultant expert teams working in municipal infrastructure as part of his research. They proposed the following weighting structure shown in Table 4-1 for WDN components to reflect their relative importance in the overall constitution of assessing reliability for a water segment. The additive weighted sum of reliability scores for the components shown in Table 4-1 represents the reliability score for each segment. This improves the accuracy in the evaluation of reliability and thus facilitates the maintenance, repair, rehabilitation planning and budget allocation processes. The same weighting structure will be adapted to the developed model as elaborated in Chapter 3.

Table 4-1: Component Weights (Salman, 2011)

Segment	Water main component	Weight (%)
Hypothetical	Pipe	38
	Hydrant	31
	Isolation Valve	28
	Control Valve	3
Total		100

4.3 City of London

According to the 2013 infrastructure report (SOI) for the City of London, the WDN is divided into two regional water systems; 1) Elgin Area Primary Water Supply System and 2) Lake Huron Primary Water Supply System.

The Lake Huron Primary Water Supply System draws raw water from Lake Huron and manages a water treatment plant located north of the village of Grand Bend in South Huron. The plant has a current rated treatment capacity of 340 Million liters per day (75 Million Imperial gallons per day) and serves a population of approximately 350,000 people.

The Elgin Area Primary Water Supply System draws raw water from Lake Erie and manages a water treatment plant located east of the village of Port Stanley in Central Elgin. The plant has a current rated treatment capacity of 91 Million liters per day (20 Million Imperial gallons per day) and serves a population of approximately 112,000 people.

The City of London supplied 44,944,353,000 liters of water and served the estimated population of about 370,000 in the year 2014 (SOI, 2014). The city covers a land area of 420.5 square kilometers and owns a water network of about 1565 km with total replacement value of $2.6 billion (SOI, 2013).

Two sub-networks are selected, one supplied by Lake Huron and the other supplied by Elgin Area (Lake Erie). These sub-networks are categorized into North Phase (Lake Huron) and South Phase (Lake Erie). These sub-networks are utilized to test and demonstrate the capabilities of the developed models in performing reliability assessment.

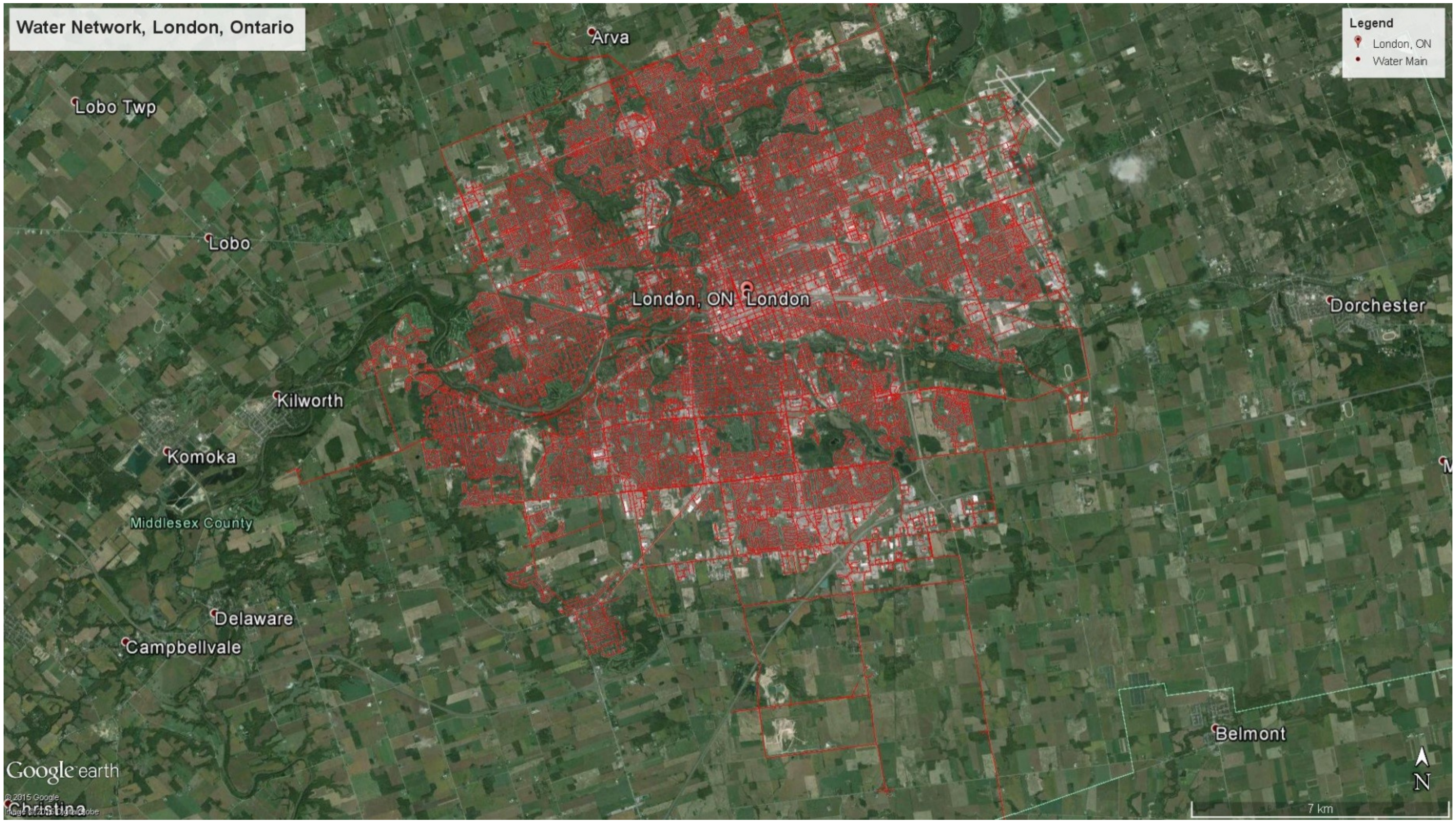


Figure 4-2: Water Network, London, Ontario

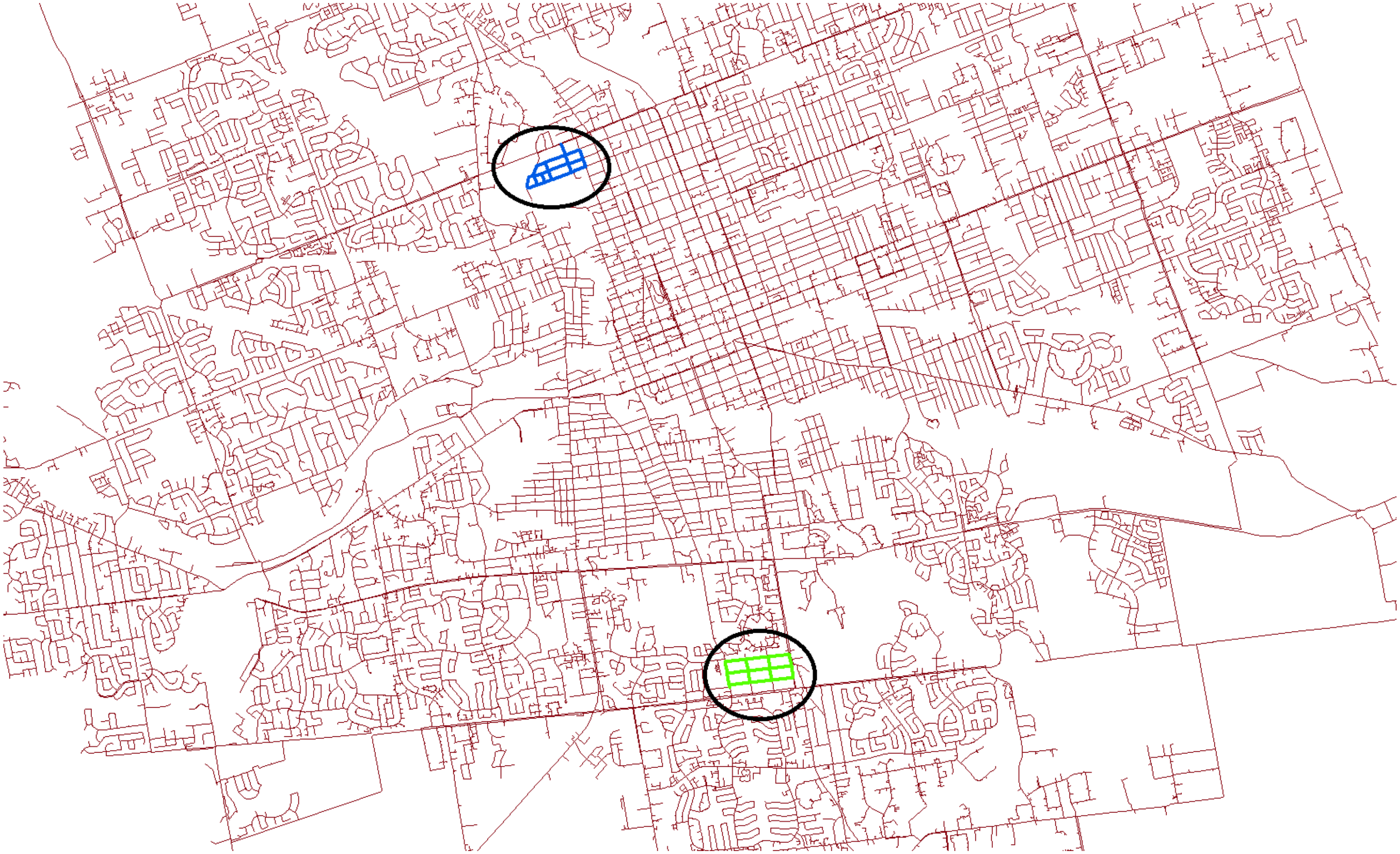


Figure 4-3: Selected Sub-Networks - City of London

The total number of pipe segments in the network are 23,855 which are clustered according to their size and material type as shown in Table 4-2. Around 93% of the total number of pipes have a diameter less than 300mm; while large diameter pipes (900mm+) constitute a small fraction of the city network (0.43%). This explains that the need for large diameter pipes is only for transmission of water from the source to the distribution pipes. Also, ductile and cast iron pipes represents 60% of the total number of the pipes followed by PVC which constitutes 28% of the total water network. Cast iron pipes occupied around 93.3% of failure records in City of London data.

Table 4-2: Percentage Composition of Pipe Attributes

Attribute	Value	Percentage
Pipe Diameter	< 300mm	93.71
	300mm – 600mm	5.18
	600 mm – 900mm	0.68
	> 900mm	0.43
Pipe Material	Cast Iron	42.04
	Ductile Iron	17.79
	PVC	27.50
	CPP	9.09
	Steel	0.56
	Galvanized	0.04
	Others	2.98

Table 4-3: Attributes from Database of London

Attribute	Minimum	Maximum
Age (Years)	28	137
Length (m)	0.6	1931
Pipe Diameter (mm)	20	1350
C Factor	25	150
Node Elevation	147.6	367.48

The condition of pipes and accessories such as valves, chambers, hydrants was measured on a 5 class scale as shown in Figure 4-4.

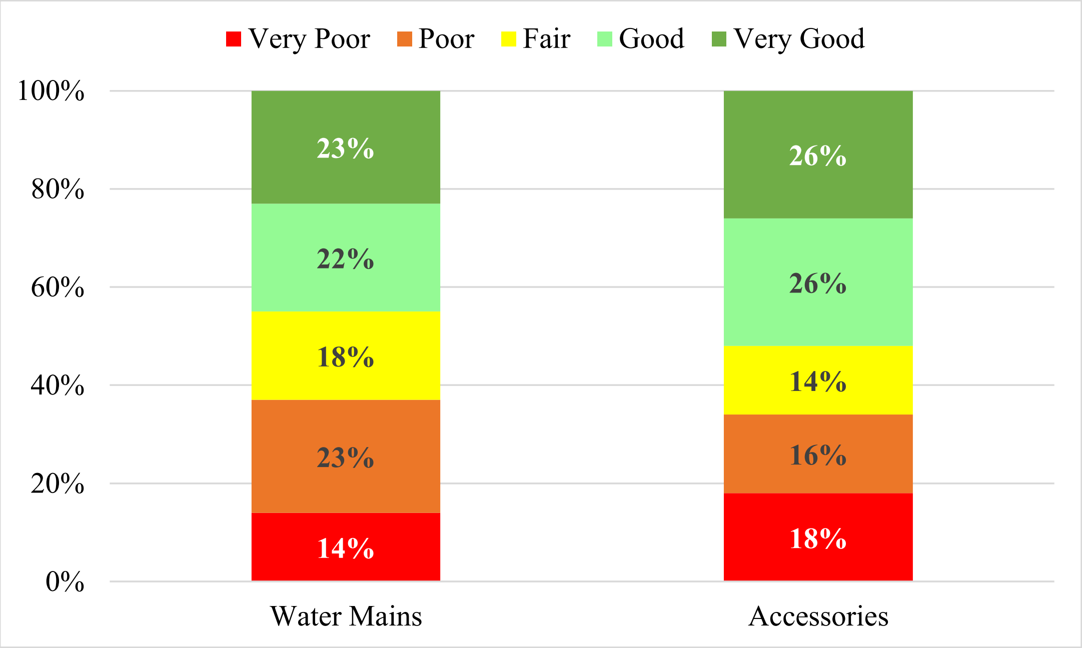


Figure 4-4: Asset Condition (State of Infrastructure Report, 2013)

4.4 City of Doha

According to the Qatar Environment & Energy Research Institute (QEERI), Qatar is one of the largest per capita water consumers in the world, with consumption levels quadruple that of the average European consumer. QEERI forecasted that by 2022 the demand for water is likely to increase by 50% due to the influx of tourists. A major challenge is to provide sufficient and sustainable water distribution networks for the State of Qatar (Al Malki 2008; Wittholz et al. 2008). Qatar has very scarce water resources. Its limited groundwater resources have been over exploited and as the reserves deplete, quality deteriorates. With an average of less than 250 m^3 available per person per year, Qatar falls far below the internationally recognized ‘water poverty line’ of 1000 m^3 per person per year (Touati et al., 2013). The State of Qatar depends on desalinated seawater to satisfy 99% of its municipal water demand (QEERI). For this purpose, currently there are five desalination plants in Qatar with a total production capacity of 217 MIGD (986,000 m^3/day), and two additional desalination plants are being constructed with a combined capacity of 108 MIGD (491,000 m^3/day). On the other hand, the northern groundwater aquifer is the major source of groundwater in Qatar, estimated to contain 550,000 MIG (2,500 million m^3) of freshwater, which is mostly used for agriculture (Atilhan et al., 2012).

The City of Doha serves the estimated population of about 797,000 as of 2010 (KNOEMA, 2014) and covers a land area of 132.1 square kilometers. Albeit there is no source of information about the length of water network in Doha; Qatar is found to own 5,400 km of transmission and distribution pipes for the safe transport of quality water to consumers (Atilhan et al., 2012).

Qatar University’s WDN (located in Doha, Qatar) was selected as a second case study. The database only had limited information about water pipelines and their accessories. Unlike the City of London, no information was recorded about the breakage rate, demand nodes and elevation, causes of each pipe failure, description of the breakage and damages caused by pipe failure.

Figure 4-5: Qatar University WDN

The total number of pipe segments in the selected sub-network is 127 which are clustered according to their size and material type (Table 4-4). Around 95% of water pipes are made of ductile iron; and the rest are made of HDPE. The pipe size ranges from 80mm to 400mm; with 300mm occupying 58% of the network.

Table 4-4: Percentage Composition of Pipe Attributes

Attribute	Value	Percentage
Pipe Size	≤ 150mm	17.32%
	150mm – 300mm	76.38%
	> 300mm	6.3%
Pipe Material	Ductile Iron	95%
	HDPE	5%

Table 4-5: Attributes from Database of Doha

Attribute	Minimum	Maximum
Age (Years)	4	33
Length (m)	0.6	658.93
Pipe Diameter (mm)	80	400

4.5 Best Practices

NRC (2006) best practice guide for assessing and reducing risks in drinking water distribution systems lists the most possible causes of failures accordingly categorizing them into mechanical and hydraulic types. This list of causes of failure aid in identifying the exact failure type and help in assessing the integrated mechanical and hydraulic network reliability. Table 4-6 demonstrates these possible causes and their consequences as adopted and listed in chapter 2.

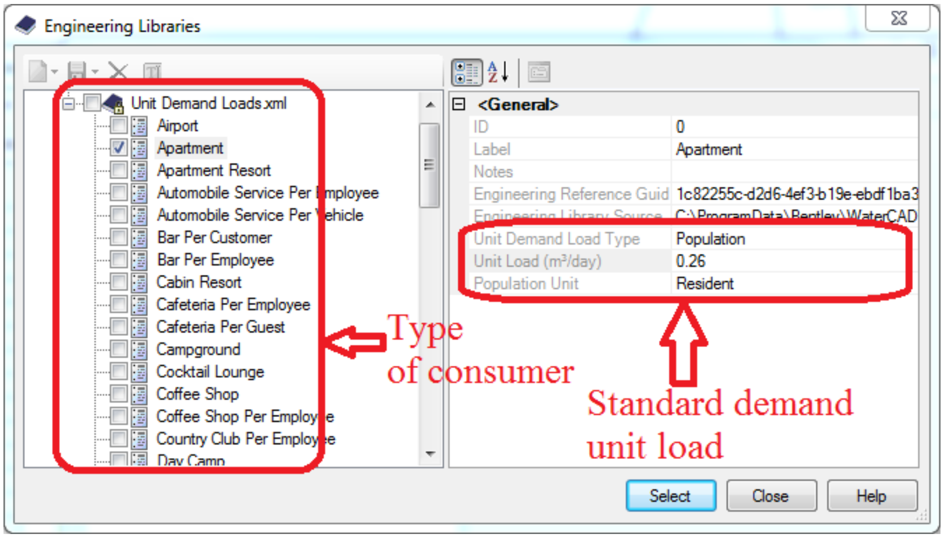
Table 4-6: Causes and Consequences of Failure (NRC, 2006)

Types of failures	Causes	Consequences
Mechanical	• Corrosion • Permeation • Too high internal water pressure or surges • Shifting earth • Exposure to UV light • Stress from overburden • Temperature fluctuations, freezing • Natural disasters • Failure due to aging and weathering	• Contamination of Mains, Fittings, and Appurtenances • Contamination of Storage Facilities • Contamination Due to the Absence or Operational Failure of Backflow Prevention Devices
Hydraulic	• Pipe Deterioration • Pressure Transients and Changes in Flow Regime • Hydraulic Changes during Maintenance and Emergencies • Tuberculation and Scale • Inadequate Operational Control	• External Contamination • Sedimentation • Reduction in Hydraulic Capacity and Associated Increase in Pumping Costs • Poor Water Quality from Sediment Suspension and Removal of Scales

Pressure requirements for assessing the hydraulic performance of the selected sub-networks are adopted as given by Design Specification and Requirements Manual (2015) for the City of London. It proposed the maximum residual pressure should not exceed 550 kPa (80 psi) and a minimum residual pressure shall not be below 275 kPa (40 psi) for designing a water distribution network. Also, Fire Underwriters Survey (1999) recommends the amount of water required for fire flow, which is specified based on average area per hydrant. These specifications were used in developing hydraulic reliability model.

4.6 Bentley WaterCAD

The collected datasets for the cities of London and Doha did not include any information regarding water demand at nodes. The absence of such crucial information would limit the ability for testing the developed hydraulic component of the reliability assessment model. The demand allocation for the selected sub-networks was created with the in-built engineering library of Bentley WaterCAD. This library contains industry used protocols for assuming demands based on the type of supplied consumers (home, café, restaurant, school, hospital…etc.). Figure 4-5 visualizes the engineering library developed by Bentley.



ID	0
Label	Apartment
Notes	
Engineering Reference Guid	1c82255c-d2d6-4ef3-b19e-ebdf1ba3
Engineering Library Source	C:\ProgramData\Bentley\WaterCAD
Unit Demand Load Type	Population
Unit Load (m³/day)	0.26
Population Unit	Resident

Type of consumer

Standard demand unit load

Figure 4-6: Engineering Library of Bentley WaterCAD

4.7 Summary

Two datasets from the Cities of London and Doha were analyzed along with concerned literature. The required data for the developed research framework were assembled from four sources and used as inputs to test the developed models using three selected sub-networks. The crucial information about water demand allocation was estimated from the engineering library of Bentley WaterCAD.

CHAPTER 5

Model Implementation

5.1 Introduction

In this chapter, two case studies are worked out to demonstrate the use of the developed research methodology for which the data were obtained from the Cities of London, Ontario and Doha, Qatar. In the first case study, two sub-networks are selected from the City of London, Ontario in order to observe any differences in the hydraulic properties, as they are supplied by different sources of water. The sensitivity analysis is done for this purpose. The flowchart of the Model Implementation stage can be seen in figure 5-1.

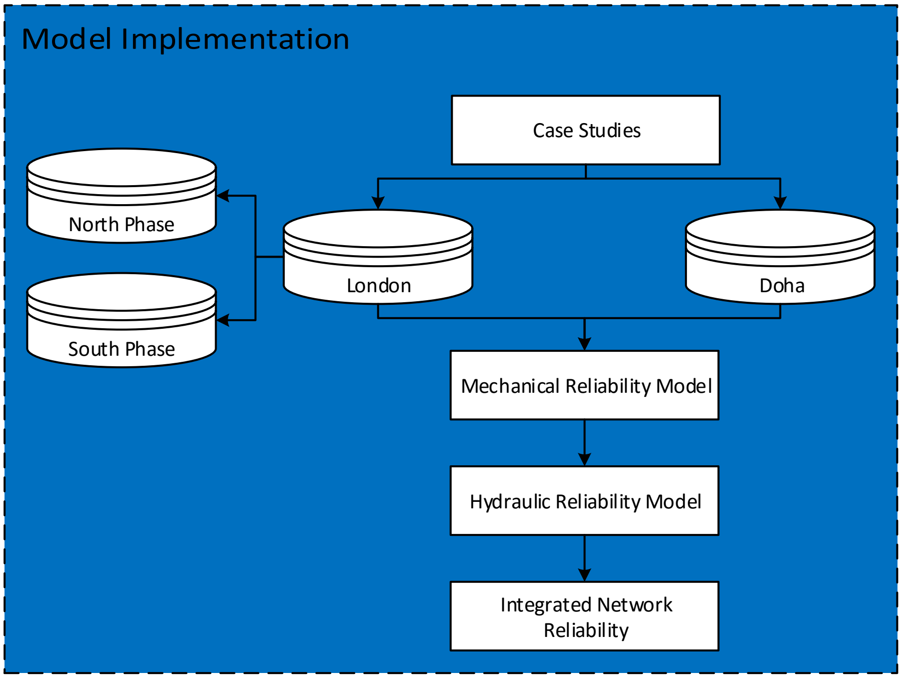


Figure 5-1: Model Implementation

5.2 City of London

As discussed in chapter 4, the City of London receives its water from two regional water systems over which the City plays a significant management role.

1. Elgin Area Primary Water Supply System
2. Lake Huron Primary Water Supply System

Figure 5-2: City of London Water System (City of London Official Website, 2015)

Two sub-networks were selected, one supplied by Lake Huron and the other supplied by Elgin Area (Lake Erie). These sub-networks were categorized into North Phase (Lake Huron) and South Phase (Lake Erie). The model implementation demonstrates the capabilities of the developed models with respect to network reliability.

5.2.1 North Phase

5.2.1.1 Mechanical Reliability Model

After extracting the required data of the selected sub network from ArcGIS, the network is analyzed for the evaluation of reliability at component and segment levels in standard Excel spreadsheets. The probability of failure of segments are also evaluated at this stage which later aids in assessing the reliability at network/sub-network level. Table 5-1 depicts the collected data and reliability calculations of segment 'a' and segment 'b' belonging to north phase sub-network as shown in figure 5-3.

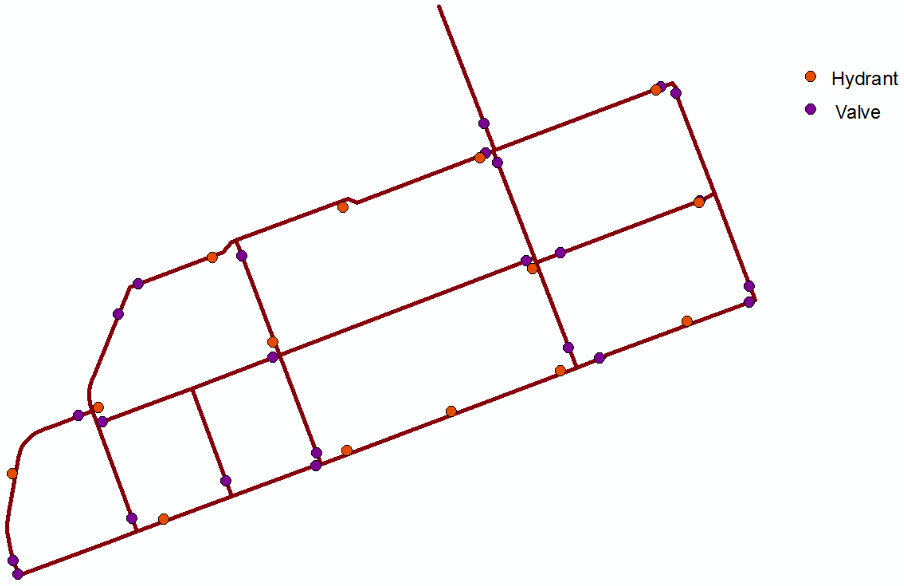


Figure 5-3: North Phase Sub-Network Model (ArcMap 10.3.1)

Segment ‘a’ is composed of two components (i.e. a pipe and a valve) whereas segment ‘b’ consists of three components (i.e. a pipe, a valve and a hydrant) as shown in column 2 of table 5-1. Total number of failures of components occurred till date are recorded in column 3. The data for the number of failures of components other than pipes was not available and hence they are assumed to aid in model implementation. In order to make the implementation more accurate, the number of failures of accessories (i.e. valves and hydrants) are assumed to reflect upon the age of the pipes contained in a segment. The failure rate of pipes and accessories are computed based on equations 3-1 and 3-2 respectively. Based on these failure rates, reliability is assessed at component level using equation 3-3. The weights of components in a typical segment are derived from table 4-1 which are normalized to find the relative weight of a component in forming a segment using equation 3-6. These relative weights aid in assessing the reliability at segment level based on equation 3-5. In addition, probability of failure of segments is also evaluated based on equation 3-7.

