SHEHAB AHMED AL AMERI

A FRAMEWORK FOR ASSESSING ROBUSTNESS OF WATER NETWORKS AND COMPUTATIONAL EVALUATION OF RESILIENCE

SCHOOL OF WATER, ENERGY AND ENVIRONMENT (SWEE)
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THE THESIS IS SUBMITTED FOR THE AWARD OF PhD
Academic Year: 2012 - 2016

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Supervisor: Dr. David Parsons and Dr. Simon Jude
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ABSTRACT

Arid regions tend to take careful measures to ensure water supplies are secured to consumers, to help provide the basis for further development. The distribution network is the most expensive part of the water supply infrastructure and it must maintain performance during unexpected incidents. Many aspects of performance have previously been discussed separately, including reliability, vulnerability, flexibility and resilience. This study aimed to develop a framework to bring together these aspects as found in the literature and industry practice, and bridge the gap between them.

Semi-structured interviews with water industry experts were used to examine the presence and understanding of robustness factors. Thematic analysis was applied to investigate these and inform a conceptual framework including the component and topological levels. Robustness was described by incorporating network reliability and resiliency. The research focused on resiliency as a network-level concept derived from flexibility and vulnerability.

To utilise this new framework, the study explored graph theory to formulate metrics for flexibility and vulnerability that combine network topology and hydraulics. The flexibility metric combines hydraulic edge betweenness centrality, representing hydraulic connectivity, and hydraulic edge load, measuring utilised capacity. Vulnerability captures the impact of failures on the ability of the network to supply consumers, and their sensitivity to disruptions, by utilising node characteristics, such as demand, population and alternative supplies. These measures together cover both edge (pipe) centric and node (demand) centric perspectives.

The resiliency assessment was applied to several literature benchmark networks prior to using a real case network. The results show the benefits of combining hydraulics with topology in robustness analysis. The assessment helps to identify components or sections of importance for future expansion plans or maintenance purposes. The study provides a novel viewpoint overarching the gap between literature and practice, incorporating different critical factors for robust performance.

Keywords:

water, networks, robustness, resiliency, reliability, flexibility, vulnerability, connectivity, topology, graph theory, hydraulic load, hydraulic distance

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Chapter 1 Introduction and research overview

This chapter outlines the work context undertaken in this thesis. This chapter is divided into four sections. Section 1.1 presents an overview of the research challenges and motivations. In section 1.2, the aim and objectives of this research are presented, together with the research programme. Section 1.3 gives a summary of the intended contribution to knowledge attributed to this work. Finally, Section 1.4 outlines the structure of the thesis with a description of each chapter, providing a depiction of the thesis.

1.1 Overview of the Research Challenge

Developing countries in the Middle East consider water an important commodity for their progress. This is mainly because it is a scarce resource and it requires funding and planning support from the governments. These developing countries pursue economic development to raise their society's standard of living. A crucial part in raising the living standard for these societies is achieved by providing suitable economic and social conditions. This is relied on providing basic infrastructure to ensure adequate availability of resources such as water and electricity (House & Simonovic 1989). Water availability is a critical element in sustaining growth in different sectors of residential and industrial sectors, thus, governments have increased investments in water production technologies using desalination. Examples of these technologies are thermal production facilities and filtration systems (Herrmann et al. 1993) to substitute for the lack of water sources in the region.

These strategies have imposed some new challenges in distributing and providing access to desalinated water (Blokker et al. 2011; Perelman & Ostfeld 2011). The challenges are underlined when considering the water distribution networks constructed and their efficiency, showing instances of over-utilising or underutilizing some of these network assets. In some cases lack of overview may lead to redundancy in some network expansion projects or insufficient utilisation of these assets. Geographical coverage is required to provide accessibility to communities; hence, water network expansion plans needs to planned and operated successfully. This is achieved by constructing suitable infrastructure to supply customer required demands and to safeguard continuous service availability. The network coverage expansion increases the level of service expectation by residential, commercial, or industrial consumers'. Such expectation increases their dependence on these networks and these services. Therefore, increased dependence increases the pressure placed on utility companies to provide a secure supply to those end users.

The role of planning in any organisation is to detect the resources and assets available to meet demands and achieve a higher level of customer satisfaction, thus part of planning objectives is to enhance networks ability to anticipate surprises and crises. This objective demands that networks have embedded flexibility to adapt to changes while providing the management with sufficient control, fostering organisational learning that enable sector effectiveness (Ramanujam & Venkatraman 1987). Water planning can be complemented with a broader view for a more comprehensive understanding of the future and how to serve the demand targets. A broader view of different criteria in serving consumers and securing supply helps maintain a balanced view of the interactions between social, economic, and technical dynamics on end user (Liu et al. 2008). Therefore, investigating a framework to include desired factors during planning stage is crucial to design a network infrastructure with anticipated ability to cover and secure consumers supply during future circumstances.

Different alternatives to ensure continuity of supply in current water practices include asset duplication, contingency storages or enhanced maintenance regime. The selection from these different alternatives is dependent on the skills and experience of the practitioners and the management strategies. Structuring an approach to provide a robust design has faced many challenges; including the lack of agreement on a universal definition of what establishes network supply security and robustness, and challenges of dealing with complexities arising from different interactions between social, economic and technological interfaces. These interfaces can compromise the achievement of planning objectives when faced with unanticipated failures or incidents impacting the level of service to consumers. It has been highlighted the need for a systematic approach during the planning of water infrastructure projects and addressing the critical factors for enhancing network robustness (Yeo 1995). One of the complexities in water networks originates from the need to consider both the hydraulic operation and the topological coverage of distribution networks (Wright et al. 2014). Developing an approach to consider both these aspects should adopt a more robust network designs.

1.2 Overview of the Research outline (Aim, Objectives and Programme)

The aim of this research is

To build up a framework supporting an assessment approach to incorporate robustness measures in water networks.

The scope of the research is water distribution networks, excluding production facilities and desalination plants.

Five research objectives have been identified to realise the research aim:

Objective 1. Identify state-of-the-art literature on robustness in water network design
Objective 2. Establish the current practices in water companies
Objective 3. Compare concepts from the literature with the current planning practices of water companies in Abu Dhabi
Objective 4. Develop a conceptual water robustness design framework integrating the critical factors
Objective 5. Develop and test an assessment approach that utilises the framework in considering robustness in networks.

The research was organised in three phases covering the relevant factors of water network robustness, then compare these concepts and factors with what is available in practice. Finally, an assessment devised in line with the conceptual framework to address robustness characteristics in water networks. An overview of the thesis structure is summarised in Table 1-1.

The first phase covered the steps necessary to identify relevant factors contributing to planning of water networks and their parameters. It began with a literature review, which included a systematic analysis of the frequency of use of key terms and their relevant evolvement over time. Further analysis of the literature led to a preliminary robustness framework. A case study consisting of semi-structured interviews conducted in distribution companies was used to gather data on how robustness and other relevant factors are incorporated in water networks practices. This is synthesised and analysed using thematic analysis of the participants' responses.

Table 1-1 Alignment of research programme and thesis chapters with objectives

Activities	Chapters	Objectives
Literature review Analysis of current concepts related to robustness	3 4	1
Conducting pilot study and full case study in Abu Dhabi.	5	2
Synthesis of factors in literature and case study to establish robustness framework		3 & 4
New metrics for resilience	6	4 & 5
Demonstration of the new framework	7	5

The second phase started by comparing the results from the literature and case study practice for the factors used in designing robust water networks. A conceptual robust design framework was derived, highlighting the definitions and parameters proposed to develop the assessment of robustness in water networks. The assessment approach included metrics from topological properties (graph theory) integrated with hydraulics to reflect the requirements of robust designs and address different constraints in networks.

In the third phase the assessment method was tested on standard networks from the literature to demonstrate the methods and compare the results with previous studies. A real case study was performed using an Abu Dhabi distribution network to test and demonstrate the method on a realistic scale. The test cases were analysed to explore the strengths of the new approach and ensure that weaknesses are identified, presenting opportunities for future development.

1.3 Overview of research contribution

The term “robustness” can cover a broad range of concepts and it is loosely used to describe system ability to overcome incidents or failures. This can include different terms and concepts that suit a specific system; hence descriptions of the critical concepts need to be understood. The objective of this research is to construct a framework linking the different concepts available in literature including reliability, vulnerability, and resilience to build-up an approach to robustness in water network design.

The research is intended to contribute to research related to robustness as a design criterion in water distribution networks in three areas. Firstly, to provide new information on the way that robustness is seen in water industry practices, in Abu Dhabi in particular, and show that the academic definitions need restructuring to align them with water network practices. Secondly, to create a hierarchal design framework that combines the academic view of robustness with the industry. Thirdly, to implement this framework by using network theory and hydraulic properties information in new metrics to assess relevant factors of robust performance.

1.4 Thesis structure

This thesis includes 8 chapters. Thesis outline is presented to show the reader the thesis skeleton. A short description of each of these chapters is introduced:

Chapter 2	presents the industrial context of this research in the area of water distribution network designs and the presence of robustness as a design criterion. The chapter introduce the motivation of the research on water network robustness.
Chapter 3	describes the methods and results of reviewing factors relevant to robust performance in water networks in the academic literature. It

	shows the terms and factors considered to construct a view of a robust performance in water networks.
Chapter 4	develops the results of the literature review to give a theoretical evaluation of designing robust water networks. It concludes with the outline of an initial water robustness framework.
Chapter 5	describes the methods and results of a pilot study that informs the semi-structured interviews with industry experts. The results discuss different critical factors. A thematic analysis of the case study interview evaluated against the current robust design practices. Combining this with the result from Chapter 4 is done to create a new hierarchical design framework and act as a guideline for an assessment approach.
Chapter 6	describes an enhanced assessment approach to enable the incorporation of robustness definitions produced in this research. This approach is based on the synthesis of definitions of critical factors to produce robust design incorporating hydraulics and mathematically modelling that using complex network theory. The resulting metrics provide a mathematical representation of key factors in robustness. The approach is addressing resiliency as a critical factor of robustness.
Chapter 7	tests the new approach using several standard networks that have been addressed in previous literature studies for different design objectives. The results of the approach are then analysed to assess the interpretation of the results. The approach is then demonstrated on a real case study.
Chapter 8	discusses the key findings from the research and compared the approach against other earlier studies; also outline this research contribution to knowledge, limitations and recommendations for future work in this research area.

Chapter 2 Geographical and industrial context

This Chapter follows with a synopsis of the practice in the water sector represented by utility companies in United Arab Emirates (UAE) (Section 2.1). Challenges facing water infrastructure plans are discussed along with the forming of regulation body to support the rapid growth of water demand through the use of a robust design.

Section 2.3 addresses the need to have a better understanding of water distribution designs. This section also goes over how the current practices fall short of providing the necessary knowledge needed for decision makers to form an informed conclusion that suits future network plans.

2.1 Water sector background on Abu Dhabi in UAE

Water in the Arabian Gulf region is a scarce commodity that requires funding and support from the government. Arabian Gulf countries have made huge investments towards relieving water shortages caused by the low precipitation found in this part of the world. These investments have been made to sustain the rapid growth of the population associated with the economic vision of these oil rich countries (Kingsley 2011). Therefore, they invest portion of their abundance of fossil fuel wealth towards strengthening water and resource supplies.

This study is utilising the practices gained from water professionals in Abu Dhabi Emirate as a selected example of network emphasis on distribution. Abu Dhabi is the capital of the United Arab Emirates (UAE), located in the Middle East and can be shown in Figure 2-1. This region is characterised by its low water sources and sub-tropical conditions with high temperatures during summers reaching 48˚C with low rain precipitation of 12cm per year. Prior to the 1970’s, Abu Dhabi was an impoverished and under-developed society. Since the discovery of natural resources, the leadership was motivated towards a rapid economic transformation. This transformation turned the area from an underdeveloped country into a thriving city with modern infrastructures. This resulted in having to meet an increase in the demand for water (Kingsley 2011).

The fast increase in the overall population has increased the pressure on Abu Dhabi's public infrastructure reflecting the increased attractiveness and interest of the city (O'Brien et al. 2007).

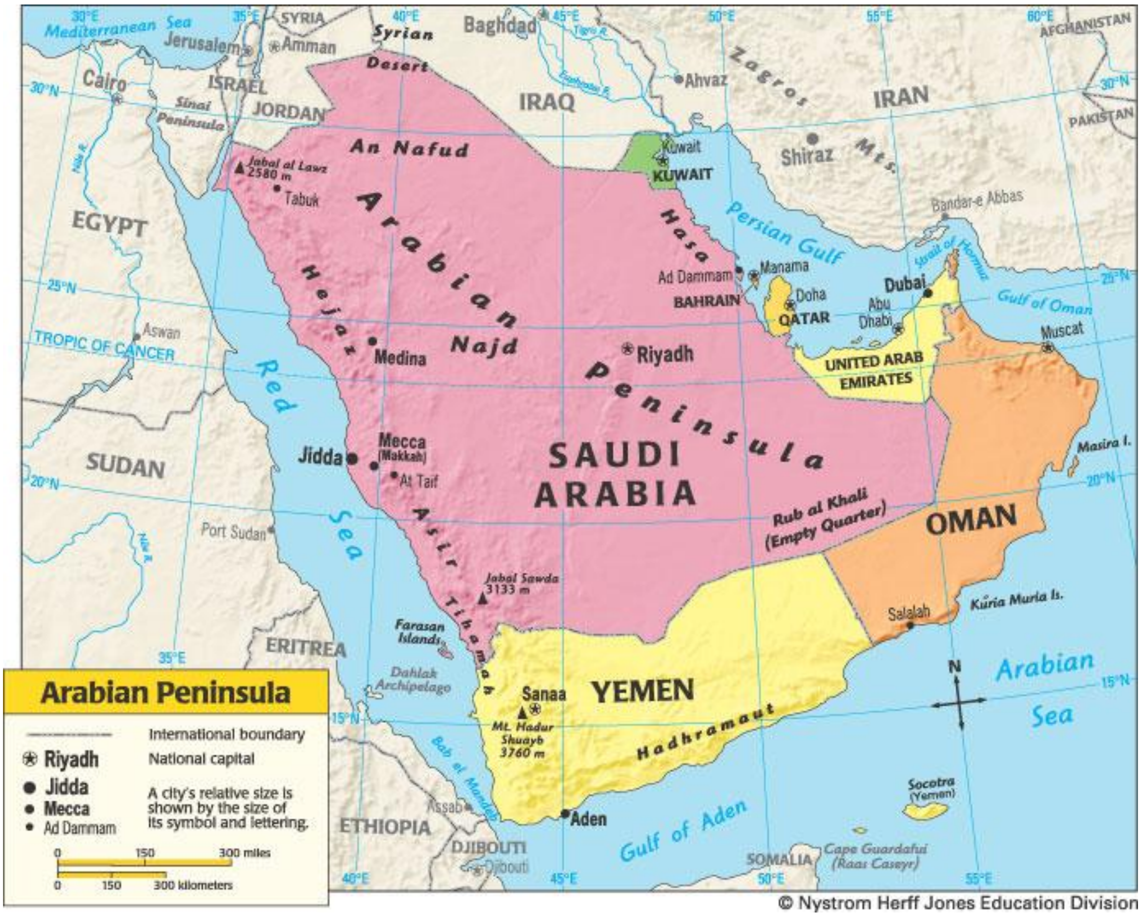

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Figure 2-1: Map of the Arabian Peninsula[1]

Abu Dhabi was selected as a case study due to the high investment in water infrastructure during recent years that was necessary to maintain the pace with the economic progress that the country has been experiencing. With desalination as the only resource for water, the need to distribute this water places a heavy burden on the government. The government has to identify and facilitate suitable designs to distribute the water to the communities. Such designs must maintain a continuous supply and avoid disturbance via robust designs that prolong network serviceability. Water consumption in Abu Dhabi

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[1] www.herffjonesnystrom.com/Information/Maps/images/ArabianPeninsula.jpg

was estimated as one of the highest water consumption per capita in the world ranging at 550litre/capita daily. This high consumption is due to high economical and societal development, alongside other reasons, reaching a water supply of 917 MIGD on 2012 (TRANSCO 2012) with a forecasted average growth rate of 3.5% annually. This high growth rate is corroborated by a high influx of expatriates to join the high development in the civil and commercial sectors. Finding means of reducing the impact of disturbances is pursued as a strategic effort. Another reason to select Abu Dhabi as a candidate is the advantage of exploring and acquiring the impacts of different planning schemes, especially since the major part of the network was constructed in the last two decades. Therefore, the findings can be captured from experts who witnessed the improvement in the distribution sector, which can illustrate the impacts on planning and operation (O'Brien et al. 2007; Alshuwaikhat & Nkwenti 2002).

Table 2-1: Water balance of Abu Dhabi Emirate year 2012[2]

System Details	Year 2012
Total installed production capacity (MIGD)	916.50
Total demand (MIGD)	859.99
Total No. of desalination plants	8
Total length of network coverage (km)	~ 2500
Overall surplus/Shortfall production vs. demand(MIGD)	56.51
Overall surplus/Shortfall transmission vs. demand (MIGD)	-58.42

This can also be compared to the available records documenting the progress of the infrastructure when analysing critical factors that construct robustness. Failure to address the distribution question has caused inefficiency in executing water distribution projects by over-utilising or under-utilising newly constructed assets. This can cause projects redundancy or insufficient utilisation of assets to meet targeted planning goals. Such inefficiency diminishes any gained value of such investments as depicted in Table 2-1, where a transmission pipeline

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[2] (TRANSCO 2012)

system restricts the shortage of demand. For these reasons, this study focuses on building a framework for arid regions that place great importance on water distribution highlighting the acceptable level of service to consumers throughout all operational scenarios.

Different approaches have been proposed to better comprehend water system performances, improving water distribution designs. Such approaches included quantitative methods such as Preis, et al., (2013) who studied the demand forecast uncertainties caused by calibration parameters. Preis, et al., (2013) proposed a genetic algorithm to provide a statistical data-driven approach to estimate future demands. The study aimed to report the impact of spatial correlation between demand forecast and errors on demand. It raised several limitations that are originated from sampling techniques and measurement uncertainties. Another study has proposed a multi-objective optimisation technique that incorporates uncertainties of nodal water demands and pipe roughness to minimise cost while maximising hydraulic reliability (Giustolisi, et al., 2009). However, Giustolisi et al. (2009) based design of robust factors on pipe roughness and demand forecast, missing other factors discussed in other literature studies (Hashimoto, Stedinger, et al. 1982; Qiao et al. 2007). On those studies, researchers approached infrastructure robustness from qualitative consideration by investigating failure events and imposed consequences on the network. This suggests the need for moving toward an integrated approach to address failures and consequences. This simplification allowed decision makers with necessary awareness when considering strategic view when making future decisions on the network. However, these studies have suggested predetermined failure events on the network and the consequences of such events are assessed by the summation of the impacted individual of unsupplied demand without taking societal impact and differences.

Different approaches and methods addressing the water robustness was highlighted by Schenk et al. (2009). They pointed out the need for a framework or evaluation to assess the effectiveness of an integrated management approach. This led some studies to approach the water complexity to apply a

System Dynamic model to investigate the interrelation of different factors to acquire new understanding of system complexities. All of this has increased the importance of water robust design objective to support development, especially under the environment constraint of arid regions (Alshuwaikhat & Nkwenti 2002).

2.2 Regulation establishment and role of robustness

The water sector is characterised as a monopolistic industry because of the high investment that it requires, which usually supported by governments, and its impact on consumers. Thus, regulations are needed to incorporate economic and service quality assessments to sustain region developments. This is done to guarantee equity, feasibility, sustainability, and cost effectiveness (Bentes et al. 2011). The regulation is set through a represented body, Regulatory Supervision Bureau “RSB” in Abu Dhabi Emirate. This was established to look after consumers’ interest and efficiency of government investments. This body set a security, quality, performance standard, and regulation of service to consumers. These regulations and standards cover technical and service guidelines to include during the established utility’s development managing security of supply and level of service expectations. The security standard is regulated by the supervision bureau to maintain an acceptable level of service for utility companies. The utility companies are obliged by these regulations to enhance the planning and maintaining of these assets.

Projects generated from the planning process can be divided into two types of projects that specifically satisfy a targeted objective. One type is demand projects, where these capital projects are initiated to fulfil an increased future demand or expand into new geographical coverage. The second type is to increase the security of supply to nodes or consumers by adding additional asset to minimise adverse impact of disturbance scenarios. In practice, these two types of projects are considered together in capital projects (Bureau et al. 2004).

Error! Reference source not found. portrays a representation of the different regions within UAE that shows some of these demand sectors (TRANSCO

2012). The water sector in Abu Dhabi is regulated by a regulatory body embodied by the Regulatory Supervision Bureau (RSB) to ensure the serviceability of these infrastructures and meeting customers' expectations. Thus, RSB role is to align the investments toward utilities objectives of maintaining continuous operation and meeting consumer satisfaction (Mott MacDonald Consultancy 2006).

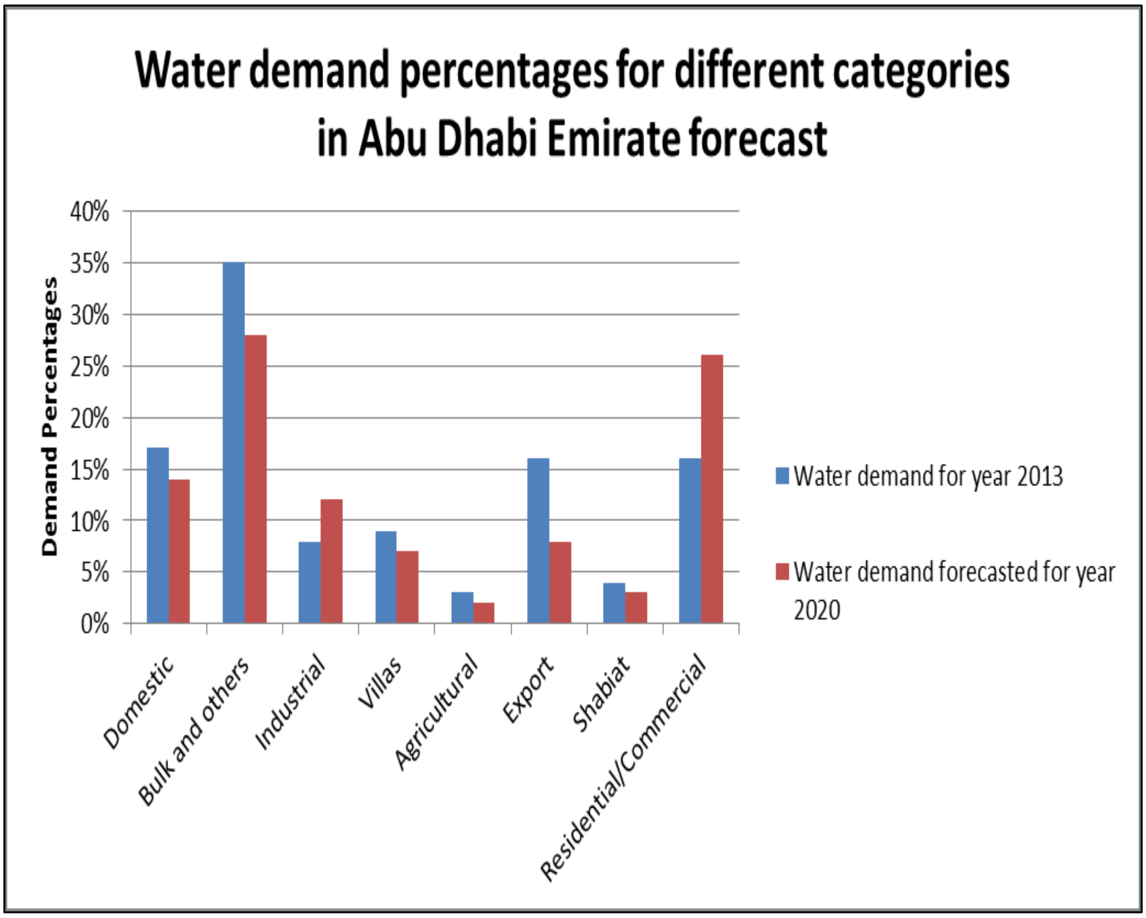

Figure 2-2 Sample of Abu Dhabi break-down demand forecast based on demand categories

The water sector in Abu Dhabi has followed a privatisation scheme to increase efficiency and balance between high investment and good service quality. This established different companies each with a specific responsibility from the overall objective of the utility sector (O'Brien et al. 2007). Thus, generation, transmission, and distribution sectors are segregated and assigned to different companies to complement each other in serving customers, while increasing efficiency and sustaining efficiency and operation of the overall sector. The transmission network for example extends over a wide geographical area of the country to fulfil strategic objective of transferring the bulk water as shown in Figure 2-3. This scheme is different than neighbouring countries that are operated as centralised agency in managing and meeting customers' current and future expectations.

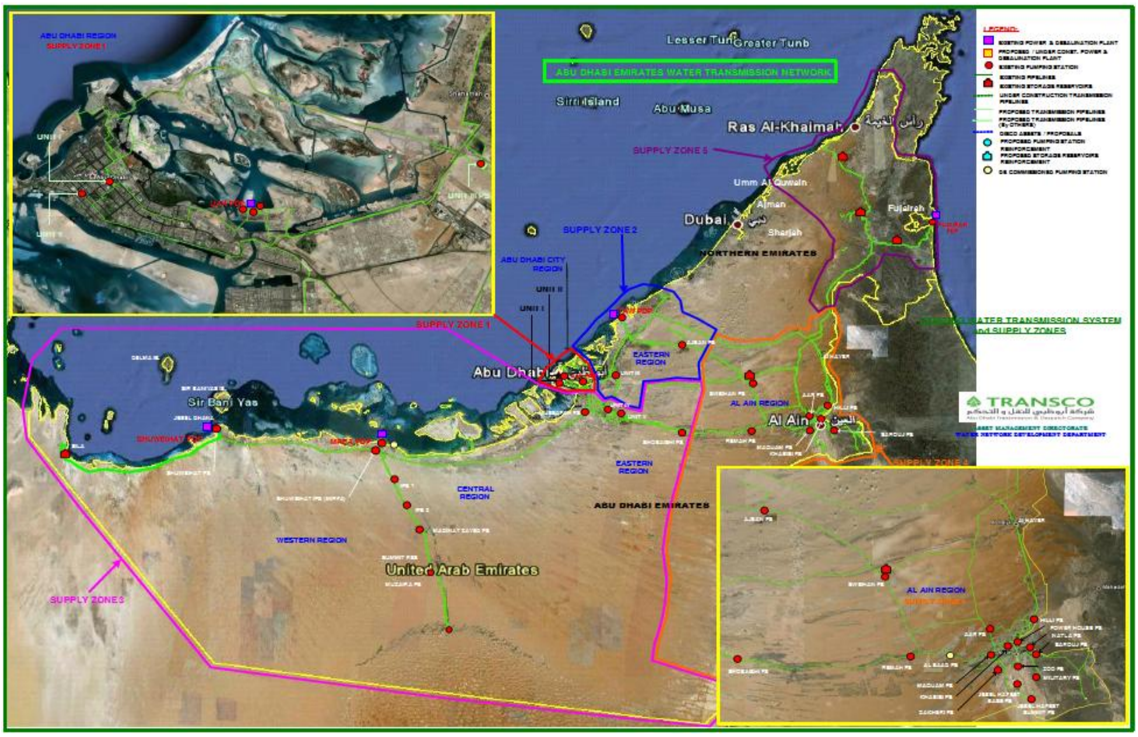

Figure 2-3 Water supplied regions of UAE showing some of the demand locations[3]

The creation of a regulatory body stressed on the primary objective of infrastructure serviceability; hence, realigning utility companies objectives with the emphasis of continuous operation and consumer satisfaction (Mott MacDonald Consultancy 2006). Utility organisations regulated by governmental supervision seek to build water networks that are capable of handling disturbances while maintaining an acceptable level of service to consumers. Many alternatives are aimed to increase components reliability to reduce failure events (Farmani, Walters et al. 2005). However, the fact remains that

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[3] TRANSCO, 2012. Seven Year Water Planning Statement (2014-2020). , (June 2013).

eliminating failure events rational is demonstrated as an impossible task that can be cost extensive with minimal return (Ahmed, Sahinidis 1998). Therefore, different models were adopted in-house for regulation purposes as an initiative to validate investments in network expansion and to quantify the level of service (ADWEA 2009).

“Level of service” is a term devised by water regulators to ensure compliance with the main objective (Mott MacDonald Consultancy 2006). This term is an index each regulator set to provide monitoring mechanisms for water utility companies to use when designing networks. The monitoring mechanism acts as a quantifying tool in assessing against a benchmark of network quality to consumers. The terminology is used to balance project capital and operational costs against the risk of service interruptions. “Level of service” can be described as a probabilistic statistical model assigning interruption risks to water networks that they use as the cut-off threshold for the acceptable design that sustains an agreed upon service level.

Regulators developed a “security of supply” code to encourage utility companies to account for a minimum level regardless of any adverse state forced on the network. “Level of service” is a term that was devised by water companies to quantify the effectiveness of security (Chandapillai et al. 2011). This term is used as a quantifying tool in assessing service to consumers (Farmani et al. 2005; Filion et al. 2007). This assessment used to balance project capital and operational costs against assumed risk of service interruptions.

Including robust design during planning is originated from the idea that water infrastructure involve interdisciplinary design teams that require structure or framework to operate within. In essence, this is to guide designers to have a coherent understanding of what water networks need (Macmillan et al. 2001). Macmillan et al. (2001) has described the design stage of any project as a dynamic and knowledge-intensive stage that experiences incomplete and uncertain information. This stage must explore alternatives to produce an optimal solution that meets the project objectives. Such a need calls for clarity of shared design strategy and agreement on factors of design. Addressing interactions between different factors during the planning stage is missing. Several research projects have taken a system approach to cover such interactions among different criteria is in the management of the water systems (Winz et al. 2009; Qi & Chang 2011). Meanwhile, numerous attempts to accommodate conflicting criteria between economical optimisation and social needs have caused unexpected consequences of either over-utilization or underutilization of assets, especially when accounting for failure incidents. In some instances, Rectification projects in the water sector were carried out to enhance the utilisation of these assets. However, the different aspects used to achieve this target produced fragmented solutions in water network structure. The result was an increase in investment inefficiency, which poses an interesting challenge to tackle (Rijsberman & van de Ven 2000; Mirchi et al. 2012).

2.3 Robustness barriers

Water distribution networks are faced with the unique challenge of dealing with the consequences of network interconnections and the impact felt over a sparse coverage of wide geographical regions. In these geographical regions, water distribution assets (e.g. pipes) constitutes 80% to 85% of the total cost (Swamee & Sharma 2008). This can be attributed to the gradual expansion of the network, posing the need to account for robustness on the entirety of a network, by maintaining an acceptable level of service to end users from both a quantity and quality standpoint. In existing design codes, new asset expansions require many inputs such as a water quantity forecast, previous operational and maintenance history, and a strategy besides the current knowledge of the water system. In practice, the security of supply and meeting an agreed level of service are based on examining case-by-case expansion plans of newly constructed networks. The current analysis looks at the history of operational failures of a component as an input to reflect the impact on demand forecast (Mott MacDonald Consultancy 2006). Another input is the type of community of interest. Each type of community has a different prediction factor that summed up to the total demand. For instance, the demands are categorised as domestic, landscaping (public/private), forestry, agriculture, industrial, developments, and also to incorporate network losses. All of these have different reactions and responses in case of disruption (Mott MacDonald Consultancy 2006). Planners and organisations aim to achieve a level of robustness despite many limitations (such as commercial aspects or lack of assessment tools) that could potentially avert the network reaching it. Therefore, investigating the network in regards to how it can acquire robustness is worthwhile. This highlights the importance of creating a framework to consider robustness on the overall of the network structure. This will provide planners further insight on ways of meeting regulation requirements.