Table 5-1: Reliability Calculations of North Phase Sub-Network

Data					**Results**					
Segment	**Comp.**	**No. of Failures**	**Age (yrs)**	**Segment Length (m)**	**Failure rate (Breaks/m)**	**Comp. Reliability**	**Weight**	**Relative Weight**	**Segment Reliability**	**Probability of failure of Segments**
a	Pipe 1	0	84	153.33	0.0785	0.9245	0.38	0.58	0.9429	0.0571
	Valve 1	5			0.0326	0.9679	0.28	0.42		
						Sum	0.66			
b	Pipe 1	0	2	189.03	0.0034	0.9966	0.38	0.39	0.9955	0.0045
	Valve 1	1			0.0053	0.9947	0.28	0.29		
	Hydrant 1	1			0.0053	0.9947	0.31	0.32		
						Sum	0.97			

The reliability of components in segment ‘a’ are found to be 0.9245 and 0.9679 where as in segment ‘b’, they are found to be 0.9966, 0.9947 and 0.9947. The difference in reliabilities of pipes in both the segments can be attributed to their age. This results in a segment reliability of 0.9429 for segment ‘a’ and 0.9955 for segment ‘b’. The relatively high reliability for segment ‘b’ than segment ‘a’ as it can be seen from table 5-1, is clearly a depiction of relatively newer components and less number of failures in segment ‘b’. Similarly, the reliabilities of all components are evaluated based on which the reliability of segments in north phase sub-network are calculated which are shown in table 5-2. Based on these results, segment ‘b’ is found to be most reliable, whereas segment ‘v’ is the least reliable and takes the priority in scheduling in case of rehabilitation.

Table 5-2: Segment Reliabilities and Failure Probabilities of North Phase Sub-Network

Segment	Segment Reliability	Probability of failure of segments
a	0.9429	0.0571
b	0.9955	0.0045
c	0.9285	0.0715
d	0.9293	0.0707
e	0.9337	0.0663
f	0.9683	0.0317
g	0.9662	0.0338
h	0.9403	0.0597
i	0.9934	0.0066
j	0.9638	0.0362
k	0.9918	0.0082
l	0.9733	0.0267
m	0.9764	0.0236
n	0.9519	0.0481
o	0.9495	0.0505
p	0.9575	0.0425
q	0.9567	0.0433
r	0.9558	0.0442
s	0.9836	0.0164
t	0.9484	0.0516
u	0.9273	0.0727
v	0.9165	0.0835

The next stage in this model is to assess the mechanical reliability at network/sub-network level, for which the sub-network is analyzed using minimum cut set method. For this purpose, the selected sub-network in north phase is constructed as shown in figure 5-4 (Mathematica 10.2).

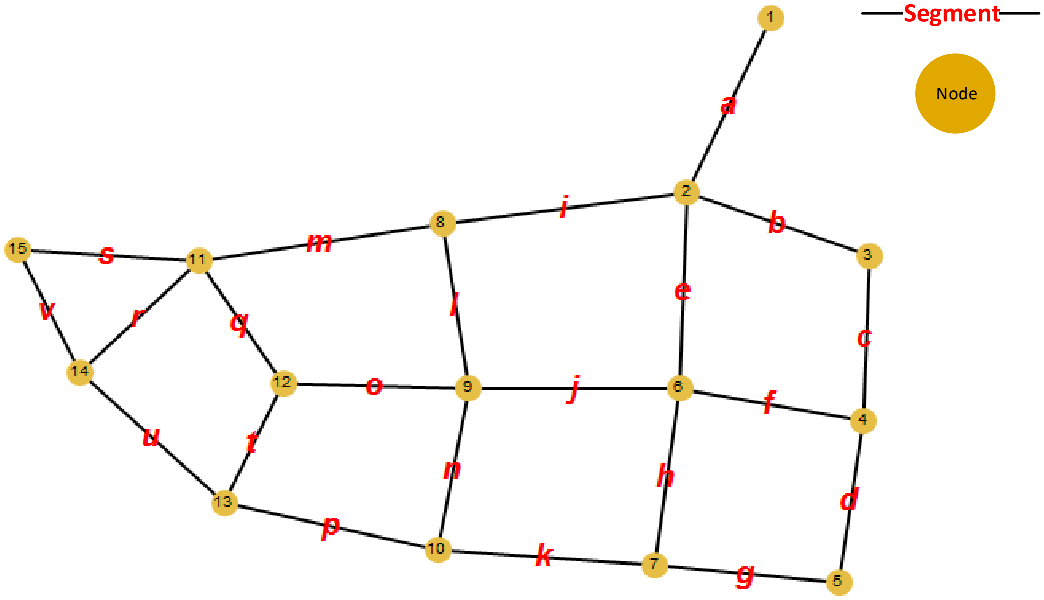


Figure 5-4: North Phase Sub-Network Model (Mathematica 10.2)

The process of minimum cut sets identification commences by inputting the WDN and enumerating all possible paths from a source node to a demand node under consideration, and constructing a path matrix for that node (Mathematica 10.2). Table 5-3 lists all possible paths from the source node 1 to demand node 4.

There are 22 segments in the north phase sub-network which forms the number of columns of a path matrix, whereas the number of rows are formed by 44 possible paths which are followed by the water to reach the demand node 4. Table 5-4 represents the path matrix for demand node 4 constructed using Mathematica 10.2.

Table 5-3: Possible Paths from Source Node to Demand Node

Demand Node	Possible Paths
4	{a,e,f}, {a,b,c}, {a,i,l,j,f}, {a,e,h,g,d}, {a,i,m,q,o,j,f}, {a,i,l,n,k,h,f}, {a,i,l,n,k,g,d}, {a,i,l,j,h,g,d}, {a,e,j,n,k,g,d}, {a,i,m,r,u,t,o,j,f}, {a,i,m,r,u,p,n,j,f}, {a,i,m,r,u,p,k,h,f}, {a,i,m,r,u,p,k,g,d}, {a,i,m,q,t,p,n,j,f}, {a,i,m,q,t,p,k,h,f}, {a,i,m,q,t,p,k,g,d}, {a,i,m,q,o,n,k,h,f}, {a,i,m,q,o,n,k,g,d}, {a,i,m,q,o,j,h,g,d}, {a,i,l,o,t,p,k,h,f}, {a,i,l,o,t,p,k,g,d}, {a,e,j,o,t,p,k,g,d}, {a,i,m,s,v,u,t,o,j,f}, {a,i,m,s,v,u,p,n,j,f}, {a,i,m,s,v,u,p,k,h,f}, {a,i,m,s,v,u,p,k,g,d}, {a,i,m,r,u,t,o,n,k,h,f}, {a,i,m,r,u,t,o,n,k,g,d}, {a,i,m,r,u,t,o,j,h,g,d}, {a,i,m,r,u,p,n,j,h,g,d}, {a,i,m,q,t,p,n,j,h,g,d}, {a,i,l,o,q,r,u,p,k,h,f}, {a,i,l,o,q,r,u,p,k,g,d}, {a,e,j,o,q,r,u,p,k,g,d}, {a,e,j,l,m,r,u,p,k,g,d}, {a,e,j,l,m,q,t,p,k,g,d}, {a,i,m,s,v,u,t,o,n,k,h,f}, {a,i,m,s,v,u,t,o,n,k,g,d}, {a,i,m,s,v,u,t,o,j,h,g,d}, {a,i,m,s,v,u,p,n,j,h,g,d}, {a,i,l,o,q,s,v,u,p,k,h,f}, {a,i,l,o,q,s,v,u,p,k,g,d}, {a,e,j,o,q,s,v,u,p,k,g,d}, {a,e,j,l,m,s,v,u,p,k,g,d}

Table 5-4: Path Matrix of a Demand Node

a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v
1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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1	0	0	1	0	0	1	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0
1	0	0	1	0	0	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0
1	0	0	0	0	1	0	0	1	1	0	0	1	0	1	0	0	1	0	1	1	0
1	0	0	0	0	1	0	0	1	1	0	0	1	1	0	1	0	1	0	0	1	0
1	0	0	0	0	1	0	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0
1	0	0	1	0	0	1	0	1	0	1	0	1	0	0	1	0	1	0	0	1	0
1	0	0	0	0	1	0	0	1	1	0	0	1	1	0	1	1	0	0	1	0	0
1	0	0	0	0	1	0	1	1	0	1	0	1	0	0	1	1	0	0	1	0	0
1	0	0	1	0	0	1	0	1	0	1	0	1	0	0	1	1	0	0	1	0	0
1	0	0	0	0	1	0	1	1	0	1	0	1	1	1	0	1	0	0	0	0	0
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1	0	0	1	0	0	1	1	1	1	0	0	1	0	1	0	1	0	0	0	0	0
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1	0	0	1	0	0	1	0	1	0	1	1	0	0	1	1	0	0	0	1	0	0
1	0	0	1	1	0	1	0	0	1	1	0	0	0	1	1	0	0	0	1	0	0
1	0	0	0	0	1	0	0	1	1	0	0	1	0	1	0	0	0	1	1	1	1
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1	0	0	1	0	0	1	0	1	0	1	0	1	0	0	1	0	0	1	0	1	1
1	0	0	0	0	1	0	1	1	0	1	0	1	1	1	0	0	1	0	1	1	0
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1	0	0	1	0	0	1	1	1	1	0	0	1	1	0	1	0	1	0	0	1	0
1	0	0	1	0	0	1	1	1	1	0	0	1	1	0	1	1	0	0	1	0	0
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1	0	0	1	1	0	1	0	0	1	1	1	1	0	0	1	0	1	0	0	1	0
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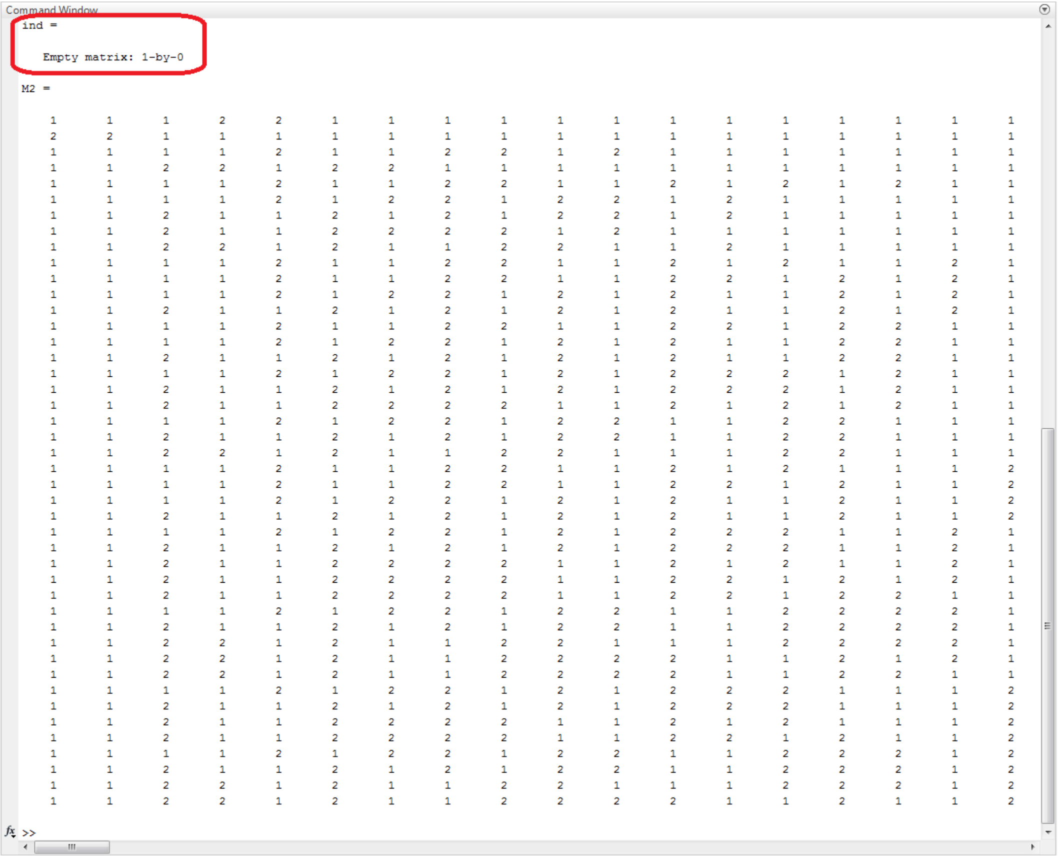
1	0	0	1	1	0	1	0	0	1	1	0	0	0	1	1	1	0	1	0	1	1
1	0	0	1	1	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	1	1

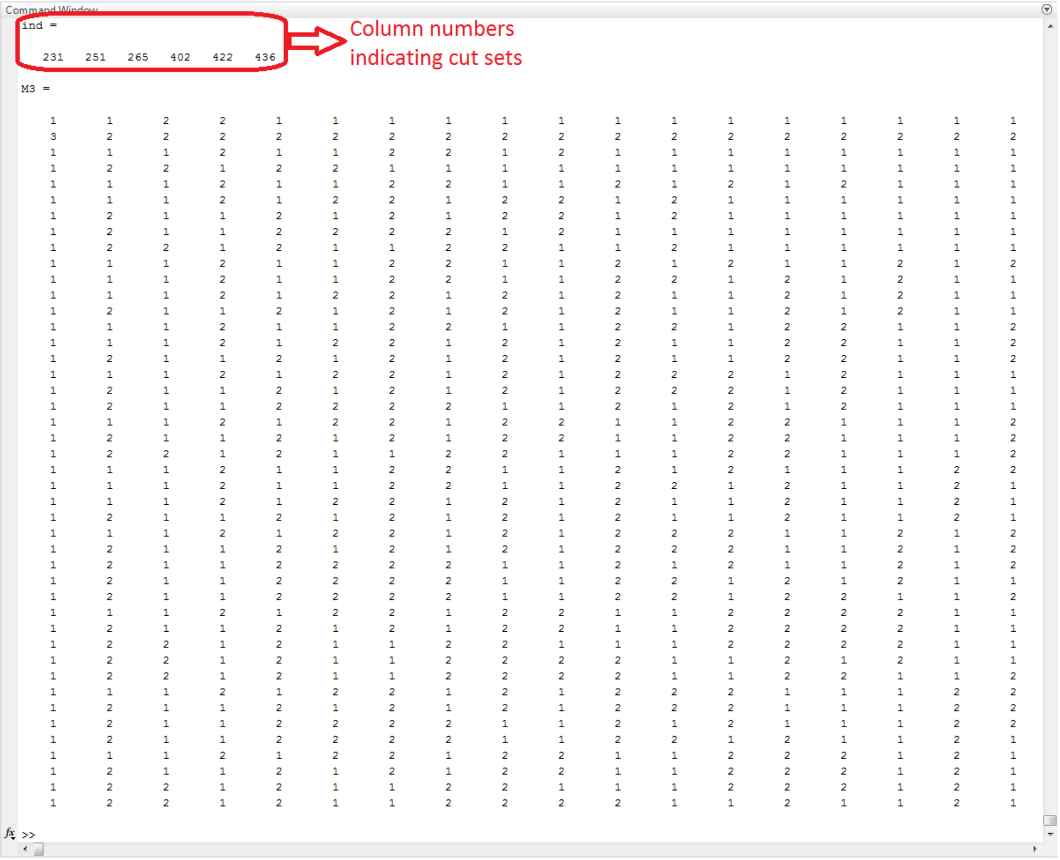
As discussed in research methodology, it is apparent from the path matrix that ‘a’ is a crucial segment, the failure of which will cause the failure of network (MATLAB R2013b). Hence it is recorded as a first order cut set. To find minimum cut sets of higher order, the columns in the path matrix are modified to represent the combination of two or more segments depending on the enumeration of required order of minimum cut sets. Using MATLAB R2013b, the number of combinations of two segments for the selected north phase sub-network are found to be 231. Hence the modified path matrix of demand node 4 consists of 231 columns.



```
ind =

   Empty matrix: 1-by-0

M2 =

     1     1     1     2     2     1     1     1     1     1     1     1     1     1     1     1     1     1
     2     2     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     2     1     1     2     2     1     2     1     1     1     1     1     1     1
     1     1     2     2     1     2     2     1     1     1     1     1     1     1     1     1     1     1
     1     1     1     1     2     1     1     2     2     1     1     2     1     2     1     2     1     1
     1     1     1     1     2     1     2     2     1     2     2     1     2     1     1     1     1     1
     1     1     2     1     1     2     1     2     1     2     2     1     2     1     1     1     1     1
     1     1     2     1     1     2     2     2     2     1     2     1     1     1     1     1     1     1
     1     1     2     2     1     2     1     1     2     2     1     1     2     1     1     1     1     1
     1     1     1     1     2     1     1     2     2     1     1     2     1     2     1     1     2     1
     1     1     1     1     2     1     1     2     2     1     1     2     2     1     2     1     2     1
     1     1     1     1     2     1     2     2     1     2     1     2     1     1     2     1     2     1
     1     1     2     1     1     2     1     2     1     2     1     2     1     1     2     1     2     1
     1     1     1     1     2     1     1     2     2     1     1     2     2     1     2     2     1     1
     1     1     1     1     2     1     2     2     1     2     1     2     1     1     2     2     1     1
     1     1     2     1     1     2     1     2     1     2     1     2     1     1     2     2     1     1
     1     1     1     1     2     1     2     2     1     2     1     2     2     2     1     2     1     1
     1     1     2     1     1     2     1     2     1     2     1     2     2     2     1     2     1     1
     1     1     2     1     1     2     2     2     2     1     1     2     1     2     1     2     1     1
     1     1     1     1     2     1     2     2     1     2     2     1     1     2     2     1     1     1
     1     1     2     1     1     2     1     2     1     2     2     1     1     2     2     1     1     1
     1     1     2     2     1     2     1     1     2     2     1     1     1     2     2     1     1     1
     1     1     1     1     2     1     1     2     2     1     1     2     1     2     1     1     1     2
     1     1     1     1     2     1     1     2     2     1     1     2     2     1     2     1     1     2
     1     1     1     1     2     1     2     2     1     2     1     2     1     1     2     1     1     2
     1     1     2     1     1     2     1     2     1     2     1     2     1     1     2     1     1     2
     1     1     1     1     2     1     2     2     1     2     1     2     2     2     1     1     2     1
     1     1     2     1     1     2     1     2     1     2     1     2     2     2     1     1     2     1
     1     1     2     1     1     2     2     2     2     1     1     2     1     2     1     1     2     1
     1     1     2     1     1     2     2     2     2     1     1     2     2     1     2     1     2     1
     1     1     2     1     1     2     2     2     2     1     1     2     2     1     2     2     1     1
     1     1     1     1     2     1     2     2     1     2     2     1     1     2     2     2     2     1
     1     1     2     1     1     2     1     2     1     2     2     1     1     2     2     2     2     1
     1     1     2     2     1     2     1     1     2     2     1     1     1     2     2     2     2     1
     1     1     2     2     1     2     1     1     2     2     2     2     1     1     2     1     2     1
     1     1     2     2     1     2     1     1     2     2     2     2     1     1     2     2     1     1
     1     1     1     1     2     1     2     2     1     2     1     2     2     2     1     1     1     2
     1     1     2     1     1     2     1     2     1     2     1     2     2     2     1     1     1     2
     1     1     2     1     1     2     2     2     2     1     1     2     1     2     1     1     1     2
     1     1     2     1     1     2     2     2     2     1     1     2     2     1     2     1     1     2
     1     1     1     1     2     1     2     2     1     2     2     1     1     2     2     2     1     2
     1     1     2     1     1     2     1     2     1     2     2     1     1     2     2     2     1     2
     1     1     2     2     1     2     1     1     2     2     1     1     1     2     2     2     1     2
     1     1     2     2     1     2     1     1     2     2     2     2     1     1     2     1     1     2

fx >>
```

Figure 5-5: Modified Path Matrix of Demand Node

The modified path matrix for combination of two segments indicates that there is not a single combination which causes the network failure by disconnecting the demand node as seemingly depicted in figure 5-5. Hence there are no second order cut sets recorded for the demand node 4. The modified path matrix for combination of 3 segments consists of 1540 columns representing 1540 combinations. Unlike the previous modified path matrix, it indicates that there are 6 third order cut sets as shown in figure 5-6. Represented by their column number, they are enumerated to be {b,d,f}, {b,e,i}, {b,f,g}, {c,d,f}, {c,e,i}, {c,f,g}.



```
ind =

   231   251   265   402   422   436

M3 =

     1     1     2     2     1     1     1     1     1     1     1     1     1     1     1     1     1     1
     3     2     2     2     2     2     2     2     2     2     2     2     2     2     2     2     2     2
     1     1     1     2     1     1     2     2     1     2     1     1     1     1     1     1     1     1
     1     2     2     1     2     2     1     1     1     1     1     1     1     1     1     1     1     1
     1     1     1     2     1     1     2     2     1     1     2     1     2     1     2     1     1     1
     1     1     1     2     1     2     2     1     2     2     1     2     1     1     1     1     1     1
     1     2     1     1     2     1     2     1     2     2     1     2     1     1     1     1     1     1
     1     2     1     1     2     2     2     2     1     2     1     1     1     1     1     1     1     1
     1     2     2     1     2     1     1     2     2     1     1     2     1     1     1     1     1     1
     1     1     1     2     1     1     2     2     1     1     2     1     2     1     1     2     1     2
     1     1     1     2     1     1     2     2     1     1     2     2     1     2     1     2     1     1
     1     1     1     2     1     2     2     1     2     1     2     1     1     2     1     2     1     1
     1     2     1     1     2     1     2     1     2     1     2     1     1     2     1     2     1     1
     1     1     1     2     1     1     2     2     1     1     2     2     1     2     2     1     1     2
     1     1     1     2     1     2     2     1     2     1     2     1     1     2     2     1     1     2
     1     2     1     1     2     1     2     1     2     1     2     1     1     2     2     1     1     2
     1     1     1     2     1     2     2     1     2     1     2     2     2     1     2     1     1     1
     1     2     1     1     2     1     2     1     2     1     2     2     2     1     2     1     1     1
     1     2     1     1     2     2     2     2     1     1     2     1     2     1     2     1     1     1
     1     1     1     2     1     2     2     1     2     2     1     1     2     2     1     1     1     2
     1     2     1     1     2     1     2     1     2     2     1     1     2     2     1     1     1     2
     1     2     2     1     2     1     1     2     2     1     1     1     2     2     1     1     1     2
     1     1     1     2     1     1     2     2     1     1     2     1     2     1     1     1     2     2
     1     1     1     2     1     1     2     2     1     1     2     2     1     2     1     1     2     1
     1     1     1     2     1     2     2     1     2     1     2     1     1     2     1     1     2     1
     1     2     1     1     2     1     2     1     2     1     2     1     1     2     1     1     2     1
     1     1     1     2     1     2     2     1     2     1     2     2     2     1     1     2     1     2
     1     2     1     1     2     1     2     1     2     1     2     2     2     1     1     2     1     2
     1     2     1     1     2     2     2     2     1     1     2     1     2     1     1     2     1     2
     1     2     1     1     2     2     2     2     1     1     2     2     1     2     1     2     1     1
     1     2     1     1     2     2     2     2     1     1     2     2     1     2     2     1     1     2
     1     1     1     2     1     2     2     1     2     2     1     1     2     2     2     2     1     1
     1     2     1     1     2     1     2     1     2     2     1     1     2     2     2     2     1     1
     1     2     2     1     2     1     1     2     2     1     1     1     2     2     2     2     1     1
     1     2     2     1     2     1     1     2     2     2     2     1     1     2     1     2     1     1
     1     2     2     1     2     1     1     2     2     2     2     1     1     2     2     1     1     2
     1     1     1     2     1     2     2     1     2     1     2     2     2     1     1     1     2     2
     1     2     1     1     2     1     2     1     2     1     2     2     2     1     1     1     2     2
     1     2     1     1     2     2     2     2     1     1     2     1     2     1     1     1     2     2
     1     2     1     1     2     2     2     2     1     1     2     2     1     2     1     1     2     1
     1     1     1     2     1     2     2     1     2     2     1     1     2     2     2     1     2     1
     1     2     1     1     2     1     2     1     2     2     1     1     2     2     2     1     2     1
     1     2     2     1     2     1     1     2     2     1     1     1     2     2     2     1     2     1
     1     2     2     1     2     1     1     2     2     2     2     1     1     2     1     1     2     1

fx >>
```

Column numbers indicating cut sets

Figure 5-6: Modified Path Matrix of Demand Node

Correspondingly, the number of minimum cut sets are enumerated for all demand nodes in a similar fashion as enumerated for demand node 4. Table 5-5 displays the final list of minimum cut sets identified for all demand nodes while analyzing the north phase sub-network. Segment ‘a’ can be attributed as the most crucial segment in the north phase sub-network as it has been identified as the first order minimum cut set for all demand nodes.

Table 5-5: Minimum Cut Sets for North Phase Sub-Network

Order of Cut Sets	List of Cut Sets
1	{a}
2	{b,c},{d,g},{s,v}
3	{b,d,f}, {b,e,i}, {b,f,g}, {c,d,f}, {c,e,i}, {c,f,g}, {d,h,k}, {g,h,k}, {i,j,k}, {i,l,m}, {k,n,p}, {m,q,u}, {o,q,t}, {p,t,u}, {r,s,u}, {r,u,v}

Finally, applying the principle of minimum cut set method using equations 3-8 to 3-12, the mechanical reliability of the north phase sub-network is calculated to be **0.9378.**

5.2.1.2 Hydraulic Reliability Model

This model commences with importing the shape files of the selected sub network along with its attributes to Bentley WaterCAD (ArcMap 10.3.1; WaterCAD V8i) for the hydraulic simulation of a WDN in normal and failure conditions. Figure 5-7 portrays the hydraulic model of the selected north phase sub-network, the shape files of which are imported from ArcMap 10.3.1. The model is labeled with the GIS IDs of the components. Because of unavailability of hydraulic data for the valves and hydrants, they are assumed to aid in model implementation. The valves are assumed to be check valves with open status whereas the demands for hydrants are added to the demands placed on nearest nodes. To add to model accuracy, these hydrant demands are obtained from Water Supply for Public Fire Protection (1999) - a practice guide prepared by Fire Underwriters Survey. As discussed in chapter 3, the accuracy of hydraulic simulation depends on how well the model is equipped with as much required data.

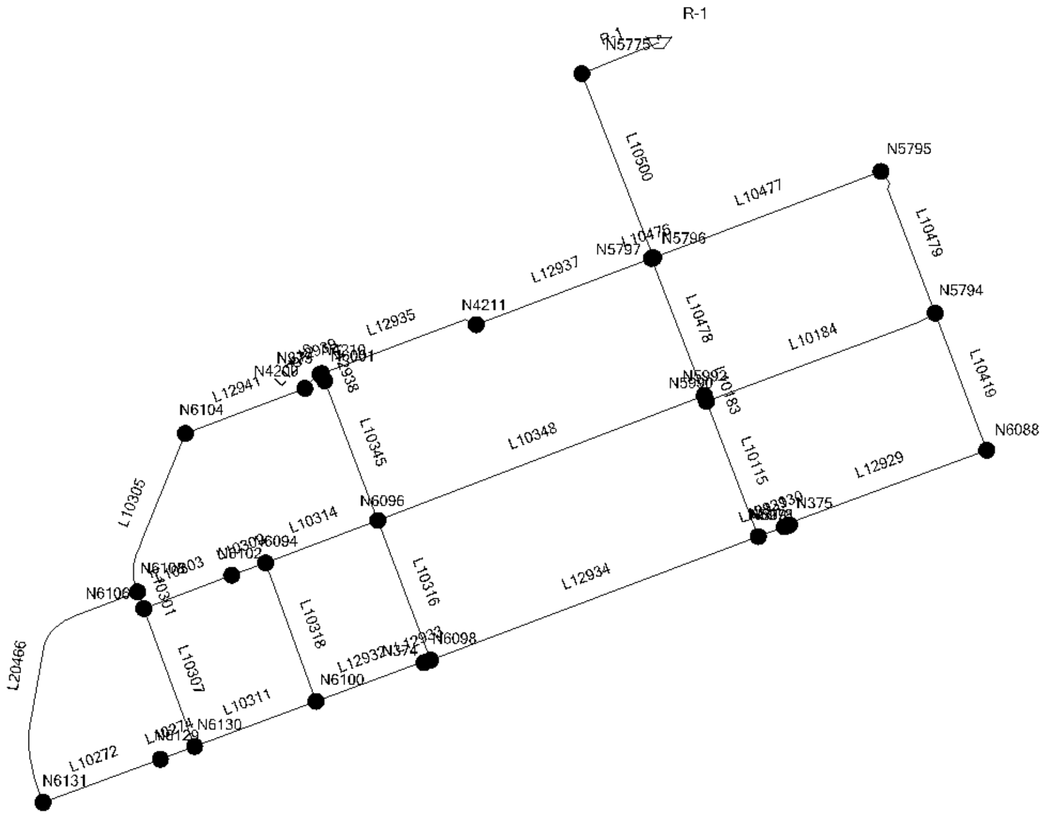
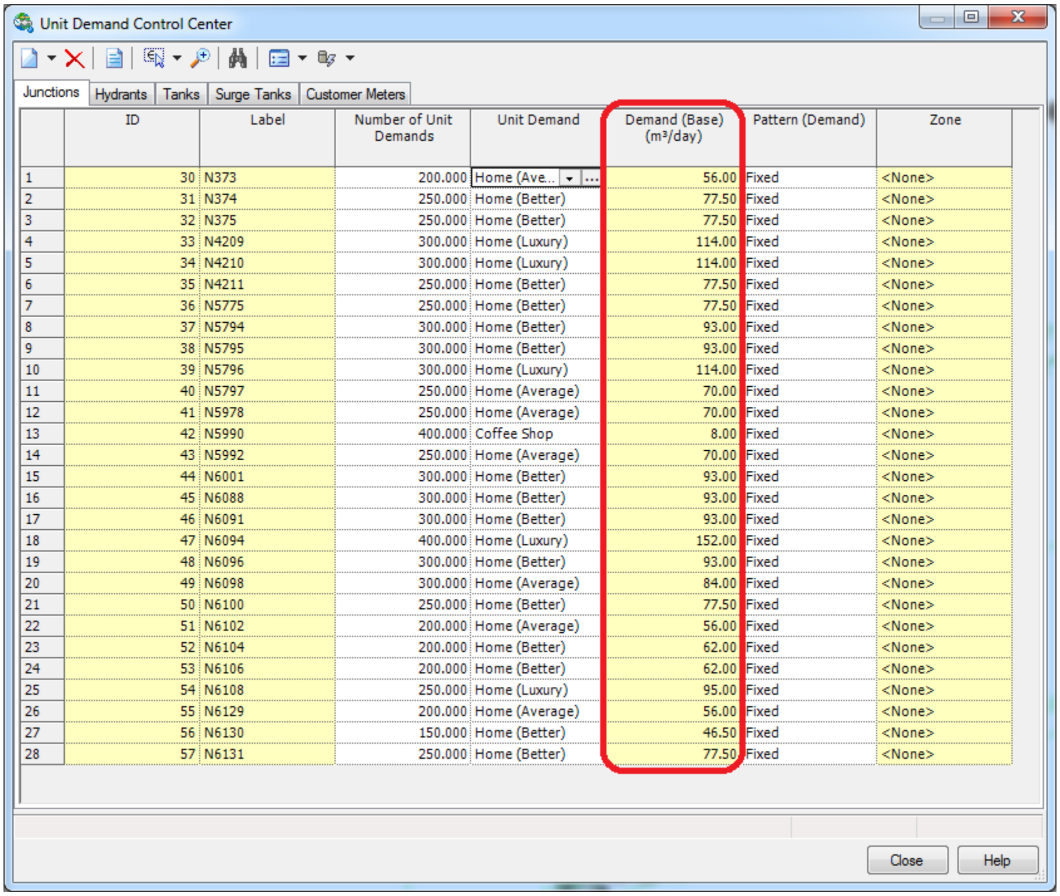


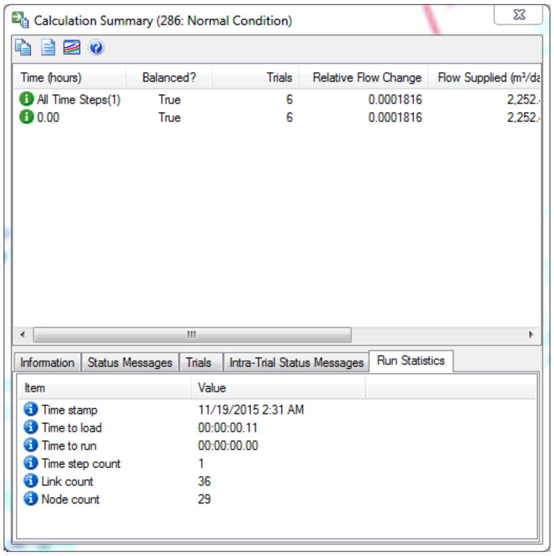
Figure 5-7: North Phase Sub-Network Hydraulic Model (WaterCAD V8i)

The next stage in this model is to allocate the demands at demand nodes. This is accomplished by using the unit demand control center tool in WaterCAD V8i. Note that the demand nodes are only those at junctions/intersections as per the definition of a segment in this thesis. Figure 5-8 demonstrates the nodal demand allocation for the north phase sub-network.



	ID	Label	Number of Unit Demands	Unit Demand	Demand (Base) (m³/day)	Pattern (Demand)	Zone
1	30	N373	200.000	Home (Ave...	56.00	Fixed	<None>
2	31	N374	250.000	Home (Better)	77.50	Fixed	<None>
3	32	N375	250.000	Home (Better)	77.50	Fixed	<None>
4	33	N4209	300.000	Home (Luxury)	114.00	Fixed	<None>
5	34	N4210	300.000	Home (Luxury)	114.00	Fixed	<None>
6	35	N4211	250.000	Home (Better)	77.50	Fixed	<None>
7	36	N5775	250.000	Home (Better)	77.50	Fixed	<None>
8	37	N5794	300.000	Home (Better)	93.00	Fixed	<None>
9	38	N5795	300.000	Home (Better)	93.00	Fixed	<None>
10	39	N5796	300.000	Home (Luxury)	114.00	Fixed	<None>
11	40	N5797	250.000	Home (Average)	70.00	Fixed	<None>
12	41	N5978	250.000	Home (Average)	70.00	Fixed	<None>
13	42	N5990	400.000	Coffee Shop	8.00	Fixed	<None>
14	43	N5992	250.000	Home (Average)	70.00	Fixed	<None>
15	44	N6001	300.000	Home (Better)	93.00	Fixed	<None>
16	45	N6088	300.000	Home (Better)	93.00	Fixed	<None>
17	46	N6091	300.000	Home (Better)	93.00	Fixed	<None>
18	47	N6094	400.000	Home (Luxury)	152.00	Fixed	<None>
19	48	N6096	300.000	Home (Better)	93.00	Fixed	<None>
20	49	N6098	300.000	Home (Average)	84.00	Fixed	<None>
21	50	N6100	250.000	Home (Better)	77.50	Fixed	<None>
22	51	N6102	200.000	Home (Average)	56.00	Fixed	<None>
23	52	N6104	200.000	Home (Better)	62.00	Fixed	<None>
24	53	N6106	200.000	Home (Better)	62.00	Fixed	<None>
25	54	N6108	250.000	Home (Luxury)	95.00	Fixed	<None>
26	55	N6129	200.000	Home (Average)	56.00	Fixed	<None>
27	56	N6130	150.000	Home (Better)	46.50	Fixed	<None>
28	57	N6131	250.000	Home (Better)	77.50	Fixed	<None>

Figure 5-8: Nodal Demand Allocation for North Phase Sub-Network (WaterCAD V8i)



Time (hours)	Balanced?	Trials	Relative Flow Change	Flow Supplied (m³/da
All Time Steps(1)	True	6	0.0001816	2,252.
0.00	True	6	0.0001816	2,252.

Item	Value
Time stamp	11/19/2015 2:31 AM
Time to load	00:00:00.11
Time to run	00:00:00.00
Time step count	1
Link count	36
Node count	29

Figure 5-9: Simulation Summary of North Phase Sub-Network Hydraulic Model (WaterCAD V8i)

The nodal demand allocation marks the completion of equipping hydraulic model, and makes it ready for simulation. Figure 5-9 shows the running time for simulating the hydraulic model, and figure 5-10 depicts the simulated hydraulic model of the north phase sub network along with the direction of flow of water in normal condition.

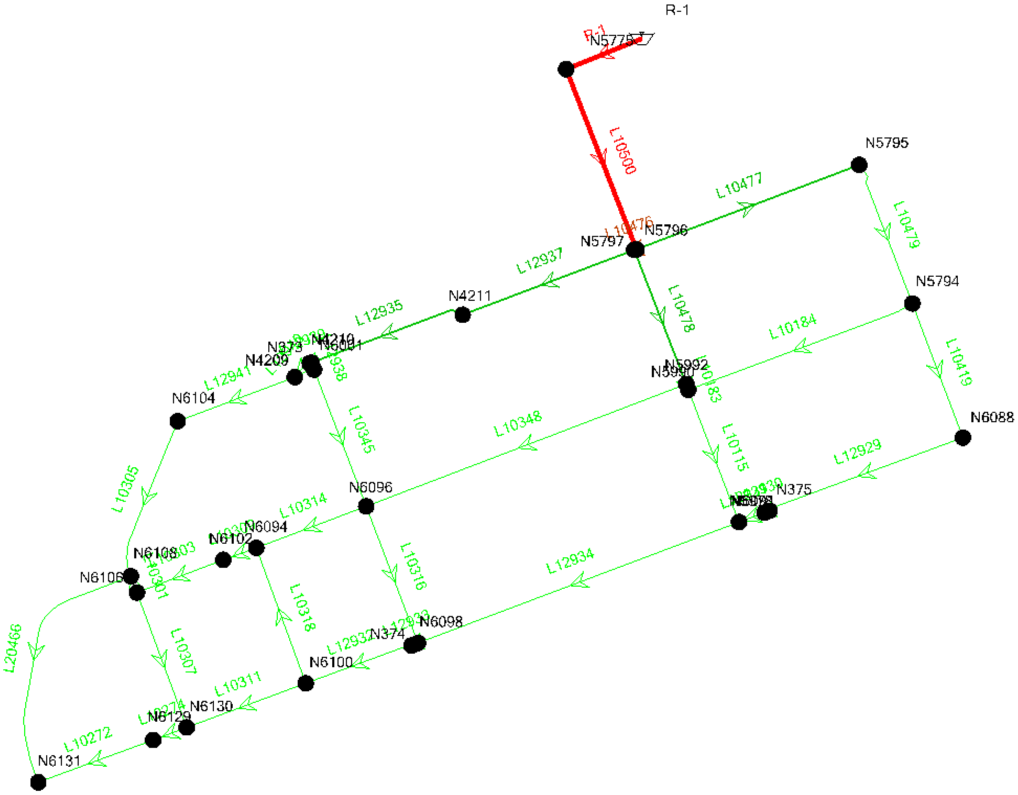


Figure 5-10: Hydraulic Simulation of North Phase Sub-Network (WaterCAD V8i)

It is apparent from figure 5-10 that most of the water is flowed through segment ‘a’. This confirms the earlier finding of segment ‘a’ to be most crucial segment while also explaining that the segment connecting the source of water delivery to the network is the most crucial segment in the whole network. Hence water utilities need to continuously monitor such segments in order to provide the water efficiently to consumers.

Table 5-6 illustrates the service pressure heads obtained through hydraulic simulation of the sub-network in normal condition. These pressure heads are required to satisfy the nodal demands.

Table 5-6: Service Pressure Heads for Demand Nodes of North Phase Sub-Network

Demand Node	GIS ID	Demand (m^3/day)	Pressure Head (m)
8	N4210	114	34.86
1	N5775	77.5	38.1
4	N5794	93	35.71
3	N5795	93	36
2	N5796	114	38.5
6	N5992	70	35.65
5	N6088	93	32.38
7	N6091	93	35.88
12	N6094	152	34.94
9	N6096	93	35.85
10	N6098	84	34.65
13	N6100	77.5	34.45
11	N6108	95	36.5
14	N6130	46.5	36.7
15	N6131	77.5	36.39

The hydraulic performance of a WDN is evaluated based on its ability to satisfy the nodal demands. To evaluate the actual demand received by consumers, the hydraulic model of the sub-network is simulated in failure condition for acquiring available pressure heads at nodes. Following the research methodology as discussed in chapter 3, the actual/available pressure heads at demand nodes are obtained through simulation in failure condition as shown in table 5-7. These pressure heads are then formulated with pressure conditions using equations 3-13 to 3-16 for assessing the available demand at nodes as shown in table 5-8.

Tables 5-7 and 5-8 depicts the available pressure heads and calculated nodal demands respectively for most of the identified cut sets but not all due to space insufficiency. Failure of segment ‘a’ disconnects the whole network from the source node, hence resulting in zero pressure head at all nodes except source node 1.

Table 5-7: Available Pressure Head at Demand Nodes of North Phase Sub-Network

	Available Pressure Head (m)									
Demand Node	**a closed**	**b + c closed**	**d + g closed**	**s + v closed**	**b + d + f closed**	**b + e + i closed**	**b + f + g closed**	**c + d + f closed**	**c + e + i closed**	**c + f + g closed**
8	0	32.73	34.59	34.86	32.54	0	33.21	32.88	0	33.11
1	38.1	38.1	38.1	38.1	38.1	38.1	38.1	38.1	38.1	38.1
4	0	32.69	35.94	35.71	0	0	0	0	0	0
3	0	0	36.16	36	0	0	0	38.29	22.5	38.18
2	0	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5	38.5
6	0	33.31	35.7	35.65	33.59	0	33.99	33.95	0	34.08
5	0	29.71	0	32.38	29.13	0	0	29.6	0	0
7	0	33.56	35.56	35.88	33.28	0	34.07	33.67	0	33.95
12	0	32.7	34.66	34.94	32.48	0	33.21	32.85	0	33.11
9	0	33.61	35.57	35.85	33.41	0	34.12	33.78	0	34.03
10	0	32.35	34.34	34.65	32.08	0	32.86	32.47	0	32.74
13	0	32.21	34.16	34.45	31.98	0	32.71	32.35	0	32.61
11	0	34.27	36.21	36.5	34.05	0	34.78	34.42	0	34.67
14	0	34.47	36.41	36.7	34.25	0	34.97	34.62	0	34.87
15	0	34.17	36.11	0	33.95	0	34.67	34.32	0	34.56

Apart from segment 'a', the combinations of segments {b,e,i} and {c,e,i} are also found to cause zero pressure heads indicating their cruciality in the sub-network. Hence water utilities need to constantly monitor them if any of these segments fails, in order to prevent network failure. Table 5-8 illustrates the available nodal demands which are calculated by comparing the available pressure heads with the required pressure heads at nodes.

Table 5-8: Available Nodal Demands for North Phase Sub-Network

	Available Demand (m^3/day)									
Demand Node	**a closed**	**b + c closed**	**d + g closed**	**s + v closed**	**b + d + f closed**	**b + e + i closed**	**b + f + g closed**	**c + d + f closed**	**c + e + i closed**	**c + f + g closed**
8	0	94.66	111.73	114.00	92.74	0.00	99.35	96.15	0.00	98.39
1	77.5	77.50	77.50	77.50	77.50	77.50	77.50	77.50	77.50	77.50
4	0	72.53	93.00	93.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0	0.00	93.00	93.00	0.00	0.00	0.00	93.00	0.00	93.00
2	0	114.00	114.00	114.00	114.00	11.00	114.00	114.00	114.00	114.00
6	0	58.32	70.00	70.00	59.84	0.00	61.94	61.73	0.00	62.40
5	0	58.11	0.00	93.00	47.24	0.00	0.00	56.21	0.00	0.00
7	0	78.12	91.09	93.00	76.13	0.00	81.62	78.89	0.00	80.81
12	0	125.09	148.90	152.00	122.12	0.00	131.70	127.07	0.00	130.43
9	0	78.62	91.33	93.00	77.21	0.00	82.12	79.80	0.00	81.51
10	0	67.94	82.02	84.00	65.80	0.00	71.81	68.87	0.00	70.92
13	0	62.61	75.74	77.50	60.88	0.00	66.23	63.65	0.00	65.52
11	0	81.59	93.37	95.00	80.15	0.00	84.85	82.56	0.00	84.15
14	0	40.10	45.72	46.50	39.41	0.00	41.62	40.56	0.00	41.32
15	0	66.46	76.20	0.00	65.26	0.00	69.10	67.26	0.00	68.53

After finding the available demands at all nodes, the hydraulic reliability of the selected north phase sub-network is calculated using equations 3-17 and 3-18, which is found to be equal to **0.7062.**

5.2.1.3 Integrated Network Reliability

The integrated mechanical and hydraulic reliability of a network/sub-network is evaluated based on the list of causes of failures as shown in table 2-1 which are proposed by NRC (2006) best practice guide for assessing and reducing risks in drinking water distribution systems. The information about the condition of a WDN and its components can be found from the operation and maintenance reports which contains the detailed information about the cause of a failure as recorded by the water utility. Due to lack of collection of such data, causes of failures are assumed and categorized in accordance with the total number of failures in the selected sub-network.

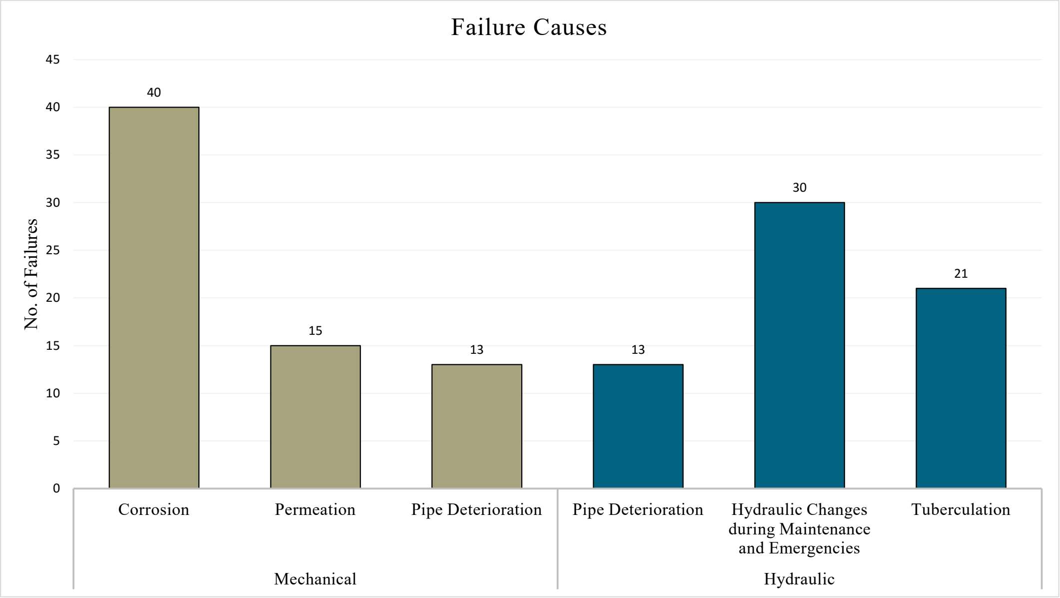


Figure 5-11: Causes of Failure in North Phase Sub-Network

In entirety, the number of failures occurred in the selected north phase sub-network are 132. As proposed by NRC (2006) best practice guide, pipe deterioration is learned to be the cause for both mechanical and hydraulic failures and hence it is categorized separately. Total number of failures caused due to structural/mechanical reasons are 68 which constitutes 51.51% of total failures, whereas hydraulic failures are enumerated to be 64, constituting 48.49% of total failures in the sub-network.

Using equation 3-19, the integrated reliability of the north phase sub-network is assessed to be equal to **0.8255.**

5.2.2 South Phase

5.2.2.1 Mechanical Reliability Model

Figure 5-12 represents the selected sub-network from south phase and table 5-9 demonstrates the computed reliabilities and failure probabilities of its segments.

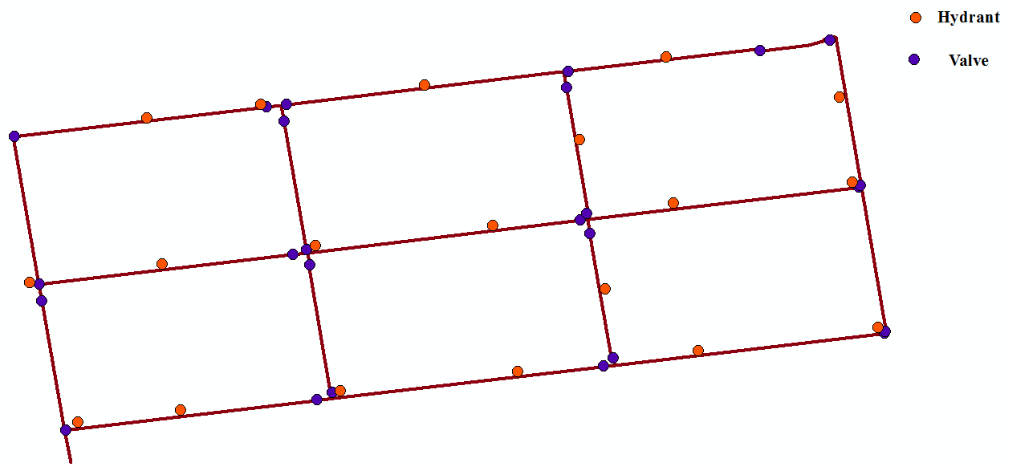


Figure 5-12: South Phase Sub-Network Model (ArcMap 10.3.1)

Table 5-9: Segment Reliabilities and Failure Probabilities of South Phase Sub-Network

Segment	Segment Reliability	Probability of failure of Segments
a	0.9687	0.0313
b	0.9762	0.0238
c	0.9797	0.0203
d	0.9946	0.0054
e	0.9937	0.0063
f	0.9913	0.0087
g	0.9921	0.0079
h	0.9912	0.0088
i	0.9942	0.0058
j	0.9942	0.0058
k	0.9905	0.0095
l	0.9893	0.0107
m	0.9914	0.0086
n	0.9889	0.0111
o	0.9906	0.0094
p	0.9831	0.0169
q	0.9895	0.0105
r	0.9870	0.0130

From table 5-9, segment ‘a’ is observed to be the least reliable among all segments, and will be prior to other segments in scheduling rehabilitation. The reliability of most of the segments in the selected south phase sub-network is nearly 1, because their components are newer with less number of failures. Moreover, the reliability of segments in the south phase sub-network are found to be comparatively higher than those in north phase. The detailed comparison will be depicted in chapter 5.2.3.

Figure 5-13 depicts the south phase sub-network, constructed to analyze the network using minimum cut set method (Mathematica 10.2). Following the same procedure as applied for north phase sub-network, all the minimum cut sets are identified as shown in table 5-10.