It is worth noting that current practices on existing water networks possess an inherent level of unplanned robustness. This robustness is created through changes in assumptions or network component overdesign, which driven by the engineering specifications used putting a burden on financial resources. These inherited robustness may cause a fragmentation of system robustness (Li & Yang 2011). This is created by the current tendency of water companies to gradually expand their assets to cover new demand areas while addressing regulatory objectives on case-by-case scenario addressing “component wise”. This may increase complexity of managing system robustness, losing the opportunity to capitalise on desired features; hence, designing to account for adverse scenarios in current practices tend to increase unintended robustness within water networks. This can also exaggerate the issue when factoring that networks are gradually expanding over the existing network. This may be originated because the current regulations are addressing regulatory objectives, which tends to focus on results rather than providing a method of acquiring such information or performance. This cause organisations to lose focus on capturing opportunities on capitalising on some desired network performances.

Despite the obvious limitations such as commercial restrictions or lack of assessment tools, organisations endeavour to achieve a certain level of robustness. This makes investigating on how to acquire robustness worthwhile, creating the need for developing a framework or an assessment approach to integrate robustness during the design on overall of the network.

Several descriptions and aspects of robustness were considered in the water industry. During this consideration, (Hashimoto, Stedinger, et al. 1982) attempted to define robustness as the network that is capable of overcoming failures while safeguarding the water network operation. Some of the researchers addressed such features on existing networks while benchmarking them commercially to select the most suitable network meeting the regulator's objectives. However, these approaches fail to enforce robustness as a framework to work with, thus creating the need for this research. Several factors are captured in this research by linking several concepts that are introduced to resist failure consequences or prolong the operation of networks such as resiliency, flexibility and vulnerability with a sublayer of the asset component reliability. These different concepts are linked with terms addressed in literature such as connectivity and Surplus capacity. The research links them to the overall of the network. These definitions related to structuring them together in a hierarchal representation of robustness.

With this paradigm shift in developing water networks, one needs to take a step back and address robustness by reviewing it in the context of water distribution dynamics; thus structuring means to gain insight of network performance. This can hold a financial motivation along with better meeting regulatory objectives. This is motivated by the fact that planning cost is considerably less than the execution of work and potentially risking overlooking of an anticipated characteristic. These characteristics require frameworks and tools to provide a method of assessment during the planning phase.

Chapter 3 Literature review

This chapter is a review of the literature viewpoint of robustness as a design criterion. It explores the following questions:

1. What is the water network and what does robust design in such a network imply?
2. What techniques are used to reinforce a robust design in networks?
3. What are the factors associated with robustness in water distribution networks?

Some literature terms of robustness in water distribution are defined in Section 3.1. Assessment and techniques to support robust design are discussed with respect to water network expansion in Section 3.2. It will also introduce literature review of different concepts and factors in the development of a robustness framework.

3.1 Importance of Robustness and resiliency in infrastructure

Several concepts were introduced in literature, including vulnerability and reliability as factors in the water sector. Some studies addressed these factors on a water network component level (e.g. pipelines, nodes), incorporating rate of failure and time of the repair to assess performance. However, the results obtained are difficult to interpret based on their priorities among the network components. This is because of the huge number of components constructing real networks (Gargano & Pianese 2000). Other studies in literature aimed at achieving a robust network without a clear definition of robust characteristic; hence, being robust or including “robustness” requires finding what constructs robustness. This is due to the different interpretation of what constitute robust performance in networks especially in presence of many terms that address a certain aspect such as reliability, vulnerability or flexibility. (Farmani, Walters et al. 2005).

3.1.1 Evolvement of flexibility, vulnerability and reliability to robustness of water networks

Researchers have investigated water distribution networks and how to manage water supply to end-users efficiently. Different approaches were taken to enhance the understanding of water supply to consumers using models and algorithms. In 1980, Coulbeck (1980) produced a method for calculating pressures and flows of a network over an extended period to model water network components considering static and dynamic solutions. Concepts of resiliency, vulnerability, and reliability were first introduced into water resource management to describe system performance under the impact of disturbances (Hashimoto, Loucks, et al. 1982). This provides a description of system reaction factors that affect performance and using these concepts in project evaluation against future uncertainties.

Hashimoto, Stedinger, et al. (1982) attempted to highlight the differences between the resiliency of a water resource system and its stability. The study defined Resiliency as the system quickness to recover after an occurrence of disturbance or failure. This differentiates it from the system stability, which refers it having a sustained system output in meeting demand requirements. However, system stability does not mean it holds the ability to absorb shocks or changes. Hashimoto, Loucks, et al. (1982) focused on system performance under failure, considering the violation of a set threshold criteria for performance. It referred sustaining system performance to utilising its reliability, representing the probability of maintaining desired performance. On the other hand, system vulnerability was also introduced as “the likely magnitude of failure, if one occurs.” Gallopín (2006) highlighted the trade-off relation between these three factors in managing water resources against changing conditions. This in part coincides with Stigler’s economic flexibility definition (Stigler 1983), which describes flexibility as anticipation of design that accommodates different future scenarios. (Hashimoto, Loucks, et al. 1982) introduced the concept of design flexibility under economic investment by presenting designs that have the potential to meet a multitude of future demand scenarios.

This main objective of design is to supply sufficient water to consumers at the acceptable pressure. This objective is met when demand is estimated from available data on consumption, population growth, and development (industrial, social, urban). Furthermore, pressures derived from the elevation of nodes and the hydraulic losses that occur used to define the acceptable pressure by Bernoulli equations. Pye (1978) attempted to provide an interpretation of flexibility within this theoretic framework, where he viewed flexibility as 'the number of future alternatives from which a choice can be made.' This is similar to the industrial flexibility-planning concept introduced by Hall et al. (1983), where plant’s flexibility explained as the capability of switching quickly from one product to another or from one part to another.

Several studies discussed and simulated water network connectivity as a main factor that contributes to network flexibility. This is realistic due to the importance of a connection between demand locations and supply sources to supply water. This augments the water network complexity due to its large spatial scale and nonlinearity. On other studies, flexibility was approached as sub-factor from reliability (Prasad & Park 2004). Those studies highlighted that increasing flexibility alone is insufficient to ensure reliability of water network design. Thus, defining redundancy allocation within an expansion plan requires investigation to minimise costs, maximise robustness, or both while satisfying connectivity among nodes and keeping costs low (Yazdani et al. 2011).

Interest in the water network reliability components has increased to approach the concept from different perspectives. Network reliability was assessed by examining the components and how they contribute to the overall network reliability (Coulbeck & Orr 1993; Walski 1993). Approaches were aimed to relate the reliability definition to outline the associations between different factors and components reliability. For example, Coulbeck & Orr (1993) explored the relationship between the hardware of water network systems and their reliability. They explored how uncertainties within the data of components can affect the risk of system failures. The literature explored the different components in water networks and roles of each in impacting the performance in networks. It highlights that components reliability relies on maintaining good bookkeeping, allowing for statistical approach in collating this information to permit a sensible prediction of asset condition.

Gupta et al. (1993) studied the long-term planning to include future requirements by exploring reinforcing existing assets or adding additional sources since water infrastructures are cost-intensive systems. Therefore, optimisation of cost has been studied to look for additional alternatives to meet different planning objectives. However, Ostfeld & Shamir (1993) noted that the optimisation of cost bypasses the need to look into other factors such as reliability of the water network design. This highlights the need to investigate methods in achieving reliability of water networks prior to exploring least cost solution alternatives. Also, it was pointed out that the relationship between connectivity and reachability can manage the impact of disturbance or failure affecting end users. Reliability definition was suggested as "the probability of that system to meet consumers' demands both in flow and pressure (Xu et al. 2003)."

Several authors highlighted the difficulty in defining reliability in water network systems, presenting different definitions suggested for reliability (Ostfeld & Shamir 1993; Vasan & Simonovic 2010). Walski (1993) took a different approach and highlighted operation, maintenance, and design as areas that contribute to reliability. It shows that reliability can be impeded by system components or organisation processes to maintain an acceptable level of service. Walski (1993) definition of reliability is derived from the concept of component redundancy in system to compensate for mechanical type failures. However, this neglects the effect of hydraulic failures.

Planning water network deals with different sources of uncertainties during the design stage. This needs to be considered to address demand uncertainties during planning and addressing lack of information and variability of daily or seasonal demand behaviour, and growth trend projections when considering failure consequences. Because demand estimate factors are not rigorously researched, attempts to study such area in association with disturbances proposed the use of water modelling, incorporating fussy logic at node demand while taking a heuristic perspective (Xu & Goulter 1999). This application is to model the uncertainty as a non-probabilistic problem. It details the magnitude of demand that relates to pressure behaviour and the gradual loss of meeting demand at nodes. This is to bridge the gap between the binary impact of failure and the gradual impact on demand nodes.

From a statistical point of view, it is difficult to model system reliability explicitly because of the different components in a network that have different impacts on the system's reliability. These may fail due to different failures attributing to hydraulic or mechanical issues. So far, there is no universally accepted definition of reliability (Todini 2000). To distinguish system reliability from components, another concept was introduced as resiliency, suggesting intrinsic capability of a system to overcome degradation. This concept can be presented as a factor to overcome the problem of the endeavour involved in collecting statistical data to define the reliability of a system. Resiliency focuses on the ability of a system to maintain energetic redundancy, minimising the internal energy loss exhibited. Applying this factor to water networks directed suggestions toward looped networks, where this provides redundancy within the networks to mitigate the impact of hydraulic and mechanical failures (Todini 2000). The looped network signifies the redundancy in water flow to nodes by increasing alternative routes to the demand node within a network. Thus, resiliency can be interpreted as the system's capability to overcome failure condition by changing network flow and configuration.

3.1.2 Robustness concepts and parameters

In the English language, robustness is defined as being strong and unlikely to break or fail (Cambridge dictionary). Using robustness as terminology can encompass the necessary performances a network needs to possess. In practice, the primary concern in executing a water infrastructure is that it satisfies the hydraulic requirement while meeting future demands. However, reliability, resiliency, and vulnerability are concepts that have emerged as features that all networks should have, attracting more attention and interest than in previous years (Gallopín 2006; Ofwat 2012). Conversely, these concepts lack a universal definition among researchers, producing different approaches (Todini 2000; Francis & Bekera 2014).

Bieupoude et al. (2012) study has described methods of optimising network construction designs using geometric analysis and investigates the architecture of a T-shape network’s performance, highlighting the strong bond between topology and performance. Optimising topological designs against the cost to achieve a reliable performance was attempted by Farmani et al. (2005). He developed a surrogate-based multi-objective optimisation method to account for network reliability formulated based on a resilience index introduced by Todini (2000). Meanwhile, a different study considered the utilisation of the Complex Network Analysis as an approach to collect necessary statistics while addressing structural topology to gain more insight into robustness (Yazdani & Jeffrey 2011). Several studies were carried out to investigate robustness elements and their ability to enhance the overall network performance. All of them stated that networks exhibit characteristics that require a holistic evaluation to address robustness (Hashimoto, Stedinger, et al. 1982; Coulbeck & Orr 1993; Ostfeld & Shamir 1993.

Other approaches were conducted to extend analysis to water network structures and hydraulics (Bureerat & Sriworamas 2013; Wright et al. 2014). They highlighted the link connectivity between user nodes and source reachability to nodes as parameters contributing to reducing failure impacts on end-users in water network performance. This holistic view is taken to suggest intrinsic system capabilities in overcoming degradations and failure events through the structure (Di Nardo & Di Natale 2011). The literature presented this capability as resiliency defined as the network ability to display resistance performance to failure modes (Baños et al. 2011).

One of the first resiliency studies was set out on reservoirs and tanks, investigating their performances and gaining an understanding of the relation between resiliency and reliability. This also pointed out the role of reservoirs in enhancing performance (Hashimoto, Stedinger, et al. 1982). The study related the capacity available and the different variation of water inflow in the reservoir to cater for drought seasons and the anticipated shortfall of supply. Other studies explored further on network responses under failure scenarios and categorised as network vulnerability by examining links and nodes that affected performance under failure incidents. Studies described network flexibility as the ability to configure its operational layout to minimise failure impact as network characteristics (Bentes et al. 2011; de Graaf & der Brugge 2010; Gallopín 2006).

In an attempt to understand complex water network robustness, several studies simulated water network connectivity as a parameter. Connectivity was identified as enabler to reconfigure water networks against failure incidents; hence connectivity and also redundancy in asset are attributed to network flexibility (Baños et al. 2011; Ostfeld & Shamir 1993; Pinto et al. 2010). The importance of connecting demand locations and supply sources is critical to successful water supply. However, flexibility alone is insufficient to ensure robustness in water network design (Prasad & Park 2004). This is because water dictated by other elements such as capacity and hydraulic parameters. However, defining connectivity and redundancy allocation within an expansion plan requires investigating network topological structure to address robustness (Yazdani et al. 2011). On the other hand Fraga et al. (2003) devised a discrete formulation using a stochastic algorithm to visualise network modelling. The visualisation allows detecting available capacity in network to be used later on expansion plans. It highlighted surplus capacity combining it with network topological structure to give users expertise the ability to tune the network.

Recently other study addressed connectivity within water networks between nodes and sources from topological point of view and incorporating energy loss of hydraulic related parameters to reflect shortest path redundancies from source. Herrera et al. (2015) have addressed nodes resiliency by detecting path redundancies from sources addressing resiliency from node centric approach. The study highlights from topological structure nodes that are of importance. This incorporation relied on hydraulic energy loss only and addressed redundancy of shortest path to assess nodes resiliency. These studies highlight connectivity as major parameter to ensure a resilient water network reflecting shortest path from hydraulic perspective to reach every node. Even though the network objective is to supply nodes, pipes/edges have been highlighted as the elements by which network extend coverages and ensure services to these nodes (Schaub et al. 2014).

The reviewed literatures explore different criteria to explore robustness and relevant factors contributing to it. This will help investigate solutions and how one can balance trade-offs. However the need to consider water network structure is important as shown and emphasise the need for a framework to provide more clarification to the minimum required acceptable service.

3.2 Current frameworks and models

Current quantitative techniques especially numerical optimisation uses different approaches to address design; however it jumps directly into optimisation against cost before constructing a common ground of what fulfils robustness and what are its relevant factors. Network robustness requires a holistic framework that enables a broader assessment to provide insights to planners while designing networks catering for demand growth.

3.2.1 Model and concepts introduced in literature

Meta-heuristic studies give the advantage of investigating solutions without the complexities faced in optimisation models. Such attempts were made to relate various factors of resiliency, reliability, and vulnerability and how these estimators can give a clue regarding water system performance. Kjeldsen & Rosbjerg (2004) showed that resiliency and vulnerability have a strong correlation, and stabilising the function of reliability, resiliency, and vulnerability could ensure system serviceability. The authors examined the overlap and the appropriate combinations among these three factors. They defined failure duration and demand shortage as elements in categorising system reliability against failures while resiliency is a measure of system reaction to failure. Vulnerability measures the likely damage caused by a failure.

Vulnerability as a factor in a network is strongly associated with resiliency, as highlighted by (Pinto et al. 2010). It attempted to present the vulnerability of a network as how the configuration can reduce or increase network significance of failure impact. This came into focus because of the rapid increase in demand combined with ageing infrastructure and how redundancy increases hydraulic reliability (Bentes et al. 2011). This draws a vulnerability measure from the structural theory to identify vulnerable parts. This concept depends on the system’s reaction to failure occurrence and the consequent level of such failure or impact. A vulnerable part in a network can be identified as a section that causes large-scale disruption to service what is proportionally small in a network. The theory of vulnerability of water pipe networks (TVWPN) was developed in Tras-os-Montes e Alto Douro University (UTAD), Portugal. This theory is based on structural vulnerability (SVT) in civil structures. (Pinto et al. 2010) presented the TVWPN to evaluate the connectivity and the quality of the pipelines in networks. It followed with a clustering method to identify the most vulnerable part of networks. This assessed the route’s connectivity to a node and how an impact on one part of the network could affect the service to other nodes.

(Bentes et al. 2011) proposed that vulnerability of water systems needs to be standardised to facilitate interdisciplinary collaboration. They found that reliability referred to the ability in providing adequate performance for end-users under abnormal conditions. The application of the vulnerability theory application was based on clustering networks by building a hierarchical model based on four different criteria: minimum head loss, maximum damage demand, maximum nodal connectivity, and maximum distance from a storage tank. A further stage has identified the failure scenarios and consequences related to such scenarios. The objective of the water network is to deliver water to users while maintaining acceptable quality. Hence, the vulnerability can include the measures of the total number of hours of failure, total water lost, and a total of the number of users affected. These considerations should be studied to allow them to be included in the vulnerability theory and compared with typical reliability indicators.

Holling (1996) have introduced resiliency as an aspect of system resistance to failure impacts by identifying two types of resiliency, engineering resilience and ecological resilience. Holling (1996) shows that engineering resiliency is accounted for system efficiency, performance consistency, and ability to predict. Bruneau et al. (2003) described the characteristics of a resilient system as follows: reduced failure probability, consequences, and rapid time recovery. It concluded that resiliency consists of four dimensions including robustness, redundancy, resourcefulness, and rapidity. These dimensions related to ecological systems in general and they defined Robustness as the extent of system function maintained while Rapidity was defined as the time required for the full system to return to operation.

Todini (2000) attempted to address the trade-off between network resilience increases and cost expenditures to balance system capability against failures with corresponding cost. Resiliency factor in water network was implied to relate to the surplus energy available to nodes that can compensate for the energy dissipation caused by system failure via alternative routes. This total system energy can be formulated by:

$$P_{tot} = \gamma \sum_{k=1}^{n_r} Q_k \, H_k$$

The above equation reflects the total power entering water distribution network where Q_k represents flow and H_k is the head, while γ is water specific gravity at every node n_r. Measuring the excess pressure at nodes against the minimum required pressure account for the surplus power remained available after internal losses. The resiliency index defined as the ratio of power input to the system to the power loss.

Network resilience was defined as the surplus of power available at each node that can be dissipated internally to counter the increase in head loss. This occurs because of failure in any water network component (Vasan & Simonovic 2010). This follows the principle of Todini (2000) which is:

$$I_r = 1 - \frac{P^*_{int}}{P^*_{max}}$$

Where

$$P^*_{int} = P_{tot} - \gamma \sum_{i=1}^{n_{ri}} q^*_i \, h_i$$

is the amount of power dissipated in network to satisfy total demand, whereas

$$P^*_{max} = P_{tot} - \gamma \sum_{i=1}^{n_{ri}} q^*_i \; h^*_i$$

is the maximum power that would dissipate internally to satisfy the constraints in term of demand and head at nodes.

This definition of resiliency as a factor was used to filter alternative solutions while optimising the cost incurred in building network tolerance against failure. Since the definition is affected by the headlosses, it is guided by the length and diameter of pipelines along the network to nodes. Practically, water networks are constrained by the predefined topology of existing infrastructure, such as road and buildings. Hence, this guides the network structure in practice. This highlighted the interest in considering resiliency as a factor in water network designs that take different network configurations and routes.

However, it is worth noting that Baños et al. (2011), evaluated the performance of three different types of resiliency indices derived by Todini (2000); Prasad & Park (2004); Jayaram & Srinivasan (2008) against investment costs. The latter two indices of the three introduced resiliency measures, called network resilience indexes. This incorporates the effects of both surplus power and network loops. Meanwhile, the modified network resilience index incorporates the use of multiple sources being highlighted. These results were obtained using Todini (2000) definition, showing it as more resilient than the other two. Baños et al. (2011) concluded that none of the three indices correctly measures the network ability to overcome failure. Hence, there is a need for a resiliency index that would consider global excess of pressure in addition to the distribution of pressure in demand nodes, i.e. the network topology, to identify the critical points. The study shows the effect of a node on the whole network performance under demand increase and how particular nodes, i.e. nodes closer to reservoirs, can impact the solution feasibility. It is necessary to highlight that the location of node experiencing increase in demand is more important than the global network feasible solution configuration. Hence, indices do not accurately show the capability of the network in handling over-demand scenarios (Baños et al. 2011).

3.2.2 Approaches to design decisions using robustness models

Several attempts were made to optimise water networks by employing stochastic algorithms and the mixed integer nonlinear programme (MINLP) in order to tackle the complexity of water network optimisation. This is due to multiple interconnections among water components and their arrangement in non-trivial configurations. As well as this, the different combination of pipe sizes, pumping stations, pumping schedule, tank capacities, control valves, and uncertainties in demand exaggerate dealing with such complexity (Yazdani & Jeffrey 2011).

For an enhanced water network performance, a method was developed using an energy perspective to assess network efficiencies. The method is based on calculating energy input into water networks and the different amounts of consumed energy dissipation in the system. This is distributed between internal losses and serving users, i.e. network dissipation and leakages (Cabrera et al. 2010). The method enables the monitoring of the performance and energy indicators to audit water networks. This builds a holistic method to produce a system evaluation, thus helping to investigate performance improvements. The method used highlights the energy consumed in a different component of the water distribution network. This gives further insight of energy outflow such as head losses, quantity delivered, leakage, etc. The utilisation of this insight indicates the excess energy available in a network, supplying nodes to reinforce or strengthen the resilience factor. These measures are impacted by the network configuration and efficiency underlining the topology of the network as criteria of network efficiency.

Di Nardo & Di Natale (2011) developed a heuristic design to support methodology, allowing locations of district metring compatible with the hydraulic system performance to be defined. They used the graph theory to identify the core layout of a water network while selecting minimum dissipation routes to nodes. This approach proposes the use of graph theory constraint by hydraulic performance and by energy dissipation. The study used resilience index as a selection criterion for the district metring region boundary. It provides a flexible approach to detecting the efficient routes while maintaining robustness of the network. However, the objective was to configure the existing network, by utilising valves through the operation of least-cost routes while overlooking the parameters that affect the system resiliency.

Other researchers (Farmani et al. 2005; Greco et al. 2012) adapted Meta-heuristic algorithms. This is similar to Geem et al. (2011), who adopted a harmony search algorithm. This method was tested and found to have the ability to consider discrete solutions as well as continuous type solutions. It enables the detection of global optimum or near optimum solutions without requiring any starting feasible assumptions. It studied the optimisation by including velocity as a criterion, which was absent from previous studies. This criterion is important because it links to transient surges in networks and could affect sedimentation, which in turn could affect the level of service (e.g. quality of the network).

Farmani et al. (2005) applied a multi-objective evolutionary algorithm to consider an “Any town” network optimisation problem, including rehabilitation, expansion, pipe sizing and tank location, simulating a relatively more practical situation of designing a real network. Minimising design cost and maximising network resiliency was also taken into account. This study considered both hydraulic and mechanical failures during the analysis of the network. The gain of using multi-objective methods is to enable coupling of design criteria such as cost and robustness, offering less subjective Pareto-optimal solutions. This type of study can provide decision makers a group of solutions depending on their preferences for a further detailed analysis. It is found that current definitions of a resilience index alone do not represent the network robustness and the definition needs to include maximum and minimum surplus head at any node demand. It is highlighted that the population growth and climate effects on water demand are known, but the relationship is uncertain.

There were attempts to apply multi-objective optimisation linked to water simulation models and located feasible solutions satisfying different criteria (Kularathna et al. 2011). The study noted the lack of popularity in most of multi-objective optimisation models in practice. This is due to several drawbacks that include model complexity, the need to simplify water systems, the formulation inflexibility of these optimisation models, the deficiencies in relation to multiple stakeholders and objectives, and the requirement of expertise to use such models. The key drivers of system performance need to be included in optimisation models; hence, constructing a framework that guides the optimisation models later. For example, Fraga et al. (2003) devised a discrete formulation using a stochastic algorithm to visualise network optimisation by highlighting excess capacity. They combined it with network pattern recognition to enable the expertise of end users to tune the network. On the other hand, the reliability definition was used in several models such as (Duan et al. 2000). This model analysed the probability of failure, cycle time between failures, expected duration of failure, and expected unserved demand. They aimed to include reliability in optimisation models using the concept of reliability as defined in Ostfeld & Shamir (1993). This considers failures on network components (e.g. pipes, valves, pumps, etc.) and meeting consumers' demands (e.g. flow, pressure and quality). These types of impacts are either linked to hydraulic or mechanical type of failures resulting in damage to consumers, residential or industrial. Minimising the impact on consumers and choosing the least-cost network was pursued. During the pursuit, an approach of augmenting the cost of network cost to include reliability was explored to come up with a model that would enable utility companies to make more informed decisions (Walski 1993).

Topological consideration was found to be important for many systems other than water. Xia et al. (2011) presented general equations to address the optimal/near optimal topological network for electricity, refrigerant, and water distribution. It is observed that optimisation of routeing can minimise power loss while transporting commodities. The study devised a method to introduce non-user nodes to reduce the total length of routes. However, the study did not tackle the converse problem of water distribution that relates to flow and pressure. Rather, it highlighted the impact of searching optimal routes on energy losses, even though the study was simplified. It also illustrated the importance of topology of a network in enhancing performance.

Advances made in graph theory to gain insights regarding water networks are applicable because these networks can be characterised as spatial and geographic systems. Such parameters like Node connectivity and topological features in water networks were found critical to system reliability and failures to resiliency (Yazdani et al. 2011). Methods in graph theory employ basic connectivity metrics, spectral gap, and algebraic connectivity, along with statistical measurements, such as clustering coefficient, meshed-ness coefficient, and central point dominance. They attempted to establish a relationship between structural features, topological distribution, and water network performance to highlight expansion strategies that can provide opportunities to service resilience.

Modelling water distribution networks using graph theory is an area of interest. It provides a promising tool to explore interconnections between system layout and performance (i.e. resiliency, cost efficiency) (Yazdani & Jeffrey 2011). Studies associated the characteristics of water network to a graph. The studies also show how indices and measures can capture some of the network features. Such studies attempted to rank the structural robustness (vulnerability/resiliency) of different types of network expansions in relation to tree branched, meshed, loop, and extra looped types. This was done while supporting budget-constrained decisions (Greco et al. 2012; Yasdani et al. 2013). They raised the importance of finding a mechanism in allocating redundancy (i.e. the existence of alternative flow routes) within the network and how to consider different strategic positioning of such plans; hence, they characterized networks via structural properties. Allocating redundancy and specifying connectivity was directed towards avoiding critical nodes and mitigate network bottlenecks. Studies justified the need for constructing a framework that allows an assessment of existing networks to identify strategic expansion strategies and inform operational policies. The need to validate alternative design strategies by heuristics, enhancing robustness in design and expansion plans, is highlighted. This was drawn from the results of the study of Kumasi distribution network, where an increase in redundancy may not necessarily result in significant improvement in network robustness (Yazdani et al. 2011).

Anderies et al. (2004); Yazdani & Jeffrey (2011) proposed frameworks to study network parameters from a topological perspective in relation to formation, structure, efficiency, and vulnerability. It is apparent that a water distribution network relies on system layout design and system operation. Water networks can be formulated as a minimising problem of cost subject to hydraulic feasibility, satisfying flow and pressure demand. In most optimisation models considering optimal connectivity and redundancy within the network, the cost objective reduces or eliminates redundant pipes. Therefore, the framework mechanism proposed in Yazdani & Jeffrey (2012) to include constraints on connectivity and redundancy measures. In real situations, network configurations are constrained by physical barriers, such as roads, buildings, rivers, and other natural or man-made structures, water connectivity and flow direction. These are determined by hydraulics and demand; hence, linking non-topological specifications, such as node size or pipe diameters, with the topological configuration characteristics to establish a realistic relationship between operational performance and topological features with reference to reliability and resiliency.

Assessment should include the sizing of linkages between nodes and the influence of such nodes on the network overall to establish a realistic correlation between topology and the operational aspect of reliability and vulnerability.

Chapter 4 Evolution of robustness and related concepts

The chapter is to outline the factors contributing toward robustness addressed in literature; hence, to establish current state-of-the-art water distribution robustness. The chapter introduce the stages robustness has been going through. Section 4.1 is set to identify state-of-the-art literature on robustness in water network. This is discussed in Section 4.2 to provide insights to the strength and opportunities of using different concepts introduced in literature collectively. Factors and definitions addressed by majority of studies are identified. A preliminary conceptual framework is an outcome of an analysis carried in this chapter, along with illustrating strengths, gaps, opportunities and limitations of this concept laying the foundation for the next stages of study. Section 4.2.1 presents the classification and summary of the factors, assumptions and solution techniques available in designing robust water networks. This section refers to the information from Section 4.2 to produce relevant definitions and identify factors that have been critically presented in literature. These factors extracted in sense of their definitions, measures, and their applicability and interpretation in practice.

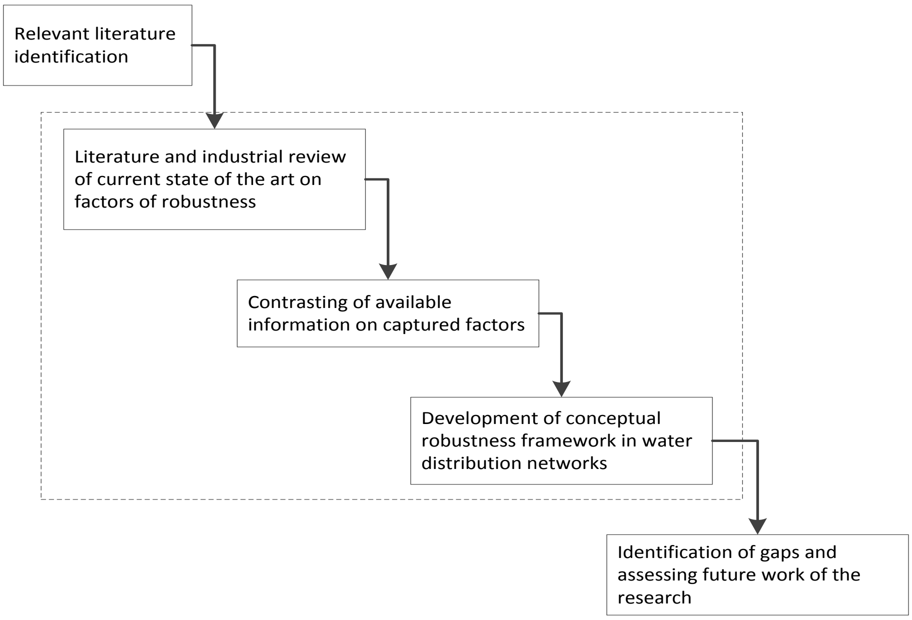


Figure 4-1 Steps to compare robustness between literature and practice

Section 4.3 provides key findings and propose and initial framework to introducing robustness as key concept in water networks. The chapter is structured to outline the following issues.

1. What are literature factors that are relevant to water network robustness design?
2. How these factors' definitions compare with literature?
3. What are the strengths, opportunities, gaps and weaknesses of the research

An analysis of the factors involved in constructing robust performance in water distribution networks is presented in Figure 4-1. This will form the basis to relate literature definitions of factors and parameters toward contributing to robustness performance.

4.1 Identification of relevant literature

Robustness has been addressed in literature in many different contexts, mainly because there is no unified definition agreed upon. Therefore, relevant literature needs to be sorted and identified. The search method for identifying relevant studies and literature is described in Section 4.1. Literature search used databases including ABI/INFORM and Web of Knowledge to assess presence of robustness concept in water networks.

Further analysis of the literature captured in Appendix B showing different concepts and definitions of terms that are in line with the research aim. This is to enable exploring relevant parameters of water network design. Figure 4-2 shows the growing interest on different terms and factors highlighted in the past two decades, displaying growing interest in this research direction and the need of a more systematic approach to design spatial networks.