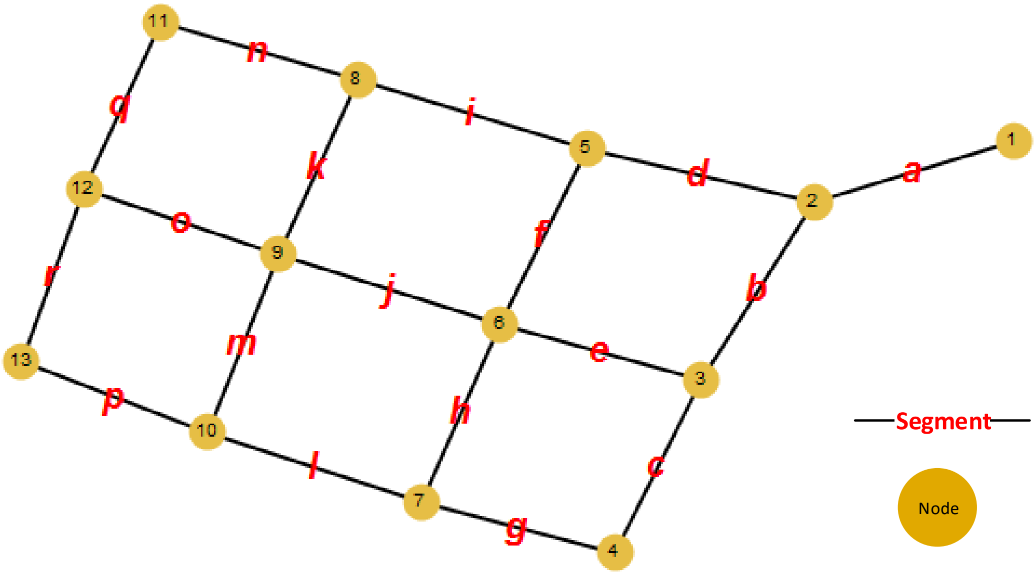


Figure 5-13: South Phase Sub-Network Model (Mathematica 10.2)

Table 5-10: Minimum Cut Sets for South Phase Sub-Network

Order of Cut Sets	**List of Cut Sets**
1	{a}
2	{b,d},{c,g},{n,q}, {p,r}
3	{b,c,e}, {b,e,g}, {b,f,i}, {c,d,e}, {c,h,l}, {d,e,g}, {d,f,i}, {g,h,l}, {i,j,l}, {i,k,n}, {i,k,q}, {l,m,p}, {l,m,r}, {n,o,p}, {n,o,r}, {o,p,q}, {o,q,r}

Applying the principle of minimum cut set method using equations 3-8 to 3-12, the mechanical reliability of the south phase sub-network is calculated to be **0.9680.**

5.2.2.2 Hydraulic Reliability Model

Figure 5-14 portrays the hydraulic model of the selected north phase sub-network, the shape files of which are imported from ArcMap 10.3.1. The model is labeled with the GIS IDs of the components.

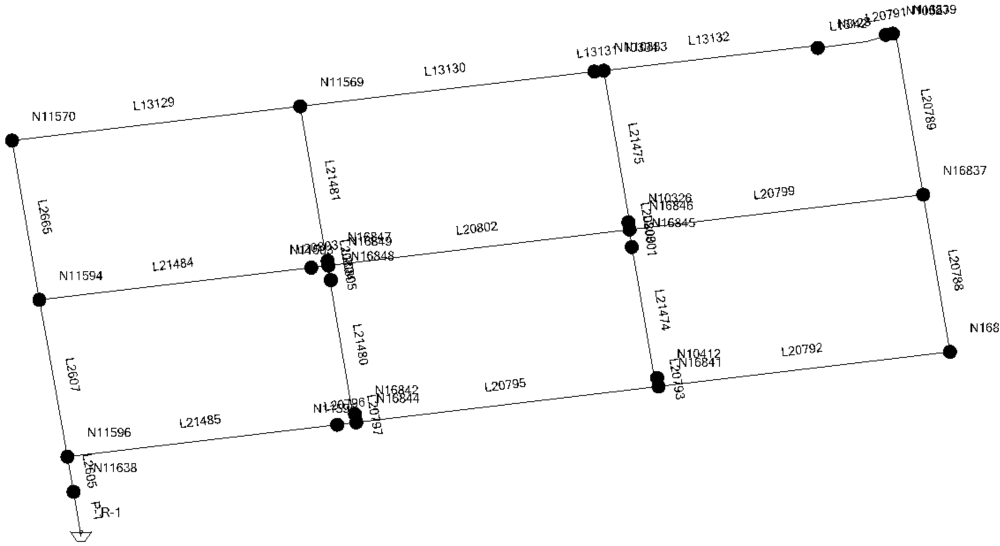
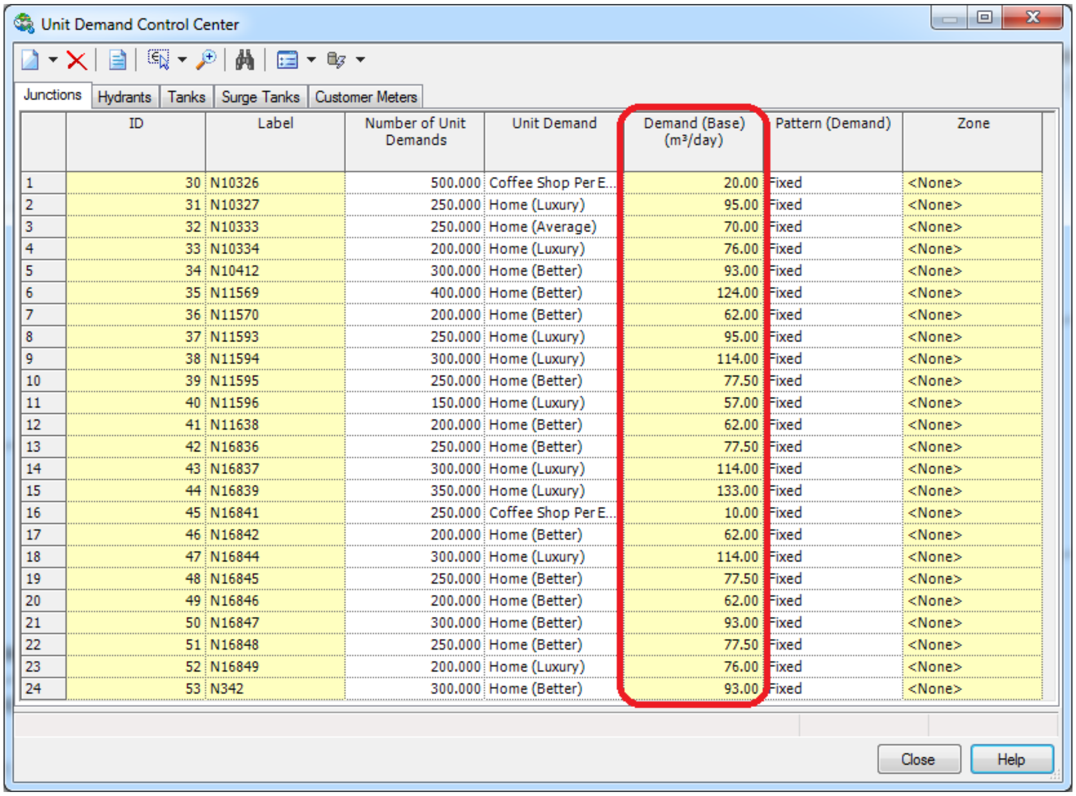


Figure 5-14: South Phase Sub-Network Hydraulic Model (WaterCAD V8i)

Following the methodology, the next step is to allocate the demands at demand nodes. Note that the demand nodes are only those at junctions/intersections as per the definition of a segment in this thesis. Figure 5-15 demonstrates the nodal demand allocation for the south phase sub-network.

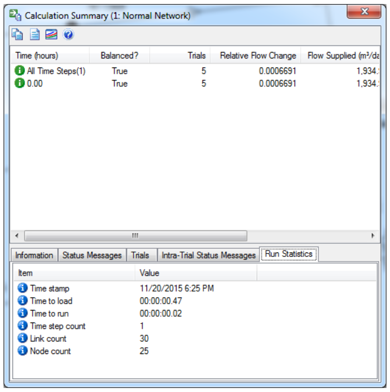
After nodal demand allocation, the hydraulic network is simulated to get the service pressure heads at nodes which are required to satisfy the demands placed on nodes. Figure

5-16 shows the running time for simulating the hydraulic model, and figure 5-17 depicts the simulated hydraulic model of the south phase sub network along with the direction of flow of water in normal condition.



	ID	Label	Number of Unit Demands	Unit Demand	Demand (Base) (m^3/day)	Pattern (Demand)	Zone
1	30	N10326	500.000	Coffee Shop Per E...	20.00	Fixed	<None>
2	31	N10327	250.000	Home (Luxury)	95.00	Fixed	<None>
3	32	N10333	250.000	Home (Average)	70.00	Fixed	<None>
4	33	N10334	200.000	Home (Luxury)	76.00	Fixed	<None>
5	34	N10412	300.000	Home (Better)	93.00	Fixed	<None>
6	35	N11569	400.000	Home (Better)	124.00	Fixed	<None>
7	36	N11570	200.000	Home (Better)	62.00	Fixed	<None>
8	37	N11593	250.000	Home (Luxury)	95.00	Fixed	<None>
9	38	N11594	300.000	Home (Luxury)	114.00	Fixed	<None>
10	39	N11595	250.000	Home (Better)	77.50	Fixed	<None>
11	40	N11596	150.000	Home (Luxury)	57.00	Fixed	<None>
12	41	N11638	200.000	Home (Better)	62.00	Fixed	<None>
13	42	N16836	250.000	Home (Better)	77.50	Fixed	<None>
14	43	N16837	300.000	Home (Luxury)	114.00	Fixed	<None>
15	44	N16839	350.000	Home (Luxury)	133.00	Fixed	<None>
16	45	N16841	250.000	Coffee Shop Per E...	10.00	Fixed	<None>
17	46	N16842	200.000	Home (Better)	62.00	Fixed	<None>
18	47	N16844	300.000	Home (Luxury)	114.00	Fixed	<None>
19	48	N16845	250.000	Home (Better)	77.50	Fixed	<None>
20	49	N16846	200.000	Home (Better)	62.00	Fixed	<None>
21	50	N16847	300.000	Home (Better)	93.00	Fixed	<None>
22	51	N16848	250.000	Home (Better)	77.50	Fixed	<None>
23	52	N16849	200.000	Home (Luxury)	76.00	Fixed	<None>
24	53	N342	300.000	Home (Better)	93.00	Fixed	<None>

Figure 5-15: Nodal Demand Allocation for South Phase Sub-Network (WaterCAD V8i)



Time (hours)	Balanced?	Trials	Relative Flow Change	Flow Supplied (m^3/da
All Time Steps(1)	True	5	0.0006691	1,934.
0.00	True	5	0.0006691	1,934.

Item	Value
Time stamp	11/20/2015 6:25 PM
Time to load	00:00:00.47
Time to run	00:00:00.02
Time step count	1
Link count	30
Node count	25

Figure 5-16: Simulation Summary of South Phase Sub-Network Hydraulic Model (WaterCAD V8i)

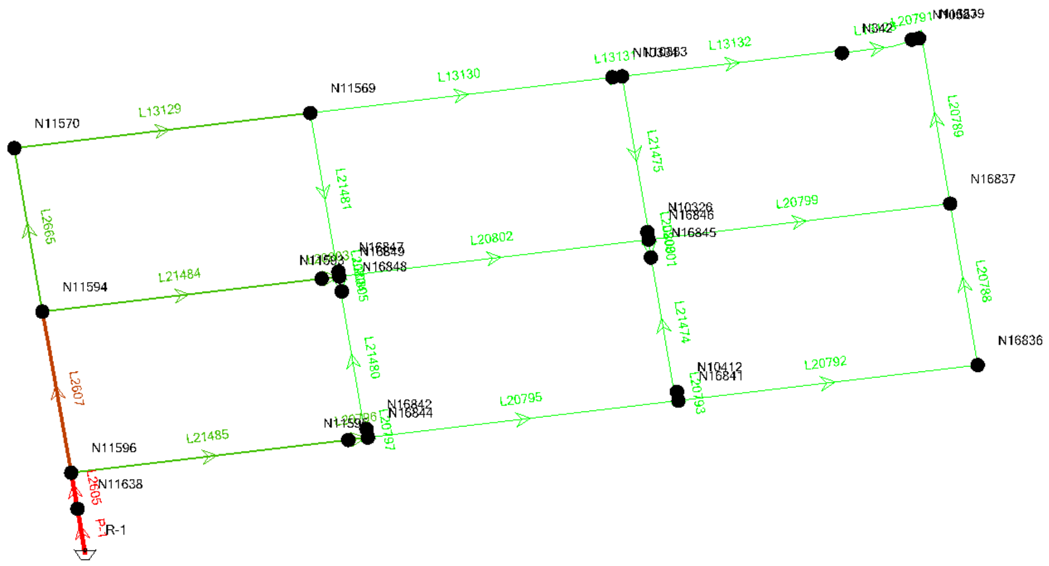


Figure 5-17: Hydraulic Simulation of South Phase Sub-Network (WaterCAD V8i)

It is apparent from figure 5-17 that most of the water is flowed through segment ‘a’. This confirms the earlier finding from north phase sub-network that the segment connecting the source of water delivery to the network is the most crucial segment in the whole network. It should be noted that segment ‘a’ was also found to be the least reliable among all segments. Hence water utilities should constantly monitor such segments which are hydraulically crucial as well as mechanically weaker in order to provide the water adequately to consumers.

Table 5-11 illustrates the service pressure heads obtained through hydraulic simulation of the sub-network in normal condition. These pressure heads are required to satisfy the nodal demands.

The actual/available pressure heads at demand nodes obtained through simulation in failure condition are as shown in table 5-12 whereas the available demand at nodes are presented in table 5-13.

Table 5-11: Service Pressure Heads for Demand Nodes of South Phase Sub-Network

Demand Node	GIS ID	Demand (m³/day)	Pressure Head (m)
10	N10333	70	39.56
7	N11569	124	37.86
4	N11570	62	34.55
3	N11594	114	40.66
2	N11596	57	43.59
1	N11638	62	41.9
11	N16836	77.5	43.06
12	N16837	114	40.51
13	N16839	133	39.94
8	N16841	10	43.96
5	N16844	114	43.29
9	N16846	62	41.56
6	N16849	76	41.09

Table 5-12: Available Pressure Head at Demand Nodes of South Phase Sub-Network

	Available Pressure Head (m)									
Demand Node	**a closed**	**b + d closed**	**c + g closed**	**n + q closed**	**p + r closed**	**b + c + e closed**	**b + e + g closed**	**b + f + i closed**	**c + d + e closed**	**c + h + l closed**
10	0.00	0.00	39.48	39.56	39.56	38.91	38.92	0.00	0.00	39.44
7	0.00	0.00	37.76	37.86	37.86	37.18	37.20	0.00	0.00	0.00
4	0.00	0.00	0.00	34.55	34.55	33.81	0.00	0.00	0.00	0.00
3	0.00	0.00	40.67	40.66	40.66	0.00	0.00	0.00	40.65	40.67
2	0.00	43.59	43.59	43.59	43.59	43.59	43.59	43.59	43.59	43.59
1	41.90	41.90	41.90	41.90	41.90	41.90	41.90	41.90	41.90	41.90
11	0.00	0.00	42.97	0.00	43.05	42.41	42.43	0.00	0.00	42.94
12	0.00	0.00	40.43	40.50	40.51	39.86	39.88	0.00	0.00	40.40
13	0.00	0.00	39.86	39.93	0.00	39.29	39.31	0.00	0.00	39.83
8	0.00	0.00	43.88	43.97	43.96	43.32	43.34	0.00	0.00	43.86
5	0.00	0.00	43.22	43.29	43.29	42.73	42.74	43.02	0.00	43.22
9	0.00	0.00	41.48	41.56	41.56	40.91	40.93	0.00	0.00	41.45
6	0.00	0.00	41.01	41.09	41.09	40.42	40.44	0.00	0.00	41.02

Table 5-13: Available Nodal Demands for South Phase Sub-Network

	Available Demand (m^3/day)									
Demand Node	**a closed**	**b + d closed**	**c + g closed**	**n + q closed**	**p + r closed**	**b + c + e closed**	**b + e + g closed**	**b + f + i closed**	**c + d + e closed**	**c + h + l closed**
10	0.00	0.00	69.76	70.00	70.00	68.00	68.03	0.00	0.00	69.64
7	0.00	0.00	123.37	124.00	124.00	119.65	119.78	0.00	0.00	0.00
4	0.00	0.00	0.00	62.00	62.00	58.39	0.00	0.00	0.00	0.00
3	0.00	0.00	114.00	114.00	114.00	0.00	0.00	0.00	113.95	114.00
2	0.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00	57.00
1	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00	62.00
11	0.00	0.00	77.27	0.00	77.47	75.81	75.86	0.00	0.00	77.19
12	0.00	0.00	113.63	113.95	114.00	111.00	111.09	0.00	0.00	113.50
13	0.00	0.00	132.55	132.94	0.00	129.33	129.44	0.00	0.00	132.39
8	0.00	0.00	9.97	10.00	10.00	9.80	9.80	0.00	0.00	9.97
5	0.00	0.00	113.74	114.00	114.00	111.89	111.93	112.99	0.00	113.74
9	0.00	0.00	61.82	62.00	62.00	60.50	60.54	0.00	0.00	61.75
6	0.00	0.00	75.77	76.00	76.00	74.03	74.09	0.00	0.00	75.80

Based on the available pressure head at nodes as presented in table 5-12, segment ‘a’ and the combined segments {b,d}, {b,f,i}, and {c,d,e} are observed to disconnect the network causing zero pressure heads at greater number of nodes. Hence these kind of segments or the segment combinations are the most crucial in the south phase network and need to be monitored constantly to prevent the network failure. Table 5-13 illustrates the available demands as a result of available pressure heads at nodes.

After finding the available demands at all nodes, the hydraulic reliability of the selected north phase sub-network is calculated using equations 3-17 and 3-18, which is found to be equal to **0.6958.**

5.2.2.3 Integrated Network Reliability

As previously mentioned, the causes of failures are assumed and categorized in accordance with the total number of failures in the selected sub-network due to unavailability of such data.

In entirety, the number of failures occurred in the selected south phase sub-network are 75. Total number of failures caused due to structural/mechanical reasons are 41 which constitutes 54.67% of total failures, whereas hydraulic failures are enumerated to be 34, constituting 45.33% of total failures in the sub-network.

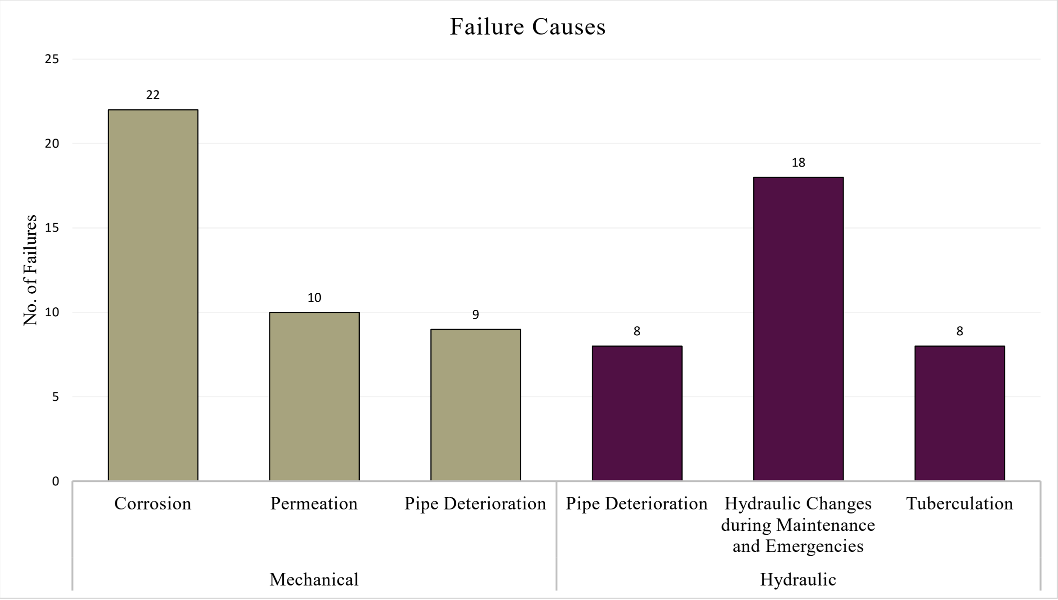


Figure 5-18: Causes of Failure in South Phase Sub-Network

Using equation 3-19, the integrated reliability of the north phase sub-network is assessed to be equal to **0.8446.**

5.2.3 Comparison of Results

The following observations/findings were recorded while implementing the developed research framework on the City of London. Two sub-networks having different sources of water were studied and the comparison of their results is presented herein.

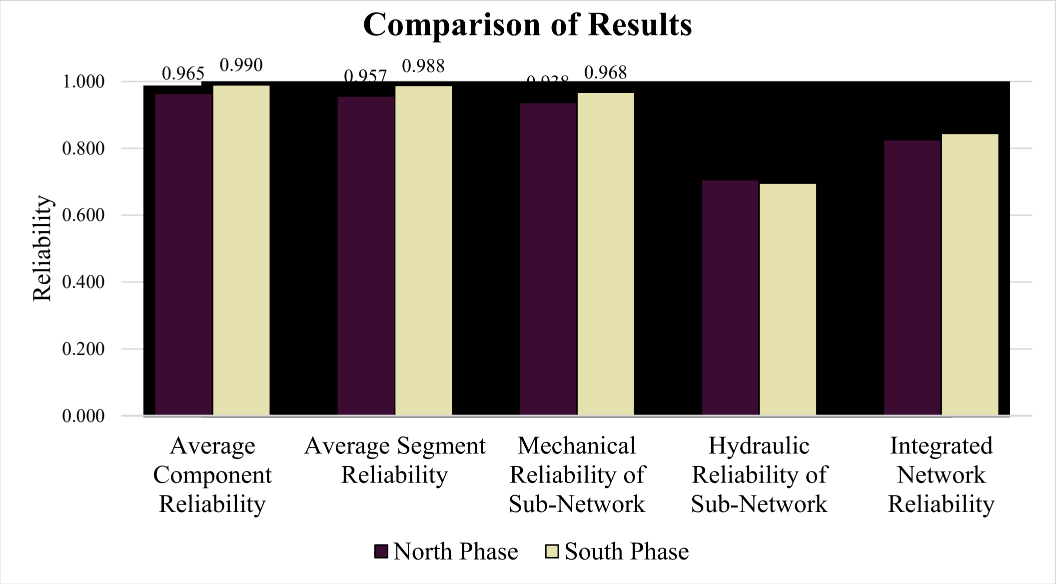


Figure 5-19: Comparison of Results

1. The segment connecting the source of water to the network is the most crucial segment of the network. In both the sub-networks, segment ‘a’ is identified as a minimum cut set for all demand nodes. Moreover, segment ‘a’ is found to cause zero pressure heads at all demand nodes when the hydraulic models of both the sub-networks are simulated, confirming the stated finding.

2. Although all the minimum cut sets are crucial segments in a network, few among them can be termed ‘more crucial’ than others. These segments/minimum cut sets are those which cause zero pressure heads at most of the demand nodes when hydraulic simulation

is run, indicating the effect/impact of disconnection caused by the minimum cut set. In the north phase sub-network, minimum cut sets {b,e,i} and {c,e,i} are identified to be most crucial whereas in south phase, {b,d}, {b,f,i} and {c,d,e} are found to be the most crucial segments/minimum cut sets than others.

3. From figure 5-19, the following comparisons are drawn.

(i) The average reliability of the component in the south phase sub-network is found greater than the north phase. This can be attributed to the age of components and relatively less number of failures in the network.

(ii) The newer components in the south phase sub-network results in greater average reliability of segments in the south phase.

(iii) The mechanical reliability of the south phase sub-network is calculated to be greater than the north phase, representing higher structural efficiency. This is because of the components encompassing the south phase sub-network, which are relatively new and has less number of failures.

(iv) Albeit the south phase sub-network consists of newer components than the north phase, the hydraulic reliability of both the networks is found to be nearly equal. This is because the demand nodes in north phase are strongly connected i.e. they have more alternate ways of receiving water in case of a segment failure, hence the impact of failure is less than that in the south phase. This explains that the structure/configuration of the network also plays an important role in affecting the network reliability.

(v) The integrated network reliability indicates that the south phase sub-network is more reliable. Therefore, the north phase sub-network takes the priority when scheduling the rehabilitation.

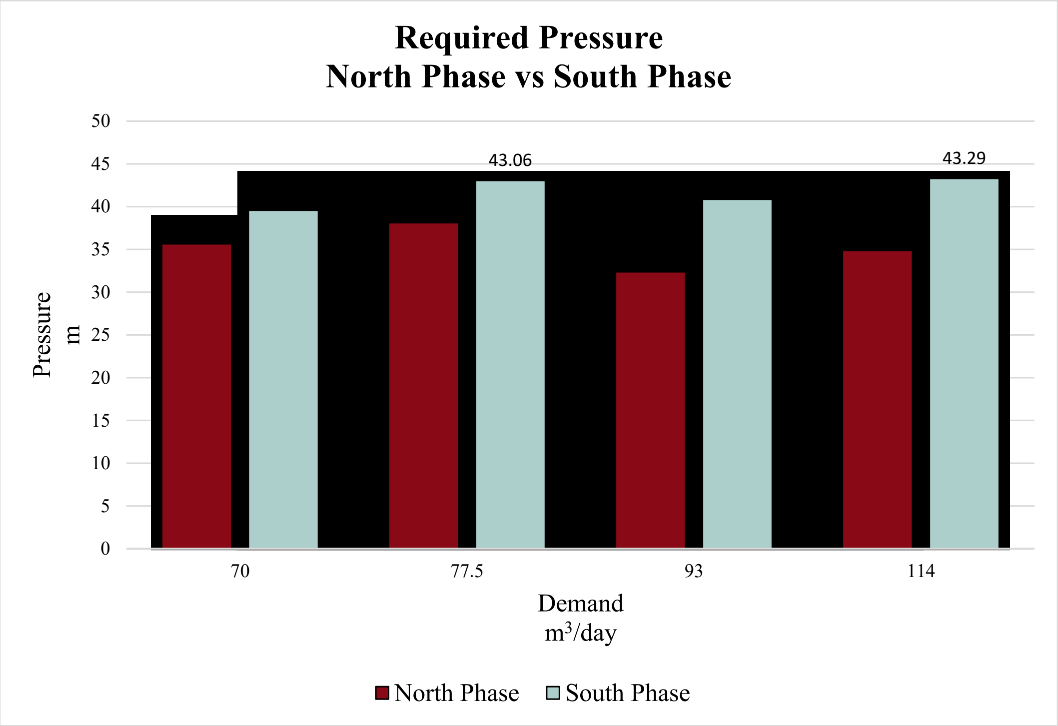


Figure 5-20: Comparison of Required Pressure Heads

4. From figure 5-20, it is evident that the south phase sub-network requires higher pressure than the north phase, to supply equal demands of water. The main rationale behind this is explained by the elevation profile of both networks (Provided in Appendix).

(i) The south phase sub-network is geographically located at a higher elevation than the source of water, and hence require higher pressure to supply the required water demand at nodes.

(ii) Whereas the north phase sub-network is located geographically at lower elevation than its source of water, and hence require less pressure than the south phase to supply the required demand at nodes. The water can be reached to the north phase by the action of gravity, and hardly requires any pumping operation.

5.2.4 Sensitivity Analysis

The sensitivity analysis is performed to study (1) the behavior of pipes with different lengths, and (2) the behavior of pipes with different diameters in north and south phases throughout their useful life. In the first case, the mechanical reliability of pipes is computed by keeping all the properties of network as constant except age and length. The computation is performed for pipes with varying lengths and the curves are constructed to represent their mechanical behavior as they deteriorate with age.

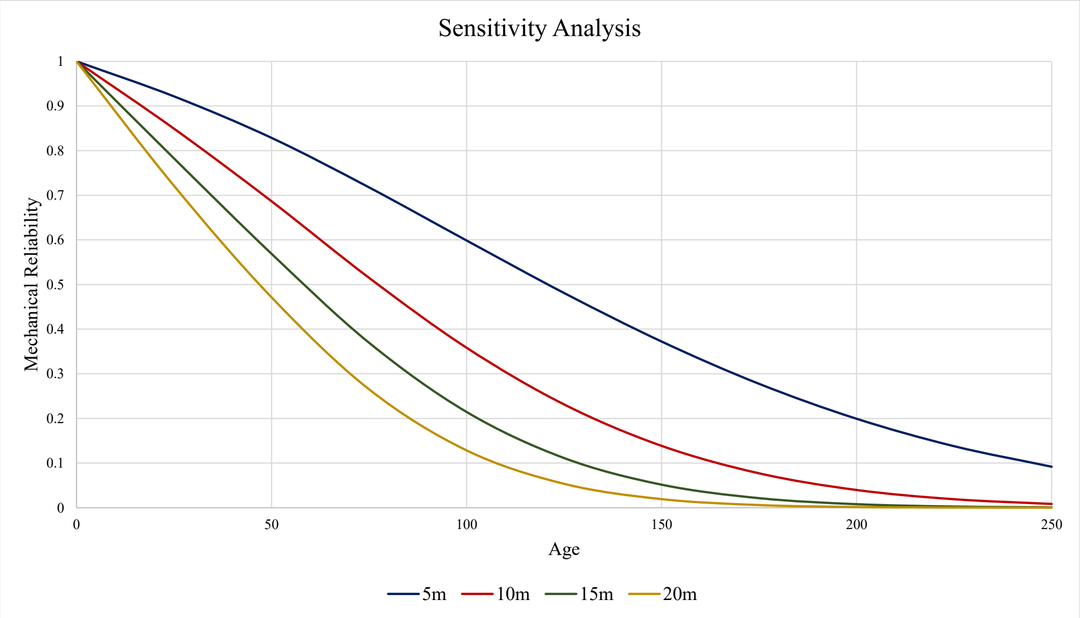


Figure 5-21: Sensitivity Analysis for Different Pipe Length

From figure 5-21, it is apparent that the shorter length pipes are mechanically more reliable than longer length pipes. It is observed that the 20m length pipe tend to fail earlier than 5m, 10m and 15m length pipes. Similarly, pipe of 15m length fails earlier than 10m and 5m pipes. This is because as the length of pipe increases, the failure tendency of a pipe increases, increasing the number of breaks and hence failure rate.

For the latter case, the constructed hydraulic models of both sub-networks are simulated in normal condition by keeping all the properties of network as constant except C factor and diameter. C factor is a numerical constant (namely Hazen William's Coefficient) which represents the amount of tuberculation in the pipe. As the pipe ages, it gets tuberculated reducing the value of C factor. Hence it is chosen as an indicator to represent the change in age of pipe.

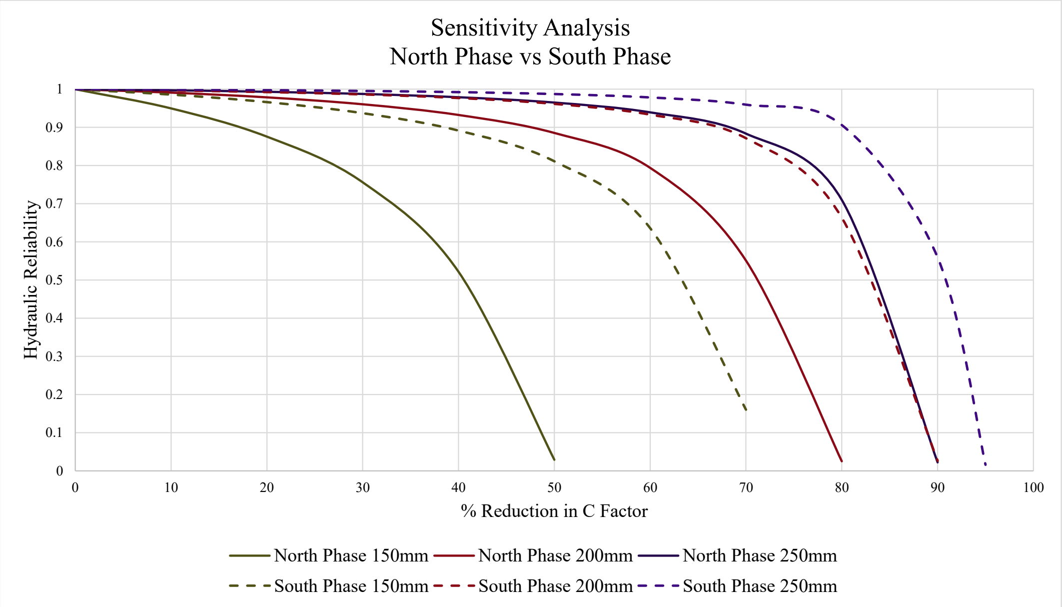


Figure 5-22: Sensitivity Analysis for Different Pipe Diameter

The same diameter pipe is simulated in normal condition by changing the C factor each time gradually reducing its value until the network fails hydraulically and in each case, the hydraulic reliability of the network is recorded. The procedure is repeated for different diameter pipes and the curves are constructed to represent their hydraulic behavior throughout their useful life using values of recorded hydraulic reliability.

From figure 5-22, it is apparent that the small diameter pipes are less reliable than larger diameter pipes. In both sub-networks, pipes with 150mm diameter tend to fail earlier than 200mm and 250mm. Similarly, pipes with 200mm diameter fails earlier than 250mm. This is because as the pipe ages, it gets more and more tuberculated and reduces the actual diameter of pipes resisting the flow of water through them. However, it should be noted that as the diameter of pipe gets increased, the failure tendency gets reduced and the pipes behave likewise. It can also be observed from figure 5-22 that the pipes with same diameter hydraulically performs better in south phase sub-network in normal condition conforming the earlier finding that the network encompassed with newer components is more reliable.

5.3 City of Doha

The developed model is also implemented on a sub-network of Qatar University, selected from the City of Doha as shown in figure 5-22. The location of demand nodes are assumed to aid in model implementation, and their respective elevation are derived using Google Earth Pro software. Based on these demand nodes, 14 segments are identified complying with their definition in this thesis.

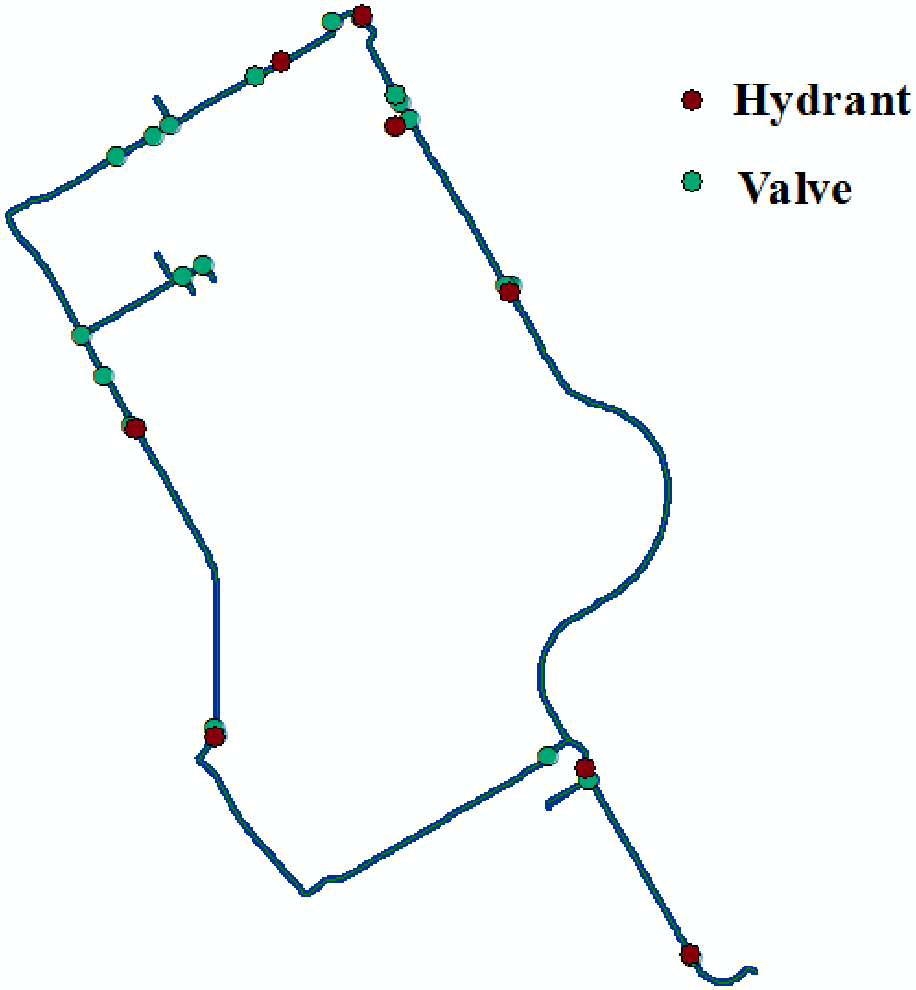


Figure 5-23: Qatar University Sub-Network Model (ArcMap 10.3.1)

5.3.1 Mechanical Reliability Model

Table 5-14 depicts the calculated reliability and failure probability of identified segments. The results reflect that the selected sub-network is newly constructed and has less number of failures, as the reliability of all segments is almost equal to 1.

Table 5-14: Segment Reliabilities and Failure Probabilities of Qatar University Sub-Network

Segment	Segment Reliability	Probability of failure of Segments
a	0.9944	0.0056
b	0.9952	0.0048
c	0.9931	0.0069
d	0.9942	0.0058
e	0.9943	0.0057
f	0.9950	0.0050
g	0.9926	0.0074
h	0.9938	0.0062
i	0.9949	0.0051
j	0.9946	0.0054
k	0.9957	0.0043
l	0.9958	0.0042
m	0.9946	0.0054
n	0.9938	0.0062

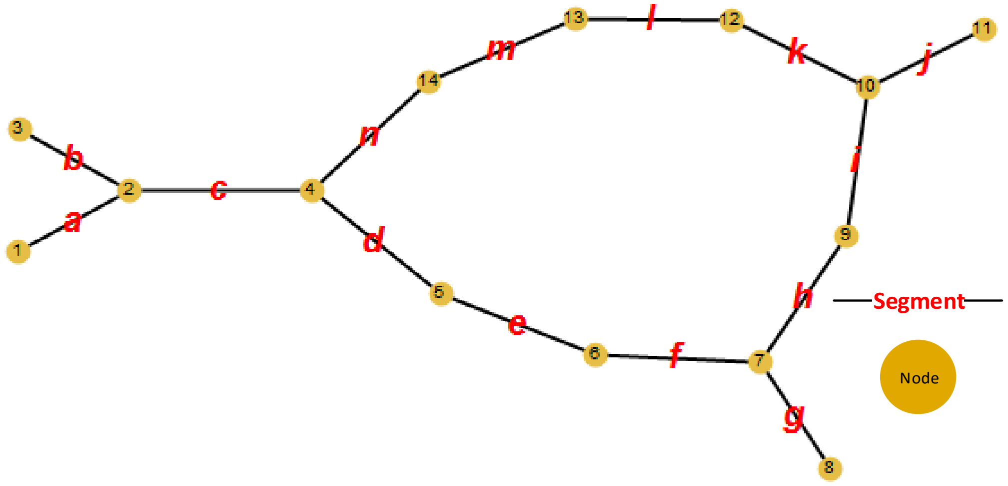


Figure 5-24: Qatar University Sub-Network Model (Mathematica 10.2)

Figure 5-23 depicts the selected Qatar University sub-network, constructed to analyze the network using minimum cut set method (Mathematica 10.2). Following the same procedure as applied for previous sub-networks, all the minimum cut sets are identified as shown in table 5-15. The highest order of cut set identified is two, and hence there are no third order cut sets.

Table 5-15: Minimum Cut Sets for Qatar University Sub-Network

Order of Cut Sets	List of Cut Sets
1	{a}, {b}, {c}, {g}, {j}
2	{d,e}, {d,f}, {d,h}, {d,i}, {d,k}, {d,l}, {d,m}, {d,n}, {e,f}, {e,h}, {e,i}, {e,k}, {e,l}, {e,m}, {e,n}, {f,h}, {f,i}, {f,k}, {f,l}, {f,m}, {f,n}, {h,i}, {h,k}, {h,l}, {h,m}, {h,n}, {i,k}, {i,l}, {i,m}, {i,n}, {k,l}, {k,m}, {k,n}, {l,m}, {l,n}, {m,n}

Applying the principle of minimum cut set method using equations 3-8 to 3-12, the mechanical reliability of the Qatar University sub-network is calculated to be **0.9689.**

5.3.2 Hydraulic Reliability Model

Figure 5-24 portrays the hydraulic model of the sub-network currently under consideration, and is labeled with the GIS IDs of the components whereas figure 5-25 demonstrates the nodal demand allocation. Note that, the total demand is calculated using the unit demand control center tool and is distributed among all nodes. Also, an additional demand (assumed) is added to each demand node to serve the hydrants.

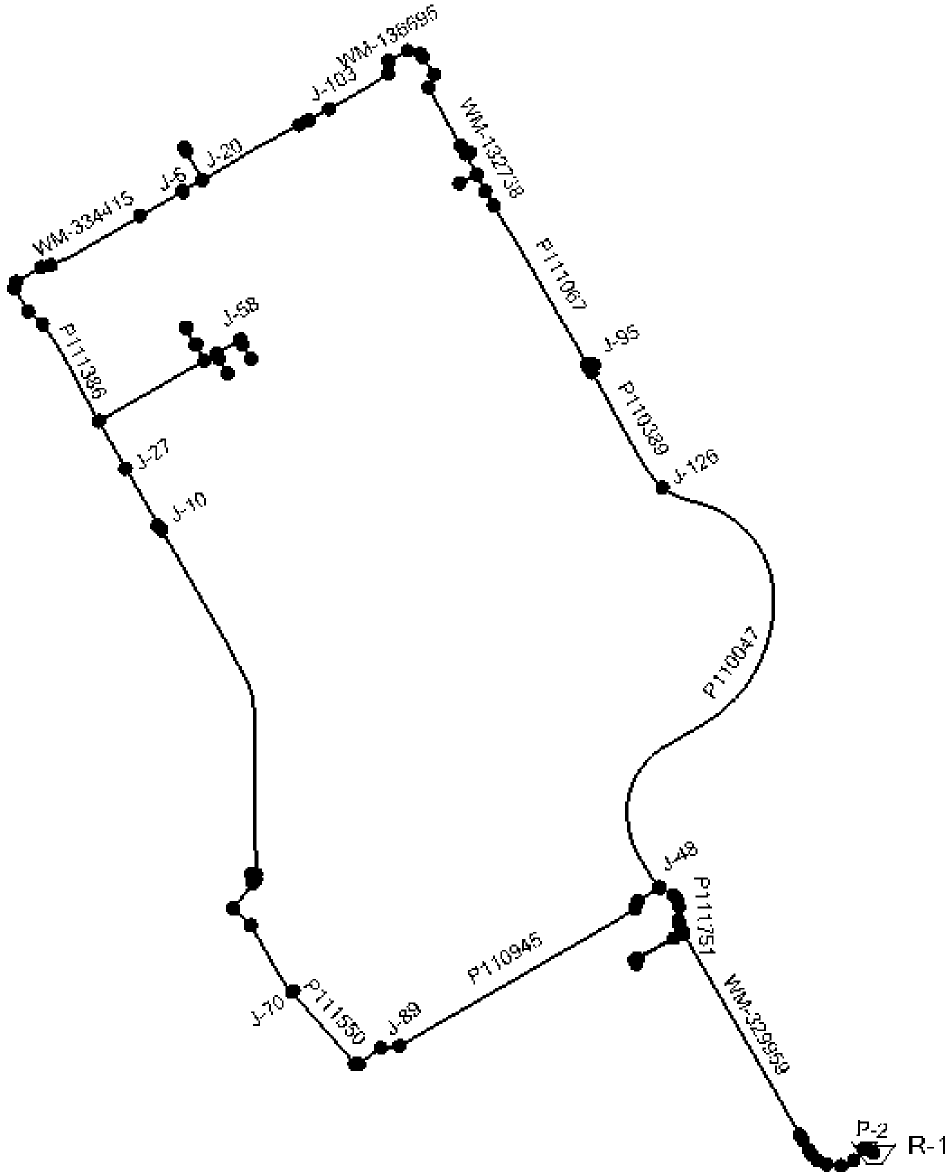
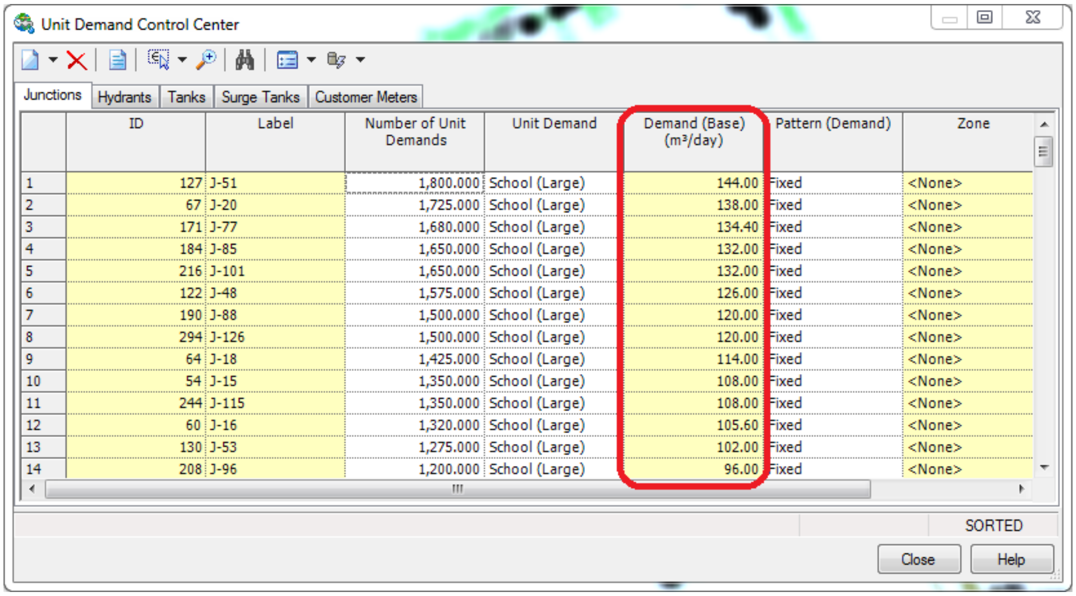


Figure 5-25: Qatar University Hydraulic Model (WaterCAD V8i)

After nodal demand allocation, the hydraulic network is simulated to get the service pressure heads at nodes which are required to satisfy the demands placed on nodes. Figure 5-26 depicts the simulated hydraulic model of the Qatar University sub network along with the direction of flow of water in normal condition.



Unit Demand Control Center

	ID	Label	Number of Unit Demands	Unit Demand	Demand (Base) (m³/day)	Pattern (Demand)	Zone
1	127	J-51	1,800.000	School (Large)	144.00	Fixed	<None>
2	67	J-20	1,725.000	School (Large)	138.00	Fixed	<None>
3	171	J-77	1,680.000	School (Large)	134.40	Fixed	<None>
4	184	J-85	1,650.000	School (Large)	132.00	Fixed	<None>
5	216	J-101	1,650.000	School (Large)	132.00	Fixed	<None>
6	122	J-48	1,575.000	School (Large)	126.00	Fixed	<None>
7	190	J-88	1,500.000	School (Large)	120.00	Fixed	<None>
8	294	J-126	1,500.000	School (Large)	120.00	Fixed	<None>
9	64	J-18	1,425.000	School (Large)	114.00	Fixed	<None>
10	54	J-15	1,350.000	School (Large)	108.00	Fixed	<None>
11	244	J-115	1,350.000	School (Large)	108.00	Fixed	<None>
12	60	J-16	1,320.000	School (Large)	105.60	Fixed	<None>
13	130	J-53	1,275.000	School (Large)	102.00	Fixed	<None>
14	208	J-96	1,200.000	School (Large)	96.00	Fixed	<None>

SORTED

Figure 5-26: Nodal Demand Allocation for Qatar University Sub-Network (WaterCAD V8i)

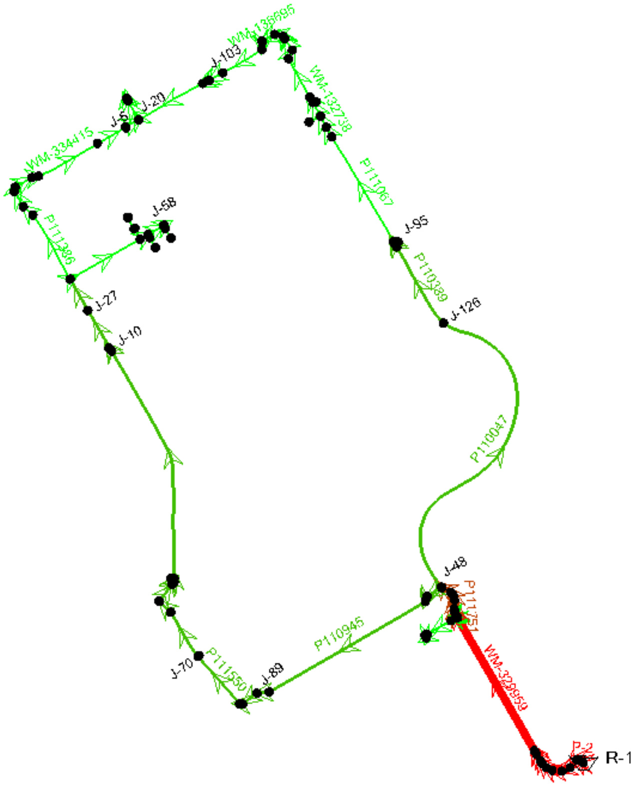


Figure 5-27: Hydraulic Simulation of Qatar University Sub-Network (WaterCAD V8i)

Figure 5-26 conforms to the observation made in previous sub-networks that the segment connecting the source of water to the network is the most crucial segment and need to be monitored constantly. Table 5-16 illustrates the service pressure heads obtained through hydraulic simulation of the sub-network in normal condition. These pressure heads are required to satisfy the nodal demands.

Table 5-16: Service Pressure Heads for Demand Nodes of Qatar University Sub-Network

Demand Node	GIS ID	Demand (m^3/day)	Pressure Head (m)
2	J-15	108.00	29.91
7	J-16	106.00	16.85
3	J-18	114.00	27.41
10	J-20	138.00	16.85
4	J-48	126.00	28.90
8	J-51	144.00	16.85
11	J-53	102.00	17.34
6	J-77	134.00	15.87
13	J-85	132.00	22.86
5	J-88	120.00	20.87
9	J-96	96.00	17.85
1	J-101	132.00	28.00
12	J-115	108.00	17.86
14	J-126	120.00	23.87

The actual/available pressure heads at demand nodes obtained through simulation in failure condition are as shown in table 5-17. These pressure heads are then formulated with pressure conditions using equations 3-13 to 3-16, for which the minimum and maximum pressure heads are assumed as **10m** and **40m** respectively for assessing the available demand at nodes. These assumptions are required to aid in model implementation due to lack of design data availability.

Table 5-17: Available Pressure Head at Demand Nodes of Qatar University Sub-Network

	Available Pressure Head (m)									
Demand Node	**a closed**	**b closed**	**c closed**	**g closed**	**j closed**	**d + e closed**	**d + f closed**	**d + h closed**	**d + i closed**	**d + k closed**
2	0.00	29.91	29.99	29.92	29.91	29.91	29.92	29.92	29.93	29.95
7	0.00	16.85	0.00	16.87	16.86	16.69	16.75	0.00	0.00	0.00
3	0.00	0.00	27.49	27.41	27.41	27.41	27.42	27.42	27.42	27.44
10	0.00	16.85	0.00	16.87	16.86	16.71	16.76	16.81	16.84	0.00
4	0.00	28.90	0.00	28.91	28.90	28.90	28.91	28.91	28.92	28.94
8	0.00	16.85	0.00	0.00	16.86	16.69	16.75	0.00	0.00	0.00
11	0.00	17.34	0.00	17.35	0.00	17.19	17.24	17.29	17.33	0.00
6	0.00	15.87	0.00	15.88	15.87	15.69	0.00	0.00	0.00	0.00
13	0.00	22.86	0.00	22.88	22.87	22.77	22.81	22.84	22.86	22.91
5	0.00	20.87	0.00	20.89	20.88	0.00	0.00	0.00	0.00	0.00
9	0.00	17.85	0.00	17.87	17.86	17.70	17.75	17.80	0.00	0.00
1	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00
12	0.00	17.86	0.00	17.87	17.86	17.74	17.78	17.82	17.85	17.91
14	0.00	23.87	0.00	23.88	23.87	23.80	23.83	23.85	23.87	23.91

From table 5-17, segments ‘a’ and ‘c’ and the combined segments {d,h}, {d,i}, and {d,k} are observed to disconnect the network causing zero pressure heads at greater number of nodes. Hence these kind of segments or the segment combinations need to be monitored constantly to prevent the network failure. Table 5-18 illustrates the available demands as a result of available pressure heads at nodes.