The keywords used were 'robustness', 'vulnerability, 'flexibility, 'water distribution', 'reliability and 'resiliency and their combinations (Table 5.1). Searches in ABI/INFORM were focused on scholarly peer-reviewed journals, whereas the Web of Knowledge searches included conference. Keyword creation list used a first review of literature and choose common terminologies to fine tune the search relevant studies. As shown in Table 4-1, keywords combinations of 'vulnerability', 'resiliency' and 'water distribution' yields most relevant results of 28, whereas other combinations shows fewer studies in these fields. A thorough search of the filtered papers was conducted to identify relevant papers and capture knowledge frontier. Studies referring to other sectors such as telecommunication, power networks, and chemical industries were filtered out from the set of related papers.

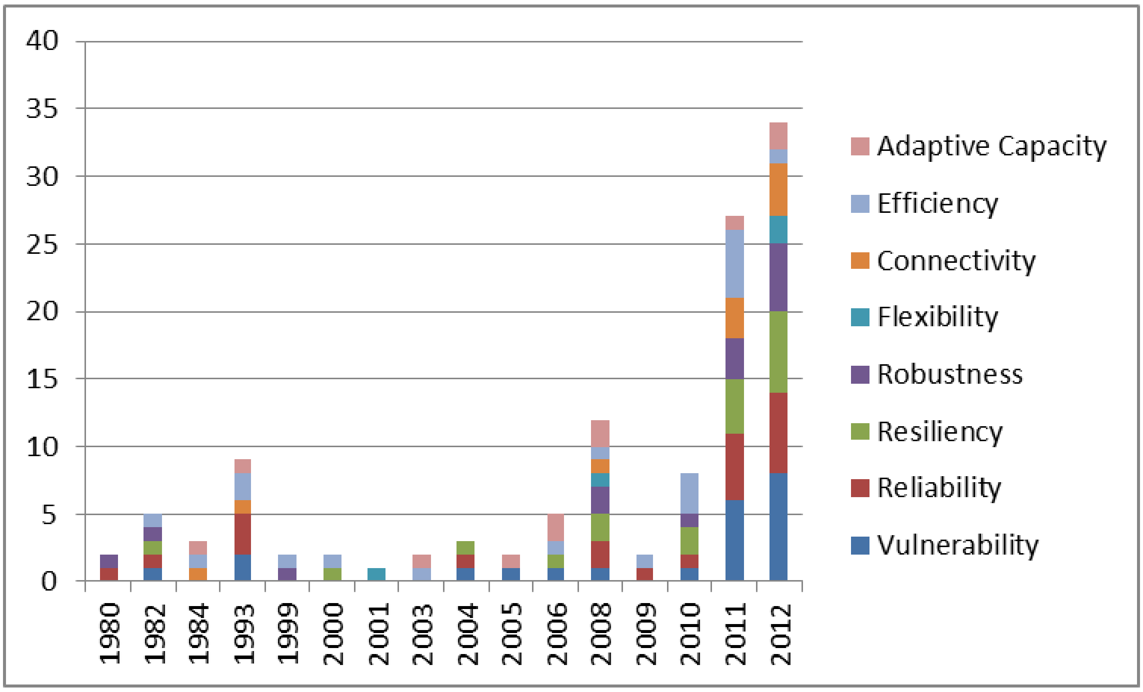


Figure 4-2: Literature of factors appeared in chronological order

Relevant papers were identified from title and then carefully considering abstract. Citations were also cross checked to identify most relevant studies that are the most important papers such as (Yazdani & Jeffrey 2011) and (Todini 2000). A search carried out to identify papers cited these studies, papers that discussed specific terms individually. Also these papers are investigated to check relevance to context of this research, otherwise it is excluded. Some of these studies reverted to ecological systems or other industry sectors such as (Dwivedi & Yu 2013a) in power grid and (McDaniels et al. 2008) in infrastructure systems in general. There are lots of studies that addressed resiliency and robustness in complex systems in general addressing topology and structure for example Reggiani et al. (2010); Zeng & Liu (2012) are describing complex interconnections and networks reaction to attacks and failures. Other studies addressing reliability have targeted optimisation against cost of network construction and implementation of algorithms to decide on suitable design (Tolson et al. 2004).

Table 4-1 Keywords and search of peer-reviewed journal paper findings from literature survey

	Terms	ABI/Informs		Terms	ABI/Informs
1	robustness	19608	**12**	1+6	65
2	vulnerability	53325	**13**	2+6	224
3	resiliency	6799	**14**	3+6	19
4	reliability	164458	**15**	4+6	2075
5	flexibility	224848	**16**	5+6	409
6	water distribution	65164	**17**	1+5+6	4
7	1+2	162	**18**	1+3+6	0
8	1+3	48	**19**	3+5+6	2
9	2+3	142	**20**	3+4+6	5
10	1+4	998	**21**	2+4+6	28
11	1+5	689	**22**	2+3+4+5	0

4.2 Concepts and conventions of robustness in water networks

This section address the evolvement of robustness terms and different perspectives investigated in literature. This section presents summary of factors and assumptions in techniques designing robustness in water network.

Hashimoto, et al. (1982 a,b) have addressed design issues and posted questions of enforcing characteristics that lessen sensitivity of the system to external influences. This paper raised issues of vulnerability, resiliency and reliability of system and how to incorporate these different terms to water resources. The paper discussed system performance under multiple scenarios of impact. The paper highlighted the different perspective between reliability and resiliency using probability of different impact conditions. Hashimoto et al. (1982) approached these perspectives for water resources devising an assessment evaluation of resiliency of such systems. Meanwhile, in other papers addressing water distribution networks, Farmani et al. (2005) approached system performance incorporating reliability of pipes in network and different failure scenarios on supply to nodes. In this paper, the approach incorporated an algorithm to iterate failure of pipe and measure the hydraulic performance. It utilises the definition of resiliency defined by Todini (2000). The definition uses the concept of available pressure at nodes exceeding the required demand to compensate for any changes in network structure.

Reliability as a factor of system robustness has been addressed extensively highlighting the linkage between system components and system performance (Tabesh et al. 2009). Papers carried out investigation to explore means of predicting components failure on the system, signifying other parameters that impact system performance such as connectivity. Pinto et al. (2010) indicated that each system components will lead to different system performance based on location and node sensitivity to disturbances. This study formulated a new theory to assess cascading impact of failures of water network components by adopting structure vulnerability of civil structure. The theory uses clustering approach that arranges the network components based on the required and available water demands of nodes. Pinto et al. (2010) shows the incorporation of connectivity and node vulnerability is critical for a robust design of water networks. Nodal vulnerability, network capacity and critical node connectivity when compared with other terms of resiliency, vulnerability and reliability shows there are relationship that needs to be clarified and structured in view of robustness. Forming a conceptual holistic framework encompassing different concepts and factors will enable investigation of water networks during planning (Tolson et al. 2004).

On the other hand, Xu et al. (2003) showed that pipe capacity can play a major role in increasing system reliability and enabling continued supply. This paper highlights the linkage between pipe deterioration and pipe capacity formulating an algorithm linking nodal demand uncertainty and pipe roughness. It addresses residual capacity of pipes as means of increasing reliability of system. The interchangeable use of reliability as system components or system reliability needed a much more structuring, thus in ecological science have addressed the different terms and their relationship to each other highlighted in Gallopín (2006). This paper attempted to differentiate between vulnerability, resilience and surplus capacity, and their relation to systems. It highlighted resilience as system quickness to recovery for disturbance, while surplus capacity as system ability to adapt, which is linked to resources availability. Meanwhile, vulnerability is linked to sensitivity to disturbances and their exposure. This paper addressed ecological systems in general thus these definition need to be tailored to water distribution systems. However it highlighted the subtle differences of these terms, guiding views to better understand relevant factors in play.

Optimisation methods were also addressed in several papers in literature. These optimisations are aimed to select most suitable designs against cost spent. Farmani et al. (2005) for example, attempted to explore most cost-effective design against different level of performances. The algorithm has different set of alternatives to select from against broad range of performance indicators that cannot be precisely categorise under which of the reviewed terms. Gupta et al. (1993) developed a nonlinear programming techniques based on interior penalty function incorporating a graph theory approach to explore least cost network. This paper although it attempts cost effective solutions, there are many implicit functions and it can take long time to process all alternatives to come up with suitable solution, also the requirement of small steps to enable the algorithm to run successfully. However, this paper highlights the need for a unified understanding of factors in play to design for. Other optimisation algorithms based on reliability in water distribution systems used genetic algorithm to capture suitable design among alternative designs.

Several papers highlighted the importance of water network connectivity related to reachability of sources to demand nodes (Mahmoudi et al. 2014; Ahmad et al. 2008). Such reachability can enhance network performance when multiple configurations can be detected to supply water to nodes in different operational scenarios. Huang (2011) highlighted the role of connectivity in enhancing flexible designs of water supply systems. It is noted that flexible designs are often much costlier than inflexible systems due to incorporation of redundancy routes of construction of loop within networks. However, the failure in inflexible networks can outweigh the cost of incorporating flexible designs. One of the reasons for integrating flexible design is the difficulty of anticipating all uncertainties that network can go through. To allocate flexibility in water supply networks, Tsegaye (2013) combined graph theory and clustering to anticipate future demand scenarios and decision taken to best optimise the cost allocated for expanding network meeting demand growth. This study attempted addressing the hydraulics and demand growth uncertainties by introducing flexibility of decision made into future scenarios.

There is new trend toward integrating topological features with water supply hydraulics. This direction consider network topological structures as additional criteria to gain insight of network performances (Di Nardo & Di Natale 2011; Di Nardo et al. 2013). The approach utilises graph theory as theoretical basis for the tools and methods to break down topological structure in water distribution contexts. Such basis are applied for similar studies in different sector such as airline systems (Reggiani et al. 2010), power grids (Sha & Panchal 2013) and ecological conservatives (Rayfield et al. 2011). These papers derive from complex network theory techniques (Newman 2003a). This linkage is proposed from the similarity of water networks to similar studies of complex networks. This led to contributions in identifying critical components of the network that drastically impact water network performances. A study of incorporating topological and hydraulics to optimise water distribution networks gaining more attention on the importance of topological features alongside hydraulic performances (Di Nardo et al. 2013).

Many studies that incorporated topological characteristics focused on node importance when studying network performance; hence recent studies approached water networks especially from edge centric view to simulate the effect of edge failures support covering of infrastructure networks such as power grid and water network. System performances of these are dependent on edges rather than nodes in case of failures or incidents (Schaub et al. 2014). Many techniques that are borrowed from complex network theory are used to address these systems using for example *Betweenness* concepts and clustering algorithms (Shih et al. 2013; Kazerani & Winter 2009). Betweenness for example was used to explore the components in systems that are in mid-way to other components to underline importance. Where clustering is to group components that have similar importance characteristics to certain performance criteria to systems, thus prioritise components of system and gain ranking priorities when operating or designing such network. Different derivations of these techniques are used to suit the application of interest in order to align interpretation of these tools to the context at hand.

Other studies focused on node vulnerability in networks suggesting significance of structure. Several descriptions were found from literature, some highlighting node criticality by its centrality within the network, where the removal of such nodes may disintegrate the network to separate groups (Trajanovski et al. 2013). Other definitions are related to bottleneck node causing failure of water supply in case of incidents. The study focuses on the rerouting of water flow that a water network experiences and uses the loop within the structure to provide the necessary supply (Shuang et al. 2014). Many studies related vulnerability integrating risk of service failure to impact on end users (Ouyang et al. 2014). Vulnerability can be defined as a measure of targeted service reaction to changes in system. This line of research is to focus on capturing components that contribute to large impact in case of failure.

In water supply systems, studies were carried to address identification of component vulnerabilities that influence performance. One of the studies that approached vulnerability from topological perspectives is by Yazdani & Jeffrey (2012), attempting to combine entropic definition derived by Tanyimboh & Templeman (1993), also including different graph theory metrics to highlight topological differences on different networks. Considering topological characteristics without considering network hydraulics causes discrepancies between study results and real networks application masking actual characteristics of a real operation. The use of graph theory tools without allowing for functionality consideration will cause the results to distort component importance in the system. Metrics in graph theory attempt to aggregate results into a global value of the network characteristics, which can cause difficulty in interpreting it on design level.

Resiliency on the other hand have been revisited by other studies to incorporate it in infrastructure real settings such as power and airline networks; hence, encompassing wider system uncertainties and behaviours while emphasising topological structures (Turnquist & Vugrin 2013). Resiliency concept have been adopted recently in water networks by practitioners (Ofwat 2012). This concept aimed at supporting network performance against incidents and changes. As conveyed by Adger & Vincent (2005) resiliency is the quickness of system restoration to normal operation. One approach as explained earlier by quantifying available supply described by Todini (2000) via “resiliency metric”. The metric measures the available pressure and flow above the required demand at nodes. The more available pressure will allow the network to utilise in case of changes to another required node. However, this definition lacks the incorporation of flexibility of topology or vulnerability of nodes against incident aspects by highlighting where to improve in the network or to allow for such characteristic. A single measure alone needs to be integrated within a framework to guide the structuring of necessary measures and metrics that will cover different performance criteria (Barker et al. 2013).

Other approaches also devised to quantify system resiliency using other methods such as surrogates such in Shibu & Reddy (2011) to capture robustness performances. They introduced entropy as a surrogate to detect least-cost network designs, optimising it against resiliency behaviour. It is worth noting that they highlighted the disadvantages of using NLP (Non Linear Programming optimisation) methods and the preferences toward meta-heuristic methods that incorporates a scientific algorithm to reach a near-satisfactory results due to ease of use and coverage of different perspectives. The study proposed the use of cross entropy method to represent an evolutionary iterative technique. This uses entropy which measures uncertainty associated with a process (Coulbeck & Orr 1993). The quantitative measure uses Shannon entropy that gives the probability distribution of events, which corresponds to randomness. Modelling water distribution, maximum entropy is met when distributions of flows are uniformly distributed. The proposition assumes that homogenous distribution of water flows can allow different configuration in case of disturbances and changes. Entropy definition was also used by (Tanyimboh et al. 2011) to assess surrogate measure of studying system reliability. The study illustrate the use of entropy can have a reasonable measurement characteristics than other previously presented approaches. Results obtained from this study display entropy having a correlation to other hydraulic reliability measures such as “resiliency index”, “network resiliency index” and “modified resiliency index” against a known literature network. Todini (2000) resiliency index provided counterintuitive results, such as decreasing index values for increasing reliability (Raad et al. 2010). This call highlights the extra caution of addressing individual designs when investigating networks. Tanyimboh et al. (2011) raised the question of whether these contrasted measures (resiliency, modified and network resiliency indices) can assess pressure-deficient water networks. This is in addition to the fact that these measures are aggregated into a global measure that can be difficult to provide more structured information to planners by highlighting parts that needs improvement.

Modelling water distribution networks using graph theory is gaining an increased interest (Yazdani et al. 2011), and it provides a promising tool to explore interconnection between system layout and performance (i.e. resiliency, efficiency). Studies addressed characteristics between water network and graph by formulating indices and measures; hence, capturing some of the network traits. This hold the potential to be able to rank structural robustness (vulnerability/resiliency) of different types of network designs and provide means of assessing future plans differentiating between different type of network structures (e.g. tree branched, meshed, loop, extra looped). This will give a better insight of the relevant properties and behaviours built-in the network when applying expansion plans while working with budget-constrained decisions (Yazdani et al. 2013; Shuang et al. 2014). Yazdani et al. (2011) raised the importance of allocating redundancy (i.e. the existence of alternative flow routes) within the network system considering different strategic positioning of such plans through structural properties (redundancy and connectivity) to strengthen critical locations and network bottlenecks. Yazdani & Jeffrey (2011) attempted to construct a framework for assessing networks to identify strategic expansion strategies and operational policies by enhancing robustness performance. It highlights the need to inspect alternative design strategies by heuristics through surrogates of reliability to maintain acceptable levels in design in terms of increased improvements against costs. At the same time results from the study on an example network (e.g. Kumasi network) shows that increase in redundancy implementation may not necessarily produce significant improvement in network robustness in all cases and that the advantages of redundancy increases diminished against costs (Yazdani et al. 2011). Thus, Yazdani & Jeffrey (2012) incorporated other constraints such as connectivity to integrate redundancy.

Despite the water configuration constraints imposed by physical barriers, such as roads, buildings, rivers and other natural or man-made structures, water connectivity and direction of flow is determined by the system and demand nodes. Hence, linking non-topological specifications such as node size or pipe diameters with the topological properties can allow for a realistic association between operation and topological properties. The need to evaluate water network resilience for non-topological properties were suggested in quantifying vulnerability of node demands in Yazdani & Jeffrey (2012). The assessment includes the linkage sizing in establishing correlation between topology and operational aspect reflecting reliability and vulnerability in the network. They highlighted the need to research issues relating to network expansion and trade-off scenarios when optimizing network connectivity as criteria.

4.2.1 Insights and strength from literature and concept classification

A synthesis of literature is carried to identify strengths of current literature, opportunities of advancement, limitations posed and gaps identified in terms of robustness in water network planning. There are multiple terms and parameters mentioned in literature, moreover there are 170 papers that collectively or partially address terms in context of water distribution that investigate robust performance. Three factors appear occasionally to be of interest, that is, resiliency, vulnerability and reliability.

These considered as factors of enhancing robust performance. Many papers addressed reliability from either mechanical or system uptime, which was evident through 19 papers available. This area has been extensively studied to formulate mathematical models for the service time of equipment. Wagner et al. (1988) explored the different criteria for operational scenarios and method of assessing equipment and failure consequences in water systems.

It is noticed that these three factors incorporate robustness from different perspective in system. However, there are other terms and concepts that are considered such as connectivity, capacity and redundancy as illustrated in 4.2. These are reflected as parameters and have more quantifying measures that demonstrate them. In summary, robustness is taken from different perspectives from components level to system level. These different views need to be consolidated to provide a broader insight of robust performance in water networks. Literature highlighted the need to research issues relating to "network expansion and trade-off scenarios of optimising network connectivity as a function of construction costs or the improvement in serviceability indicators".

It developed a statistical approach to assess system reliability by studying different possibilities of failure occurrences as highlighted in (Xu & Goulter 1999). However, reliability approach for covering equipment uptime and their corresponding failure event on systems proved to be statistically extensive highlighting the need for different approaches (Gargano & Pianese 2000). Nevertheless, reliability is a major factor allowing for components performance and functionality. Reliability definitions spans over probabilistic view in maintaining a level of performance as depicted in Hashimoto, Loucks, et al. (1982) underlined role of redundancy in order to compensate for failures. It is pointed out that failure duration and demand deficiency can act as measures to consider system reliability (Kjeldsen & Rosbjerg 2004), this is alongside the standard definition on probability of failure and cycle time between failures discussed in (Barone & Frangopol 2014)

Since reliability traditionally concerned with component lifecycle, other studies focused toward addressing the consequences of any failure, considering network vulnerability. This refocuses on network consequences, which are linked to structure (Huang et al. 2014). These studies explored using graph theory complex network identifying means of measuring vulnerability depending on linkages (Newman 2003a) and further extend it to infrastructures emphasising dependency and criticality as in (Rourke 2006). This allowed to further attempt these concepts on water networks (Narayanan et al. 2014). It is noticed that there is surge in studies of water system vulnerabilities to gain insights on network structures; hence, enhance the design guidelines and better allocate redundancies and efforts of network enforcements. Vulnerability was defined as likely magnitude of failure and others approached vulnerability as system parts that are prone to failure (Gallopín 2006). An attempt to extend vulnerability concept to water distribution was shown in (Bentes et al. 2011). The tendency when addressing vulnerability is to refer to segments or components that their failure will cause major disruption in system performance compared to the size of failure.

Resiliency on the other hand was conceptualised to address the changing regime a system can perform to counter incidents or events. From system perspective, resiliency has been linked to system quickness to restore operation or performance (Tsegaye 2013). When this concept extended to water systems, resiliency is explained as the intrinsic capability of system to overcome degradation (Todini 2000). As a concept or factor to design for, resiliency is considered a fairly new and many studies are becoming interested to explore resilient systems. Gallopín (2006) described resilience measure as system reaction to compensate for failure. This highlights the perspective of resiliency to address system behaviour towards changes or disturbances. The prevalent measure of resiliency in water systems have been adopted from Todini (2000), who designated it through the extra available pressure in network to be used during changes in system topology caused by disruptions or failures. Many other derivations from this understanding were attempted to incorporate other parameters such as redundancy (Raad et al. 2009).

4.2.2 Limitations and gaps identified from current research

Main shortcoming of the current literature is the lack of any comprehensive robustness model addressing the different concept presented earlier. This is may be due to absence of universal agreement of definitions on these different factors (Fu et al. 2012). This can also be due to the different properties water systems operate under, thus definitions need to be modified to allow for such behaviours.

The lack of framework and broad view of these concepts makes it difficult to build a holistic approach when assessing robustness systematically. Even though, there are attempts to create measures to capture resiliency such in (Pandit & Crittenden 2012) or for vulnerability in (Bentes et al. 2011) or reliability (Tabesh et al. 2009). These studies overlooked the linkages among these terms. Other studies investigated with deriving surrogate measures stipulating a global measure while borrowing tools from other areas such as entropy (Czajkowska & Tanyimboh 2013) or resiliency index by (Todini 2000). Aggregate measures, however, losses their value when used to improve and expand existing water network; this is because these are global measures and cannot be transferred to component and segment level. Therefore, the transfer of the knowledge to practices can be challenging. Needless to say optimisation against cost can shift the interest from investigating robustness to focus on cost view, missing important insight that could impact water networks.

There are terms that are presented in literature mentioned such as surplus capacity and connectivity. These terms hold a high importance to robustness in water networks. Although they have been addressed partially (Shuang et al. 2014; Kabir et al. 2015), they need to be addressed systematically with the other main factors of reliability, vulnerability and resiliency. It is worth noting that lack of agreement on definitions or availability of a guiding framework causes many of these terms to produce different terminologies, thus may refer to the same thing. For example, redundancy and connectivity can be interpreted the same since both play a role in maintaining continuous supply.

The literature available was not integrated in general framework of robustness. The work encountered is well developed but the focus of different robustness performance of component and system levels are lacking. This creates inherent threat that the various factors suggested in literature are not used, which is evident by lack of industrial case to implement such frameworks. In addition, works in this field are suffering from missing consensus on the inclusion of factors and parameters involved in impacting robustness. This may lead to inability to find industrial data, which compares the different factors and develops a reference list based on importance.

There are studies carried out resilience on infrastructure systems that addresses different terms that considered generic terms that can be difficult to transfer to practices (Turnquist & Vugrin 2013; Francis & Bekera 2014); thus, water distribution properties needs to be considered to have a real depiction of these measures as underlined by other studies (Yazdani & Jeffrey 2011). An evident gap is that there is no model which is sufficiently holistic to handle all factors deemed important for water network robustness. Similarly, there is limited information about how to apply models or examples of application in real industrial cases.

An anticipated gap is the insufficient resources to carry a full model of the major factors, however resiliency and vulnerability and their relevant parameters will be included under this research constructing a corresponding mathematical model. Reliability was pushed aside due to couple of reason; one because it is well researched and have applicable measures that can be used in future work to incorporate reliability. Second reason is because resiliency and vulnerability are fairly new terms and require the focus to cover the construction and definition involved under this research.

Identifying gaps in this work provides essential starting point for the future work in this area. These opportunities can be modified through constructing set of factors and their relevant definitions to cover areas of interest in water distribution systems. Understanding these factors will be the initial step to develop a structured framework of water systems.

Additional prospect is the knowledge base this area would benefit from when incorporating industrial based perspective on available techniques. Ideally, case studies should be conducted in a variety of systems so that a broad appreciation can be developed for the validity and rigor of models.

4.3 Key findings and proposed initial framework

The current literature has its strengths in current state in considering factors and model representation. Most of these papers focus on financial aspect which may deter the focus of the factors and parameters toward financially feasible solution. The solution techniques attempted by them are rigorous in nature and considerable effort has been made to ensure optimal solutions are generated.

Several gaps have been highlighted which provide opportunities for future work in this field. One major opportunity is developing a holistic framework that addresses the different factors and parameters in water distribution systems. Summary of strengths, gaps and limitations are shown in Table 4-2. Finally, industrial implementation details of robust water networks can give an additional insight from realistic view, allowing for adoption in industrial sector.

A major key opportunity in this research is to construct a holistic robust framework that can be applicable to industry that revolves in providing tools to evaluate networks features and characteristics. Therefore, a significant gain is to report more widely on the application of robustness in industry. This can be achieved via case studies to investigate presence of these terms and factors or any additional terms that needs to be included.

Table 4-2 A summary of the current condition of literature in water distribution robustness

Opportunities	Gaps
• Development of holistic framework and construct definitions incorporating water systems properties. • Construct a mathematical model that assess these factors and evaluate robustness	• No holistic framework that handles all factors together • No coherent definitions of these different factors • Other terms that are discussed separately such as capacity and connectivity need to be incorporated. • Guidelines for industrial adoption are lacking
Strengths	**Limitations**
• Three factors are considered important • Solution techniques are rigorous providing different methods to achieve near optimal solutions	• Inability to cover all factors in this research • Definitions may still not gain consensus

Different terms where gathered and depicted in Figure 4-3 to cross reference and investigated.

From the previous interpretations of different factors found in literature, this research assign specific definitions in comparison with the literature introduced in Table 4-3 as an initial step for a unified description of each of these factors in the context of water distribution. Figure 4-3 demonstrates the main factors of robustness and related parameters as explored from literature. Here, it is portrayed that robustness reflects the overall characteristic from the different critical factors identified.

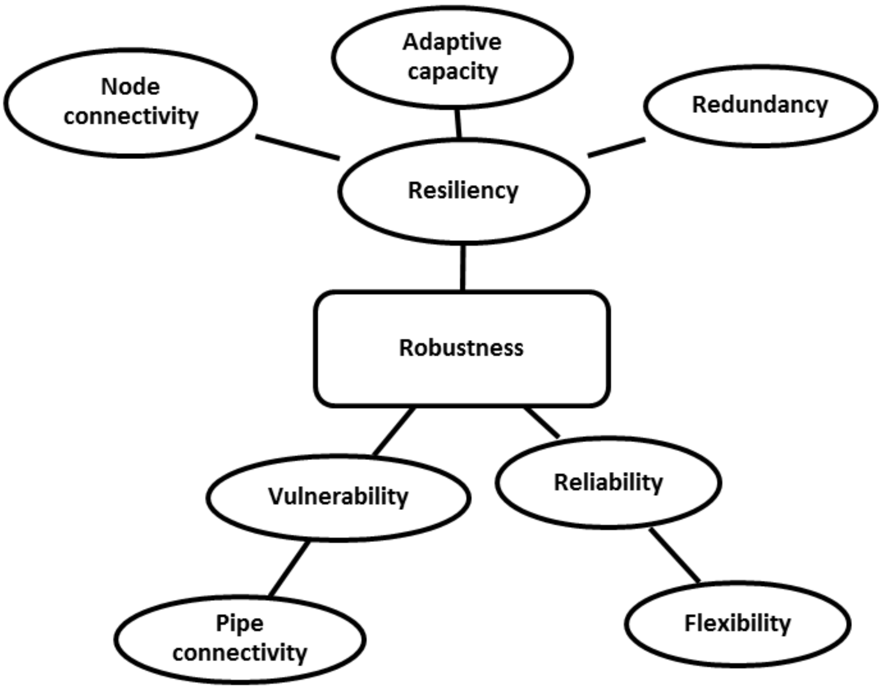


Figure 4-3: Robustness factors presented in literature

The research will envisage robustness as three critical factors developed from reliability, resiliency and vulnerability of water systems. This research presumes surplus capacity and flexibility as parameter to one or more of the critical factors. These parameters are used as parameters due to the introduction in many studies as a tool of achieving desired performance. These parameters fall under one of the factors that can be described conceptually to refer to system failure probability indicated by reliability, while referring to the degree of impact on system as vulnerability. Meanwhile, studies have referred to system recovery of incidents and failures as resiliency of the system against adverse effects of such.

It is worth noting the relationship between reliability, resiliency and vulnerability and their direct or indirect impact on each other. The definitions propose reliability and resiliency can be proportionally linked together where resiliency overcomes degradation. Meanwhile, vulnerability is somewhat inversely proportionate to the other two factors. Vulnerability can be the negative impact of not having a reliable or a resilient system. Water networks performance can be determined by the connection with these three factors. Developing an assessment approach to investigate these three dimensions will provide a transparent view of their presence in the system during water planning system stage.

The following table introduces the definitions gathered for different factors and parameters presented in the literature:

Table 4-3: Literature review definitions of factors

Factors/ *parameters*	**Literature**
Resiliency	Capacity of system recovery represented by the intrinsic ability to overcome degradation, which is linked to (Gallopín 2006): • Surplus capacity • Node connectivity and Redundancy
Vulnerability	Measure of failure magnitude on water network as a function of risk exposure, and sensitivity based on TVWPN characterised of pipe connectivity (Pinto et al. 2010)
Reliability	Probability of network components to accommodate demand, referring to asset components level (Tabesh et al. 2009)
Flexibility	Prospect of the network to different future scenarios (Farmani et al. 2005)
Surplus capacity	This is interlinking between resiliency and vulnerability.

These three highlighted factors can be depicted from different tools discussed in literature. Reliability, for one, is affected by the operational and maintenance regime that have a direct reflection to the life-time of the components in the system, whereas resiliency is drawn from the different indices introduced in the literature to capture the desired performance. This is summarised in Table 4-4.

Table 4-4: Tools and parameters of factors measurements

Robustness Factors	Tools
Reliability	Design, operation and maintenance are areas contributing towards reliability of the system
	Redundancy components
Resiliency	Resiliency index, network resiliency index and modified resiliency index
	Graph theory by examining node connectivity and topological features of the network
Vulnerability	Theory of vulnerability for water pipe network (TVWPN)
	Likely damage caused by failure

Chapter 5 Understanding concepts of robustness in the water supply industry

This commences Industrial network evaluation step. The purpose of this chapter is to investigate robustness factors in industry and available assessments used to monitor it. The research method for Development stage is described (Section 6.1) and issues outlined. These issues are addressed in Section 6.2 – Section 6.4.

The methodology describes the use of literature framework as basis to investigate robustness in water sector practices. This will inform the robust design model when incorporating robustness during planning practices.

5.1 Research method

This chapter commences from research Objective 2. The purpose of this chapter is to investigate robustness as concept in utility practices context. As outlines in 8.5A.1.2, case study based research is adopted to capture research relevancy to real cases. The following needs to be addressed in the following chapter:

1. What are critical concepts practices focuses on that contribute to robust performance?
2. How does concepts found in literature compare with water sector practices?
3. How water distribution robustness is structured according to available information?

A pilot unstructured study was initiated to explore feasibility of these terms in the industry. The pilot study is to build-up the subsequent case study interviews; hence formulating initial concepts which will construct the case study interviews to assess their applicability and basis in the sector. The pilot study will feed into constructing intensive semi-structured interviews to capture the factors and their alignment in the business and to further develop these relevant concepts.

5.1.1 Industrial pilot study design

The pilot study was carried out to formulate the practical use of robustness factors in real network and their perceived definition if available. This pilot interview was to identify the as-is situation and capture the current practical framework used to consider robustness in water networks. These interviews were conducted using unstructured questions to form basis for further intensive interviews covering robustness design during water systems. The unstructured approach is to overview application and/or introduction of robustness as a concept. Interviews were carried in an informal setting (Café) to enable comfortable conditions. Two interviews were carried out with two different companies that work in the water and electricity utility sector.

Each of the two pilot interviews are conducted in a different company that deals with one aspect of water sector. A transmission company is working under Abu Dhabi Water and Electricity Authority “ADWEA” that deals with transferring bulk quantities of water and electricity from production facilities to demand location. The demand locations are handled by distribution companies (DISCO) to serve end-users and distribute the necessary water and electricity to the numerous types of consumers. Each type of company operates within a service license set by Regulatory Supervision Bureau “RSB”.