Table 5-18: Available Nodal Demands for Qatar University Sub-Network

	Available Demand (m^3/day)									
Demand Node	**a closed**	**b closed**	**c closed**	**g closed**	**j closed**	**d + e closed**	**d + f closed**	**d + h closed**	**d + i closed**	**d + k closed**
2	0	108	108	108	108	108.00	108.00	108.00	108.00	108
7	0	106	0	106	106	104.75	105.22	0.00	0.00	0
3	0	0	114	114	114	114.00	114.00	114.00	114.00	114
10	0	138	0	138	138	136.58	137.09	137.60	137.90	0
4	0	126	0	126	126	126.00	126.00	126.00	126.00	126
8	0	144	0	0	140	142.31	142.95	0.00	0.00	0
11	0	102	0	102	0	100.95	101.30	101.65	101.93	0
6	0	134	0	134	134	131.93	0.00	0.00	0.00	0
13	0	132	0	132	132	131.54	131.74	131.90	132.00	132
5	0	120	0	120	120	0.00	0.00	0.00	0.00	0
9	0	96	0	96	96	95.08	95.39	95.69	0.00	0
1	132	132	132	132	132	132.00	132.00	132.00	132.00	132
12	0	108	0	108	108	107.17	107.45	107.72	107.93	108
14	0	120	0	120	120	119.70	119.83	119.91	120.00	120

After finding the available demands at all nodes, the hydraulic reliability of the Qatar University sub-network is evaluated using equations 3-17 and 3-18, which is found to be equal to **0.6775.**

5.3.3 Integrated Network Reliability

As discussed earlier, the causes of failures are assumed and categorized in accordance with the total number of failures in the selected sub-network due to unavailability of such data.

In entirety, the number of failures occurred in the Qatar University sub-network are 55. Total number of failures caused due to structural/mechanical reasons are 32 which constitutes 58.18% of total failures, whereas hydraulic failures are enumerated to be 23, constituting 41.82% of total failures in the sub-network.

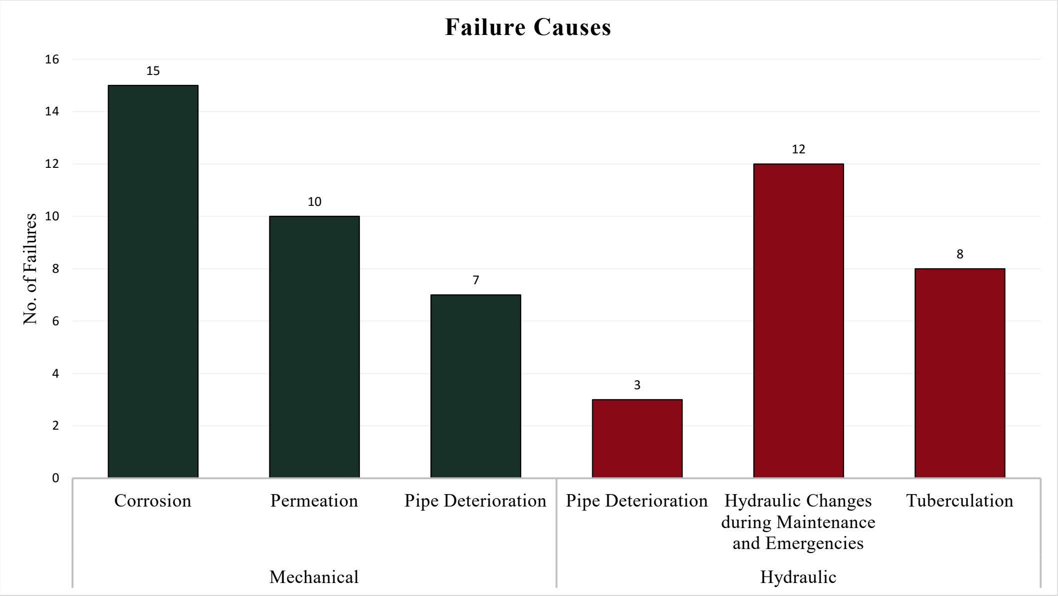


Figure 5-28: Causes of Failure in Qatar University Sub-Network

Using equation 3-19, the integrated reliability of the north phase sub-network is computed to be equal to **0.8471.**

5.4 Summary

In this chapter, the developed research framework is implemented on two case studies to demonstrate its exploitation. In the first case study, two sub-networks are selected based on their source of water supply and their corresponding data are extracted from ArcGIS. At first, the failure rate of all components is computed to aid in the evaluation of their reliabilities. Furthermore, the reliability and failure probability of segments is evaluated based on their components' composition. With failure probabilities of segments known, the following step is to perform minimum cut set analysis for evaluating mechanical reliability. For this purpose, the selected sub-network is constructed in Mathematica 10.2 and analyzed to derive path matrices of all demand nodes. These path matrices are modified in accordance with segment combinations to identify and enumerate all minimum cut sets, based on the formulation of which mechanical reliability of the sub-network is assessed.

After determining the mechanical reliability, the hydraulic model is constructed in WaterCAD V8i simulation engine by importing the shape files of the sub-network. The hydraulic model is then equipped with all the required data for the hydraulic simulation of a WDN in normal and failure conditions. The simulation results aid in obtaining the required as well as actual pressure head at demand nodes. The model is then formulated with pressure conditions to evaluate the available demand at demand nodes which in contrast to the required demand aids in predicting the hydraulic reliability of the sub network. Finally, the sub-network is assessed for integrated mechanical and hydraulic reliability based on failure causes.

The results of two sub-networks selected from the City of London, are compared to discuss the findings and draw the observations found common between them with the help of graphs. Additionally, sensitivity analysis is performed to study the behavior of pipe with contrasting diameters in different sub-networks throughout their useful life. The chapter concludes by extending the implementation of developed model to a sub-network selected from the City of Doha as a second case study, following the same procedure with required assumptions.

CHAPTER 6

Conclusions and Recommendations

6.1 Summary

Water distribution networks (WDNs) are complex interconnected networks that require extensive planning and maintenance to ensure good quality water is delivered to all consumers. They are vital part of urban infrastructure and require high investment, operation and maintenance costs. The main task of a WDN is to provide consumers with a minimum acceptable level of supply (in terms of pressure, availability, and water quality) at all times under a range of operating conditions (Mohammed et al., 2015). However, the water infrastructure in North America signifies an urgent need of upgrading the aging and deteriorating distribution systems if they are to continue to provide consumers with reliable and safe water supplies. In this context, this research is proposing a new reliability model for assessing the structural as well as hydraulic condition of a WDN to identify failure-prone components and prioritize their renewal.

The developed methodology is encompassed by the modeling aspects of mechanical reliability, hydraulic reliability, and integrated reliability assessment. The first model commences with the computation of the failure rate of all components which aid in the evaluation of their reliabilities. Proceeding further, the reliability and failure probability of segments is evaluated based on their components' composition. At this stage, the segments can be prioritized for rehabilitation based on their reliability. With failure probabilities of segments known, the following step is to perform minimum cut set analysis for the purpose of which the selected sub-network is constructed in Mathematica 10.2 and analyzed to derive path matrices of all demand nodes. These path matrices are modified in accordance with segment combinations to identify and enumerate all minimum cut sets, based on the formulation of which mechanical reliability of the sub-network is assessed. To facilitate this tedious process, it has been coded in MATLAB R2013b programming environment along with the utilization of Wolfram Mathematica 10.2 and Microsoft Excel 2013.

After determining the mechanical reliability, the second model is initiated in an attempt to assess the hydraulic reliability of the sub-network. Aspired by this, the hydraulic model is constructed in WaterCAD V8i simulation engine by importing the shape files of the sub-network. The hydraulic model is then equipped with all the required data about components for the hydraulic simulation of a WDN in normal and failure conditions, the results of which aid in obtaining the required as well as actual pressure head at demand nodes. The model is then formulated with pressure conditions to calculate the available demand at demand nodes which in contrast to the required demand aids in predicting the hydraulic reliability of the sub network. Finally, the sub-network is assessed for integrated mechanical and hydraulic reliability based on types of failure causes. The integrated reliability of different sub-networks are then employed in prioritizing their rehabilitation.

Two case studies are presented to demonstrate the application of the developed framework and its expected contributions using data obtained from the Cities of London, Ontario and Doha, Qatar.

6.2 Conclusions

Following conclusions can be inferred from the development and implementation of proposed reliability model.

1. The mechanical reliability of a network encompassed by newer components with less number of failures is greater than that of other networks. It was found **0.9378** for the north phase and **0.9680** for the south phase sub-networks, representing the south phase as newer than north phase.
2. The structure/configuration of the network also plays an important role in affecting the overall network reliability. The hydraulic reliability of selected sub-networks from the City of London are found almost equal albeit the south phase sub-network is relatively new as compared to the north phase, conforming the current conclusion.
3. The elevation profile of the network affects its hydraulic performance. It is deduced by comparing the north and south phase sub-networks' pressure heads that are required for supplying equivalent demands of water. It is observed that the south phase sub-network is geographically located at a higher elevation than the source of water, and hence require higher pressure to supply the required water demand at nodes.
4. The segment connecting the source of water to the network is identified as the most crucial segment of the network. The failure of this segment disconnects the whole network from the source causing zero pressure heads at all demand nodes. The

results of minimum cut set analysis and the hydraulic simulation of selected sub-networks from both case studies provides a testimony to this conclusion.

5. Although all the minimum cut sets are crucial segments in a network, few among them can be termed ‘more crucial’ than others. These segments/minimum cut sets are those which cause zero pressure heads at most of the demand nodes when hydraulic simulation is run, indicating the effect/impact of disconnection caused by the minimum cut set. In the north phase sub-network, minimum cut sets {b,e,i} and {c,e,i} are identified to be most crucial whereas in south phase, {b,d}, {b,f,i} and {c,d,e} are found to be the most crucial segments/minimum cut sets than others.
6. The integrated network reliability of sub-networks decides the priority of their rehabilitation in a network. The results indicate that the south phase sub-network is more reliable. Therefore, the north phase sub-network takes the priority when scheduling the rehabilitation.

6.3 Research Contributions

The most significant contributions towards this research are listed as follows:

1. The reliability indices are provided at hierarchical levels of component, segment and network. This provides a room for prioritizing rehabilitation at all levels.
2. An integrated model is developed for assessing segment reliability based on its composition of pipes and accessories.
3. The algorithm of minimum cut set analysis of a network is extended to identify the minimum cut sets for all demand nodes i.e. to identify the pipes the failure of which will cause disconnection, for all demand nodes.

4. The process of analyzing a water distribution network for its mechanical reliability evaluation is automated to curtail its tediousness. It is coded in MATLAB R2013b programming environment along with the utilization of Wolfram Mathematica 10.2 and Microsoft Excel 2013.
5. The hydraulic reliability of a water distribution network is evaluated considering the effect of pressure in achieving required demands of water. Moreover, the hydraulic performance is evaluated based on simulation which improves its accuracy.
6. An integrated reliability assessment model is developed to evaluate the overall condition of a water distribution network accounting for structural as well as hydraulic performances.

6.4 Research Limitations

The developed methodology possesses some limitations which are summarized in the following list:

1. The proposed model requires a detailed historic break data of all the components including pipes. But many municipalities are not equipped to collect such detailed data.
2. The failure rate of pipes is computed based only on their age even though the failure can occur due to one or more factors such as the diameter, weather condition and the surrounding soil condition.
3. The reliability is assessed over the useful life of components without taking into consideration the effect of rehabilitation.

4. The accuracy of the hydraulic model depends on the accuracy of the data used to build it. It requires detailed attributes of components encompassing a water distribution network.
5. The hydraulic reliability is based on nodal demands that are calculated for an instant point of time whereas in reality, the demands change over a period of time affecting the hydraulic performance of a network.
6. An automated tool is not provided for implementing and validating the developed model. Rather the model is automated using coded scripts.

6.5 Recommendations for Future Work

Although the developed methodology has achieved the objective of this research in the form of integrated reliability assessment model, it still has some room for improvement. The recommendations for possible future work are summarized in two categories as follows:

6.5.1 Research Enhancement

1. Consider more factors to compute the failure rate of pipes. The failure rate prediction can be made more realistic by considering effective factors such as soil condition and diameter.
2. Develop a failure rate prediction model for water distribution network components other than pipes. It will enhance the computation of segment reliability and ultimately improves the accuracy of network reliability evaluation.

3. Enhance the developed model by considering the effect of rehabilitation. The reliability of water mains increase when they are rehabilitated. Therefore develop a dynamic reliability index to cover the properties of components throughout their lifecycle.
4. Develop a criticality model for studying the relation among different factors affecting the water main condition, and combine with the reliability model to prioritize the rehabilitation more accurately.
5. Investigate the nodal demands over a period of time for identifying the demand multipliers to consider running the hydraulic simulation in extended period mode.
6. Develop an automated tool for exploiting the developed research framework in implementing and validating the model. It will facilitate the users in employing this method without requiring them to perform enormous calculations.

6.5.2 Research Extension

1. The integrated reliability assessment model can be extended to also account for the evaluation of reliability related to water quality. This will eventually form a model than can predict all quantitative and qualitative aspects of a water distribution infrastructure.
2. The developed model can be supplemented with rehabilitation scheduling, budget allocation and life cycle cost models, ultimately forming a complete water assets management tool.
3. Moreover, the developed model can be integrated with reliability prediction models of sewer and road infrastructure by exploring and understanding interdependencies

among them. This will aid the municipalities to have a comprehensive overview of the city infrastructure condition.

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APPENDIX A: Data Collection

Components Data of Selected Sub-Networks

Table A-1: North Phase Sub-Network Component Data

Segment	Component	GIS IDs	No.of Failures	Age X (yrs)	Length (m)	Diameter (mm)	Start Node	End Node	Material	C Factor	Location X (m)	Location Y (m)
a	Pipe 1	L10500	0	84	153.33	100	N5775	N5796	CI	25	-	-
	Valve 1	V10122	N.A	N.A	N.A	100			N.A	N.A	478566.094	4761372
b	Pipe 1	L10477	0	2	189.03	150	N5796	N5795	CI	30	-	-
	Valve 1	V4972	N.A	N.A	N.A	150			N.A	N.A	478741.688	4761409
	Hydrant 1	H4286	N.A	N.A	N.A	N.A			N.A	N.A	478737.562	4761405.5
c	Pipe 1	L10479	0	93	117.97	150	N5795	N5794	CI	31	-	-
	Valve 1	V1961	N.A	N.A	N.A	150			N.A	N.A	478757.125	4761402.5
d	Pipe 1	L10419	0	91	113.78	150	N5794	N6088	CI	32	-	-
	Valve 1	V2558	N.A	N.A	N.A	150			N.A	N.A	478830.094	4761210
e	Pipe 1	L10183	0	84	4.92	150	N5796	N5992	CI	34	-	-
	Pipe 2	L10478	0	84	113.81	150			CI	34	-	-
	Valve 1	V4422	N.A	N.A	N.A	150			N.A	N.A	478579.062	4761333.5
f	Pipe 1	L10184	0	72	190.56	150	N5990	N5794	CI	40	-	-
	Valve 1	V6108	N.A	N.A	N.A	150			N.A	N.A	478781.219	4761295.5
	Valve 2	V10357	N.A	N.A	N.A	150			N.A	N.A	-	-
	Hydrant 1	H8101	N.A	N.A	N.A	N.A			N.A	N.A	478780.125	4761293.5
g	Pipe 1	L12929	0	96	164.14	150	N6091	N6088	CI	31	-	-
	Pipe 2	L12930	0	24	4.38	200			PVC	130	-	-
	Pipe 3	L12931	0	24	21.57	200			PVC	130	-	-
	Valve 1	V2196	N.A	N.A	N.A	150			N.A	N.A	478830.219	4761194.5
	Valve 2	V8929	N.A	N.A	N.A	200			N.A	N.A	478681.031	4761138.5
	Hydrant 1	H4408	N.A	N.A	N.A	N.A			N.A	N.A	478768.5	4761175.5
h	Pipe 1	L10115	0	91	112.52	150	N5990	N6091	CI	32	-	-
	Valve 1	V2573	N.A	N.A	N.A	150			N.A	N.A	478650.188	4761149
	Hydrant 1	H4398	N.A	N.A	N.A	N.A			N.A	N.A	478613.844	4761228

i	Pipe 1	L10476	0	16	1.90	150	N5796	N4210	CI	30	-	-
	Pipe 2	L12937	0	2	145.36	150			CI	30	-	-
	Pipe 3	L12935	0	24	128.52	150			DI	120	-	-
	Valve 1	V2686	N.A	N.A	N.A	150			N.A	N.A	478567.188	4761342.5
	Hydrant 1	H4287	N.A	N.A	N.A	N.A			N.A	N.A	478561.781	4761338.5
	Hydrant 2	H3614	N.A	N.A	N.A	N.A			N.A	N.A	478425.594	4761288.5
j	Pipe 1	L10348	0	67	271.75	150	N6096	N5992	CI	43	-	-
	Valve 1	V4377	N.A	N.A	N.A	150			N.A	N.A	478608.031	4761236
k	Pipe 1	L12934	0	25	272.11	200	N6098	N6091	PVC	130	-	-
	Hydrant 1	H3615	N.A	N.A	N.A	N.A			N.A	N.A	478642.25	4761126.5
	Hydrant 2	H3616	N.A	N.A	N.A	N.A			N.A	N.A	478532.906	4761085.5
	Hydrant 3	H3617	N.A	N.A	N.A	N.A			N.A	N.A	478429.125	4761046.5
l	Pipe 1	L12938	0	24	6.10	150	N4210	N6096	DI	120	-	-
	Pipe 2	L10345	2	67	115.83	150			CI	45	-	-
	Valve 1	V563	N.A	N.A	N.A	150			N.A	N.A	478324.312	4761240.5
	Hydrant 1	H8117	N.A	N.A	N.A	N.A			N.A	N.A	478355.438	4761155
m	Pipe 1	L12939	0	24	1.40	150	N4210	N6108	DI	120	-	-
	Pipe 2	L12940	0	24	16.40	100			DI	120	-	-
	Pipe 3	L12941	0	60	99.21	150			CI	47	-	-
	Pipe 4	L10305	2	62	131.26	150			CI	47	-	-
	Valve 1	V11024	N.A	N.A	N.A	150			N.A	N.A	478221.062	4761213
	Valve 2	V13360	N.A	N.A	N.A	150			N.A	N.A	478201.344	4761182.5
	Hydrant 1	H4399	N.A	N.A	N.A	N.A			N.A	N.A	478295	4761238.5
	Hydrant 2	H4410	N.A	N.A	N.A	N.A			N.A	N.A	478181.75	4761090
n	Pipe 1	L10316	0	65	116.03	150	N6096	N6098	CI	45	-	-
	Valve 1	V9052	N.A	N.A	N.A	N.A			N.A	N.A	478398.844	4761044.5
o	Pipe 1	L10314	0	62	93.20	150	N6094	N6096	CI	47	-	-
	Valve 1	V2612	N.A	N.A	N.A	150			N.A	N.A	478355.594	4761139.5
p	Pipe 1	L12933	0	25	5.52	200	N6100	N6098	PVC	130	-	-
	Pipe 2	L12932	0	91	89.43	150			CI	32	-	-
	Valve 1	V11653	N.A	N.A	N.A	200			N.A	N.A	478398.156	4761032
q	Pipe 1	L10309	0	60	28.00	150	N6108	N6094	CI	49	-	-
	Pipe 2	L10303	0	56	73.10	150			CI	53	-	-

	Valve 1	V3388	N.A	N.A	N.A	150			N.A	N.A	478185.375	4761075.5
r	Pipe 1	L10301	1	62	13.78	150	N6108	N6130	CI	47	-	-
	Pipe 2	L10307	2	62	114.45	150			CI	47	-	-
	Valve 1	V7829	N.A	N.A	N.A	150			N.A	N.A	478214.719	4760979.5
s	Pipe 1	L20466	0	47	211.20	150	N6131	N6108	DI	120	-	-
	Valve 1	V11217	N.A	N.A	N.A	150			N.A	N.A	478161.719	4761081.5
	Valve 2	V5677	N.A	N.A	N.A	150			N.A	N.A	478096.656	4760937
	Valve 3	V5847	N.A	N.A	N.A	150			N.A	N.A	478101.469	4760924
	Hydrant 1	H4411	N.A	N.A	N.A	N.A			N.A	N.A	478095.469	4761023.5
t	Pipe 1	L10318	0	70	114.59	150	N6100	N6094	CI	41	-	-
	Valve 1	V6649	N.A	N.A	N.A	150			N.A	N.A	478308.344	4761017
u	Pipe 1	L10311	0	91	100.74	150	N6130	N6100	CI	32	-	-
	Hydrant 1	H2830	N.A	N.A	N.A				N.A	N.A	478246.5	4760978.222
v	Pipe 1	L10274	0	91	28.39	150	N6131	N6130	CI	32	-	-
	Pipe 2	L10272	0	89	97.06	150			CI	32	-	-

Table A-2: South Phase Sub-Network Component Data

Segment	Component	GIS IDs	No. of Failures	Age X (yrs)	Length (m)	Diameter (mm)	Start Node	End Node	Material	C Factor	Location X (m)	Location Y (m)
a	Pipe 1	L2605	0	44	32.76	300	N11638	N11596	DI	120	-	-
b	Pipe 1	L2607	1	44	146.29	300	N11596	N11594	DI	120	-	-
	Valve 1	V8333	N.A	N.A	N.A	300			N.A	N.A	480634.812	4754736
c	Pipe 1	L2665	0	44	148.4	300	N11594	N11570	DI	120	-	-
	Hydrant 1	H6967	N.A	N.A	N.A	N.A			N.A	N.A	480623.094	4754754.5
d	Pipe 1	L21485	0	11	250.031	200	N16844	N11596	PVC	130	-	-
	Pipe 2	L20796	0	12	17.72	200			PVC	130	-	-
	Valve 1	V15500	N.A	N.A	N.A	200			N.A	N.A	480658.419	4754608.88
	Valve 2	V14987	N.A	N.A	N.A	200			N.A	N.A	480907.306	4754638.34
	Hydrant 1	H10685	N.A	N.A	N.A	N.A			N.A	N.A	480772.303	4754628.253
	Hydrant 2	H10686	N.A	N.A	N.A	N.A			N.A	N.A	480670.482	4754616.197
e	Pipe 1	L21484	0	11	252.097	200	N16849	N11594	PVC	130	-	-
	Pipe 2	L20803	0	12	15.822	200			PVC	130	-	-
	Valve 1	V15499	N.A	N.A	N.A	200			N.A	N.A	480632.565	4754752.863
	Valve 2	V14994	N.A	N.A	N.A	200			N.A	N.A	480883.46	4754782.486
	Hydrant 1	H10684	N.A	N.A	N.A	N.A			N.A	N.A	480753.861	4754773.078
f	Pipe 1	L20797	0	12	7.61	200	N16844	N16849	PVC	130	-	-
	Pipe 2	L21480	0	11	125.965	200			PVC	130	-	-
	Pipe 3	L20805	0	12	13.518	200			PVC	130	-	-
	Valve 1	V14988	N.A	N.A	N.A	200			N.A	N.A	480922.385	4754646.27
	Valve 2	V14996	N.A	N.A	N.A	200			N.A	N.A	480899.704	4754772.333
g	Pipe 1	L13129	0	23	267.1	200	N11570	N11569	PVC	130	-	-
	Valve 1	V209	N.A	N.A	N.A	200			N.A	N.A	480857.312	4754928.5
	Valve 2	V7987	N.A	N.A	N.A	200			N.A	N.A	480607.812	4754899
	Hydrant 1	H3556	N.A	N.A	N.A	N.A			N.A	N.A	480739.344	4754917.5

	Hydrant 2	H3555	N.A	N.A	N.A	N.A			N.A	N.A	480851.562	4754930.5
h	Pipe 1	L21481	0	11	144.616	200	N16849	N11569	PVC	130	-	-
	Pipe 2	L20804	0	12	4.306	200			PVC	130	-	-
	Valve 1	V15497	N.A	N.A	N.A	200			N.A	N.A	480874.581	4754913.868
	Valve 2	V14995	N.A	N.A	N.A	200			N.A	N.A	480897.205	4754786.941
i	Pipe 1	L20795	0	12	280.12	200	N16841	N16844	PVC	130	-	-
	Valve 1	V14986	N.A	N.A	N.A	200			N.A	N.A	481190.849	4754671.943
	Hydrant 1	H10408	N.A	N.A	N.A	N.A			N.A	N.A	481105.63	4754666.725
	Hydrant 2	H10409	N.A	N.A	N.A	N.A			N.A	N.A	480930.466	4754647.118
j	Pipe 1	L20802	0	12	279.223	200	N16846	N16849	PVC	130	-	-
	Valve 1	V14993	N.A	N.A	N.A	200			N.A	N.A	481167.192	4754816.233
	Hydrant 1	H10412	N.A	N.A	N.A	N.A			N.A	N.A	481081.125	4754810.588
	Hydrant 2	H10413	N.A	N.A	N.A	N.A			N.A	N.A	480905.615	4754791.201
k	Pipe 1	L20801	0	12	16.07	200	N16841	N16846	PVC	130	-	-
	Pipe 2	L21474	0	11	123.345	200			PVC	130	-	-
	Pipe 3	L20793	0	12	8.012	200			PVC	130	-	-
	Valve 1	V14992	N.A	N.A	N.A	200			N.A	N.A	481177.327	4754803.239
	Valve 2	V14984	N.A	N.A	N.A	200			N.A	N.A	481200.491	4754679.633
	Hydrant 1	H10680	N.A	N.A	N.A	N.A			N.A	N.A	481192.148	4754748.281
l	Pipe 1	L13130	0	23	272.56	200	N11569	N10333	PVC	130	-	-
	Pipe 2	L13131	0	23	8.71	200			PVC	130	-	-
	Valve 1	V8155	N.A	N.A	N.A	200			N.A	N.A	480877.312	4754931
	Hydrant 1	H3554	N.A	N.A	N.A	N.A			N.A	N.A	481013.75	4754949.5
m	Pipe 1	L21475	0	11	141.482	200	N16846	N10333	PVC	130	-	-
	Pipe 2	L20800	0	12	6.85	200			PVC	130	-	-
	Valve 1	V15493	N.A	N.A	N.A	200			N.A	N.A	481153.779	4754947.475
	Valve 2	V14991	N.A	N.A	N.A	200			N.A	N.A	481173.934	4754823.077
	Hydrant 1	H10681	N.A	N.A	N.A	N.A			N.A	N.A	481167.008	4754895.658
n	Pipe 1	L20792	0	12	270.032	200	N16836	N16841	PVC	130	-	-
	Valve 1	V14983	N.A	N.A	N.A	200			N.A	N.A	481468.025	4754704.8
	Hydrant 1	H10406	N.A	N.A	N.A	N.A			N.A	N.A	481462.219	4754710.373
	Hydrant 2	H10407	N.A	N.A	N.A	N.A			N.A	N.A	481283.991	4754687.155
o	Pipe 1	L20799	0	12	272.089	200	N16837	N16846	PVC	130	-	-

	Valve 1	V14990	N.A	N.A	N.A	200			N.A	N.A	481443.286	4754849.071
	Hydrant 1	H10410	N.A	N.A	N.A	N.A			N.A	N.A	481436.474	4754854.037
	Hydrant 2	H10411	N.A	N.A	N.A	N.A			N.A	N.A	481259.711	4754833.226
p	Pipe 1	L13132	0	23	199	200	N10333	N16839	PVC	130	-	-
	Pipe 2	L13128	0	62	64.59	150			CI	47	-	-
	Pipe 3	L20791	0	12	6.626	200			PVC	130	-	-
	Valve 1	V5202	N.A	N.A	N.A	200			N.A	N.A	481345.625	4754984
	Valve 2	V5707	N.A	N.A	N.A	150			N.A	N.A	481414.219	4754994.5
	Hydrant 1	H3553	N.A	N.A	N.A	N.A			N.A	N.A	481252.375	4754978
q	Pipe 1	L20788	0	12	146.371	200	N16836	N16837	PVC	130	-	-
	Valve 1	V14981	N.A	N.A	N.A	200			N.A	N.A	481469.535	4754706.22
r	Pipe 1	L20789	0	12	152.954	200	N16837	N16839	PVC	130	-	-
	Valve 1	V14982	N.A	N.A	N.A	200			N.A	N.A	481444.911	4754850.579
	Hydrant 1	H10405	N.A	N.A	N.A	N.A			N.A	N.A	481423.857	4754938.079

Table A-3: Qatar University Sub-Network Component Data

Segment	Component	GIS IDs	No.of Failures	Age X (yrs)	Length (m)	Diameter (mm)	Start Node	End Node	Material	C Factor	Location X (m)	Location Y (m)
a	Pipe 1	P110440	0	8	14.34	400	J-101	J-15	DI	130	-	-
	Pipe 2	P111886	0	8	5.60	400			DI	130	-	-
	Pipe 3	P111222	1	8	18.85	400			DI	130	-	-
	Pipe 4	P111221	0	8	20.11	400			DI	130	-	-
	Pipe 5	P112177	1	8	38.20	400			DI	130	-	-
	Pipe 6	P110535	0	8	3.96	400			DI	130	-	-
	Pipe 7	P111267	0	8	3.93	400			DI	130	-	-
	Pipe 8	P109984	0	8	2.28	400			DI	130	-	-
	Pipe 9	P110178	1	8	11.23	300			DI	130	-	-
	Pipe 10	P110460	0	8	12.34	300			DI	130	-	-
	Pipe 11	P111689	0	8	16.74	300			DI	130	-	-
	Pipe 12	WM-329959	0	8	289.54	300			DI	130	-	-
	Valve 1	V021462	1	8	N.A	300			N.A	N.A	228,162.80	401,495.53
	Hydrant 1	HD-128512	0	3	N.A	N.A			N.A	N.A	228,161.29	401,498.99
b	Pipe 1	WM-348467	0	4	51.61	300	J-15	J-18	HDPE	130	-	-
	Pipe 2	WM-333799	0	4	1.21	300			HDPE	130	-	-
	Pipe 3	WM-333801	0	4	1.74	250			HDPE	130	-	-
	Pipe 4	WM-333802	0	4	10.48	250			HDPE	130	-	-
	Pipe 5	WM-329869	0	8	0.49	250			DI	130	-	-
	Pipe 6	WM-329961	0	8	0.69	150			DI	130	-	-
	Pipe 7	WM-348918	0	4	0.38	150			DI	130	-	-
	Pipe 8	WM-348919	1	4	6.23	150			DI	130	-	-
	Pipe 9	WM-348920	1	4	54.41	150			HDPE	130	-	-
	Pipe 10	WM-348921	0	4	1.70	150			HDPE	130	-	-
	Pipe 11	WM-333694	0	4	13.04	150			HDPE	130	-	-

	Valve 1	SV-72405	1	4	N.A	150			N.A	N.A	228,015.94	401,749.26
	Valve 2	SV-72397	1	4	N.A	300			N.A	N.A	228,016.00	401,750.72
	Valve 3	SV-72406	1	4	N.A	300			N.A	N.A	228,015.43	401,751.49
	Valve 4	SV-72407	0	4	N.A	250			N.A	N.A	228,014.39	401,752.24
c	Pipe 1	P111651	1	8	18.53	300	J-23	J-48	DI	130	-	-
	Pipe 2	P110133	0	8	5.13	300			DI	130	-	-
	Pipe 3	P110046	0	8	1.23	300			DI	130	-	-
	Pipe 4	P111625	0	8	8.38	300			DI	130	-	-
	Pipe 5	P112334	1	8	8.64	300			DI	130	-	-
	Pipe 6	P110973	1	8	16.54	300			DI	130	-	-
	Pipe 7	P111751	0	8	3.30	300			DI	130	-	-
	Pipe 8	WM-329962	0	8	8.13	300			DI	130	-	-
	Hydrant 1	H011715	1	8	N.A	N.A			N.A	N.A	228,009.67	401,766.46
d	Pipe 1	P112024	0	8	4.54	300	J-48	J-88	DI	130	-	-
	Pipe 2	P110915	1	8	4.93	300			DI	130	-	-
	Pipe 3	P110945	1	8	340.52	300			DI	130	-	-
	Pipe 4	P110254	1	8	32.32	300			DI	130	-	-
	Pipe 5	P110249	0	8	23.23	300			DI	130	-	-
	Pipe 6	P111329	0	8	34.04	300			DI	130	-	-
	Pipe 7	P112123	0	8	5.42	300			DI	130	-	-
	Valve 1	V021170	1	8	N.A	300			N.A	N.A	227,957.22	401,785.94
e	Pipe 1	P111749	0	8	40.20	300	J-88	J-77	DI	130	-	-
	Pipe 2	P111550	0	8	118.86	300			DI	130	-	-
	Pipe 3	P111122	0	8	2.65	300			DI	130	-	-
	Pipe 4	P110396	0	8	98.09	300			DI	130	-	-
	Pipe 5	P110830	0	8	1.51	300			DI	130	-	-
	Pipe 6	P111488	0	8	3.60	300			DI	130	-	-
	Pipe 7	P110624	0	8	2.84	300			DI	130	-	-
	Pipe 8	P110533	1	8	29.66	200			DI	130	-	-
	Valve 1	V021082	1	8	N.A	300			N.A	N.A		
	Hydrant 1	H011677	1	8	N.A	N.A			N.A	N.A	227,478.48	401,812.15
f	Pipe 1	P111434	0	8	2.56	300	J-77	J-16	DI	130	-	-
	Pipe 2	P111773	0	8	4.73	300			DI	130	-	-

	Pipe 3	P110157	0	8	458.68	300			DI	130	-	-
	Pipe 4	P110127	1	8	0.32	300			DI	130	-	-
	Pipe 5	P111660	1	8	67.49	300			DI	130	-	-
	Pipe 6	P111383	0	8	5.54	300			DI	130	-	-
	Pipe 7	P110287	0	8	1.29	200			DI	130	-	-
	Pipe 8	P110842	0	8	0.36	200			DI	130	-	-
	Pipe 9	P110294	0	8	0.87	200			DI	130	-	-
	Pipe 10	P110505	0	8	81.18	200			DI	130	-	-
	Pipe 11	P110511	0	8	0.45	100			DI	130	-	-
	Pipe 12	P110965	0	8	5.94	100			DI	130	-	-
	Valve 1	V021326	0	8	N.A	200			N.A	N.A	227,476.60	401,824.18
	Valve 2	V021451	1	8	N.A	300			N.A	N.A	227,363.81	402,254.97
	Valve 3	V021363	1	8	N.A	100			N.A	N.A	227,358.36	402,258.98
	Valve 4	V021471	1	8	N.A	200			N.A	N.A	227,319.58	402,330.14
	Hydrant 1	H011644	1	8	N.A	N.A			N.A	N.A	227,365.19	402,252.81
g	Pipe 1	P111984	0	8	151.59	300	J-16	J-51	DI	130	-	-
	Pipe 2	P111480	0	8	1.53	300			DI	130	-	-
	Pipe 3	P110845	0	8	23.62	300			DI	130	-	-
	Pipe 4	P111870	0	8	5.95	300			DI	130	-	-
	Pipe 5	P111447	0	8	1.30	300			DI	130	-	-
	Pipe 6	P112271	0	8	34.19	200			DI	130	-	-
	Pipe 7	P111313	0	8	1.54	200			DI	130	-	-
	Pipe 8	P110497	0	8	1.10	200			DI	130	-	-
	Pipe 9	P110306	1	8	0.48	200			DI	130	-	-
	Pipe 10	P111437	0	8	0.49	200			DI	130	-	-
	Pipe 11	P112133	1	8	22.94	200			DI	130	-	-
	Pipe 12	P110884	0	8	17.13	200			DI	130	-	-
	Pipe 13	P111747	0	8	5.59	200			DI	130	-	-
	Pipe 14	P110399	0	8	0.37	200			DI	130	-	-
	Pipe 15	P006088	3	33	20.81	150			DI	130	-	-
	Pipe 16	P006083	4	33	22.21	150			DI	130	-	-
	Valve 1	V021090	1	8	N.A	300			N.A	N.A	227,286.61	402,389.56
	Valve 2	V021275	1	8	N.A	200			N.A	N.A	227,432.33	402,472.35

	Valve 3	V021206	0	8	N.A	200			N.A	N.A	227,462.01	402,490.32
h	Pipe 1	P112046	0	8	33.26	300	J-16	J-96	DI	130	-	-
	Pipe 2	P110412	0	8	8.24	300			DI	130	-	-
	Pipe 3	P111386	0	8	140.44	300			DI	130	-	-
	Pipe 4	P112174	0	8	23.91	300			DI	130	-	-
i	Pipe 1	P112288	1	8	1.22	300	J-96	J-20	DI	130	-	-
	Pipe 2	P110698	0	8	0.15	300			DI	130	-	-
	Pipe 3	P112297	0	8	0.06	300			DI	130	-	-
	Pipe 4	P112292	1	8	12.51	300			DI	130	-	-
	Pipe 5	P110275	1	8	36.20	300			DI	130	-	-
	Pipe 6	P110723	0	8	28.58	100			DI	130	-	-
	Pipe 7	WM-334320	0	4	0.37	100			DI	130	-	-
	Pipe 8	WM-334414	0	8	61.13	100			DI	130	-	-
	Pipe 9	WM-334415	0	8	127.49	80			DI	130	-	-
	Valve 1	SV-74964	0	4	N.A	150			N.A	N.A	227,337.64	402,645.31
	Valve 2	V021232	0	8	N.A	100			N.A	N.A	227,392.02	402,674.80
j	Pipe 1	P111297	0	8	3.58	100	J-20	J-53	DI	130	-	-
	Pipe 2	P112155	1	8	0.98	100			DI	130	-	-
	Pipe 3	P111338	1	8	0.39	100			DI	130	-	-
	Pipe 4	P111014	0	8	1.39	100			DI	130	-	-
	Pipe 5	P111787	0	8	40.93	100			DI	130	-	-
	Valve 1	V021098	0	8	N.A	100			N.A	N.A	227,414.93	402,690.40
k	Pipe 1	P111273	0	8	138.45	300	J-20	J-115	DI	130	-	-
	Pipe 2	P110492	0	8	10.88	300			DI	130	-	-
	Pipe 3	WM-130418	1	6	0.25	300			DI	130	-	-
	Pipe 4	WM-131014	1	6	2.75	300			DI	130	-	-
	Pipe 5	WM-131866	0	6	2.57	300			DI	130	-	-
	Pipe 6	WM-132275	0	6	26.20	300			DI	130	-	-
	Pipe 7	WM-130841	0	6	29.25	300			DI	130	-	-
	Pipe 8	WM-145974	0	6	85.49	300			DI	130	-	-
	Pipe 9	WM-146209	0	6	14.19	300			DI	130	-	-
	Pipe 10	WM-146248	1	6	17.87	300			DI	130	-	-
	Pipe 11	WM-146076	0	6	16.11	300			DI	130	-	-

	Pipe 12	WM-135277	0	6	0.44	300			DI	130	-	-
	Pipe 13	WM-136231	0	6	0.91	300			DI	130	-	-
	Pipe 14	WM-136695	0	6	26.91	300			DI	130	-	-
	Pipe 15	WM-307986	0	6	1.74	300			DI	130	-	-
	Pipe 16	WM-307399	0	4	0.54	300			DI	130	-	-
	Valve 1	SV-26338	0	6	N.A	300			N.A	N.A	227,648.38	402,838.84
	Valve 2	SV-22655	0	6	N.A	300			N.A	N.A	227,647.86	402,839.43
	Valve 3	SV-22919	0	6	N.A	300			N.A	N.A	227,689.71	402,843.88
	Valve 4	SV-67649	1	4	N.A	300			N.A	N.A	227,691.27	402,844.59
	Valve 5	A004254	0	7	N.A	80			N.A	N.A	227,535.86	402,758.67
	Hydrant 1	HD-11487	1	6	N.A	N.A			N.A	N.A	227,574.27	402,778.61
	Hydrant 2	HD-11613	1	6	N.A	N.A			N.A	N.A	227,688.51	402,845.77
l	Pipe 1	P111067	1	8	229.40	300	J-115	J-85	DI	130	-	-
	Pipe 2	P134882	0	8	21.17	300			DI	130	-	-
	Pipe 3	WM-133554	0	6	83.22	300			DI	130	-	-
	Pipe 4	WM-132738	0	6	29.29	300			DI	130	-	-
	Pipe 5	WM-133604	0	6	0.73	300			DI	130	-	-
	Pipe 6	WM-131022	1	6	2.97	300			DI	130	-	-
	Pipe 7	WM-131109	0	6	0.71	200			DI	130	-	-
	Pipe 8	WM-132898	0	6	0.58	200			DI	130	-	-
	Pipe 9	WM-146222	0	6	11.66	200			DI	130	-	-
	Pipe 10	WM-146135	0	6	23.20	200			DI	130	-	-
	Pipe 11	WM-138892	0	6	2.44	150			DI	130	-	-
	Pipe 12	WM-136696	0	6	0.43	150			DI	130	-	-
	Pipe 13	WM-136561	0	6	23.04	150			DI	130	-	-
	Valve 1	SV-22654	0	6	N.A	150			N.A	N.A	227,736.76	402,686.14
	Valve 2	SV-26983	0	6	N.A	150			N.A	N.A	227,757.43	402,695.63
	Valve 3	SV-22653	0	6	N.A	200			N.A	N.A	227,745.09	402,722.55
	Valve 4	AV-1050	0	6	N.A	150			N.A	N.A	227,737.84	402,732.57
	Hydrant 1	HD-11610	0	6	N.A	N.A			N.A	N.A	227,737.12	402,685.82
m	Pipe 1	P111991	1	8	7.31	300	J-85	J-126	DI	130	-	-
	Pipe 2	P110244	1	8	4.81	300			DI	130	-	-
	Pipe 3	P110072	0	8	1.16	300			DI	130	-	-

	Pipe 4	P112311	0	8	6.17	200			DI	130	-	-
	Pipe 5	P110389	0	8	168.85	200			DI	130	-	-
	Valve 1	V021198	0	8	N.A	200			N.A	N.A	227,902.72	402,459.05
	Valve 2	V021190	1	8	N.A	300			N.A	N.A	227,894.62	402,460.87
	Hydrant 1	H011668	1	8	N.A	N.A			N.A	N.A	227,902.43	402,449.73
n	Pipe 1	P110047	1	8	658.93	300	J-126	J-48	DI	130	-	-

Node Elevation Data

Table A-4: North Phase Sub-Network Node Elevation Data

Node (GIS IDs)	Location X (m)	Location Y (m)	Elevation (m)
N373	478317.062	4761255.5	240.70
N374	478397.781	4761031.5	240.90
N375	478681.906	4761138.5	240.35
N4209	478305.25	4761244.5	240.70
N4210	478318.375	4761256	240.70
N4211	478438.438	4761294	241.50
N5775	478520.531	4761489	241.90
N5794	478795.125	4761303	240.80
N5795	478753	4761413	241.50
N5796	478576.312	4761346	241.50
N5797	478574.531	4761345.5	241.50
N5978	478677.812	4761137	240.35
N5990	478617.406	4761234.5	240.90
N5992	478615.75	4761239	240.90
N6001	478320.562	4761250.5	240.70
N6088	478835.219	4761196.5	243.60
N6091	478657.625	4761129.5	239.70
N6094	478274.75	4761109	240.40
N6096	478361.938	4761142	239.70
N6098	478402.969	4761033.5	240.90
N6100	478313.938	4761001.5	240.90
N6102	478248.469	4761099.5	239.47
N6104	478212.375	4761209.5	239.80
N6106	478180.062	4761073.5	238.80
N6108	478175.219	4761086.5	238.80
N6129	478192.938	4760956.5	238.60
N6130	478219.562	4760966.5	238.60
N6131	478101.812	4760923	238.90

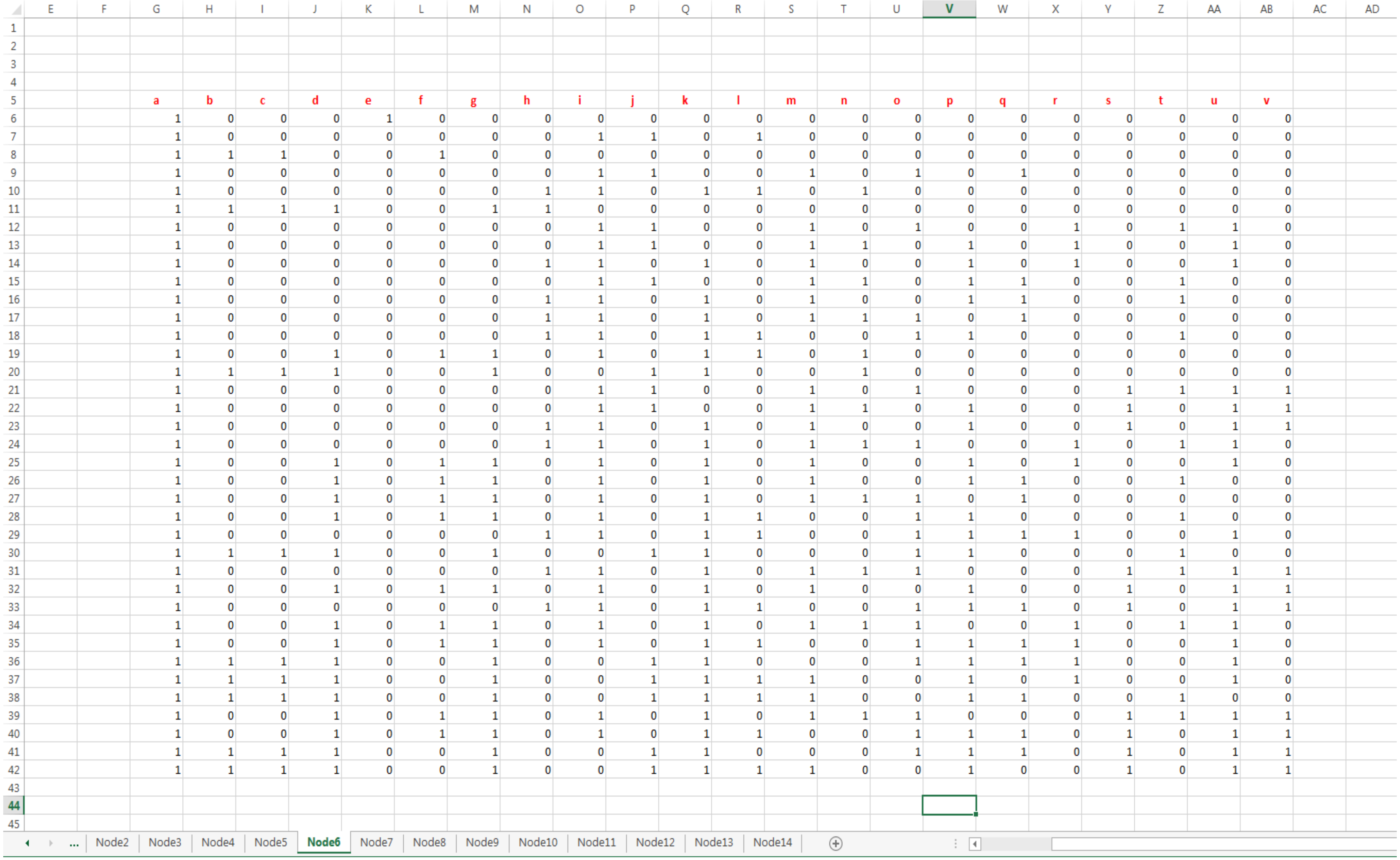
Table A-5: South Phase Sub-Network Node Elevation Data

Node (GIS IDs)	Location X (m)	Location Y (m)	Elevation (m)
N10326	481173.792	4754823.91	273.3
N10327	481410.719	4754996.005	277.2
N10333	481151.107	4754963.104	275.3
N10334	481142.44	4754962.276	275.55
N10412	481200.238	4754681.113	270.85
N11569	480871.752	4754930.407	277.028
N11570	480606.5	4754899	280.4
N11593	480881.97	4754782.289	273.64
N11594	480631.609	4754752.75	274.3
N11595	480905.827	4754638.087	271.6
N11596	480657.52	4754608.774	271.4
N11638	480663.156	4754576.5	273.1
N16836	481469.743	4754705.004	271.8
N16837	481445.132	4754849.291	274.34
N16839	481417.25	4754997.123	274.905
N16841	481201.588	4754673.216	270.9
N16842	480922.131	4754647.75	271.594
N16844	480923.415	4754640.249	271.6
N16845	481176.912	4754801.206	273.45
N16846	481174.947	4754817.155	273.3
N16847	480896.952	4754788.421	274
N16848	480899.957	4754770.853	271.462
N16849	480897.678	4754784.177	273.8
N342	481348.031	4754984	274

Table A-6: Qatar University Sub-Network Node Elevation Data

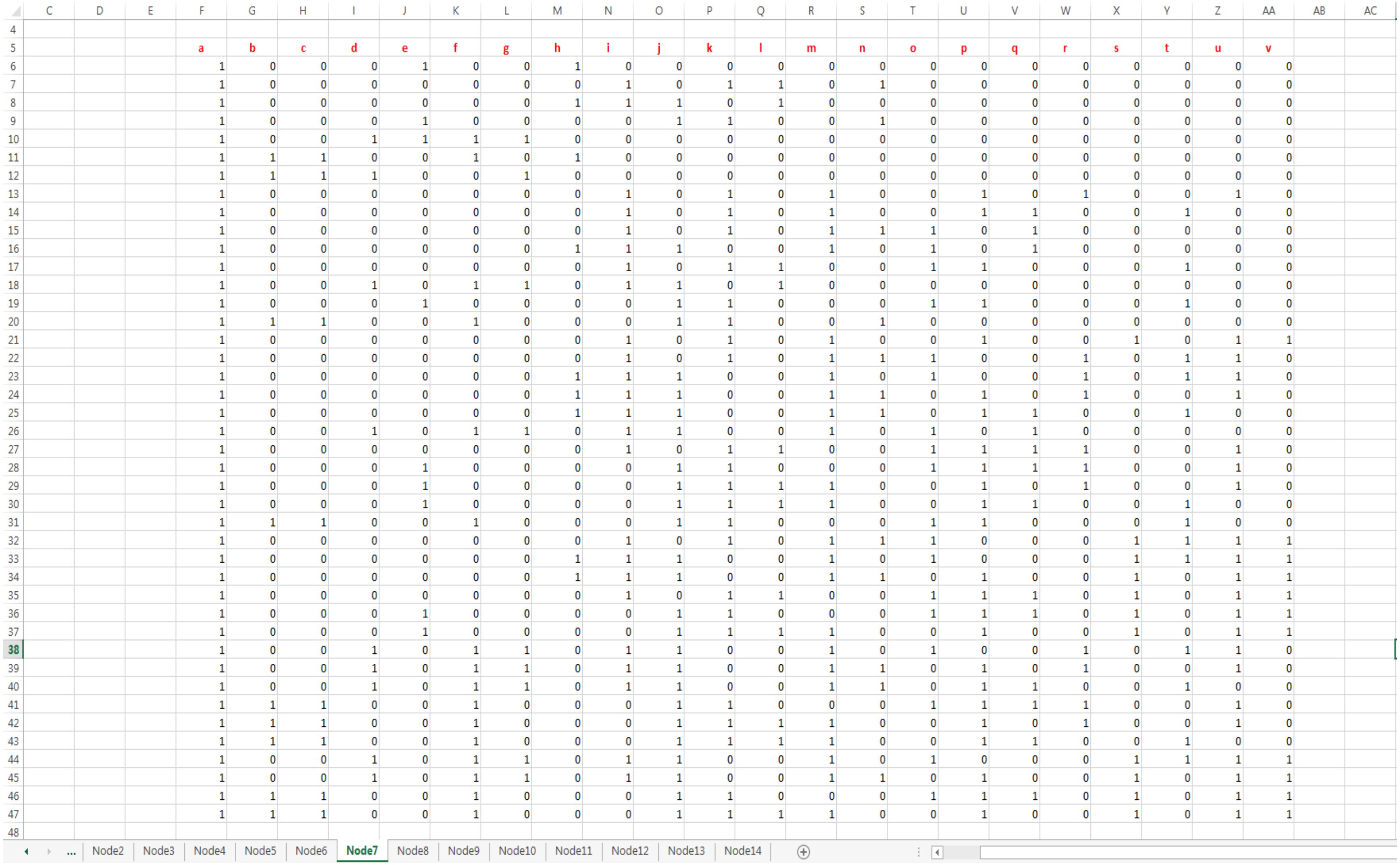
Node (GIS IDs)	Location X (m)	Location Y (m)	Elevation (m)
J-101	228,252.29	401,476.08	7
J-15	228,015.97	401,749.80	5
J-18	227,957.10	401,712.29	7.5
J-48	227,985.67	401,807.77	6
J-88	227,605.43	401,587.33	14
J-77	227,482.05	401,817.96	19
J-16	227,286.30	402,389.02	18
J-51	227,463.62	402,491.03	18
J-96	227,182.94	402,562.88	17
J-20	227,415.46	402,690.40	18
J-53	227,392.75	402,730.63	17.5
J-115	227,697.63	402,805.42	17
J-85	227,895.30	402,460.19	12
J-126	227,989.55	402,306.37	11