Table 5-1: Organisations profile

	Case study 1	**Case study 2**
Water supplied in 2011	154,820 million imperial gallon per day	216,026 million imperial gallon per day
No. of customers	225,000 customers	DISCO companies
Total length of pipeline	7,350 km	2,355 km

The analysis of the pilot study is based on the interviewees’ perception on robustness and their related definitions on these factors. The following table profiles the interviewees:

First interview was conducted with a representative from asset management who is involved in overseeing the asset operational, and controlling capital expenditures. The duties involve monitoring the operational aspect of the asset and utilise asset capability to meet current and future growth on demand. The objective is to forecast the need and propose the best way to utilise current asset in delivering the service reliably and safely.

Table 5-2: Interviewees' details

	No. 1	No. 2
Position	Asset management	water planning
Duties	Utilisation of asset and monitor performance and expenditure. Set annual strategy	Network hydraulic and plan expansion
Duration in position	3 years	5 years
Length of interview	2 hours	2 hours

Second Interview is done with planning responsible staff involved in future expansions. Their duties revolve around conducting a hydraulic analysis of water networks to ensure the asset capability of delivering the required service. This to ensure evacuation of bulk quantities produced from generation facilities to demand locations. Also they are responsible is to phase the needed expansions into phases to address gradual future growth by planning suitable assets.

5.1.2 Capturing key concepts from industry

To verify the factors and parameters detected in the pilot study and literature, a set of semi-structured interviews are initiated to examine practitioners' perspective based on the initial framework on a wider segment. This case study investigates factors/parameters, namely: resilience, vulnerability, flexibility, reliability, surplus capacity and connectivity. Eight interviews were carried out that spans over different departments between operational and management organizational personal. The investigation tests the existing understanding of each of the factors and their relevancy against each other with their explicit consideration of each during building water networks. Additional data are collected through the use of survey for each of the factors from secondary source highlighted in Appendix B (e.g. procedures, archive, calculation sheets …). The survey used available documents and procedures that are relevant to network robustness.

The interviews were produced to reflect different themes in order to cover these factors with the targeted interviewees. These themes follow from the initial framework derived from literature and the pilot study described in Figure 5-4. The themes are focused on resiliency, flexibility and vulnerability as major terms in this research. Reliability, on the other hand, are set aside and only considered conceptually in relation to the robustness framework. Reliability is not considered in interviews to allow for the interviewees to refocus their attention on system wise robustness rather than components. The framework informs the relation of these different concepts together considering hierarchy robustness built-up in water systems.

The interviews conducted with staff of two different departments in different sector of the industry in the same manner done in the pilot study however in bigger scale. Namely, transmission and distribution segment of the business, are used for the case study with Abu Dhabi and another UK based Water Company for benchmarking and cross-reference purposes. Interviews are conducted with different level of management to capture the different aspects of robustness done with asset management or maintenance management. The advantage seen from selecting these two different levels of organization, it can shape a broader look of robustness in the sector. The outcome of the interviews insight and analysis are to produce robustness conceptual framework.

Table 5-3: Case studies interviews

	UAE	UK
Company	From two different utility companies	From one utility company
Position	Asset management, planning department and operation and maintenance	Asset management and risk department
Number of interviews	• Eight interviews: o 2 with asset management o 4 planning department o 2 operation and maintenance	• Two interviews: o 1 with risk department o 1 with asset department
Length of interview	40 to 90 min	Approximately 1 hour

Yin (2009) argues that the minimum required number of interviews needed dependent on the case at hand and other factors such as type of questions asked, level of knowledge needs to be achieved and the level of expertise the interviewee has to make an informed answers, but in general eight interviews can be sufficient to investigate case study at hand in order to minimize the biases and allow for a sufficient outcome. Ten interviews of approximately 60 to 90 minutes each were used to carry out this case study. In-person interviews were conducted to provide smoother access to and enforce open communication channels between respondents and the researcher. The interviews were conducted with senior executives from planning, asset management, and operations and maintenance divisions. Interviews were directed with executives from UAE and two additional executives from UK based water companies as mentioned in Table 5-3.

A semi-structured interview template used *a prior* themes to construct questionnaires exploring evidence and relevance of these factors in practice (Coolican 2009; Bryman 2012). The themes used for the interviews and analysis are shown in Table 5-4. These themes are explained to show the justification of using the theme in constructing the questions, which will be used to analyse the output as well. A semi-structured approach used to allow interviewee to expand on specific subject promoting coverage and depth. The purpose was to drive maximum benefit from expert knowledge and aim to draw information on the intended question at hand, allowing segregation among answers to allow for comparison during analysis stage. The interview questions are constructed to cover factors from the initial framework and parameters of flexibility and surplus capacity.

Table 5-4: Priori-themes used in constructing interview questionnaires and analysis

Themes	Denotes
Definition	What is the respondent's explanation of the concept under questioning
Process	Where in the organisation the concept and the parameter are accounted for in their processes
Element	What are the parameters affecting the concept and factor under review
Measure	What indicators or measures are available in practice to assess and manage the factor or concept
Tool	Are there tools or solutions (methodology) available to manage the performance of the concept or factor for robust design in network
Limitation	What are the limiting conditions of these factors or concepts in network robustness behaviour

The interviewer used judgement to decide on any additional questions and when to direct back to the semi-structured template. The interviewer avoided pointing out specific problems and allowed the respondent to lead the answer giving specific examples from real situations. Topics were covered as time and respondent permitted. Some factors were covered in greater depth by individual respondents.

5.2 Pilot study of current planning processes and security of supply

The pilot study produced an insight to the water sector in Abu Dhabi. The insights provided an overview of the planning process for the water system that starts by producing demand forecast generated by other parties. This demand forecast is analysed against assigned supply source. Once the source and demand location is set, alternative designs are produced. Then design of supply security is carried out to assess operational scenarios and the inclusion of redundancy and storage to safeguard against mechanical failure scenarios. For instance, storage is assessed via historical pipe failures and repair time probabilities to cover 90% of the failure scenarios. The 90% security is an arbitrary value that the norm has accepted to maintain a high level of service to consumers. Another term also was referred to during the interviews when discussing reliability of supply, namely level of service. It was defined as design consideration of most of the events that may take place on assets operation. This introduced calculating a statistical return period of the asset designed to maintain an acceptable level of service to consumers. The level of service is compared against the cost of introducing redundancy or storage to the design to compensate for failure scenarios. The main part of incorporating robustness as a design is evaluated statistically using per capita and the type of customer combined with development plans to reproduce demand curve for seven years horizon planning duration. The utility companies look at the average daily demand to analyse the existing system and gauge the needed assets to supply the required water from supply sources to consumers’ tanks.

5.2.1 Abu Dhabi network structure and process of robustness inclusion

Storage tanks are used to reinforce supply designed to buffer peak demands during the day and to cater for operational matters by allowing for a reserved storage of 24-hour daily demand. A subsequent hydraulic analysis is conducted to obtain the required pressure based on the forecasted demand. This is traced back to available facilities from pumping stations. It is highlighted that there are two types of pumping stations that exist in Abu Dhabi network, a production pumping station, located at the desalination plants, and an intermediate pumping station (hubs), used to push water further to consumers. These pumping stations feed the transmission networks, which in turn feeds the distribution networks. It was further explained that the difference between transmission and distribution networks is that transmission networks deal with the flow. This means that the transmission network delivers the required quantities of water from producer to distribution boundaries; hence, the distribution network deals with delivering the required pressure of any quantity to consumers. Ideally, the boundary between the two networks is a tank to compensate for the fluctuation of demand. This is to deliver the water to demand location at the lowest possible cost. Based on this code, the transmission system is usually flow-controlled to deliver the necessary amount of water while the distribution network is pressure controlled to meet service level satisfaction at consumers' nodes. However, the exception in the transmission network occurs when a direct connection is mandated. These may exist because of political or emergency needs. These direct connections are handled by identifying the required pressure at these direct connections and comparing it to the residual pressure and flow at such connection, making sure it would not impact the system hydraulics.

The objective of the water is to support the development of economic and social status, thus the cost aspect of these projects has lower priority. This is especially true in this part of the world. However, once the need for a water supply is acknowledged, the design of the project and alternatives are assessed to obtain the least cost solution. Meanwhile, direct connections addressed by modifying the existing assets are done to build contingency in the new asset's planning. It was expressed that direct connections affect the lifetime of assets since connections shorten the capacity horizon of the network. So at the end of the year, these direct connections are integrated into the horizon plan for the next seven years. Planning is looking iteratively every year at the next horizon phase, calibrating the demand growth per year by locating it at each node while inspecting the condition of the pipes and inspecting the capacity that serves the demand expected. This results in producing the necessary projects. When exploring issues related to planning, it was highlighted that one of the under-utilisation reasons is the non-materialisation of expected demand. The result of this is a reduction of efficiency in the asset available, causing different sorts of problems in relation to water quality, cost, and energy efficiency.

5.2.2 Current planning framework for robust network

It is worth noting that the literature defines flexibility as a network's ability to satisfy different foreseen or unforeseen scenarios without much-needed assets. The pilot study attempts to capture definitions and applications of robustness in practice to explore their associations in practices. The definitions provided for the factors and parameters covers mixture of descriptions. In resiliency, interviewees described it as network flexibility to allow for compensation in a different operational scenario by changing flow routes and ability to supply alternative flow configurations. They correlated flexibility to the ability to supply water from different sources to different nodes compensating for failure situations. However, it is noticed that resiliency was often interchanged with reliability of components to resist failures. Flexibility attributed as a common factor between resiliency and security of supply; hence, there was no specific definition of flexibility in isolation of network security and resiliency as shown in Figure 5-1.

The parameters the pilot study measure in order to assess performance of the water networks is based on general objectives. They are considering three dimensions:

- Security of supply and the redundancy within the system ensuring a continuous flow of water to demand nodes in most circumstances,
- Level of service reflect interruption rates and water quality delivered to consumers, and
- Flexibility representing the ability of the network to modify flow patterns within existing configuration to serve specific needs.

Meanwhile, resiliency as a performance criterion was perceived in the pilot as a new concept and interviewees struggled to provide specific definition. Thus, there was a tendency to replace it with reliability or security of supply.

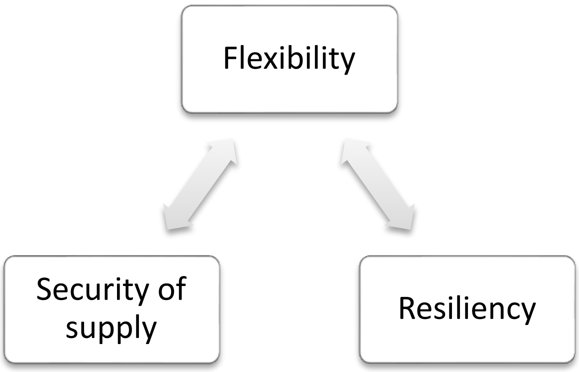


Figure 5-1: Flexibility perception

The security of supply role in practice was also questioned and was described as an agreement between companies and regulator on the acceptable standard for quality and quantity on service delivery. The standard is used to incorporate safeguards in securing supply to consumers and justify efforts (e.g. redundancy). For instance standard specifies the uptime and condition of an asset as parameters to reflect reliability of the network as main criteria.

In practice, the water network is designed to satisfy maximum demand in the future. This is set by the growth forecast triggered by either natural growth (e.g. increased birth members in a household) or the new growing demand (e.g. new immigration due economic growth). The future demand forecast might not materialise due to several reasons, such as economic crisis, affecting the new development projects. Such case would results in extra network capacity leading; thus, they try to utilize this extra capacity in the next planning horizon process. The capacity is inferred by planning as the remaining capacity of the asset (pipeline) to reach the full capacity, which can be referred as surplus capacity. It was associated with the forecast accuracy of the planning horizon. It is noted by the interviewee that having an increased surplus capacity can impact water quality due to low utilization, which can adversely lower the water quality caused by water age, residual chlorine, stagnation, etc. The network reliability is maintained by the security of supply countering mechanical failure of a component in the network, such as a pipe burst or a pumping station failure. The impact of these types of failures can be minimised by flexibility via means of alternative connectivity, redundancy, and storage to diminish a failure's impact as described.

Depicted from the pilot study, difficulties in designing such networks can be defined in three inquiries:

1. Where the demand is and how accurate it is. Does it materialise?
2. Where does the production source supplies from and does it cover the needed quantities?
3. What is the state of the current assets?
4.

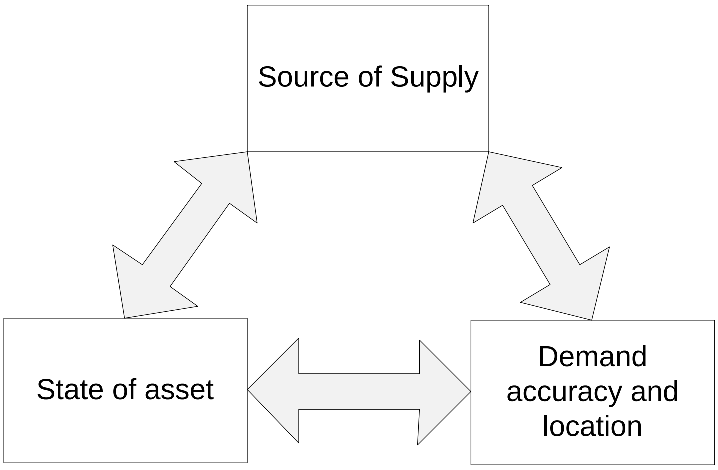


Figure 5-2 Current practice in addressing robust design on case-by-case approach

These three enquiries can act as current planning pillars as shown in Figure 5-2; to produce accurate planning. It is highlighted that once one of the three enquiries of planning is compromised, the planning accuracy suffers; hence, scenario planning emerges to compensate for such shortages. Due to the fast growth enforced by the rapid economic growth in Abu Dhabi, fast track projects are imposed to keep up with rapid growth. This urgency may handle accuracy issues and impact of utilisation poorly. Thus, alternatives in design are produced during planning to minimise some of these shortcomings by considering network structure loops and redundancies, increasing the flexibility of adapting to several scenarios at the same time.

The current plan alternatives is using scenario planning to allow for contingency planning of “what-if” scenarios. The scenario planning is prioritising how to build up robustness from supply performances point of view. The interviewee described the dependency of incorporating resiliency on the remaining capacity “surplus capacity” and demand location in the network (near source, network boundary). The current plan for the perceived resilience can be related to where to produce, where to consume, and the state of the network. Therefore, resiliency, flexibility, and security all play a major role in securing the supply in the network.

5.3 Findings from pilot study

The outcome of the interviews highlights two different aspects in relation to robustness, which can be categorised into process led-perception and technical led-perception:

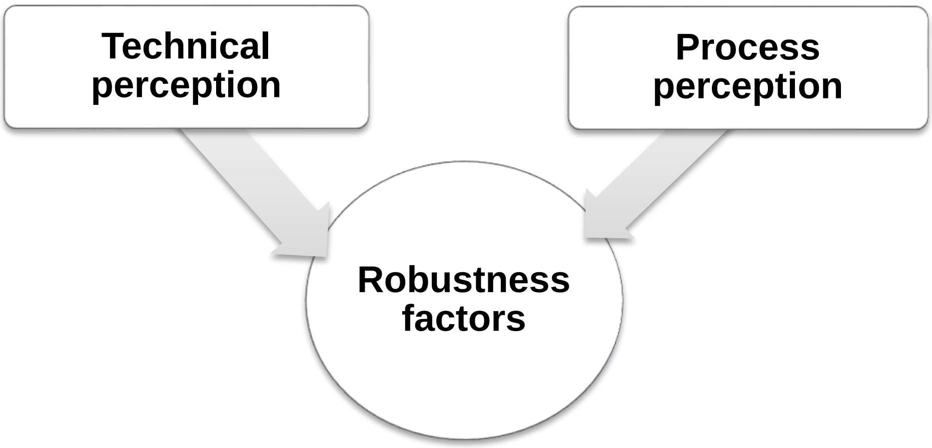


Figure 5-3: Interview perception

These perceptions are driven from the interviewee’s viewpoint on factors and parameters. For example, the process perception of surplus capacity is driven from the demand estimation and the accuracy impeded in such estimation. On the other hand, the technical perception is the flexibility of the network, where the connectivity enables the network to meet demand in different route configurations. The table below highlights the factors and their relevant perception in accordance to the pilot study results:

Table 5-5: Pilot study factors perception

Factor / Perception	Process	Technical
Resiliency	☑	☑
Connectivity		☑
Redundancy		☑
Vulnerability	☑	☑
Surplus capacity	☑	
Flexibility		☑
Reliability		☑

The definitions in literature are contrasted with the pilot study findings on robustness factors and parameters described earlier. There is a necessity to standardize the terminology used during this research. These definitions are based on the proximity of the descriptions found in literature and pilot study, which are compared and summarised in Table 5-6.

The comparison of the two found description from each of literature and pilot study shows that there are some differences and similarities between the two perspectives. Reliability is approached similarly from both literature and practice by considering the uptime of the asset life to operate without failure. Vulnerability from literature was considered more abroad in literature to consider exposure risk on assets against failures whereas the pilot specified a more specific definition that relates to the impact suffered consumers in case of failure. Resiliency on the other hand, have spanned from translation definition by literature to the parameters highlighted by the pilot to include flexibility as parameter in resiliency. Flexibility, meanwhile, shows a cross reference between anticipation of different scenarios and more accurate depiction to reconfigure network structure to meet required demands. In surplus capacity, the table highlights that surplus capacity in literature addressed in both of the two terms, namely vulnerability and resiliency.

Table 5-6: Factors definitions

Factors/ Sources	Literature	Pilot study
Resiliency	Capability of system recovery represented by the intrinsic ability to overcome performance degradation	The flexibility of the network to compensate for any operational scenario
Vulnerability	Measure of failure magnitude on water network, which is a function of risk exposure, sensitivity, and surplus capacity of the system	This factor is the other face of reliability and the impact on consumers in case of incidents
Surplus capacity	This tends to be a variable parameter in resilience and vulnerability	The variance of the planned capacity of asset and actual utilization
Flexibility	Anticipation of the network in relation to different future scenarios	The ability of a network to adapt to a different flow patterns
Reliability	Probability of network to accommodate demand and asset statues for serviceability	The security of supply and operation of components

This pilot study constructs a basis for the research and devises a methodology to capture the essence of robustness in practice. These findings will inform the subsequent investigation to build up a framework that enables planning of robustness in design of water networks. This pilot shows the misalignment between the knowledge in practice and the literature available concerning resiliency specifically. However, this pilot can construct an initial framework as nucleus for a conceptual framework. The initial framework developed to consider three dimensions of network performance, namely: resiliency, vulnerability and reliability. This initial framework highlights the research consideration. Based on the literature review and the pilot study, the initial framework has three factors that have an influence on robustness.

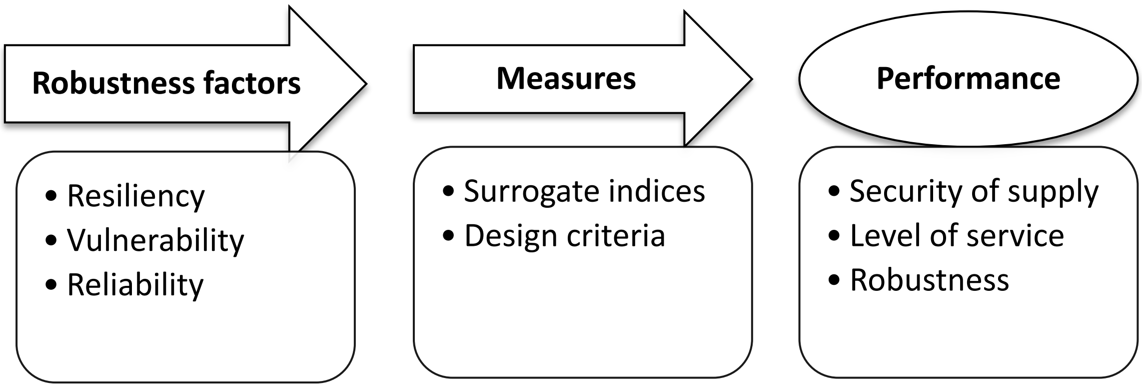


Figure 5-4: Initial research framework

The pilot study shows the need to understand more on what robustness in water networks. There is a valid need on the approach to robustness considering the factors underlined by both literature and practice. A further investigation is needed from practice to cross check the available information and processes in practice to understand ways of incorporating it into network designs. A case study of water industry is sought after gaining more resolution on the important factors, their connection and their relevant parameters. The case study investigation used Abu Dhabi and UK as candidates for water sector.

5.4 Thematic analysis of case studies Capturing key concepts in water practices

Interview transcripts were analysed using thematic template analysis (King et al. 2004) described in the next section. The information gathered categorised against ‘a priori’ template established on semi-structured template shown in Table 5-4. Comparison table of interviewees’ responses is constructed to allow the detection of cross case similarities and differences.

Collection of secondary data type is conducted using organisation documents and extracted data. Some of these extracted documents are shown in Appendix D. These records and documents are highly reliable, accurate and some of them are not available for public due to confidentiality. Planning, decision making process and organisation policy rely on these records, thus, quality assurance department confirms and makes it their job to ensure credibility and consistency of the data provided. The uses of secondary data not just help increase the research validity, but also save time. The types of data in these records are quantitative and help highlight the areas of expansion issues and elements; hence help identify critical factors affecting the planning a robust network.

The results of the interviews are further investigated and discussed addressing the findings of the factors of resilience, vulnerability and flexibility and where these factors or components present themselves in practice. These factors and parameters are structured using the themes used in structuring the interviews to capture them from practice in forming a new conceptual framework of robustness for the design of water distribution networks.

Interviews are designed to cover robustness factors by considering two perceptions: process perception and technical perception. These two perceptions were observed when the exploratory interview conducted earlier highlighting tendency of referring to robust performance either by process through the procedure conducted in the organisation or by technical perceptions involving analytical tool in designing or incorporating security of supply and level of service that revolves in robustness concept. Therefore, in this research the two designed perspectives are referred to as follows: Technical perception is where techniques or quantitative tools used in practice to interpret robust design, such as hydraulic tools used in simulating supply scenarios, and process perception involving business processes addressing factors that impact robustness, such as statement plans, forecasts that are delivered from different entities and the operational and maintenance strategies deployed to efficiently secure supply. These perceptions were organised to form critical factors for water network robustness while investigating each of the mentioned themes to construct conceptual framework. The target from the framework is to be used as guideline in quantifying relevant factors while maintaining holistic view of water system planning. Figure 5-5 illustrates the phases streamlining the analysis of interviews using thematic approach and industry perception.

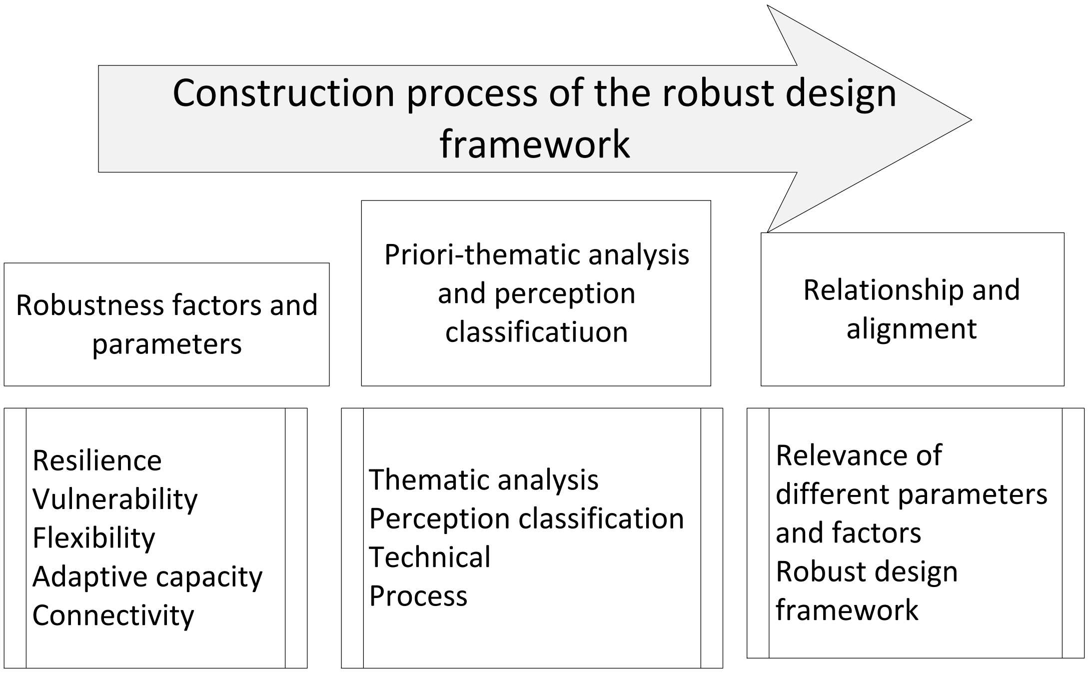


Figure 5-5 Construction process of water network robustness framework

The current practices for designing a robust network reflect O&M feedback on the network; hence, dependent on the learned experiences by O&M from existing system. This is realised from interviews when referred in responses to history documented by O&M. It is a critical step in order to adopt interruption scenarios for expansion plans during planning stage. It is evident from the interviews that reliability frequently confused when attempting to distinguish between it and the other factors under question. One reason for such confusion originated from the recent introduction of the other factors into professional sector, which currently can be challenging to determine. Therefore, the researcher decided to consider the literature and current theories of reliability as sufficient sources of information when examining robustness; hence avoid confusion and to capture essence of the other terms. Reliability is considered as term that addresses the decay and deterioration of components in networks.

Respondents presented the current framework by satisfying three aspects to allow for robustness in water networks, which are represented by the availability of source supply, accuracy of demand prediction and location, and the reliability of asset condition. This framework is addressing operational scenarios for case-by-case expansion plans. Figure 5-2 shows the current design practice in justifying robustness in designs to regulators.

Interviewees attempted to explain other parameters that contribute to robust designs, which are explicitly or implicitly understood from their perspectives. For instance, allowances and specification margins in the design of water network components are an implicit representation of robustness; this relates to component reliability incorporating design safety margins. Also the inclusion of buffer tanks in networks to ensure sufficient storage and continuation of service in case of failure, in addition to assets duplication to act as component standby. These mentioned fragments are considered by the interviews ways to enhance robust performance in water systems.

Security of supply and meeting levels of service in practices are based on examining existing networks and expansion plans separately using case-by-case analysis. Service-level quantification is dependent on probability events from historical information sourced from O&M data, and experience gained internally to assess designs during expansion plan. Thus current practices rely on expert opinion and book keeping in addressing a robust performance. Interviewees explained that there are many external inputs can influence network planning when taking a robust perspective. Those influences include demand forecast set by external entities (mainly consumers), Operation and Maintenance (O&M) history and strategy, cooperation with interface users, and regulation set for sector by (RSB).

On different note, when assessing vulnerability in current practices, interviewees explained that level of service calculations is a base to quantify it. The level of service is based on the failure frequency of network component, based on O&M history, and different operational scenarios on case-by-case basis. This is to determine acceptable level of impacts and measures to be included in the network; selecting designs that meets threshold benchmark set by regulators after incorporating financial life cycle cost assessment. The current analysis of robust performance shows a fragmented system robustness build-up. It was expressed by the interviewees that the current system is:

'…robust on micro level of the network; however, on the macro level, the big picture, it is not robust since we are looking into zones or sections of the network'. The current analysis examines materials history via operational component failures as an input; thus incorporating robust performance implicitly into water networks. The micro level referred to the components of the material and equipment used in the system, while macro level is the system performance led by the interconnection between components to meet targeted performance.

The following 5.4.1 to 5.4.3 demonstrates an in-depth analysis of the factors at hand highlighting particular similarities and differences on key factors among conducted interviews.

5.4.1 Resiliency

Pertinent to resilience concept, interviews with experts have expressed resilience in wide spectrum as depicted in Appendix G, showing the themes covering robust performance in water networks. Some of these responses came in alignment with available literature definition, discussed earlier, as quickness of network restoration. This may highlight that some experts are updated with relevant literature. However, there was no evident proof of this understanding in the organisation or documents. This reflected in the low percentage of this definition given in responses (1 in 10 of the conducted interviews) indicates that this definition is individually understood rather than on organisational level. Other responses noted that to achieve a resilient network, there must be a balance between flexibility and system security. Interviewees highlight flexibility as major parameter used in water network to create resiliency. Their understanding of flexibility in water networks involves operational flexibility to manoeuvre and change configuration to change direction of supply or route; hence, satisfying required demands. Flexibility was mentioned several times when speaking of system resiliency and ability to restore operation. It was highlighted by many interviewees that identifying available routes and capacities to reconfigure supply avoid impacts of failure or also to satisfy sudden demands. Flexibility, as explained, relates to the hydraulic feasibility to reroute or to supply nodes. It was pointed out by one of the interviewees that available capacity in the network can be used to absorb sudden changes, which will be explained in Section 5.4.3.

Meanwhile, others have described resiliency as network ability to deliver some water to consumers in all circumstances rather than quickness of restoration. Interviewees who responded as such referred to Ofwat UK based regulation set in the document Resilience – Outcomes published in May 2012. This considers resiliency from a different approach by considering reachability. This parameter is to incorporate the ability to supply water to any node at all times irrespective of the quantity supplied, even though, it is highlighted that this concept is still premature and was recently introduced by regulations in the utility business. In order to adopt such concept, it was noted that tools are still developed accordingly.

Companies are aiming to construct robust design guidelines. In instances, interviewees related this concept as part of meeting security codes set by regulators. It was mentioned in the interviews that resilience as a concept have been recently introduced in practice to address the increased challenges faced with long term planning and considering network expansion plans. This recent interest is driven by the infrastructure regulators, who started emphasising on introducing resilient networks forcing utility organizations to revisit their network design; hence, utilize existing assets in meeting demands and resisting failure scenarios.

Other responses pointed out that reduction of incident detection time can contribute to network resiliency as a parameter. This provides O&M the opportunity to react rapidly and attend to any incidents. This shows that resilience can address detection, assessment and action. However, detection tackles the operational stage, but the need here is emphasised on more insight during planning stage. The detection time is essential because it will determine the level of impact on consumers. Meanwhile, one of the respondents explained that a network is labelled resilient network if the repair time of any failure does not exceed 6 hours. Currently planning guidelines set by regulators require network planners to account for 24-hour buffer supply available at each consumer, which is enforced by the current building permits required within premises. This enables an embedded failure tolerance by end user averagely approximated of 6-hour repair window as described by O&M. It was introduced by interviews that detection and repair time can vary depending on the type of consumer impacted. This can reflect the consequence damages imposed on end users, which will be referred in vulnerability Section 5.4.2.

It is interesting to note that material design during construction should consider repair purposes emphasising easy handling and durability to maintain 6-hour repair time window, minimising surprises during repairs. Therefore, resilience factor can improve efficiency of O&M strategies. However it was noted by others that detection and repair alone is not sufficient to ensure quick restoration, and that network connectivity should be preserved to increase system output to consumers. Connectivity as a parameter has been expressed to be an important element for O&M in mitigating the negative effects of failures while addressing affected sections sustaining acceptable services. Connectivity related to topological configuration of networks by providing alternative routes from source supply to nodes or regions. Therefore, considering connectivity during design stage enhances overall network performance. Connectivity is addressed as tool for O&M that is utilised in network reconfiguration to meet different operational scenarios. Meanwhile, from planning perspective, connectivity is considered from hydraulic feasibility to allow for contingency sources in the case at hand. This parameter plays different role depending on the part of the sector.

For O&M, it is considered vital to tackle incidents, but they work with what connectivity and topology are available. In case of planning, they are concerned with hydraulic connectivity of expansion sites and available supplies to nodes. The view of connectivity considers reachability of supply sources within the network. This is because availability of multiple sources decreases risks of a single source interruption in networks. Parameters that have a direct relationship during design, as expressed by the interviewees, are network connectivity, hydraulic feasibility, multiple node supplies and capacity. These parameters highlight the need for sufficient connectivity within the network while guaranteeing source availability to nodes that are feasible hydraulically. Network reconfiguration is a design parameter for resilient network represented.

5.4.2 Vulnerability

Vulnerability is scrutinised to capture respondents' views of the origin of vulnerability in water systems and how sector is responding to it and depicted in Appendix G. Interviewees attempt to address vulnerability in the current planning processes. Interview responses on vulnerability definitions covers both technical and customer perceptions. For example, one of the interviewees explained vulnerable nodes by considering hydraulic perspectives. It has been explained that vulnerable nodes are called 'Control Node', which hydraulically is sensitive to changes within the system and can be used as surrogate for performance of the network. These control nodes are operating at the most extreme range hydraulically. If they are not satisfied, it causes the network to perform poorly in case of incidents. Other responses described vulnerability as categorisation of the end user type and importance. This is linked to end user tolerance and behaviour to water shortages. It is worthy to highlight that control node terminology is considered by planning perspective; however, end-user tolerance categorisation is considered by O&M perspective.

The interviewees loosely identified with vulnerability because it is difficult to justify or define, particularly because there are no available definitions or measures in practice. Current practices can explore network vulnerability through scenario planning scheme to assess assumed failure frequency, thus severity level is evaluated against an agreed threshold (e.g., set by regulator in service level). This is by conducting different operational scenario simulations under disruption generation. Although regulations try tackling network vulnerability while motivating experts to consider it, current design criteria are still driven by the commercial efficiency view when choosing expansion designs. This is due to missing clear criteria to describe vulnerability, making it difficult to justify any additional investment on safeguarding against vulnerability. However, interviews with O&M highlight that restoration is prioritised against the type of end user (residents, industrial or agricultural). Thus, identifying vulnerable nodes through consumer type can support restoration activities more effectively. They explained that current indicators of vulnerability in existing networks are explored through customer complaints.

Vulnerability can be assigned to pipe segments that are important for the network water delivery. These segments can be critical due to closeness to source or it is sole feeder to an area, which increases vulnerability in case of failure.

It was also highlighted that network components can be vulnerable if it keeps breaking down frequently. However it is pointed that such case is due to component reliability, which can be evaded by following acknowledged specifications and good practices. Connectivity and type of consumer are two things that affect network vulnerability. It was indicated that highlighting vulnerability during the planning stage has the potential to provide a new perspective when expanding networks.

Moreover, it is noted that emergency planning is an indirect way of addressing network vulnerability. However, vulnerability is examined on the existing network to mitigate failure incidence consequences rather than enforce supply abilities through design. An interesting assumption is stated by one of the respondents that having a vulnerable network lead to a compromise in resiliency. This statement assumed that reconfiguration requires different routes, yet more vulnerable nodes can limit the network configuration. From the interviews it is referred to resiliency as continuation of service to the most affected nodes while considering end user requirements. Emergency planning underlined the level of emergency by the status of the region’s socio-political conditions and linked to strategic national security coordinating and facilitating available resources. Due to confidentiality and sensitivity of this subject the depth of information was limited, however, this highlights that vulnerability can be adjusted according to the strategic statues of the emergency level. Hazard identification (HAZOP) was identified as a tools to assess vulnerability. Interviewees highlighted the use of risk calculation derived from frequency and severity to reflect impact. However, such calculation covers wide spectrum of environmental, socio-economical influences and not only the design parameters of water systems, also it can be considered too generic for specific evaluation.

Interviewees are asked about parameters that measure network vulnerability. Their responses highlighted demand elevation, high capacity nodes, type of consumer, and location from major city-centres as a few. Current approaches to counter identified vulnerabilities can include introducing buffers within the network, which is defined by the amount of reserved water available within the network (e.g., tanks) serving consumers in case of supply disruption. This method is used to increase the tolerance level of consumers and allow for extra time for O&M to react to such events. This approach is designed after exploring extensively other options such as connectivity to alternative sources. Other mitigation tactics adopted during planning stage is through using redundancy in assets or creating supply loops within the network allowing for routes from sources. The emphasis is on generating a multiple routes to consumers through hydraulic reconfiguration “flexibility” employing connectivity. Therefore a quantitative measure of these concepts can promote a more systematic view of vulnerability in design. As one of the respondents put it, *“the main threat faced by a water network is the lack of statistical knowledge of the system”*, thus understanding the network can help avoid unacceptable impacts.

5.4.3 Flexibility

Term of flexibility is loosely used in water distribution systems. Interviewees defined network flexibility as the ability to mitigate failures, the ability to utilise available capacity, and the ability to configure the network as shown in the summary of the interview responses collected and depicted in Appendix G. Or put differently, flexibility referred to the network’s ability to be resilient and efficient enough to utilise spare capacities within the network through reconfiguration. It is advantageous to have flexibility in the network, thus ensuring network asset to be utilised for end user interest. Although there is no formal definition of flexibility, there is inclination to use network manoeuvrability as a form of flexibility to mitigate failure impacts. Responses in flexibility find it difficult to separate between flexibility and connectivity and they both enforce each other. Also flexibility is linked, as explained by O&M, to surplus capacity within the network for operational use.

Flexibility expressed as a property that makes assets (e.g. pipeline, tanks and pressure) operationally available to cater for existing and future demands. This shows that flexibility is a desirable aspect in water networks. However, assessing it is still ambiguous. By inspecting where flexibility is initiated, an interviewee point out that it starts from the planning outlook or master plan, and abide by design code set by the regulator. The master plan highlights the capacity needed for the long term demand prospect, this form the surplus capacity, which is defined by the capacity available between the actual current demands against the designed/maximum demand. This spare capacity can be utilised as margin for planners to use for any unforeseen changes equipping water system with surplus capacity. The current assessment method for this parameter is not clear, but it is referred to as the network flexibility. However, the current practices use hydraulic scenario analysis, alongside planners' expertise and knowledge in making design decisions. There is a consensus among interviewees on flexibility, which can be linked to network ability to modify flow patterns to serve a specific flow scheme. One perspective of the flexibility benefits that it can be used to satisfy different foreseen or unforeseen scenarios without many added assets. This interprets spare designs to adapt to changes.

There has been a tendency to confuse flexibility and security of supply in practice. When asked about ways to measure flexibility, the interviewees note that sector analysis and level of service calculation describe network flexibility, however, the lack of guidelines or frameworks set by regulations or consensus causes misinterpretation of flexibility. The approximation of flexibility currently can be assessed on case-by-case basis scenarios. Yet, considering parts of the expansion network in the case-by-case can contradict the overall or macro network design of an integrated flexibility. It is mentioned that such effect can be minimised by having a master plan, underlining the importance of forecasting in rendering networks flexible. Currently there are mechanisms used to improve so called flexibility and that is either by doubling assets or the addition of buffer capacity, or providing alternative supplies. However, there is a need to balance between adding redundancy and providing alternative routes to enable effective designs.

From O&M perspective, they mention flexible system operation period by considering the daily demand supply duration. This is explained by the design assumptions considered by planners, who use 24 hours supply period as a daily supply demand to satisfy consumers for maximum designed flow and pressure. However, due to different behaviour of consumers and system external influences, the scenario is only applicable for limited time during the year on high demands days. This discrepancy allows the usual supply period to be reached within 18 hours of supply rather than the planned 24 hour assumption, yielding 6 hours of leeway to satisfy any daily shortages. This is applicable because of the storages available in each of consumer premises absorbing short system interruptions and minimising the impact on end-users.

5.5 Conceptual framework of water network robustness: Comparison between practice and literature

Firstly, the interviews findings are categorised against priori themes set in Table 5-4 to enable capturing of the different views in practice. This is depicted in Appendix G to illustrate the method adopted in categorising different perspectives from interviews. This is to streamline the findings and structure the motivation or the tool enabling these concepts. For example, in Figure 5-2, it shows the different definitions described from interviews under definition theme. Also it shows the tools described to assess the factor of interest. The alignment of definitions is summarised in Table 5-7. This table summarise the findings of the following discussions and qualitative analysis.

Second, these factors and parameters are compared with literature to show the range of spectrum these are going under. It is noted that parameters are inclusive within factors; such connectivity is a parameter within flexibility. The literature outcomes are drawn from Section 4.3 with closest referenced literature available within in that context. In the following Table 5-7, it is illustrated the variance between literature and practice although they can become subtle, as in flexibility, other terms can diverge, as in resiliency. The mapped concepts and different parameters mentioned in interviews or found in literature introduce comparative review between the two. There are misalignments between literature and codes or standards set in practice that describes relations of robustness concept differently emphasising the need to have new framework. From literature and interviews conducted, the concepts are organised against parameters. The research checks structure of different views and terms. The misalignment can be detected in alignment sheet depicted in Figure 5-7. This is to construct a conceptual framework that will be used as a basis for the quantitative analysis of relevant parameters.

5.5.1 Practices interpretation of literature concepts

The breakdown of each factor to their relevant parameters allows constructing associations among them using interviews illustrated in Table 5-8. It shows that in practice, these concepts are done on observing the micro level of network systems, not considering a macro level design representing topological connectivity and users behaviours. This is perceived on level of service calculations and risk analysis when considering a case-by-case scenario. Meanwhile, forecast factor in literature has not been addressed extensively to link forecast to flexibility and vulnerability, which can be one area for future work not covered under this research scope.

A preliminary framework is outlined to capture experts' knowledge of how these different factors relate shown in Figure 5-6. This framework was presented to three of the recognised experts in water planning field to give their feedback on areas of improvement. The feedback revolved around showing a hierarchy depiction of these factors to each other is needed. Also factoring in other elements of management strategy and available resources to consider robustness as whole is critical to planning function in the organisation. The management needs to consider necessary database for a further analysis of the network performance and characteristics.

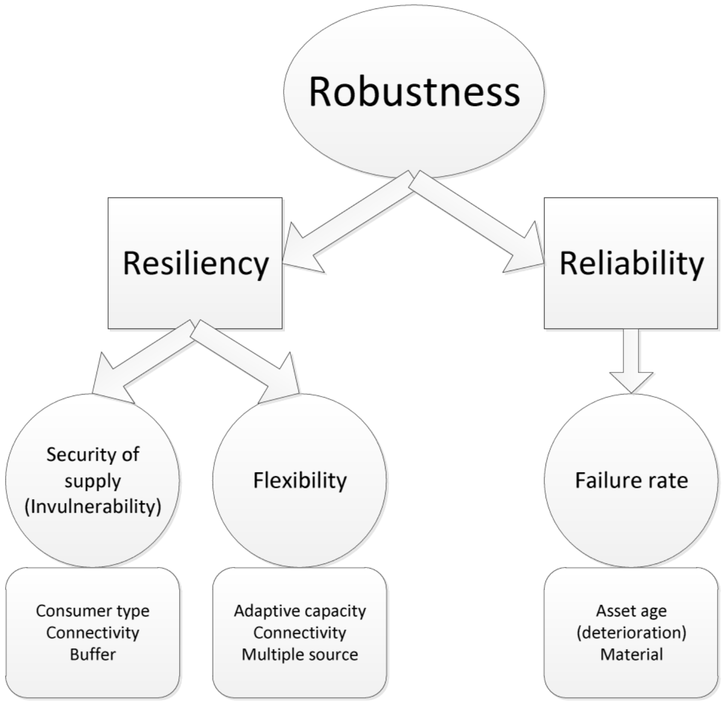


Figure 5-6: Preliminary robustness framework

Reliability on the other hand, refers to component levels in literature and is referred in practice to deal with the engineering specifications of assets in addition to component aging and deterioration. These terms of, namely engineering specification and asset aging, are incorporated into two different practice process, namely risk index and level of service respectively. It is obvious that reliability can be linked to network micro level, which is their component. This will help inform the framework to have different layers reliability plays a major role in obtaining a consistent operation of assets. This can be used as a parameter that strengthen or improves them. It is noted that surplus capacity and flexibility can be covered by the other terms shown in Table 5-7.

The security of supply code shows redundancy as a parameter to enhance robustness. However it fails to mention residual pressure that is considered a level of service. Additionally, consumer impact is considered during emergency plans and operational level and it is overlooked during planning phase.

Table 5-7 Comparison table of available definitions of robustness concepts and parameters between the literature and interviews collected.

Factors/ Sources	Literature	Semi-structured interview
Resilience	Quickness of system recovery represented by the intrinsic capability to overcome degradation (Baños et al. 2011; Di Nardo & Di Natale 2011)	The network ability to compensate for any operational scenario using flexibility to minimise impact on users
Vulnerability	Measure of failure magnitude on water network which is a function of risk exposure, sensitivity and surplus capacity of the system (Di Nardo & Di Natale 2011; Bentes et al. 2011; Gallopín 2006)	The impact caused by lack of reliability of asset condition. The importance and tolerance of users/nodes by disturbance scenarios
Reliability	Probability of network uptime to accommodate demand before failure of a component (Baños et al. 2011; Farmani et al. 2005)	Security of supply to maintain flow. Statistical probability of system components to operate without failure
Surplus capacity	This tends to be a variable in resiliency and vulnerability (de Graaf & der Brugge 2010; Gallopín 2006)	The variance of the planned maximum capacity of asset and actual utilisation
Flexibility	Anticipation of the network to different future scenarios (Gargano & Pianese 2000; de Graaf & der Brugge 2010; Yasdani & Jeffrey 2011)	The ability of network to reconfigure supply through connectivity and capacity utilising existing asset to meet demands

This does not include all necessary parameters to serve robustness. In practice, the design of water network is based on O&M history book-keeping and experience. Thus, design relies heavily on the expertise of the planner and the O&M knowledge of the network.

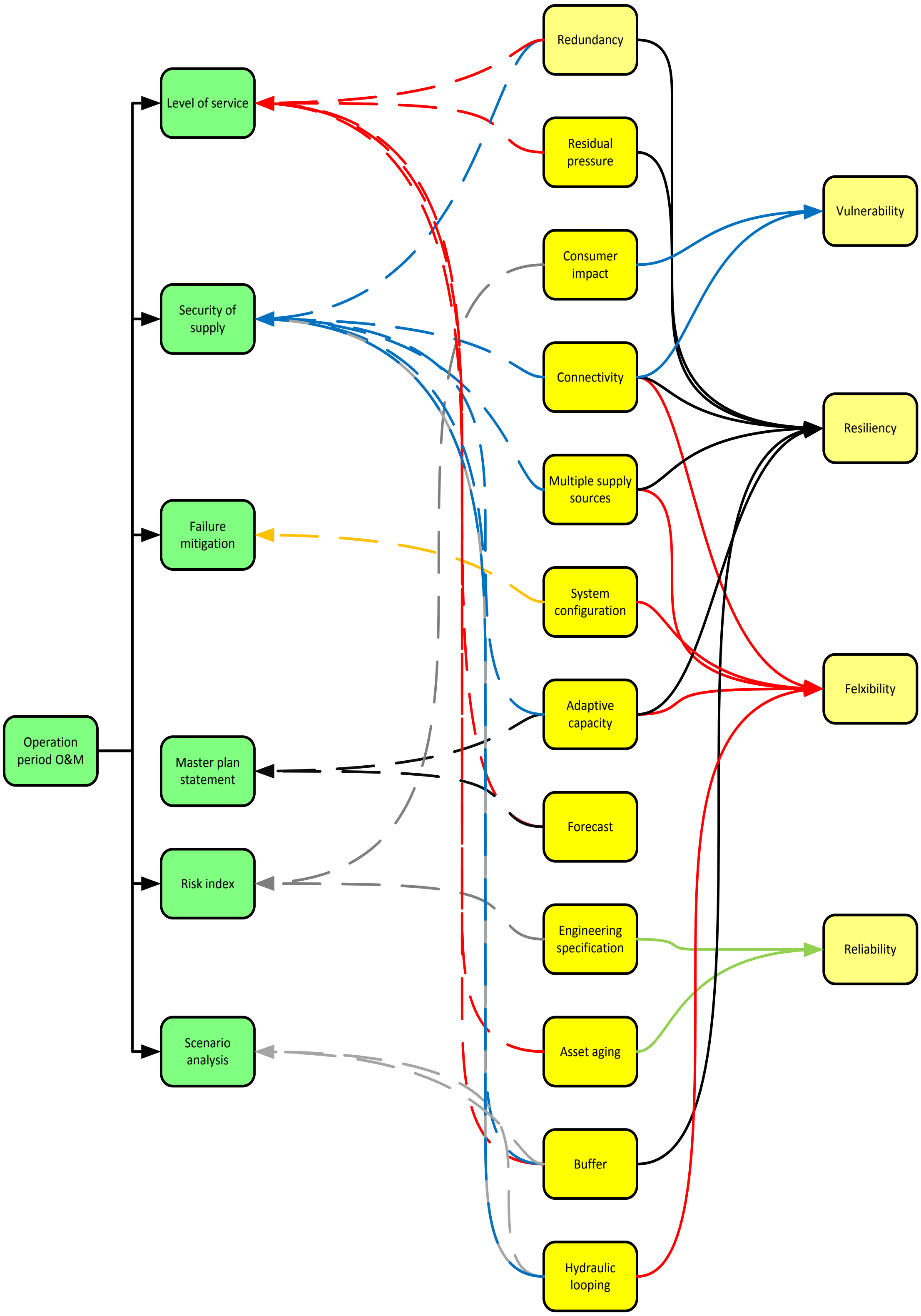


Figure 5-7: Robustness concepts alignment sheet between literature and practice

The resilience helps to maximise the use of the existing network to meet prioritised consumer demands. Looking back on the overall parameters to describe these terms, we can propose that resiliency is a function of both vulnerability and flexibility. Table 5-7 demonstrate the differences take on the concerned concepts between literature and practice. This may be due to recent application of these concepts in practice. The table shows flexibility used to define resilience; meanwhile it is defined as the network to reconfigure operational structure. Meanwhile, surplus capacity can be found in two different concepts, that is, resiliency and vulnerability; it has more concise definition in practice, which identified by the variance between maximum design and actual operation level.

5.5.2 Conceptual framework of robustness in water distribution networks: Resiliency and reliability

To logically relate resiliency to vulnerability, it must be recalled that vulnerability reflects network weakness, while resiliency explores network safety. This is in line with industry practices for meeting network supply security at an acceptable level of service. Therefore, ‘invulnerability’ can be related to supply security where it was introduced in literature recently (Yasdani & Jeffrey 2012). Thus a relationship can be formed between resiliency and vulnerability, as described from gathered information to be inverse-proportionally to each other. So the more vulnerable the network is, the less resilience as it pointed out earlier in the case study.

Moreover, the configuration of the network should support consumer types, since type impacts the level of emergency, network priority configuration and actions prioritised in correspondence to vulnerable nodes. This is evidently demonstrated when considering agricultural demand type and city resident demand type, where city residents generally require a much faster solution than agricultural locations, setting aside exceptional cases.

Flexibility as a parameter provides the advantage of reconfiguring the network to counter any adverse impact caused by failures. This research highlights the vulnerability of a network by consequences of failures on end users.

The research constructs a conceptual framework from the outlined Table 5-8 by mapping different found quantified parameters against the critical factors highlighted in this research; exploring the coverage of them to each other. The Table shows resiliency as an overarch factor that contains the parameters from both flexibility and vulnerability. This implicitly highlights the role of both flexibility and vulnerability in creating resiliency in water systems. The research proposes in view of the gathered information to represent resiliency as a function of both vulnerability and flexibility.

Table 5-8 Mapping of robustness factors against parameters based on interviews

	Concept		
Parameter	Vulnerability	Resilience	Flexibility
Surplus capacity		✓	✓
Consumer type	✓	✓	
Connectivity	✓	✓	✓
Buffer	✓	✓	
Multiple sources		✓	✓

From Table 5-8, the conceptual framework needs to build a holistic depiction model of water network robustness while showing resiliency association with parameters of both flexibility and vulnerability.

Robustness conceptual framework is guided by the definitions adopted to structure the relevant factors. Table 5-9 summarises the definitions embraced in this research, which is produced to bridge the gap between literature and practice. Accordingly the conceptual framework is shown in Figure 5-8.

Table 5-9 Summary definition table proposed by this research

Term	Adopted definitions
Robustness	The degree to which the network is able to react to different scenarios while maintaining water supply
Resiliency	The ability to manipulate the network by employing reachability and surplus capacity (flexibility) to serve users, highlighting network sensitivity of users to failures and incidents (representing the vulnerability of the network)
Reliability	Component durability to continue to work without failure
Flexibility	Reachability of sources within network using surplus capacity to secure water supply
Vulnerability	Sensitivity to shortages within the network from the consumers point of view, dictated by consumer type and level of tolerance

The framework shows that resiliency can encompass the features of both vulnerability and flexibility. This is found to be in line with interview findings discussed earlier and the literature whereby resiliency acts on system level of the water network. It is worth noting that resiliency acts as a higher level of water system addressing macro level characteristics residing over reliability of network components, which act as micro level characteristics. Reliability is described by the network component failure rate, which is affected by environmental factors and deterioration. Resiliency is redefined as manipulation of network in order to address weaknesses in network (represented by its vulnerabilities) through utilising connectivity and surplus capacity (represented by flexibility). This illustrates the need to ‘balance [the network] between flexibility and invulnerability.

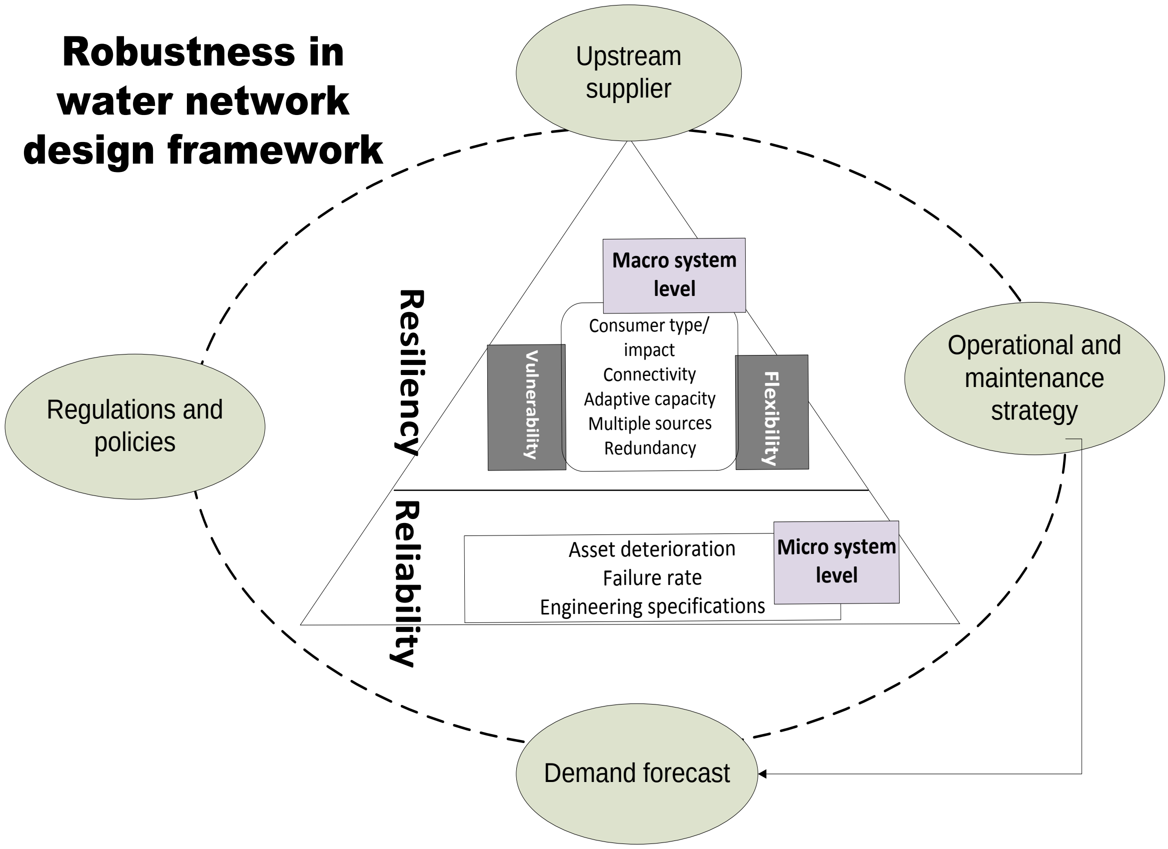


Figure 5-8 Hierarchal design framework of robustness factors and parameter with their external influences

The robustness framework is constructed around network planning. This framework operates around different boundary elements affecting planning, which can be summarised as: O&M strategy, the forecast accuracy of master plans, cooperation with upstream suppliers, and the regulations imposed by regulators. These external influences feed the input from external organisations into the design of networks, thus impacting robustness integration into water networks. In Figure 5-8, the conceptual framework visualise robustness from planning context. This suggests the terms found in literature constructing the building blocks for establishing robustness in design of water networks.

The hierarchal design framework is synthesising different information and was presented to water experts and academics for their feedback. This framework depicted the interrelationship with different sectors from planning perspective to design robustness in water networks. They agreed that these factors are the major elements to produce a robust design of water networks, although there are detailed parameters such as hydraulic features (e.g. flow, pressure, and head losses) and meeting practice codes when considering quantitative approach. They expressed that the framework shows a generic representation of robust characteristic design overview.

This conceptual framework represent as generic model to allow the transition from real system to scientific model as described by Kolkman et al. (2005). They highlight the need to abstract the criteria of interest in order to allow making a suitable transition from real system to model. This conceptual framework points out the relevant factors to focus on to achieve the targeted aim. The framework highlights approaching robustness design require a two-level approach covering both micro and macro levels. The micro level accounts for reliability as a factor for assessing system components reliability (e.g.: pipes, valves, pumps… etc.). The macro level is represented by resiliency founded on vulnerability and flexibility of the network. The research will deploy next the conceptual framework to act as a road map in creating a quantitative robustness model.

5.6 Chapter summary

This chapter reviews practices perspectives and explore terms and concepts against literature. The misalignment in Figure 5-7 between terms and aspects of robustness in water practice makes terms intertwined and difficult to distinguish. Furthermore, it can be promoted that resiliency is encompassing factor that includes flexibility and vulnerability as operating parameters to enhance resiliency as shown in Table 5-8. This information matched with the proposed conceptual framework in Figure 5-8 representing different level of robustness in context of water network planning.

This conceptual framework is proposed foundation for the quantitative measures under this research. It will be informed by different principles in the robustness assessment. It should be noted that the upcoming quantitative work conducted under this research is limited to resiliency. The research is seeing resiliency an area of increased interest since it addresses an emerging need that requires more attention due to increased complexity in network expansions; also it addresses a macro level that is founded on micro level of reliability. Reliability is much founded science in literature that can be incorporated under the premise of this research in future work. Resiliency holds more potential in exploring the fundamental of allocating macro properties in water networks, thus structuring it as planning guidelines is critical need.

Chapter 6 – Network analysis model formation

This Chapter describes the development of quantitative approach utilising the premises suggested in the framework. The purpose of this chapter is to form assessment method to approach factors of resiliency factor in water networks. The consideration of resiliency concept due to its recent emergence in the industry, which needs to be further analysed in the context of water networks. The assessment model of resiliency thereafter is grounded on the conceptual framework in 5.5. This is decision took to focus more on the newer concepts of resiliency rather than more established concept of reliability in water network planning. The chapter considers different parameters of resiliency in terms of flexibility and vulnerability to construct model of resiliency quantitatively. Both of these parameters have a different centric view in calculating their relevant metrics. Flexibility allow of capturing configuration ability of networks via reachability ability and surplus capacity. Meanwhile, vulnerability detects the sensitivity impacted on nodes that are guided by the available walks to node and population density.

6.1 Introduction: complex network theory model of water networks: quantitative formulation of resiliency

This chapter explores the use of *"complex network theory"* to approach integrating hydraulic properties with topological structure in evaluating resiliency. As presented from the conceptual framework, resiliency can be described by network flexibility and vulnerability parameters:

$$(Flexibility) and\ (Vulnerability) \rightarrow Resiliency$$

Networks in general are characterised by their connectivity and topological feature to carry out the tasks they are designed for. Many studies considered different networks such as power utility networks (Dwivedi & Yu 2013b), transportation networks (Winters 2000), airline networks (Reggiani et al. 2010) and even information and social communication (Braha & Bar-Yam 2006; Solé & Valverde 2004) as complex networks to explore features and structural attributes related to their characteristics and performances. These studies use principles and tools borrowed from *Complex network theory,* which is a branch from *"graph theory"*. This is in order to explore topology structures, connectivity, and to examine reaction of different structures to changes.

Newman (2003b) has consolidated tools derived from *graph theory* to analyse complex structures and their connectivity to demonstrate different properties in withstanding adverse changes and reaction. Increased interests were given to the field of complex networks in recent years due to applicability in many sectors. This research constructs different measures to represent characteristics and features of flexibility and vulnerability in the context of water networks. These measures were synthesised with hydraulic properties to reflect resiliency concept since it builds on topological and hydraulic features.

A "*geodesic path"* (shortest path) is the path with fewest edges between two nodes. The *distance* between two nodes is the number of edges in a walk or a path. Both (N) and (E) can take weights to reflect characteristic of relevance to a specific behaviour or a feature in a network. To apply network theory to water systems, pipes are treated as edges, while pumping stations, demand locations and junctions are treated as different types of nodes. Nodes can be categorised into three types: transfer nodes that have no demand, source nodes (e.g. reservoirs) that output a net non-zero flux of flow, and sink nodes (e.g. consumers) that receive a net non-zero flux.

Water systems are considered in this research as a *directed* and *acyclic* network. In a directed network, each edge has a direction; in this research the direction will represent the water flow direction in edges. Acyclic is a network that has no loops, where they start at a source and cannot end at same stating point, while on the contrary a cyclic network has walks, which follow the edge directions, start and end at the same node. To resemble water systems, each edge will have a maximum flow and pressure capacity that dictates the supply performance (Bureerat & Sriworamas 2013). The net incoming flow to every transfer node balances with the net flow received by demand nodes in the network.

Statistical approaches addressing topological structural are developed to extend to water systems. However the current approaches are covering analysis of network topologies, exploring connectivity from a purely structural perspective (Ostfeld & Shamir 1993; Yazdani & Jeffrey 2011). These statistical approaches are hampered by the challenges associated with obtaining sufficient, appropriate and accurate network representation of practical networks; hence, providing meaningful results (Burn et al. 2003; Jafar et al. 2010).

Purely topological approaches were used in several previous studies used flow paths and node topological measures to analyse water network structures (Yazdani & Jeffrey 2011). These approaches can be improved by incorporating hydraulic properties of water systems, thus capturing real system behaviour. The water properties obey the flow-head relationship modelled by Bernoulli’s energy fluid principle where centrality metrics need to incorporate these properties. Centrality is a measure of nodes or edges frequency occurrence among walks or paths. However flow direction in water network is determined by pressure, not the number of nodes, so it is not restricted to geodesic paths. In this research, water flow will follow all feasible walks rather than shortest paths. These walks must link sources to demand nodes and should be hydraulically feasible. Modifying current centrality measures will give insights of the critical elements in water network.

Previous studies have modelled network behaviour by studying their reaction against failures by removing nodes to evaluate network performance to emphasise node importance (Tabesh et al. 2009). Connectivity in water systems is affected by edge failures instead. Similarly, water systems expand their coverage by adding edges to supply new demand nodes (Tanyimboh & Kalungi 2008; Chenoweth 2008). Therefore, changing the focus from nodes to edges (pipes) provides information more relevant to planners helping them to explore parts of the network that needs attention. This will also enable better utilisation of surplus capacity network expansion.