APPENDIX B: Sample Path Matrices



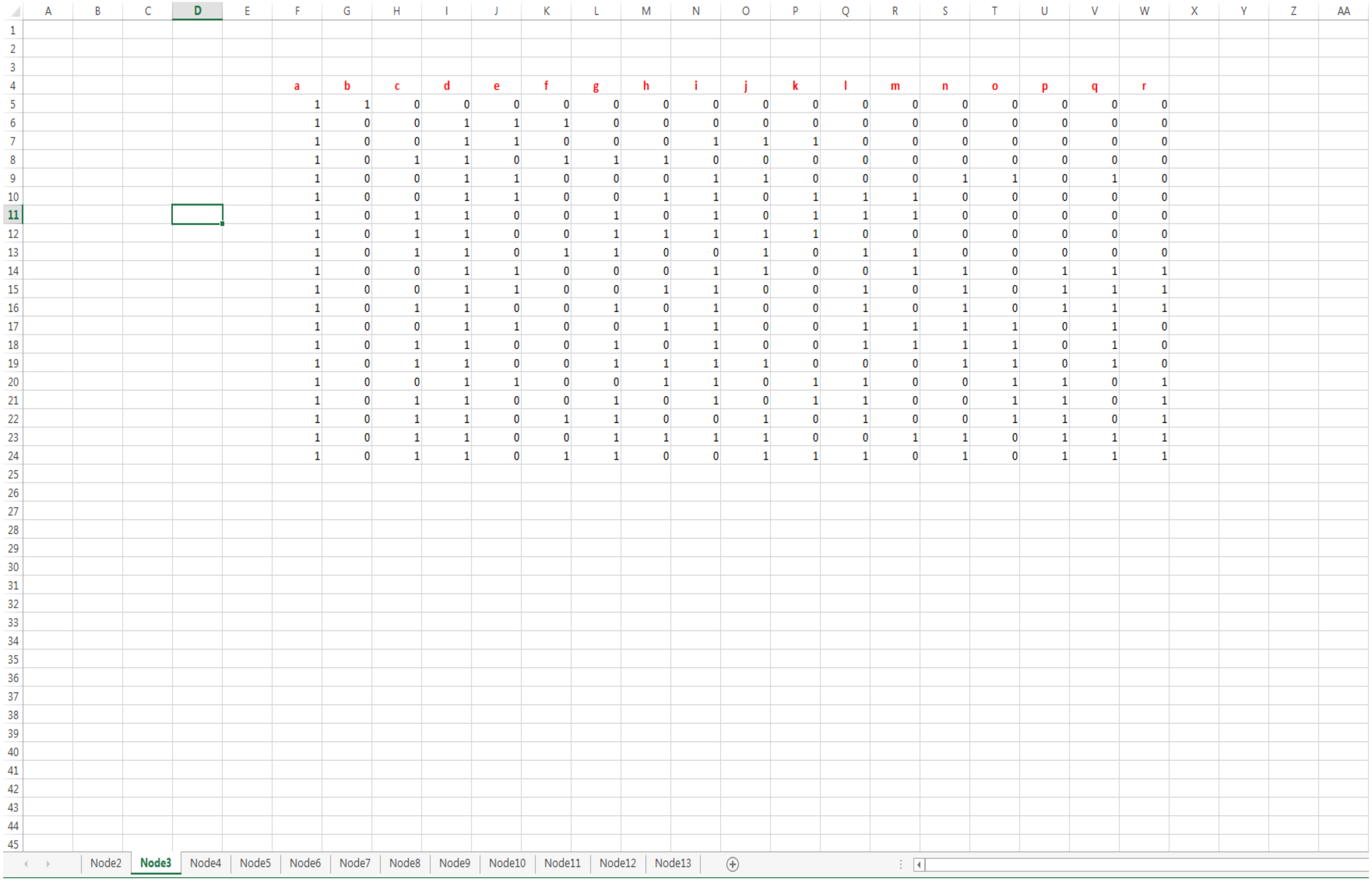
5	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v
6	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0
8	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	0	0	0	0	1	1	0	0	1	0	1	0	1	0	0	0	0	0
10	1	0	0	0	0	0	0	1	1	0	1	1	0	1	0	0	0	0	0	0	0	0
11	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	1	1	0	0	1	0	1	0	0	1	0	1	1	0
13	1	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1	0	1	0	0	1	0
14	1	0	0	0	0	0	0	1	1	0	1	0	1	0	0	1	0	1	0	0	1	0
15	1	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1	1	0	0	1	0	0
16	1	0	0	0	0	0	0	1	1	0	1	0	1	0	0	1	1	0	0	1	0	0
17	1	0	0	0	0	0	0	1	1	0	1	0	1	1	1	0	1	0	0	0	0	0
18	1	0	0	0	0	0	0	1	1	0	1	1	0	0	1	1	0	0	0	1	0	0
19	1	0	0	1	0	1	1	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0
20	1	1	1	1	0	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0
21	1	0	0	0	0	0	0	0	1	1	0	0	1	0	1	0	0	0	1	1	1	1
22	1	0	0	0	0	0	0	0	1	1	0	0	1	1	0	1	0	0	1	0	1	1
23	1	0	0	0	0	0	0	1	1	0	1	0	1	0	0	1	0	0	1	0	1	1
24	1	0	0	0	0	0	0	1	1	0	1	0	1	1	1	0	0	1	0	1	1	0
25	1	0	0	1	0	1	1	0	1	0	1	0	1	0	0	1	0	1	0	0	1	0
26	1	0	0	1	0	1	1	0	1	0	1	0	1	0	0	1	1	0	0	1	0	0
27	1	0	0	1	0	1	1	0	1	0	1	0	1	1	1	0	1	0	0	0	0	0
28	1	0	0	1	0	1	1	0	1	0	1	1	0	0	1	1	0	0	0	1	0	0
29	1	0	0	0	0	0	0	1	1	0	1	1	0	0	1	1	1	1	0	0	1	0
30	1	1	1	1	0	0	1	0	0	1	1	0	0	0	1	1	0	0	0	1	0	0
31	1	0	0	0	0	0	0	1	1	0	1	0	1	1	1	0	0	0	1	1	1	1
32	1	0	0	1	0	1	1	0	1	0	1	0	1	0	0	1	0	0	1	0	1	1
33	1	0	0	0	0	0	0	1	1	0	1	1	0	0	1	1	1	0	1	0	1	1
34	1	0	0	1	0	1	1	0	1	0	1	0	1	1	1	0	0	1	0	1	1	0
35	1	0	0	1	0	1	1	0	1	0	1	1	0	0	1	1	1	1	0	0	1	0
36	1	1	1	1	0	0	1	0	0	1	1	0	0	0	1	1	1	1	0	0	1	0
37	1	1	1	1	0	0	1	0	0	1	1	1	1	0	0	1	0	1	0	0	1	0
38	1	1	1	1	0	0	1	0	0	1	1	1	1	0	0	1	1	0	0	1	0	0
39	1	0	0	1	0	1	1	0	1	0	1	0	1	1	1	0	0	0	1	1	1	1
40	1	0	0	1	0	1	1	0	1	0	1	1	0	0	1	1	1	0	1	0	1	1
41	1	1	1	1	0	0	1	0	0	1	1	0	0	0	1	1	1	0	1	0	1	1
42	1	1	1	1	0	0	1	0	0	1	1	1	1	0	0	1	0	0	1	0	1	1

Figure B-1: North Phase Sub-Network Path Matrix for Node 6



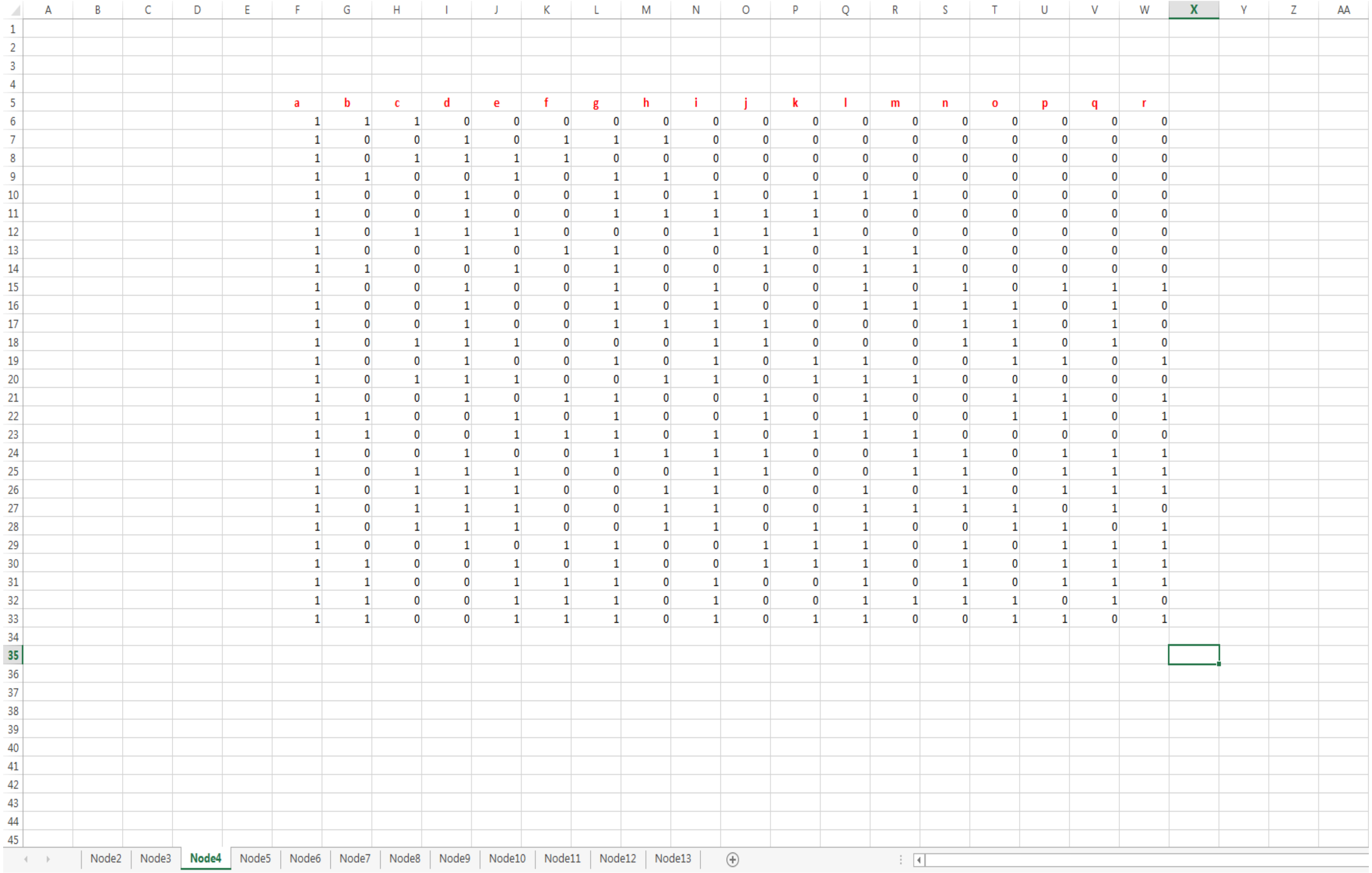
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s	t	u	v
6	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0
9	1	0	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0
10	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	1	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	1	1	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	1	0	1	0	0	1	0
14	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	1	1	0	0	1	0	0
15	1	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	1	0	0	0	0	0
16	1	0	0	0	0	0	0	1	1	1	0	0	1	0	1	0	1	0	0	0	0	0
17	1	0	0	0	0	0	0	0	1	0	1	1	0	0	1	1	0	0	0	1	0	0
18	1	0	0	1	0	1	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0
19	1	0	0	0	1	0	0	0	0	1	1	0	0	0	1	1	0	0	0	1	0	0
20	1	1	1	0	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0
21	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	1	0	0	1	0	1	1
22	1	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	0	1	0	1	1	0
23	1	0	0	0	0	0	0	1	1	1	0	0	1	0	1	0	0	1	0	1	1	0
24	1	0	0	0	0	0	0	1	1	1	0	0	1	1	0	1	0	1	0	0	1	0
25	1	0	0	0	0	0	0	1	1	1	0	0	1	1	0	1	1	0	0	1	0	0
26	1	0	0	1	0	1	1	0	1	1	0	0	1	0	1	0	1	0	0	0	0	0
27	1	0	0	0	0	0	0	0	1	0	1	1	0	0	1	1	1	1	0	0	1	0
28	1	0	0	0	1	0	0	0	0	1	1	0	0	0	1	1	1	1	0	0	1	0
29	1	0	0	0	1	0	0	0	0	1	1	1	1	0	0	1	0	1	0	0	1	0
30	1	0	0	0	1	0	0	0	0	1	1	1	1	0	0	1	1	0	0	1	0	0
31	1	1	1	0	0	1	0	0	0	1	1	0	0	0	1	1	0	0	0	1	0	0
32	1	0	0	0	0	0	0	0	1	0	1	0	1	1	1	0	0	0	1	1	1	1
33	1	0	0	0	0	0	0	1	1	1	0	0	1	0	1	0	0	0	1	1	1	1
34	1	0	0	0	0	0	0	1	1	1	0	0	1	1	0	1	0	0	1	0	1	1
35	1	0	0	0	0	0	0	0	1	0	1	1	0	0	1	1	1	0	1	0	1	1
36	1	0	0	0	1	0	0	0	0	1	1	0	0	0	1	1	1	0	1	0	1	1
37	1	0	0	0	1	0	0	0	0	1	1	1	1	0	0	1	0	0	1	0	1	1
38	1	0	0	1	0	1	1	0	1	1	0	0	1	0	1	0	0	1	0	1	1	0
39	1	0	0	1	0	1	1	0	1	1	0	0	1	1	0	1	0	1	0	0	1	0
40	1	0	0	1	0	1	1	0	1	1	0	0	1	1	0	1	1	0	0	1	0	0
41	1	1	1	0	0	1	0	0	0	1	1	0	0	0	1	1	1	1	0	0	1	0
42	1	1	1	0	0	1	0	0	0	1	1	1	1	0	0	1	0	1	0	0	1	0
43	1	1	1	0	0	1	0	0	0	1	1	1	1	0	0	1	1	0	0	1	0	0
44	1	0	0	1	0	1	1	0	1	1	0	0	1	0	1	0	0	0	1	1	1	1
45	1	0	0	1	0	1	1	0	1	1	0	0	1	1	0	1	0	0	1	0	1	1
46	1	1	1	0	0	1	0	0	0	1	1	0	0	0	1	1	1	0	1	0	1	1
47	1	1	1	0	0	1	0	0	0	1	1	1	1	0	0	1	0	0	1	0	1	1

Figure B-2: North Phase Sub-Network Path Matrix for Node 7



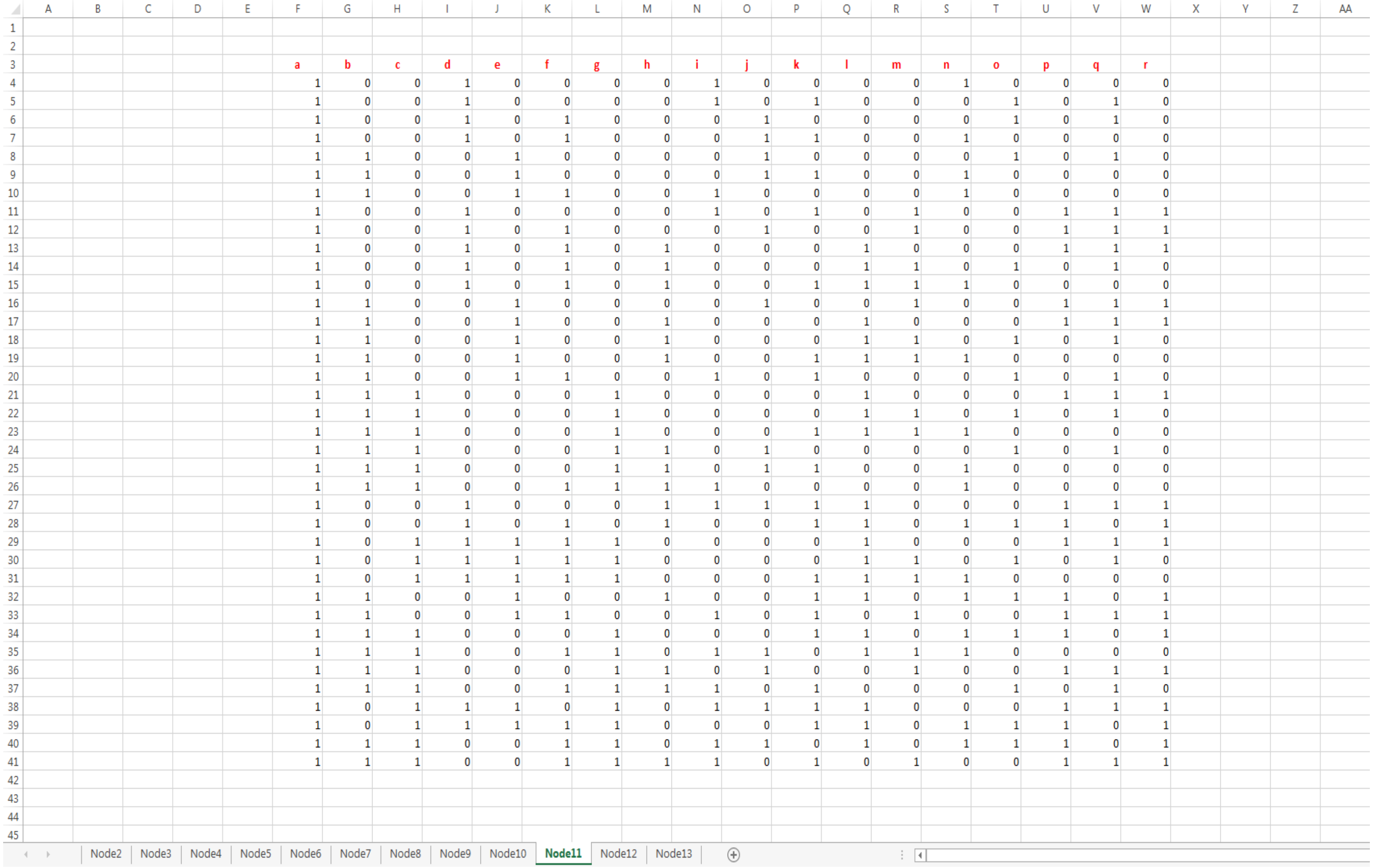
a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0
1	0	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	0	0	0	1	1	0	0	0	1	1	0	1	0
1	0	0	1	1	0	0	1	1	0	1	1	1	0	0	0	0	0
1	0	1	1	0	0	1	0	1	0	1	1	1	0	0	0	0	0
1	0	1	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0
1	0	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0	0
1	0	0	1	1	0	0	0	1	1	0	0	1	1	0	1	1	1
1	0	0	1	1	0	0	1	1	0	0	1	0	1	0	1	1	1
1	0	1	1	0	0	1	0	1	0	0	1	0	1	0	1	1	1
1	0	0	1	1	0	0	1	1	0	0	1	1	1	1	0	1	0
1	0	1	1	0	0	1	0	1	0	0	1	1	1	1	0	1	0
1	0	1	1	0	0	1	1	1	1	0	0	0	1	1	0	1	0
1	0	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	1
1	0	1	1	0	0	1	0	1	0	1	1	0	0	1	1	0	1
1	0	1	1	0	1	1	0	0	1	0	1	0	0	1	1	0	1
1	0	1	1	0	0	1	1	1	1	0	0	1	1	0	1	1	1
1	0	1	1	0	1	1	0	0	1	1	1	0	1	0	1	1	1

Figure B-3: South Phase Sub-Network Path Matrix for Node 3



	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r
6	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0
8	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
9	1	1	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0
10	1	0	0	1	0	0	1	0	1	0	1	1	1	0	0	0	0	0
11	1	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	0	0
12	1	0	1	1	1	0	0	0	1	1	1	0	0	0	0	0	0	0
13	1	0	0	1	0	1	1	0	0	1	0	1	1	0	0	0	0	0
14	1	1	0	0	1	0	1	0	0	1	0	1	1	0	0	0	0	0
15	1	0	0	1	0	0	1	0	1	0	0	1	0	1	0	1	1	1
16	1	0	0	1	0	0	1	0	1	0	0	1	1	1	1	0	1	0
17	1	0	0	1	0	0	1	1	1	1	0	0	0	1	1	0	1	0
18	1	0	1	1	1	0	0	0	1	1	0	0	0	1	1	0	1	0
19	1	0	0	1	0	0	1	0	1	0	1	1	0	0	1	1	0	1
20	1	0	1	1	1	0	0	1	1	0	1	1	1	0	0	0	0	0
21	1	0	0	1	0	1	1	0	0	1	0	1	0	0	1	1	0	1
22	1	1	0	0	1	0	1	0	0	1	0	1	0	0	1	1	0	1
23	1	1	0	0	1	1	1	0	1	0	1	1	1	0	0	0	0	0
24	1	0	0	1	0	0	1	1	1	1	0	0	1	1	0	1	1	1
25	1	0	1	1	1	0	0	0	1	1	0	0	1	1	0	1	1	1
26	1	0	1	1	1	0	0	1	1	0	0	1	0	1	0	1	1	1
27	1	0	1	1	1	0	0	1	1	0	0	1	1	1	1	0	1	0
28	1	0	1	1	1	0	0	1	1	0	1	1	0	0	1	1	0	1
29	1	0	0	1	0	1	1	0	0	1	1	1	0	1	0	1	1	1
30	1	1	0	0	1	0	1	0	0	1	1	1	0	1	0	1	1	1
31	1	1	0	0	1	1	1	0	1	0	0	1	0	1	0	1	1	1
32	1	1	0	0	1	1	1	0	1	0	0	1	1	1	1	0	1	0
33	1	1	0	0	1	1	1	0	1	0	1	1	0	0	1	1	0	1

Figure B-4: South Phase Sun-Network Path Matrix for Node 4



	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r
4	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
5	1	0	0	1	0	0	0	0	1	0	1	0	0	0	1	0	1	0
6	1	0	0	1	0	1	0	0	0	1	0	0	0	0	1	0	1	0
7	1	0	0	1	0	1	0	0	0	1	1	0	0	1	0	0	0	0
8	1	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	1	0
9	1	1	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0	0
10	1	1	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0
11	1	0	0	1	0	0	0	0	1	0	1	0	1	0	0	1	1	1
12	1	0	0	1	0	1	0	0	0	1	0	0	1	0	0	1	1	1
13	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0	1	1	1
14	1	0	0	1	0	1	0	1	0	0	0	1	1	0	1	0	1	0
15	1	0	0	1	0	1	0	1	0	0	1	1	1	1	0	0	0	0
16	1	1	0	0	1	0	0	0	0	1	0	0	1	0	0	1	1	1
17	1	1	0	0	1	0	0	1	0	0	0	1	0	0	0	1	1	1
18	1	1	0	0	1	0	0	1	0	0	0	1	1	0	1	0	1	0
19	1	1	0	0	1	0	0	1	0	0	1	1	1	1	0	0	0	0
20	1	1	0	0	1	1	0	0	1	0	1	0	0	0	1	0	1	0
21	1	1	1	0	0	0	1	0	0	0	0	1	0	0	0	1	1	1
22	1	1	1	0	0	0	1	0	0	0	0	1	1	0	1	0	1	0
23	1	1	1	0	0	0	1	0	0	0	1	1	1	1	0	0	0	0
24	1	1	1	0	0	0	1	1	0	1	0	0	0	0	1	0	1	0
25	1	1	1	0	0	0	1	1	0	1	1	0	0	1	0	0	0	0
26	1	1	1	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0
27	1	0	0	1	0	0	0	1	1	1	1	1	0	0	0	1	1	1
28	1	0	0	1	0	1	0	1	0	0	1	1	0	1	1	1	0	1
29	1	0	1	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1
30	1	0	1	1	1	1	1	0	0	0	0	1	1	0	1	0	1	0
31	1	0	1	1	1	1	1	0	0	0	1	1	1	1	0	0	0	0
32	1	1	0	0	1	0	0	1	0	0	1	1	0	1	1	1	0	1
33	1	1	0	0	1	1	0	0	1	0	1	0	1	0	0	1	1	1
34	1	1	1	0	0	0	1	0	0	0	1	1	0	1	1	1	0	1
35	1	1	1	0	0	1	1	0	1	1	0	1	1	1	0	0	0	0
36	1	1	1	0	0	0	1	1	0	1	0	0	1	0	0	1	1	1
37	1	1	1	0	0	1	1	1	1	0	1	0	0	0	1	0	1	0
38	1	0	1	1	1	0	1	0	1	1	1	1	0	0	0	1	1	1
39	1	0	1	1	1	1	1	0	0	0	1	1	0	1	1	1	0	1
40	1	1	1	0	0	1	1	0	1	1	0	1	0	1	1	1	0	1
41	1	1	1	0	0	1	1	1	1	0	1	0	1	0	0	1	1	1

Figure B-5: South Phase Sub-Network Path Matrix for Node 11