6.1.1 Flexibility and vulnerability Concepts

The robustness framework will be approached in this research using metrics for resiliency through flexibility and vulnerability. Currently these are derived from historical data and expert opinion highlighting the need for a more structured network analysis while combining topologies and hydraulics. Two parameters seen in Table 5-8 are important to enhance “Flexibility”, connectivity and surplus capacity. Connectivity has been underlined as one of water network attributes to resiliency requiring a closer look of the network topology. This attribute caught attention in many studies aimed to assess it. Complex network theory used as candidate to explore this attribute in water networks (Di Nardo et al. 2013; Yasdani & Jeffrey 2011). Surplus capacity is another attribute that emphasised at network capability to utilise that capacity. This parameter was highlighted earlier through *“resiliency index”* by Todini (2000) to capture spare residual pressure at nodes demonstrating network resiliency.

$$Connectivity\ and\ Adaptive\ capacity \rightarrow Flexibility$$

The second factor “Vulnerability” is a measure of node or end-user susceptibility to disturbance. Parameters of this factor are depicted in Table 5-8 showing consumer type, connectivity and buffer. The vulnerability factor can be assessed by the node type and the behaviour against water shortages. Connectivity shows again in vulnerability, which illustrate the role of topology of in impacting vulnerabilities. The use of buffers increases the tolerances of end-user to water shortages as explained earlier in Chapter 5. Therefore, end-user importance in network can dictate vulnerabilities in a network and their behaviour towards water shortages. In this research categorising end-user will be considered from hydraulic perspective. This is relevant to the quantity demand at nodes which can be related to importance of such node in the network. Also the number of end-users served at each of nodes can play a role since residential nodes carry more importance than an agricultural node. Therefore vulnerability can be described as follows:

$$Demand\ type, high\ capacity\ nodes, location \rightarrow Vulnerability$$

6.1.2 General aspects to be incorporated in robustness measures

Parameters of resiliency are required to incorporate water hydraulics to reflect close depiction of system characteristics. Previous studies proposed different measures that suffered from several drawbacks; for example, most measures overlooked variances in nodes importance which represented in vulnerability. Although some studies attempted the consideration of different node attributes to measure network resiliency, yet it covers narrow interpretation such as basic demand (Yazdani & Jeffrey 2012). Therefore, modified measures should consider hydraulics alongside topology for successful supply distribution. These aspects are extracted from the case study interviews carried out under this research cross checked with literature. For example, networks should be linked to at least a source node in all cases otherwise it fails to supply a node. Although this is obvious, this needs to be incorporated in the modified measure or index. This can be considered as specific consideration of connectivity called “reachability” whereby source can reach and supply all nodes via network connectivity (Gheisi & Naser 2013). Another aspect to be considered is hydraulics as mentioned earlier, which is driven by energy equations and energy losses; thus utilising network connectivity to dictate flow regime to end-users (Rossman 2000). Meanwhile to address different node importance, reflected by type of end-users, volume supplied and importance criteria should be considered in constructing relevant measure (Shuang et al. 2014). All these aspects highlight the need of a toolkit assessment approach to cover different performance measures to gain deeper insight of the parameters that enhances or deteriorates performance of a network resiliency (Yazdani et al. 2013). Developing suitable measures with all these aspects poses challenge to allow for a clearer assessment. Overcoming this challenge will help in gaining insights on expansion designs.

Current practices use hydraulic scenarios alongside planner’s experience and intuition to make decisions on flexibility. The lack of universal consensus on water network flexibility definition adds to the difficulty of assessing it. For instance flexibility is perceived, as explained earlier, network’s ability to satisfy different foreseen or unforeseen scenarios without significant additional assets in existent network (Di Nardo & Di Natale 2011). Therefore, water network planners often address flexibility on case-by-case basis either through doubling pipelines, adding buffer capacities in consumers’ premises, or exploring the addition of interconnections to increase supply routes. Balancing these interventions is required to reach a desirable performance of networks. Studies in recent years have started incorporating topology alongside hydraulics to identify flexibility (Saleh & Tanyimboh 2014; Kabir et al. 2015). Flexibility can be used as planning criteria while addressing existing and future demands, however identifying it requires more investigation. Current practices need the inclusion of the overall network coverage and employing the contemporary parameters in identifying network flexibility.

This research presents an approach to address flexible designs of water distribution networks. Meanwhile, it attempts to interpret flexibility by quantifying hydraulic and topological parameters in water networks, enabling the construction of flexible networks and apprising planning decisions.

6.2 Complex network theory application on water networks

The research approach commences by examining available indices representing resiliency in Complex network theory. These indices are to be analysed and evaluated to form a base to structure in this research. The literature describes different approaches to tackle such design. For instance, literature introduced entropy measure as surrogate of water network robustness using the concept of entropy as discussed in Section 4.2 that is defined as a measure of uncertainty related to a process, which correlates a the most resilient network as level of entropy of 1 to design water network. (Awumah et al. 1990; Tanyimboh & Templeman, 2000)

Resiliency measure in literature focuses on the ability of system to maintain energetic redundancy, minimizing the internal energy dissipation. Linking this factor of robustness to practice, it is usually addressed by providing redundancy measure to networks mitigating impact of either hydraulic or mechanical failures. The looped network also represents a type of redundancy in water flow to nodes by increasing alternative routes within the network to each demand node. Based on Todini (2000), resiliency factor in water network implied that a surplus of energy per unit at nodes could compensate the energy dissipation in the system when it is changed to account for system failure by choosing alternative routes. This can be denoted with:

$$P_{tot} = \gamma \sum_{k=1}^{n_r} Q_k H_k \tag{1}$$

The above equation reflects total power entering water distribution system where Q_k represents flow and H_k is head per demand node k, while γ is water specific gravity of water supplied to nodes n_r. Measuring the excess pressure reached at nodes against the minimum required pressure to supply the required demand, this accounts for the surplus power remained available from the total power available to source after the dissipated internal losses created by hydraulic supply. Todini (2000) defined the resiliency index as the ratio of power input to the system to the power loss. Other modified resiliency index is called "Network resilience". This was modified to account for the surplus of power available at each node after the dissipated internal energy, this to counter the increase in head loss that occurs because of failure in any water network component and the required of rerouting flow to nodes. This follows the principle of Todini (2000) which is:

$$I_r = 1 - \frac{P_{int}^*}{P_{max}^*} \tag{2}$$

Where $P_{int}^* = P_{tot} - \gamma \sum_{i=1}^{n_{ri}} q_i^* h_i$ is the amount of power dissipated in network to satisfy total demand, whereas $P_{max}^* = P_{tot} - \gamma \sum_{i=1}^{n_{ri}} q_i^* h_i^*$ is the maximum power that would dissipate internally to satisfy the constraints in term of demand and head at nodes. Both of these indices provide a global indicator to system resiliency. These indices focus on node maximum supply can be achieved by node. This consideration needs to be shifted to edges rather than node, since limitations and maximum restrictions in reality produces from edges physical characteristics that relates to size and pressure rating and not node. Also these indices does not account for connectivity failures imposed on water networks.

This is important because edge failure downstream a source has profound impact on the overall network than a periphery edge existed in the same network.

Nodal demand, hydraulic heads and number of consumers served can be input to weighting network nodes to provide insight to their importance. Studies' deploying Complex network theory in analysing network topology suffers from prospect drawback since these measures are computed on a global basis. Although it is useful for benchmarking purposes, it does not give a clear insight in knowing which part of the network structure requires more attention, or it may overlook hydraulic properties. To quantitatively assess network resiliency, this research shifts assigning weights from nodes to edges considering mainly their interconnections, physical attributes (i.e. diameter, length) and demand to account for both hydraulic and topological features. Yazdani & Jeffrey (2012) used ranking of network nodes (V) based on their level of centrality and connectivity by studying operational consequences of failures on network by using demand-adjusted entropic degree reflecting demand and definition of entropy. This study suggests the advantage of the use of betweenness centralities in extracting network importance.

There are several indices and ratios borrowed from *Complex network theory* were employed analysing the concept of robustness, reflecting water topological characteristics. Some of these measures are presented in Appendix C for easy reference. Complex network theory metrics can be used to establish relationship between network structures and their performances. Modifying these metrics in line with the developed framework can provide clearer idea of the measures needed for specific factor or parameter, while incorporating robustness (Narayanan et al. 2014). Betweenness centrality have been described as $C_b(k) = \sum_{s \neq k \neq t \in V} \frac{\sigma_{st}(k)}{\sigma_{st}}$, where $\sigma_{st}$is the total number of shortest paths from node s to node t and $\sigma_{st}(k)$ is the number of paths going through node k (Narayanan et al. 2014).

Flexibility as a parameter of resiliency in water distribution network has traditionally been expressed in terms of sufficient network interconnections between source and end-user. Ostfeld & Shamir (1993) have characterised networks based on the connectivity and reachability between nodes and sources, contributing towards supply security. Network connectivity was highlighted as a critical parameter in meeting demand and the role it presumes to satisfy demands during failure incidents. It enhances water network performance to maintain certain supply security when considered during design. Quantitative methods in assessing network connectivity were focused on topological features, thus the need for utilising hydraulic properties in investigating feasible interconnections in water networks are needed. Water network redundancy as an approach in practice potentially enable mitigations of mechanical-type failures and sustaining system performance (Walski 1993; Diao et al. 2010). However, a significant limitation with redundancy is that it provides no real financial incentive to the overall network connectivity coverage (Yazdani et al. 2011; Yazdani & Jeffrey 2011). Although redundancy can strengthen the supply of a certain link, it falls short of improving system overall performance. The trade-off between scenario expansion planning approach and network topology ratios need to be structured to take into consideration connectivity of overall network designs. The global system connectivity achieved usually are an outcome of rapid developments and growing expansions addressing new demands (Di Nardo et al. 2013).

Some studies have highlighted node reachability as a parameter in describing hydraulic properties of water distribution (Di Nardo & Di Natale 2011). It addresses reachability to nodes as a parameter to describe hydraulics and system ability to adjust network structures through hydraulic surplus and connectivity to mitigate any performance degradations (Di Nardo & Di Natale 2011). Simulating connectivity in water networks, suggest that connectivity contributes toward flexibility as expressed in several studies (Baños et al. 2011; Ostfeld & Shamir 1993; Pinto et al. 2010). Moreover, network capacity is another parameter that can be used to describe system's ability to cater for varying demands. Fraga et al. (2003) used capacity parameter to visualise spare hydraulic capacity to suggest that flexibility as a parameter utilises spare capacity to end-users (Gallopín 2006). Combining both spare capacity and network topological features has the potential opportunity to enhance water utilities in meeting required demand and ensure an acceptable level of service.

6.3 Modelling flexibility and its parameter using network theory and hydraulics

This research highlights that centrality can be used to characterise network connectivity and identify which of the nodes are important. Betweeness can be used as a metric to model network components needed to connect two nodes in the network. In other terms, betweenness defined by considering the frequency of involved component in a network that contribute in supplying water from source to nodes in the network. Now taking this definition further in terms of water operation, betweeness centrality can reflect connection between source and node demands. Since water networks typically have limited number of sources; water network supply should consider routes or walks between all sources to all demand nodes. Thus this index can consider frequency of network components that involve in hydraulic feasible supply (walks) routes. Supply route in Complex network theory should consciously consider walks rather than paths, since paths may misrepresent the actual supply in water networks. This is because; water is supplied through hydraulic behaviour involving nonlinear relationship of flow and pressure. Considering Complex network theory techniques for this type of analysis, edges weight therefore should reflect hydraulic information to model a typical network.

6.3.1 Hydraulic betweenness based on feasible hydraulics

In general, b*etweenness centrality* (β) of a node or edge can identify critical components in a network. It is proportion to the total geodesic paths that passes through a given node or edge (Zeng & Liu 2012). The conventional node and edge betweenness metrics denoted here as β_N and β_E respectively:

$$\beta_N(k) = \sum_{\mathrm{i} \neq \mathrm{k} \neq j} \frac{\sigma_{ij}(k\ )}{\sigma_{ij}} \quad (3)$$

$$\beta_E(e) = \sum_{\mathrm{i} \neq j} \frac{\sigma_{ij}(e\ )}{\sigma_{ij}} \quad (4)$$

σ_{ij} is the number of shortest paths between nodes *i* and *j*, and $\sigma_{ij}(k)$ and $\sigma_{ij}(e)$ are the numbers of shortest paths between *i* and *j* passing through node *k* and edge *e* respectively. The higher the betweenness ratio, the higher the involvement of a given components (node or link) in the network, giving it a higher criticality. In other terms, it will reflect the participation ratio of this link to supply the total nodes in the network.

The edge betweenness centrality measure is developed in this research to track hydraulically feasible flows, linking sources to demand nodes. Feasibility of flow paths are met under two conditions: the path connecting a source to demand node via the flow directions is existent. Secondly, the cumulative head-loss does not exceed the available source pressure as it will be discussed in Section 6.1.2. In calculating hydraulic betweenness ratio will follow hydraulically feasible paths that are used to account for the number of component involvement in supplying all nodes for each operational supply scenario. Therefore, this research suggests modifying edge betweenness centrality to hydraulic edge betweenness centrality (β_H). This centrality will consider all hydraulic feasible walks from sources in *S* to demand nodes in *N*. The derivation uses walks rather than geodesic paths to ensure inclusion of all potential routes, which are then, filtered to give feasible paths by comparing cumulative head-loss to source pressure. For an edge e ∈ *E*,

$$\beta_H(e) = \sum_{i \in S} \sum_{j \in N} \frac{\upsilon_{ij}(e)}{\upsilon_{ij}} \quad (5)$$

where υ_{ij} is the number of hydraulically feasible walks from source *i* to node *j*, and $\upsilon_{ij}(e)$ is the number that pass through edge *e*

The interpretation of this measure is the contribution of each edge towards all available walks from all *S* to all *N*. It will be used as a modified version of β_E to detect which of these edges are critical to the overall feasible hydraulic routes. The higher the value of β_H, the more this edge is employed in supplying water to nodes making it more critical to connectivity at that operational scenario. In other terms, this can reflect reachability of sources to nodes and how each of the edges contributes to those nodes.

6.3.2 Hydraulic load metric for network Surplus capacity

The surplus of networks will be assessed using the hydraulic edge load derived by (Todini 2000; Farmani et al. 2005) utilising hydraulic power formulation and incorporating it on edge-wise of supplied flows in network against the maximum flow allowed due to physical supply limitation of these edges. This is formulated and shown in (1). The hydraulic power of an edge is

$$\mathcal{P}(e) = \gamma \, Q_e H_e \tag{6}$$

$$\mathcal{P}(n) = \gamma \, Q_n H_n \tag{7}$$

Q_e is the volumetric flow rate; H_e is the upstream pressure of an edge, and the water specific gravity (γ). Whereas n is node reflecting the minimum required flow Q at that node against the required pressure H.

To assess the utilised and available capacity, (*e*) must be related to edge maximum capacity. This restriction imposed on how much an edge can tolerate hydraulically to form a metric of surplus capacity (Atkinson 2013). The inclusion of physical limitation is related to the material of each edge, size and hydraulic limitations of flow velocity. This is obtained from physical and engineering specifications. For instance, cement mortar lined ductile iron pipes are restricted to water velocities of 2–3 m/s (Saint-Gobain Pipelines 2006). The maximum flow capacity of an edge can be approximated by the following:

$$Q_{\text{max}} = V_{\text{max}} A \tag{8}$$

"A" is the cross-sectional area of the edge/pipe and $V_{\max}$ is the maximum water velocity. When multiplied by the maximum design edge pressure can give the maximum hydraulic capacity $\mathcal{P}_{\max}$ of that edge. On the other hand, minimum hydraulic power ($\mathcal{P}_{\min}$) is derived from the minimum flow and pressure required to satisfy downstream nodes. This ensures that edges should meet minimum demands to satisfy downstream nodes. This definition can incorporate other issues such as sedimentation risks or water stagnations in pipeline, which could impact water quality supplied to end-users.

Defining $\mathcal{P}_{\min}$ simply as the product of minimum L(e) and minimum demand of downstream node was found to produce in negative results during initial testing for several edges. Examining these edges, it was found that nodes fed by more than one edge simultaneously divides the required demand among these edges, so the sum of all supplied flows to a node can meet the required demands of the downstream node. To model this, the minimum demand used to calculate $\mathcal{P}_{\min}$ of an edge feeding a downstream node was adjusted in proportion to the cross-sectional areas of all simultaneous edges feeding the same node:

$$Q_{\min}(e) = Q_{\min}(n_e)\left(\frac{D_e^2}{\sum {D_i}^2}\right) \tag{9}$$

Where $Q_{\min}(n_e)$ is the minimum demand at the node supplied by e, D_e is the diameter of e and the sum in the denominator is taken over all the edges' diameters supplying n_e. Incorporating this derivation emphasise the equivalent load from edges to nodes concept and highlight edges that contributes less than expected.

Incorporating the two limitations of maximum and minimum power, the surplus capacity metric is formulated for each edge as the hydraulic edge load L(e):

$$L(e) = \frac{\mathcal{P}(e) - \mathcal{P}_{\min}(e)}{\mathcal{P}_{\max}(e) - \mathcal{P}_{\min}(e)} \tag{10}$$

$L(e)$ is the ratio of the available edge hydraulic power (in excess of $\mathcal{P}_{\text{min}}$) to the maximum available hydraulic. L(e) can be interpreted as indicating the status of each edge in a water system as follows:

$$L(e)\begin{cases} > 1 \text{ if } \mathcal{P}(\mathrm{e}) \text{ exceeds the maximum design load} \\ = 1 \text{ if } \mathcal{P}(e) \text{ is operating near boundary design} \\ = 0 \text{ if } \mathcal{P}(e) \text{ has no flow or operating at minimum load} \\ < 0 \text{ if } \mathcal{P}(e) \text{ does not meet the equivalent demand} \end{cases} \tag{11}$$

6.3.3 Edge flexibility overall metric

The hydraulic edge load and hydraulic betweenness metrics, which relate to surplus capacity and connectivity, are combined to give a measure of the contribution of an edge to network flexibility:

$$\mathcal{F}(e) = L(e) \times \beta_H(e) \tag{12}$$

The research proposes that flexibility considered the ability to reconfigure the hydraulic structure, based on *hydraulic connectivity* and *surplus capacity*. It utilises the concept of betweenness centrality as surrogate for connectivity using hydraulically feasible paths, and the use of pipe capacity as a surrogate for surplus capacity. The metric is a relative value that needs to be considered in the context of other values obtained from all edges to enable comparison and check which of these edges are important to supply. These equations use the total power supplied from source as a way to normalise the values on edges against the total source supply; hence, the values are related to each other, other rather than giving absolute values.

6.4 Modelling vulnerability and its parameters incorporating network theory and hydraulics

Complex network theory studies have approached vulnerability to assess impact of an incident or failure on overall system performance. Shuang et al. (2014) have formulised vulnerability to account for cascading effect of failure in water system. The method used to study the impact of node removal, as failure representation, on system performance. The study shows a prioritisation metric to sort out importance of nodes in the network accounting for capacity and betweenness index as primary measures of calculation. This suggests that water networks need to be prioritised according to the risk exposed on nodes. Fowllowing the same philosophy, this research proposes that vulnerabilities are led by the impact on nodes and their sensitivity against failures. Thus level of impact exposed to demand nodes need to guide the level of vulnerability latent within a network.

Pinto et al. (2010) developed a structural vulnerability theory that adopts the same principles from structural perspectives for water networks. The main purpose is to identify vulnerable parts based on structural connectivity to underline vulnerable parts. Vulnerability is defined under Pinto et al. (2010) as parts where small damage leads to disproportionately large consequences. It highlights criteria to identify these parts, which are: nodal connectivity to indicate available alternative supply paths to each of the nodes, damage demand as a measure to identify level of damage consequence on the network, and separateness caused by the failure on water network corresponding to increased hydraulic headlosses. The study suggests that vulnerability is guided by the node sensitivity to shortages or failures. This understanding agrees with the findings of the qualitative reviews highlighted under this research where vulnerability is dictated by user sensitivity to failures or shortages, which is mentioned in Section 5.4.2.

6.4.1 Outlining vulnerability in water networks

Interviews shows that practice suggest that vulnerability originates from the impact on end users and their sensitivity. This can be best observed when comparing between residential regions, which carry more importance, and agricultural regions. This can be usually denoted to residents’ tolerance of water shortages is very low. This implies city centres usually captures more attention from strategy and decision makers to minimise consequences from failures or incidents on networks. Therefore, repair time for example is strictly held for 6 hours window of repair time in case of required maintenance in case of Abu Dhabi water utility as performance indicator. The window time is strictly held based on experience and time of day. Interviewed Operational and

Maintenance staffs have highlighted available buffers in each of end user premises plays a major role in minimising mitigating effects. Vulnerability of network components can be experienced much clearer when incidents affect edges that are near to sources or transmission mains. Therefore, utilities tend to focus more on near source components in networks when dealing with level of service calculations that deal with case-by-case scenario planning. The guiding factor is to allow for continuing supply from different routes or securing supply through buffer tanks to avoid a full case shutdown. These different measures tackling vulnerability can be used to construct model vulnerability in water networks; however this will differ from flexibility model because it will be a node centric perspective. This was implied by the views from practice interviews and cross referenced to literature emphasising node reaction as a measure of node vulnerability.

Using the concept of user reaction to disruption as a measure of node vulnerability; this should be considered from node centric view in contrast to flexibility, which is edge centric. The research utilises the concepts drawn from practice and study conducted by Gallopín (2006), which highlighted that vulnerability can be expressed as a function of node sensitivity to incidents, the capacity for response and the exposure level to incidents. Based on the findings from literature and practice, there are four elements vulnerability can be identified with which are: type of user, quantity of water supplied, available capacity in hydraulic routes to user, and available hydraulic routes to user. These elements will be used to construct the vulnerability model under this research.

The type of user as mentioned earlier closely interlinks with node category, such as residential, agricultural or industrial type. However this is only one aspect of it. There were few aspects that been mentioned by interviewees such as high value customers and VIPs. This shows the role of political aspect in addressing these nodes during supply and planning, which originates from their influence on the sector. Additionally, social impacts also can be included under this aspect, where schools, hospitals and governmental locations have higher priority when planning or operating for water networks. Nodes can be prioritised and categorised according to emergency plans that are considered under strict confidentiality to plan for any anticipated external or internal risks that poses on risks on national security. This is an area that is mentioned by planning to address national strategic level.

Quantity of water supplied is measure used by operational and maintenance to highlight importance of node. Quantity can reflect the density of node supplying to and also the number of users fed through these nodes. Although this might not indicate the type of users, it can reflect the supply focus.

Hydraulic walk capacity to nodes is the third element that affects vulnerability. Operational and maintenance uses the spare capacities on routes or walks to users to push more water in order to cater for any incidents or shortages that occur in networks. This capacity is determined by the location of the node within the network; addressing surplus capacity considered under flexibility. Therefore, vulnerability metric needs to explore available capacity on the cumulative edges that connect it to a source.

The fourth aspect is addressing redundancy of hydraulic walks from sources. Modelling different routes to supply water to a specific node can affect the level of its vulnerability. The higher the number of available hydraulic walks, the better chance that this node will have an available alternative supply source that mitigate failure impact.

6.4.2 Modelling Vulnerability using network theory and hydraulics

Based on the qualitative structuring of vulnerability components, the research proposes the following definition of vulnerability:

$$\mathcal{V}(n) = f(\mathcal{P}, \mathrm{C}, U, \bar{\hbar}) \tag{13}$$

Where $\mathcal{V}(n)$ is the vulnerability of node n and $\mathcal{P}$ is the power required for the node n, C is the available capacity of the hydraulic walk from the source. U is the population at that node and $\bar{\hbar}$ depends on the hydraulic distance from source to that node. This hydraulic distance is related equal to the head losses accumulated through specific walk. On the other hand, $\bar{\hbar}$ is used to approximate redundancies in walks between source and node. This is evaluated by using the shortest hydraulic distance among all walks multiplied by the inverse of each available walk. Therefore, if there is only one walk available, this will be the shortest distance and $\bar{\hbar}$ will equal to one. Otherwise $\bar{\hbar}$ will be the sum of all available inverses of hydraulic distances times the shortest distance between sources to node to normalise all walks:

$$\bar{\hbar} = \sum^{walks} \frac{\hbar_{shortest}}{\hbar} \tag{14}$$

The shortest distance is determined by the head losses of each hydraulic walk, therefore, the summation of the number of shortest head-loss distance to all walks to a node, thus the more number of shortest distance available the more likely that node have available redundancy walks.

The proposed vulnerability metric will depend on the network properties, therefore, these elements will be normalised against the total source supply power to allow for comparison. The definition of $\mathcal{V}$ is based on nodes and considers the power using hydraulic head-losses to reach node. This description is reflecting the location of node against sources available hydraulically rather than topologically. $\mathcal{P}_n$ definition will use the average head-losses from source to node over all routes as an approximation since the different routes will account for different head-losses. Also to capture path routes those are partially shared to reach a node. This will be multiplied by the total flow reaching the node via all edges upstream of the node.

$$\mathcal{P}_n = \widetilde{\mathrm{H}}\,\overrightarrow{\mathcal{Q}_n} \tag{15}$$

In the above equation, $\widetilde{\mathrm{H}}$ denotes the average head-losses over all hydraulic walks from all sources available to node (n). $\overrightarrow{\mathcal{Q}_n}$ represents the total flow reached from these hydraulic walks upstream of this node (n), and $\mathcal{P}_n$ reflects the vulnerability the node possesses hydraulically from node topological view to model it proportionally to the flow upstream of the node. To cater for the type of node, the research uses population of users to factor it into the vulnerability measure. Therefore, the supply power ratio is adjusted against consumers supplied to put more emphasis on nodes that deals with residential nodes using ratio of ${}^{U_n}/_{U_t}$. U_n is the population or consumers supplied at node to the total population fed by the network U_n. Then ${}^{U_n}/_{U_t}$ is ratio to highlight how many people living at that node consuming water. This ratio indicates the density of people at every node compared to the total population. This would presumably account for the city centres and high density residential concentration in the network. Vulnerability is suggested to be impacted by the population as a major criterion against the level of network performance.

Meanwhile, C indicates the hydraulic capacity available on hydraulic walks feeding the node. The research uses the hydraulic walks available to node in order to reflect it using the minimum available spare capacity on the hydraulic walks and it is the complement of (10):

$$C = 1 - \frac{\min[L(e)]}{Total\ network\ power} \tag{17}$$

And for the case for multiple walks available to the same node, C is the maximum from that alternative walks. This convention is used because the capacity that can be spared from the load edges will be the minimum spare from all connected edges in the same walk/path to that node. On the same note, if redundant pipeline feeds same node, the higher capacity will be approximated to supply the node from hydraulic point of view, e.g., higher pressure will push the water to the node.

Vulnerability needs to be adjusted for these parameters of remaining capacity and number of shortest hydraulic walks available to node are discounted for “C” and “$\bar{\mathcal{k}}$”, thus formalising $\mathcal{V}$ as follows:

$$\mathcal{V}(n) = \left(\frac{\mathcal{P}_n}{\mathcal{P}_t}\right)^{\frac{U_n}{U_t}} \left[\frac{1}{(1+\mathrm{C})^{\bar{\hbar}}}\right] \tag{18}$$

$^{\mathcal{P}_n}/_{\mathcal{P}_t}$ is the ratio of the demand required water power as per (15) to the total power supplied by network source. This is to indicate the importance of that node according to the hydraulic power available upstream of node out of the total supplied to the network. $\mathcal{P}_t$ is the sum of all flow supplied by all S multiplied by the highest pressure among sources to node.

Based on the mentioned rational used to structure a vulnerability model, (18) is used to assess node vulnerabilities. This value will indicate the node susceptibility to failure. This value increases, as the vulnerability of the node increases to a maximum of $\mathcal{V}$=1. The relationship has been derived by considering spare capacity available to that node, which minimise vulnerability when it is increased. Also as the increased required demand by node, this will increase the corresponding vulnerability. Redundancy is captured by allowing for the available hydraulic walks, which decreases vulnerability consequently. This reflected by using head-losses of these alternative walks of $\bar{\hbar}$ to highlight redundancy in water networks.

Chapter 7 Testing of model using integrated hydraulic analysis approach

This Chapter will demonstrate the use of the metrics developed in Chapter 6. Flexibility and vulnerability will be applied on different networks. The purpose here is to gain quantitative understanding of the network performance using these developed metrics. The chapter will outline techniques used to run the model and present the obtained results of each of these networks. A real case water network of Abu Dhabi is used as a step-by-step example in Section 7.6 and to apply the model on a real setting model to evaluate model’s applicability and usefulness.

7.1 Introduction

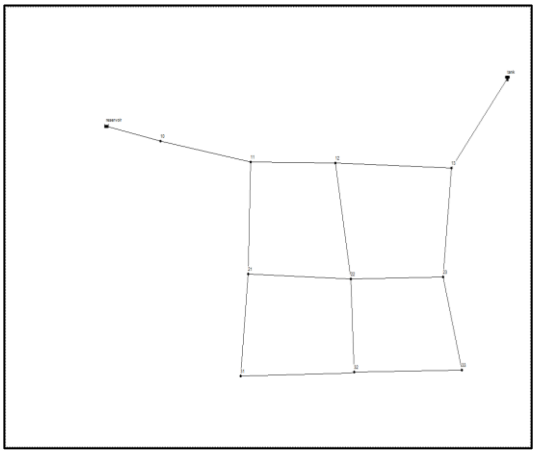
In this section, several literature case studies are selected in order to enable comparison with the current obtained results using the newly devised models. Three proposed literature networks are used to test the devised model under this research. These networks differ in topological complexity and number of components that are found in other studies from literature. These networks are used as benchmark networks for this type of studies on water systems. The networks selected are: Two-Source (Ang & Jowitt 2006), Anytown (Farmani et al. 2005) and Transmission network (Pathirana 2006). The advantage from these networks offer the opportunity to compare against previously published results, thus assessing applicability of the approach in considering inherit resiliency in water sector. The main network features of these selected networks are summarised in Table 7-1. The hydraulic details of each of the networks are provided in 0.

Following the application on these networks, a real case study of Abu Dhabi network is used to assess results produced in real context. The case will be also used to illustrate it as an example for running the model using practical settings.

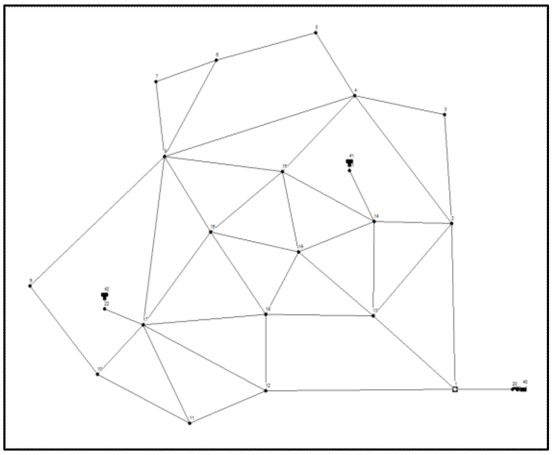
Table 7-1 Summary of literature benchmark network features

Number Of	Two-Source Network	Anytown Network	Transmission Network	Real Case Abu Dhabi Network
Junctions	10	22	92	3904
Reservoirs	1	1	2	7
Tanks	1	2	3	19
Pipes	15	43	117	4670
Pumps	0	3	2	59
Valves	0	0	0	155

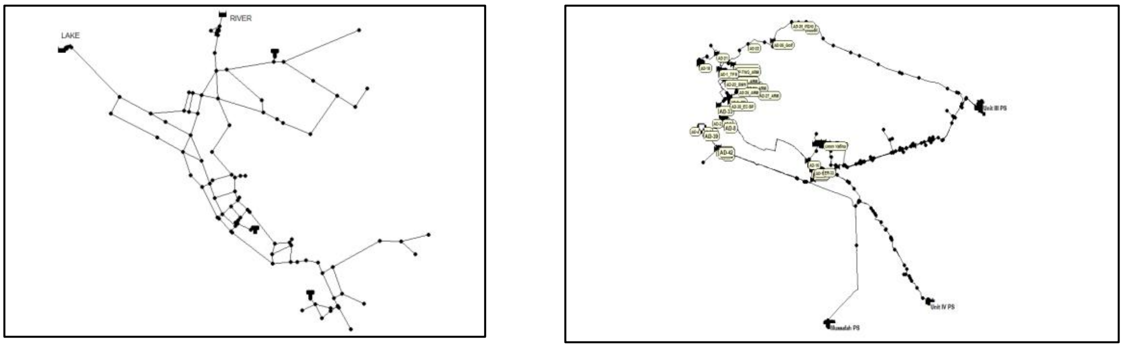
The assessment will use the constructed ratios from Chapter 6 to interpret robustness in different networks and compare results. Chapter 7 is arranged to start with application of flexibility metrics on literature networks described in Table 7-1, then followed with application on vulnerability.



a) Two-Source network



b) Anytown network



c) Trasnmission network example **d) Abu Dhabi network (real network)**

Figure 7-1: Benchmark literature networks used in this research and Abu Dhabi network

7.2 Flexibility application on literature networks

To obtain hydraulic information for different water distribution networks, the public domain hydraulic software EPANET 2.0, developed by the United States Environmental Protection Agency, was used (Rossman 2000). This software is used to model network flows, pressures and node state (open or closed), simulating steady state water hydraulic scenarios. Each scenario represents a snapshot of water system performance against different variations of demand and supply. The obtained data from the software is used to calculate flexibility and vulnerability measures using flow in pipes, pressure at nodes and flow quantity and direction.

Flow-driven simulation of EPANET was used to produce preliminary hydraulic assessment of these networks to assess the inherent resiliency in each of these hydraulic scenarios. These data are fed into the model to evaluate β_H, L and $\mathcal{F}$ for each edge as per (5), (10) and (12) respectively in 6.2. The metrics are calculated in several steps, which are initiated by collecting necessary information using a “Python” program that commences with calculating β_H. This is done through producing list of all feasible hydraulic walks using a breadth first search algorithm (Skiena 2008). The edge direction in the network follows the flow directions depicted in EPANET. Meanwhile, pressures and hydraulic head-losses are used to filter out those that were hydraulically infeasible. This filtration is executed by comparing the accumulated edge head losses through a hydraulic walk from source to demand node against the available head at source to omit infeasible walks.

The benchmark literature networks depicted in Table 7-1 are used for testing and validation purposes. These provide the opportunity to test results and compare findings if available from well-documented networks to weigh the applicability of the approach in managing network flexibility and vulnerability. These selected networks differ in complexity, where Two-source is much simpler in topological structure and components than Anytown network. Meanwhile, Anytown is larger and simulates a 24 hour supply scenario. Transmission Example network is a larger network and has several pumps and tanks with a more complicated topological structure. Finally a real case network represented by Abu Dhabi transmission network is used to compare against actual circumstances and to refer back to utility professionals for feedback on the obtained results.

7.3 Two source benchmark network

The Two-source network (Ang & Jowitt 2006) is shown in Figure 7-2 with numbered edges and nodes. Hydraulic walks analysis produce a total of 30 routes from the sources (a reservoir and a tank) to all the other 10 demand nodes (10, 11, 12, 13, 21, 22, 23, 31, 32 and 33).

The network was used as a simple example to test and develop the necessary program code using Python. This simple network allowed the execution of the code and the results to be examined to verify they behaved correctly. The results on this network are presented separately for flexibility and then for vulnerability covering the metrics and indices proposed earlier.

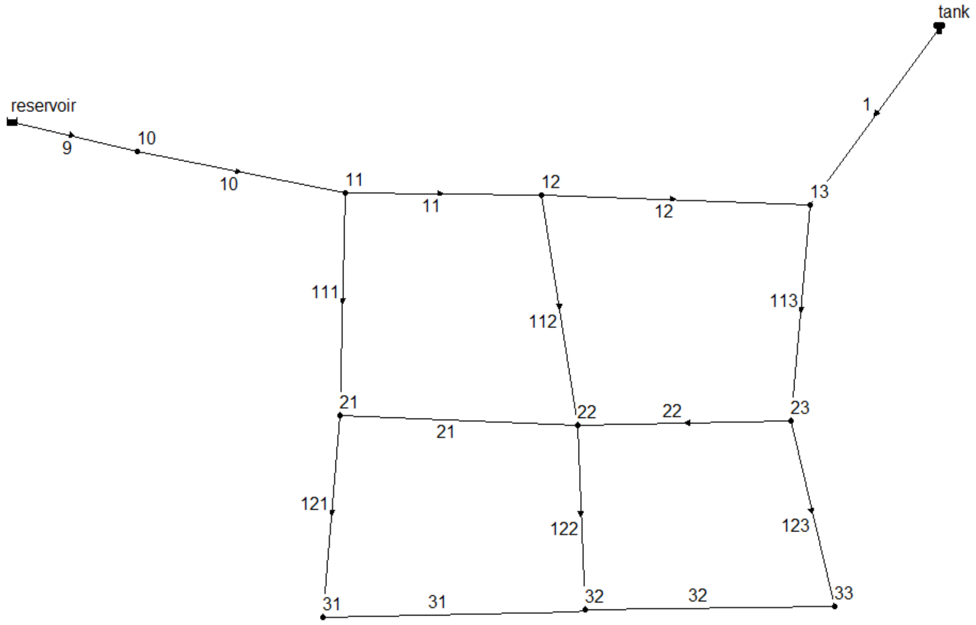


Figure 7-2: Two-source network with numbered edges and nodes

7.3.1 Flexibility findings

The calculated water velocities and head-losses are presented in Table 7-2 produced from a steady state simulation in EPANET. These are used to derive values for L, β_H and $\mathcal{F}$. The results in Table 7-2 for each metric are ranked with super scripts showing the top five. The order shows edge 11 having the largest L(e), followed by edges 10 and 111, signifying that these edges utilise the highest hydraulic power to satisfy the demands in this demand scenario of the network. Looking at the hydraulic edge betweenness centrality (β_H), edges 9, 10 and 113 have the highest values, with edge 11 ranking fourth highest. On the other hand, using the combined flexibility measure ($\mathcal{F}$), edges 11, 10 and 113 have the highest values, with edge 1 ranking fifth, after edge 12.

Table 7-2. Hydraulic analysis and flexibility calculation for Two-source network. Bold face marks the five highest values for each measure and superscripts 1-5 show the top 5 in descending ranking.

Edge ID	Velocity, m/s	Head-loss, m/km	L(e)	β_H	$\mathcal{F}$	Edge hydraulic availability
11	0.36	0.52	**0.0395**^{1}	**53%**^{4}	0.0209^1	0.9605
12	0.13	0.07	0.0153	30%	0.0045^4	0.9847
111	0.24	0.40	**0.0243**^{3}	7%	0.0017	0.9757
112	0.16	0.14	**0.0176**^{5}	17%	0.0030	0.9824
113	0.14	0.09	**0.0177**^{4}	**60%**^{3}	0.0106^3	0.9823
21	0.01	0.00	-5.05E-5	20%	-1E-05	1.0001
22	0.06	0.03	0.0071	30%	0.0021	0.9929
121	0.09	0.07	0.0085	13%	0.0011	0.9915
122	0.09	0.07	0.0102	13%	0.0013	0.9898
123	0.10	0.08	0.0135	17%	0.0023	0.9865
31	0.00	0.00	-0.0008	17%	-0.0001	1.0008
32	0.01	0.00	0.0007	13%	0.0001	0.9993
1	0.22	14.60	0.0107	**33%**^{5}	0.0035^5	0.9893
9	0.31	0.44	0.0000	**67%**^{1}	0.0000	1.0000
10	0.31	0.27	**0.0340**^{2}	**63%**^{2}	0.0214^2	0.9660

L(e) can also show edges of low utilisation. The results show that edges 21 and 31 have L(e) values of less than zero, signifying almost non-utilisation of these edges. Running EPANET simulation while removing these three edges shows minimal changes while satisfying all network demands, reflecting their low score for L(e); however this may not be significant because the network is simplistic and does not carry high demand values to be supplied. Nevertheless, L(e) can highlight edges with surplus capacity, thus during expansion plans can use this information to utilise these to secure supply, or reinforce supply of loaded edges (e.g.: 11, 10, 111, 113 and 112). The complement of L(e) can be used as a measure of the available hydraulic capacity for each edge, which can be expressed as edge hydraulic availability.

Edge 9 shows highest on β_H metric among hydraulic walks to supply the network. The value of β_H can be interpreted as saying that 67% of the hydraulically feasible walks supply nodes pass through edge 9. This follows the definition to calculate β_H to indicate the role of each edge in the network supply to nodes. However, $\mathcal{F}$ of edge 9 scores zero because the edge is experiencing a zero hydraulic load. Edge 9 can reflect that flow flexibility is zero due to zero value of utilised capacity. This is because the upstream head is supplied by gravity from the reservoir, which is at atmospheric head. It is noted that each calculated metric individually of β_H and L(e) provides a different piece of information than the aggregated score, which need to be used to prioritise edges according to flexibility in a network.

7.3.2 Vulnerability findings

The vulnerability follows the definition introduced in Section 6.4.2. It considers the same flow power definition used in Section 6.3 in order to quantify nodes importance in the network while incorporating hydraulics performance and topological characteristics of each supply scenario. Literature Two-source network used also to examine the results produced for vulnerability scores derived in (18). Testing this definition on Two-Source network, there are assumptions prior to carrying calculations are adjusted against to avoid unrealistic results that are:

- Node vulnerability considers the required power demands a measure to reflect node's importance and correspond it to the head-losses consumed within the network to supply nodes.
- The population ratio is taken as 1 to produce homogenous distribution of residents at every node. This assumption taken to reflect vulnerability on the basis of location in network and hydraulic performance.
- The vulnerability metric also introduces the importance of nodes by tracking the head-losses needed to deliver quantities to these nodes; hence the power dissipating to allow for such supply.

Table 7-3 shows the results of the calculation carried out on Two-source network. The table highlights nodes 13 and 23 scoring the highest on vulnerability index. These two nodes can be referred to as vulnerable nodes in network performance. Both of these two nodes require higher hydraulic headlosses to supply them with the required demand pressure of 3.73 and 3.89 m. respectively ranking those top highest headlosses consumption. The score is low in the available capacity through these nodes restricting their ability to expand for this specific supply scenario. In addition, those nodes experience low number of hydraulic walks available to supply them from sources scoring 1.178 and 1.198 equivalent hydraulic shortest hydraulic walks respectively.

Table 7-3: Vulnerability metric outcome for Two-source network, bold font of node ID to show the highest vulnerability in nodes

Node ID	Node Vulnerability	Average headloss walks	Total flow via node	Min Capacity via walks	No. of hydrualic routes
11	0.0009	0.6150	38.4748	32.1740	1.0000
12	0.0019	1.0683	25.7872	18.0978	1.0000
13	0.0184	3.7323	12.9835	1.8387	1.1781
21	0.0032	2.6116	7.6876	0.9218	3.2009
22	0.0046	3.0451	7.8037	1.3662	2.2009
23	0.0145	3.8894	10.0088	1.8387	1.1980
31	0.0091	3.1595	2.8959	0.0411	6.6440
32	0.0089	3.5065	2.8992	0.1211	3.4293
33	0.0080	4.0268	3.2048	0.8333	1.2146
10	0.0006	0.3808	38.4748	32.1740	1.0000

On the other hand, Nodes 10, 11 and 12 score low in vulnerability index. Those nodes show lower hydraulic headloss required to supply the total flow. Those nodes score highest on the scale of the (non-utilised) available capacity to expand. However the number of walks to reach these three nodes is only one route. Examining the network, these nodes are located near the source; hence the low vulnerability is reflected based on hydraulic head losses perspective. It is worth mentioning that these nodes failure will lead to network shutdown, but the vulnerability assessed here is relative to vulnerability compared to other nodes sensitivity in each supply scenario. Therefore, vulnerability of these nodes is assessed for each supply scenario following vulnerability equation (18). Because of Two-source relative simplicity, the calculation approach need a bigger network to test on.

7.4 Anytown benchmark network

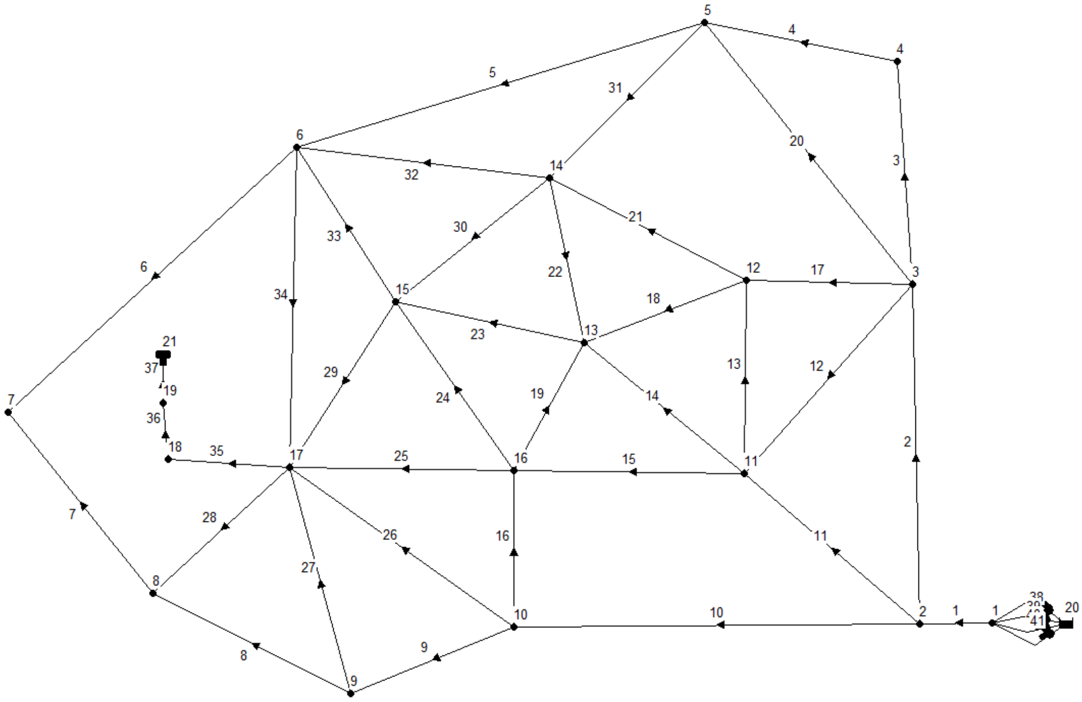


Figure 7-3. Anytown network with numbered edges and nodes

The Anytown network model runs an extended period simulation (EPS), which includes varying demands throughout the day. The EPS covers the simulation of 24 hours of supply, with different peak demand factors reflecting the change in demand during the day (Bose et al. 2012). Figure 7-3 shows the Anytown network with edges and nodes numbered along the flow directions from steady-state evaluation of the simulation for the first period.

7.4.1 Flexibility findings

A preliminary analysis of the first time step demand scenario simulation was carried out and found a total of 679 hydraulic walks from sources to nodes. Table 7-4 gives the calculated water velocity and head-losses from a steady state simulation in EPANET and the derived values for L, β_H and $\mathcal{F}$ for that scenario as an example.

Table 7-4. Hydraulic analysis and flexibility calculation for the Anytown network. Bold face marks the five highest values for each measure with descending superscript order using metrics.

ID	Dia	Flow	Velocity	Head-loss, m/km	L(e)	β_H	$\mathcal{F}$
1	30	7826.27	3.55	1.32	**0.3309**^{4}	**1.000**	**0.3309**^{1}
2	12	2491.53	7.07	15.94	**0.6573**^{1}	**0.3962**	**0.2604**^{2}
3	10	701.59	2.87	3.71	0.1308	0.0736	0.0096
4	10	461.59	1.89	1.71	0.0785	0.0722	0.0057
5	8	278.47	1.78	1.98	0.0543	0.0236	0.0013
6	8	176.43	1.13	0.85	0.0042	0.0412	0.0002
7	8	63.57	0.41	0.13	-0.0242	0.0810	-0.0020
8	8	144.53	0.92	0.59	-0.0179	0.0029	-0.0001
9	8	315.82	2.02	2.51	0.0346	0.0132	0.0005
10	12	1637.12	4.64	19.87	**0.4280**^{3}	0.0795	**0.0340**^{4}
11	16	3097.62	4.94	15.94	**0.4582**^{2}	0.1649	**0.0756**^{3}
12	12	15.64	0.04	0.00	-0.0030	0.1649	-0.0005
13	12	793.63	2.25	5.20	0.1007	0.1679	**0.0169**^{5}
14	10	662.01	2.70	9.03	0.1229	0.0471	0.0058
15	12	1057.62	3.00	8.85	0.1402	0.1119	0.0157
16	8	111.56	0.71	0.99	0.0213	0.0560	0.0012
17	10	842.73	3.44	5.20	**0.1586**^{5}	0.0839	0.0133
18	10	416.73	1.70	3.83	0.0634	0.0707	0.0045
19	10	80.57	0.33	0.18	0.0038	0.0707	0.0003
20	10	691.56	2.83	3.61	0.1324	0.0722	0.0096
21	12	619.62	1.76	3.29	0.0679	0.1767	0.0120
22	10	145.39	0.59	0.55	0.0142	0.1178	0.0017
23	10	104.69	0.43	0.30	0.0014	**0.2872**	0.0004
24	12	219.11	0.62	0.48	0.0090	0.0663	0.0006
25	8	269.50	1.72	1.87	0.0308	0.0265	0.0008
26	10	609.74	2.49	2.86	0.0769	0.0088	0.0007
27	10	171.29	0.70	0.23	-0.0179	0.0088	-0.0002
28	10	159.04	0.65	0.24	-0.0027	0.1591	-0.0004
29	8	229.62	1.47	1.39	0.0144	0.1856	0.0027
30	10	183.84	0.75	0.84	0.0164	0.1105	0.0018
31	10	634.69	2.59	3.08	0.1023	0.1178	0.0121
32	10	325.08	1.33	0.89	0.0349	0.0589	0.0021
33	8	38.03	0.24	0.05	-0.0046	**0.2474**	-0.0011
34	8	225.15	1.44	1.34	0.0255	**0.2474**	0.0063
35	12	386.25	1.10	0.50	0.0092	**0.2386**	0.0022
36	12	386.25	1.10	0.50	0.0092	0.1591	0.0015
37	12	386.25	1.10	0.71	0.0092	0.0795	0.0007

Table 7-4 show edges with the highest five values for L, β_H and $\mathcal{F}$ in bold font. Edge 1 has the highest value of $\mathcal{F}$, agreeing with its location where it is linked to the only source. The hydraulic betweenness centrality for edge 1 was β_H,= 1. Meanwhile, edge 1 scored only the fourth highest value in terms of L(e), due to its diameter (30 in), showing a utilisation of an approximately 60% of the designed capacity. Conversely, edge 2 shows high utilization from edge capacity, giving it the highest L(e) ranking. The edges displaying high scores of L(e) compared to the rest in Anytown network are edges 2, 11, 10, 1 and 17. Edges 1, 2, 11 and 10 have the highest values of the combined metric ($\mathcal{F}$) in descending order. This agrees with the topological structure where those edges are connected to the source. It is noticeable that edges 1 and 2 had higher hydraulic betweenness centrality due to their closeness to source. Meanwhile, edge 23 is the third highest, even though it is positioned away from source, it experiences high flow passing through the node to the rest of the network. On the other hand, edges 1 and 2 are ranked against L(e) as fourth and first respectively, while edge 23 is ranked in the bottom five when assessed against the utilised capacity. The three edges with the highest L(e) scores are 2, 11 and 10, located close to source and carries the network flow to the rest of demand nodes. The rest of the network edges scores are comparable to each other.

Conducting the calculation for all different demand scenarios represented by time steps, the metric calculation are iterated to introduce L(e) of all edges of Anytown network during all simulated time steps. Figure 7-4 portrays the metric L(e) for each edge (edges in Figure 7-4 depicted as series) during the day. Examining the Figure 7-4, there are 4 edges operating in the range between 0.2 to 0.5 of L(e). Those edges are 2, 1, 11 and 10. The rest of edges are operating under 0.2 except for edges 35 and 36, which are coupled together during the simulation since they feed tank 21, and overshoot the 0.2 margin to 0.35 and 0.37. When examining overshooting, by referring to the simulation. It was found they occur at times when, the demand from downstream demand nodes drops; hence redirecting the flow to supply the overhead tank “tank 21” in the network.

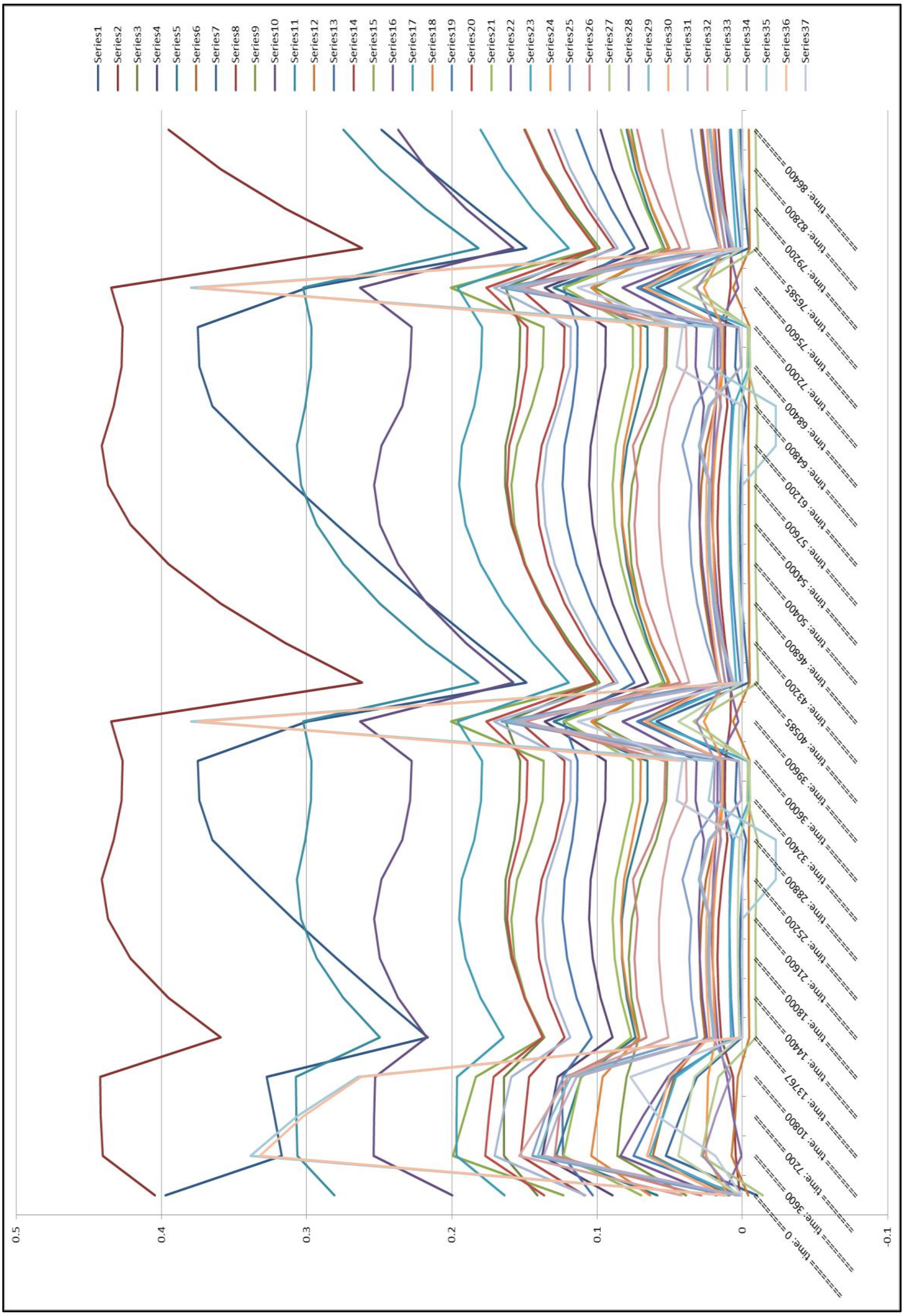


Figure 7-4 Extended period simulation for Anytown network and the relevant L for each edge represented as series

The hydraulic flow betweenness was calculated for the extended period simulation (EPS) to show the different variations in supply scenarios against hydraulic walks within the network Figure 7-5. Edge 1 and 2 rank the highest in supplying 100% and above 60% of the network edges respectively. This is in line with the position these two edges are located at to supply the network, which are near the only source (pumps).

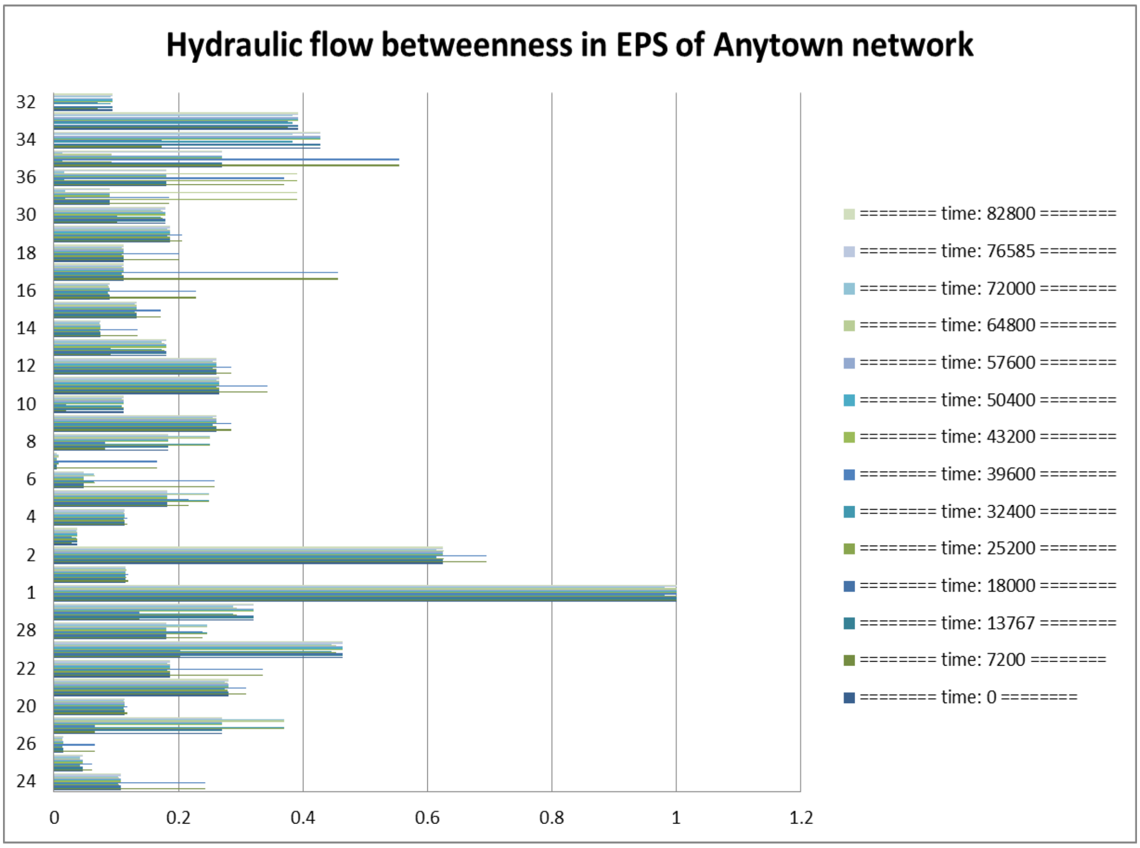


Figure 7-5: Bar chart of β_H in extended simulation of Anytown network with edges on Y-axis and scores on X-axis

Investigating hydraulic betweenness of edges during the EPS, we can highlight edges that undergo variations in supply route dependency. This enables detection of edges that experience varying betweenness supply signifying varying loading on these edges in the network. To locate those edges, standard deviation of the metric β_H can be used. This will indicate the edges that experiance changes of supply patterns during the supply depicted in Table 7-5:

Table 7-5: Average and standard deviation of hydraulic betweenness metric β_H for EPS of Anytown network using blue font for the highest two edges showing source edges. The bold font used to highlight edge IDs with high standard deviation of hydraulic betweenness values with a corresponding yellow highlight of the values. The ascending superscript ranking used to order the lowest standard deviations to indicate edges with low variation in flows

Edge ID	Average β_H	Std Dev	Edge ID	Average β_H	Std Dev
1	*0.9974*	0.0064	**19**	0.1731	0.1320
2	*0.6359*	0.0276	20	0.1143	0.0018^3
3	0.1161	0.0016^1	21	0.2841	0.0113
4	0.1143	0.0018^2	22	0.2127	0.0575
5	0.0355	0.0036^4	**23**	0.4127	0.0981
6	0.0904	0.0787	24	0.1303	0.0527
7	0.2083	0.0290	25	0.0472	0.0066
8	0.1861	0.0564	26	0.0239	0.0196
9	0.0341	0.0609	**27**	0.2642	0.1019
10	0.0950	0.0354	28	0.2108	0.0312
11	0.2647	0.0097	29	0.2787	0.0672
12	0.2647	0.0097	30	0.1629	0.0288
13	0.2780	0.0299	31	0.1894	0.0076
14	0.0850	0.0230	32	0.0888	0.0089
15	0.1627	0.0334	33	0.3879	0.0061^5
16	0.1139	0.0533	34	0.3698	0.0937
17	0.1390	0.0150	**35**	0.2800	0.1699
18	0.1276	0.0345	**36**	0.1928	0.1112
			37	0.0982	0.0528

Edges 35, 19, 36, 27 and 23 in order (highlighted in yellow) show a high deviation representing different supply schemes during EPS. This can be of interest when considering variation of loading is a criterion to failure of extreme varying loading on edges/pipes. On the contrary, edges 3, 4, 20, 5 and 33 (in bold font) scores low in deviation signifying a consistent supply pattern in the network. Also, from this table, we can see that the averages of betweenness have been calculated showing edge 1 accounting for 99% of the supply to all nodes of the network and edge 2 accounts for 63% of the nodes supplied (in blue font).

7.4.2 Vulnerability findings

Conducting vulnerability assessment of Anytown network, the Table 7-6 presents the first time step of the Anytown hydraulic performance results as an example to demonstrate the results for a specific supply scenario.

Table 7-6: Vulnerability scores of Anytown network over first time step simulation. Yellow highlight used for the lowest node in vulnerability amd bold for the highest node vulnerability

Node ID	**Node Vulnerability**	**Average walks Headlosses**	**Total flow via node**	**Min Capacity via walks**	No. of hydrualic **routes**
2	*0.0001*	0.0574	7836.4340	2.6E-05	1
3	0.0667	83.2583	2494.3720	3.0E-06	1
4	0.0210	92.9291	702.3759	3.0E-06	1
5	0.0145	97.3876	462.3759	3.0E-06	2
6	0.0097	107.7690	279.1050	3.0E-06	28
7	0.0065	112.4061	180.6233	3.0E-06	135
8	0.0038	112.1107	106.6674	3.0E-06	107
9	0.0119	111.2366	333.8477	3.0E-06	54
10	0.0548	104.0043	1640.9040	2.6E-05	1
11	**0.0829**	83.2727	3101.1570	3.0E-06	2
12	0.0247	96.8389	794.5370	3.0E-06	3
13	0.0228	106.8514	662.9489	3.0E-06	13
14	0.0210	105.4281	620.7670	3.0E-06	5
15	0.0036	107.6321	105.2742	3.0E-06	21
16	0.0362	106.3900	1059.5030	3.0E-06	3
17	0.0096	111.2291	268.7340	3.0E-06	53
18	0.0056	111.2332	156.4336	3.0E-06	53
19	0.0056	111.2374	156.4336	3.0E-06	53
21	0.0056	111.2949	156.4336	3.0E-06	53

The highest scoring node in vulnerability index is node 11. This can be attributed to relatively high hydraulic headloss and the high volume of flow supplied through the node. Inspecting location of node 11 in the network, the node is mid-way between the source and high demand node 13. Meanwhile the lowest node in vulnerability is node 2. This node is connected to the source, downstream of the pumps.

Carrying out this calculation for extended period simulation, results are shown in Figure 7-6. First inspection of the chart displays a pattern that can be grouped into 5 groups. This grouping is done using comparable vulnerability index from the figure. These groups of nodes can be segregated to be G1=[18, 19, 21], G2=[3, 10, 11, 16], G3=[12, 13, 14], G4=[4, 5, 6, 7, 8, 9, 15, 17] and G5=[2].

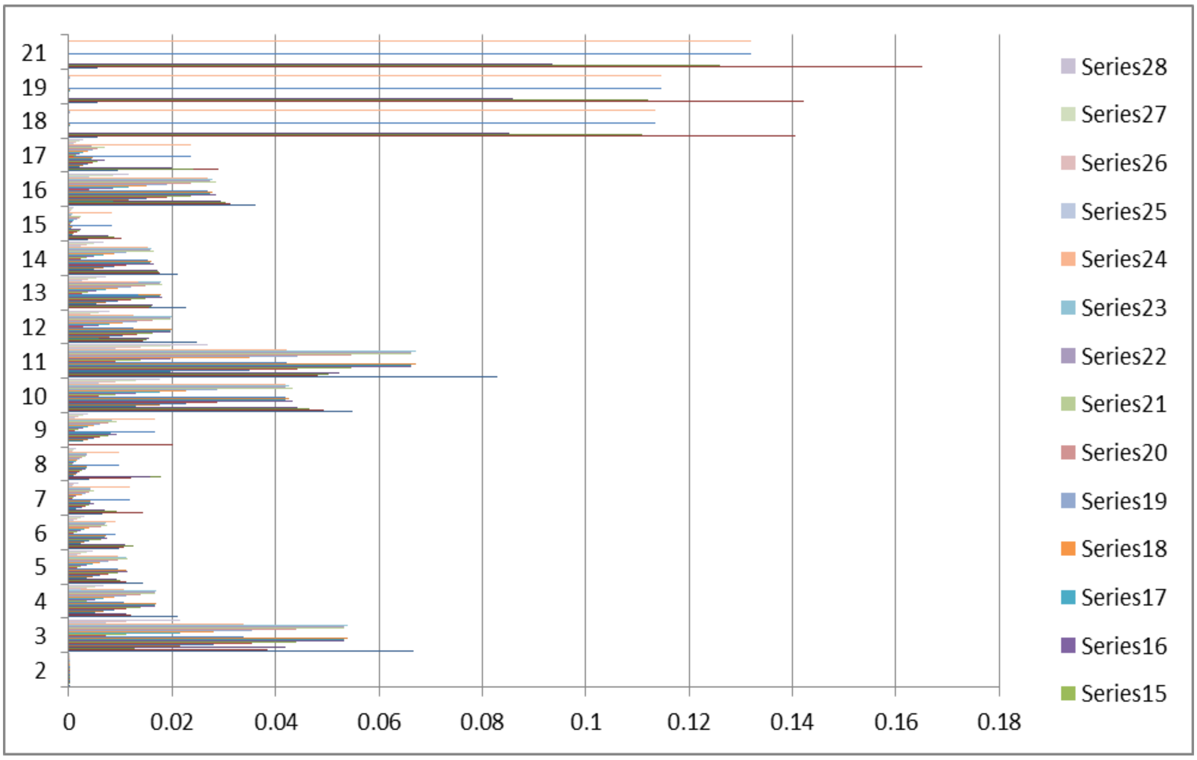


Figure 7-6: Vulnerability index for Anytown network carried for extended period simulation with series as scenarios

G1 when inspected, these nodes are found linked to the tank. These nodes are experiencing two type of supply, either from the pumps at node 1; hence the hydraulic losses to feed these nodes are significant with low flow supplied via these nodes to tank, or the tank are supplying the network along with the pumps during peak demands, thus these nodes experience low headlosses. Therefore, these nodes oscillate in flow direction depending on the supplied source. When fed from pump, they score high in vulnerability and when fed from tank, they score zero in vulnerability due to the low headlosses. Meanwhile, G2 nodes location can be considered mid of the network. Looking up the required headlosses for example node 3, we see the average headlosses is ~ 44m. with average flow of 1720 (gallon/min). G2 can be characterised by high flow, medium headlosses positioned so to transmit the flow generated from the source of the network. Meanwhile, G3=[12, 13, 14] positioned central in the network and scores an average vulnerability index of 0.01243, 0.0117 and 0.0112 respectively. Also it is noted that the average headlosses to these nodes are comparably close scoring [51.76, 57.47, 56.78] m. head respectively. G4=[4, 5, 6, 7, 8, 9, 15, 17] are grouped and when inspected, the location of these nodes are mostly at the boundary of the network topology except for node 15 and 17. Table 7-7 shows the average values for G3 nodes with vulnerability index of 0.0025 to 0.0106. G3 scores lower vulnerability than G2 attributed to high number of hydraulic walks available to reach these nodes except for node 4.

Table 7-7: Average values for vulnerability index, headlosses, crossing flow and number of walks to node for G3 in anytown network hydraulic simulation

Node ID	Vulnerability Index	Avg. Headloss	Avg. Flow	Avg. No. routes
4	0.0106	49.6635	484.4734	1.00
5	0.0076	52.2236	330.1877	2.00
6	0.0054	58.8472	207.8913	29.07
7	0.0046	63.0735	153.5798	98.45
8	0.0033	63.5518	108.6103	81.54
9	0.0066	59.0098	247.3946	38.89
15	0.0025	58.6230	93.9669	22.0714
17	0.0075	63.3492	238.3918	62.2106

On the other hand G5 with node 2 is representing the network source downstream of the main source (pumps) with low vulnerability index of 7.27E-05 due to low headloss expended to reach the node. Although node 2 can be critical from topological point of view, hydraulically is experiencing least headloss requirement due to its closeness to the source to supply required flow quantity.

7.5 Transmission network example

A larger and more detailed network was needed to test the approach devised to calculate resiliency parameters of flexibility and vulnerability. This third network shown in Figure 7-7 contains several sources feeding the network (Pathirana 2006). This network can be considered a transmission network due to missing details of distribution to areas and locations.

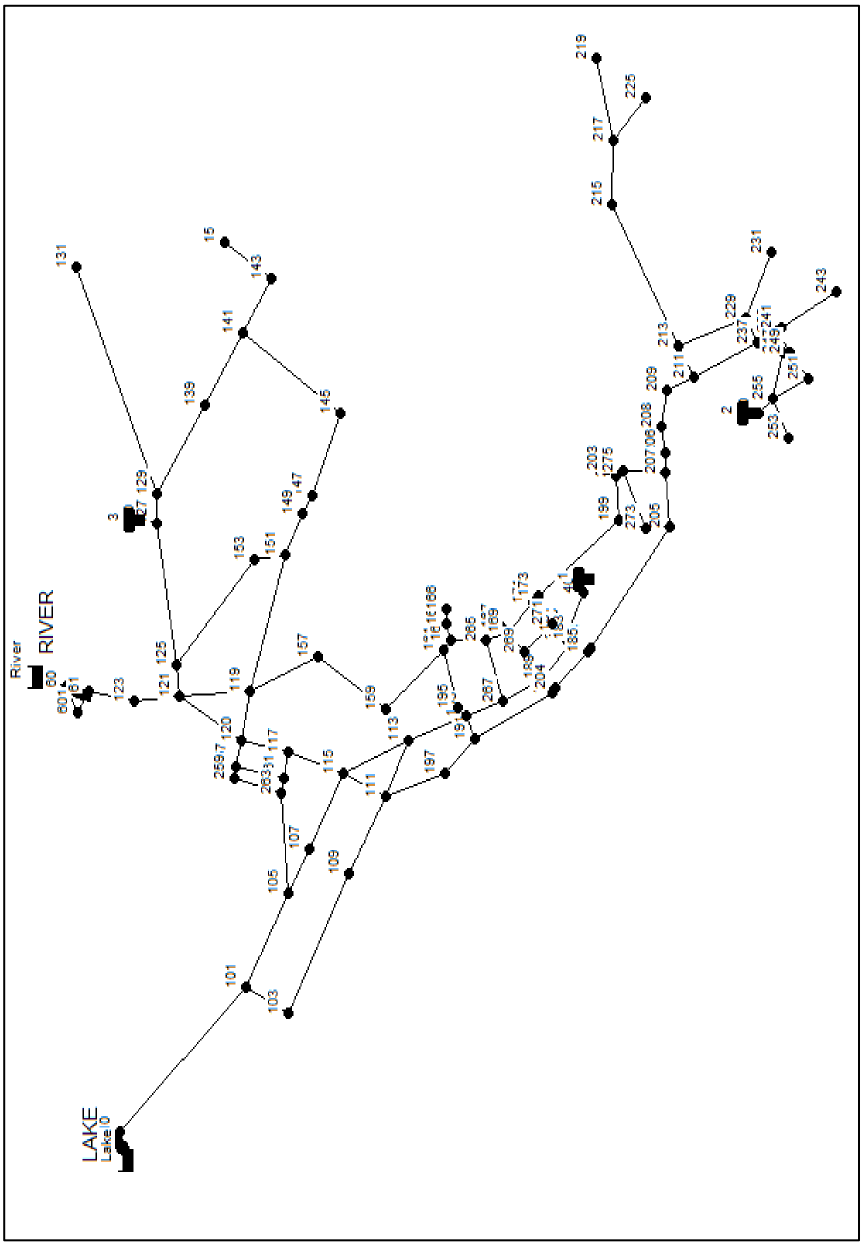


Figure 7-7: Transmission network example with Node IDs shown

Continuing with the approach devised in this research, the results outlined next will commence with flexibility metric followed by vulnerability index.

7.5.1 Flexibility findings

Figure 8-4 shows the different values for the hydraulic edge load of edges in the network. The different variations of edge load shows several edges experiencing load of 0.1 with maximum load at edge 60 for scoring between 0.2–0.5. Edge 60 is the downstream of the river supplying the majority of flow to the network. Figure 7-9 shows the averages the edges in the network experiencing during the extended simulation along with the standard deviations. Edges 330 and 333 experience large hydraulic variations compared to the load operated at in the network.

For more readability, Figure 7-9 shows the average hydraulic edge load at each edge for the extended simulation. Figure 7-9 shows edges 20 and 40 loads are close to zero. Inspecting these two edges depicts that these two edges connected to tank 3 and tank 1 respectively, thus alternate between supplying from the tanks (negative flows) and then reverse the flow to feed the tanks from the network, this is depicted in Figure 7-8.

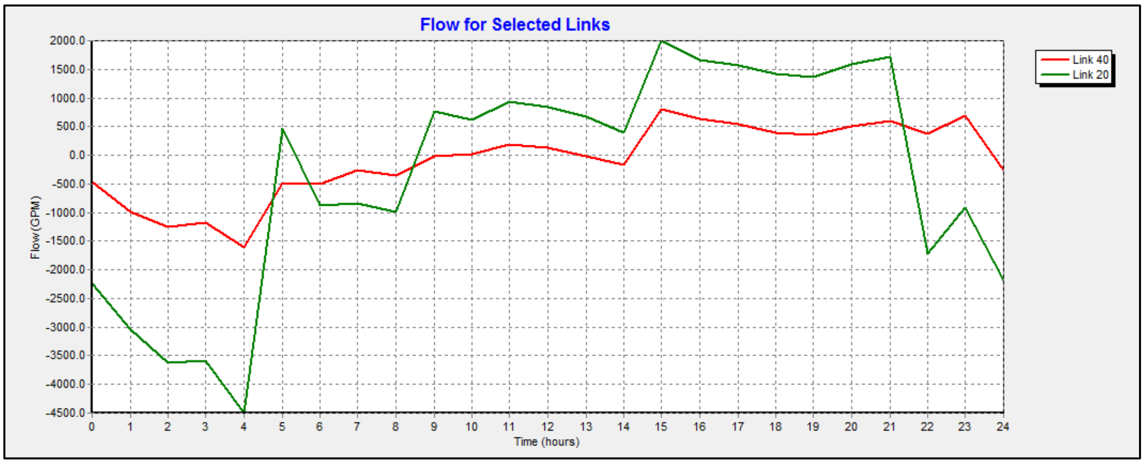


Figure 7-8: Edge 20 and 40 flow pattern during the extended simulation

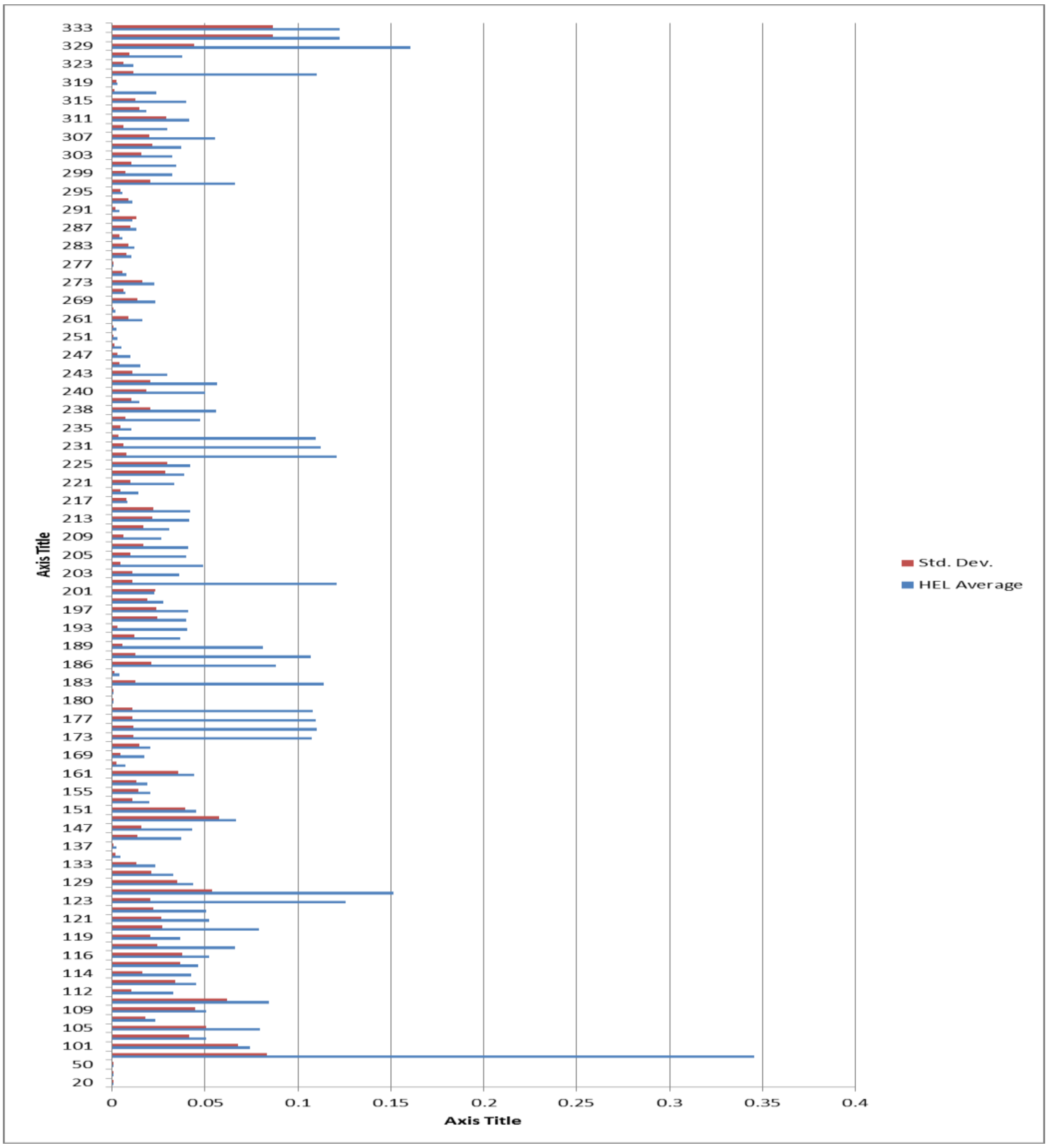


Figure 7-9: Averages and standard deviations over the extended simulation for the hydraulic edge load for all edges in the transmission network

Inspecting their locations, they are located as bypass of the pumps downstream of the “River” source. These two edges operate from 4:00 to 22:00 out of 24 hr daily operation constituting 75% of the daily operation and then the pumps operates the remaining 25% of the time from 22:00 till 4:00 as shown Figure 7-10. Whereas Edge 60 scores the highest hydraulic load metric which is located downstream of “River” feeding the network.

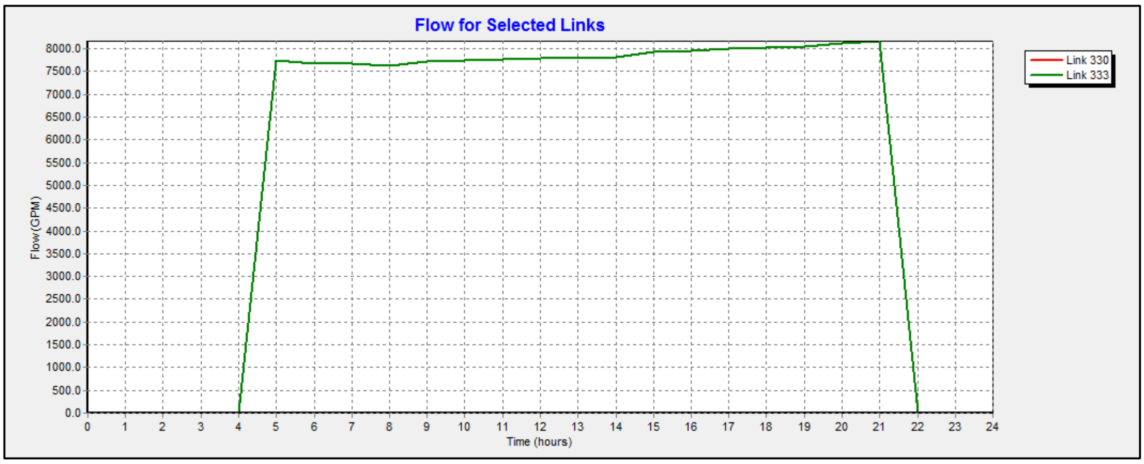


Figure 7-10: Edges 330 and 333 flow operation during the extended simulation

Meanwhile for Hydraulic betweenness metric, Figure **7-11** shows the averages of all edges in the network.

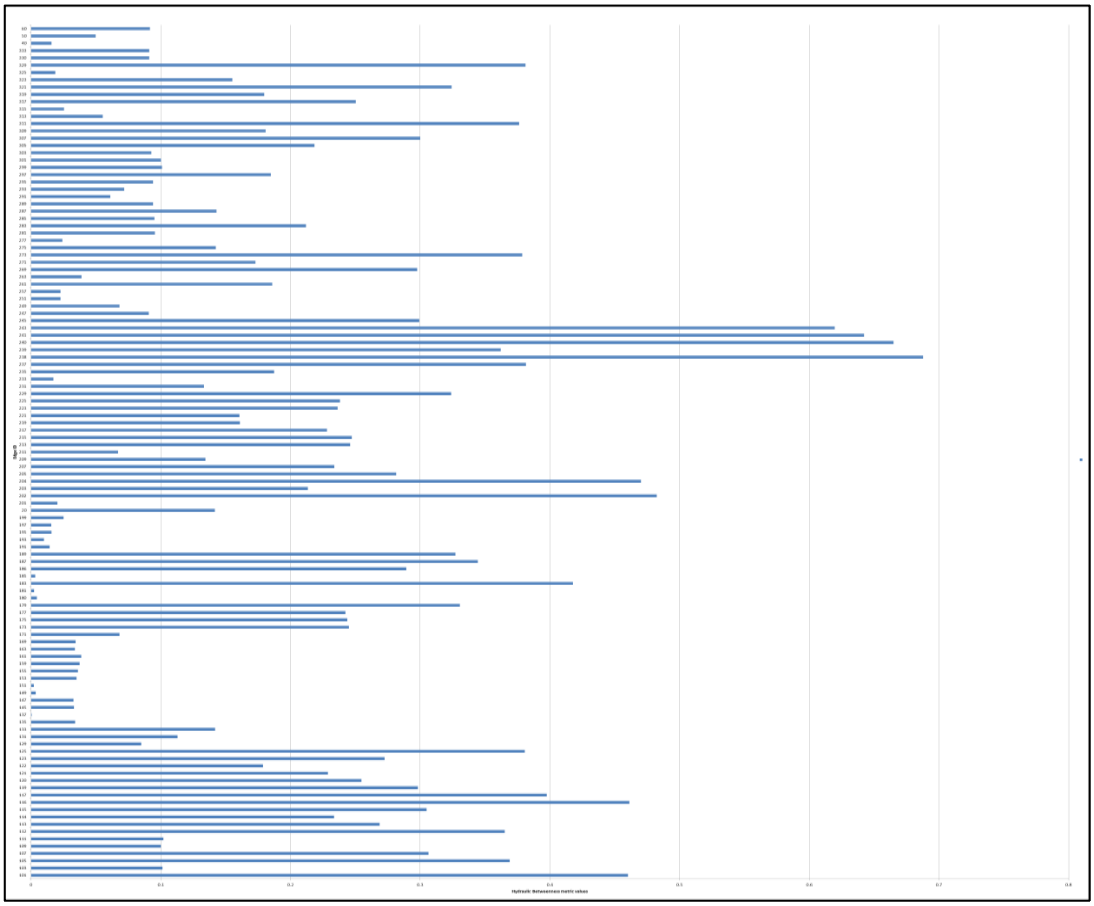


Figure 7-11: Averages of the hydraulic betweenness metric for all edges for the extended simulation

The topological locations of the top ten edges are mostly located in the middle of the network. When inspecting the downstream edges from the network sources, the average β_H shows values smaller than the average of averages (0.1865) except for edges supplied from “River” in **bold** in Table 7-8. This can be attributed to the main part of the nodes at the centre of the network. This indicate that β_H and Hydraulic edge load are separate metrics that assess two distinct characteristics of the network. The edge with most reliance to deliver water in the network shown in Table 7-8

Table 7-8: Sample of edges of the top ten βH averages. The table also shows the sources in the Transmission network with the corresponding sources and the relevant hydraulic betweenness metric. The bold font used to highlight the edges near sources with high betweenness, indicating main source of supply to the network (River, Lake)

Edge ID	**Top ten Averages β_H**	**Network sources**	**Downstream Edge ID**	**Averages β_H**
238	0.6876	**River**	60	0.0916
240	0.6649		330	0.0911
241	0.6422		333	0.0910
243	0.6196		**329**	**0.3812**
202	0.4824		**125**	**0.3806**
204	0.4702	**Lake**	**101**	**0.4601**
116	0.4613	**Tank 1**	40	0.0158
101	0.4601		201	0.0203
183	0.4177	**Tank 2**	50	0.0497
117	0.3975		289	0.0940
		Tank3	20	0.1416
			133	0.1419

7.5.2 Vulnerability Findings

Carrying the calculation of vulnerability index for the transmission example network, we obtain the following results shown in Figure 7-12. These scores highlight the nodes that present vulnerability on the network based on topological and hydraulics information obtained from an extended period simulation (EPS). Several nodes show higher vulnerability than the rest. These nodes are [119, 121, 123] exceeding 0.15 and [157, 159, 161, 163, 169, 171, 199, 265] exceeding 0.1 as depicted in Figure 7-12.

Inspecting their location, the first group are connecting “River” and “Tank 3” with the bulk of the network. These nodes experience high flow and headlosses to feed other nodes downstream.

These nodes are tracing highest flows and hydraulic headlosses, showing that nodes in the first group is linking sources to the bulk of the network as mentioned earlier. Nodes with low vulnerability are [253, 243, 231, 225, 219, 167, 166, 164, 131] scoring index of approximately zero. Looking their details depicted in Table 7-9. These nodes when located in the network share same topological characteristics and that is they are all located at boundary of the network with low flow as depicted in Figure 7-7.

Table 7-9: Lowest vulnerability nodes in the newtork

Node ID	Vulnerability Index	Headloss m.	Flow via node GPM
131	0.00113	61.60	71.39
164	0.000074	66.02	4.34
166	0.000074	66.02	4.34
167	0.000417	66.74	24.31
219	0.001045	71.07	55.37
225	0.000577	71.06	30.55
231	0.000417	71.11	22.08
243	0.00011	71.11	5.81
253	0.001217	41.68	58.33

The vulnerability scores can be interpreted as relative values of nodes importance from both topological and hydraulic perspectives to each other at every supply scenario.

Figure 7-12: Maximum Vulnerability index scores for nodes in the extended simulation on Transmission Example network

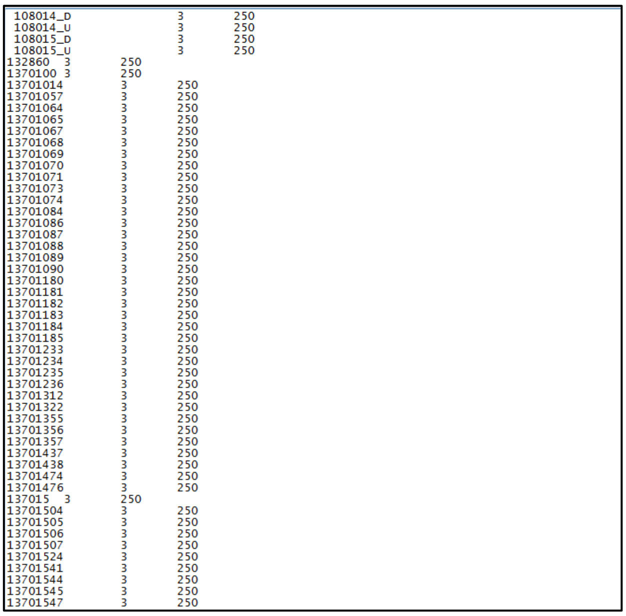
7.6 Application of the assessment on Abu Dhabi transmission water network

The case study of the Abu Dhabi transmission network (Figure 7-1**d)** was used to test the assessment method on a full-scale network. It aims to explore the characteristics of resiliency in the network and measure how the network components rank in importance against capacity and connectivity. A step-by-step guide is included below, with screenshots of the accompanying EPANET model, Python code and post-processing.

7.6.1 Resiliency assessment illustration

Assuming that an EPANET model of the network exists, the steps in the assessment are:

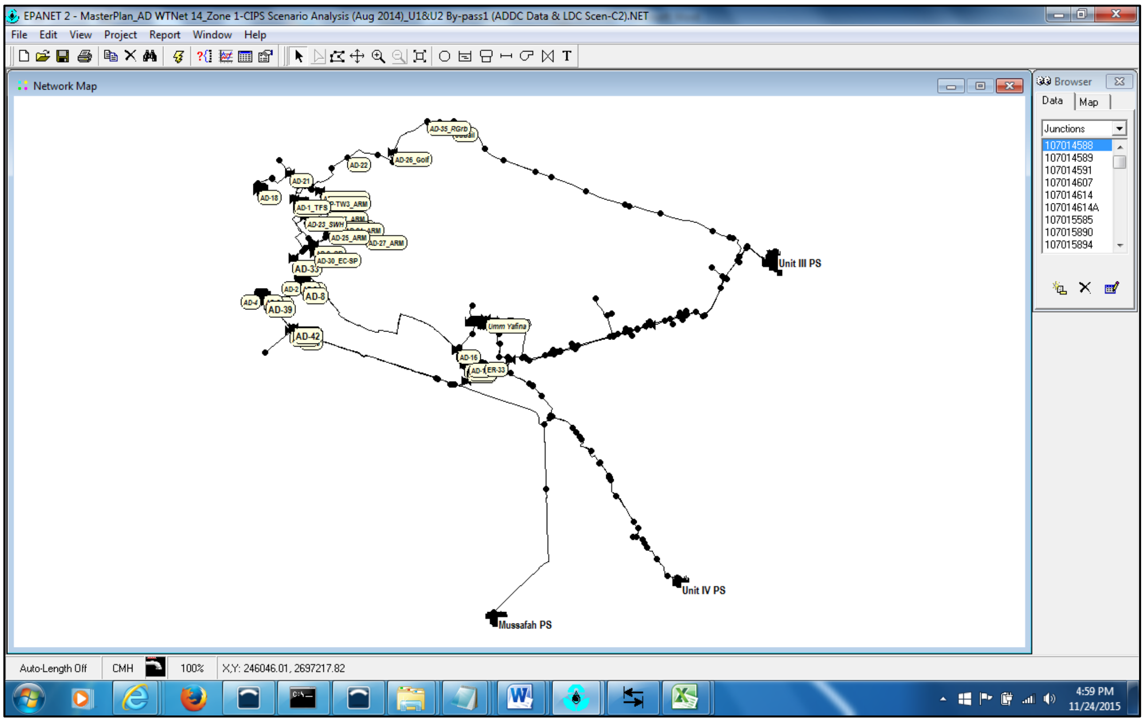
1. Scope the network to be assessed. This requires defining inputs that is used to carry the calculation for edge capacity. This input defines the maximum velocity and pressure for each edge as specified against the material and size available of the pipes constructed.
2. Produce a that contains engineering specification for all pipes tolerances in terms of maximum velocity and maximum operating pressure. The txt file contains three columns of pipe/valve IDs, velocity with units similar to units used in EPANET and maximum operating pressure for each corresponding pipe as shown in Figure 7-13. In this case Abu Dhabi network contains 1709 pipes and 85 valves. In this illustration the maximum velocity in all network components are restricted to 3 m/s water velocity, while pressure are assumed to be equivalent to 250 m water head.



```
 108014_D               3       250
 108014_U               3       250
 108015_D               3       250
 108015_U               3       250
132860  3       250
1370100 3       250
13701014        3       250
13701057        3       250
13701064        3       250
13701065        3       250
13701067        3       250
13701068        3       250
13701069        3       250
13701070        3       250
13701071        3       250
13701073        3       250
13701074        3       250
13701084        3       250
13701086        3       250
13701087        3       250
13701088        3       250
13701089        3       250
13701090        3       250
13701180        3       250
13701181        3       250
13701182        3       250
13701183        3       250
13701184        3       250
13701185        3       250
13701233        3       250
13701234        3       250
13701235        3       250
13701236        3       250
13701312        3       250
13701322        3       250
13701355        3       250
13701356        3       250
13701357        3       250
13701437        3       250
13701438        3       250
13701474        3       250
13701476        3       250
137015  3       250
13701504        3       250
13701505        3       250
13701506        3       250
13701507        3       250
13701524        3       250
13701541        3       250
13701544        3       250
13701545        3       250
13701547        3       250
```

Figure 7-13: Case study illustration - preparation of maximum pipe file for the network

3. Ensure EPANET file can run hydraulic analysis successfully; EPANET uses a flow driven simulation. Therefore, insufficient pressure will give false results.



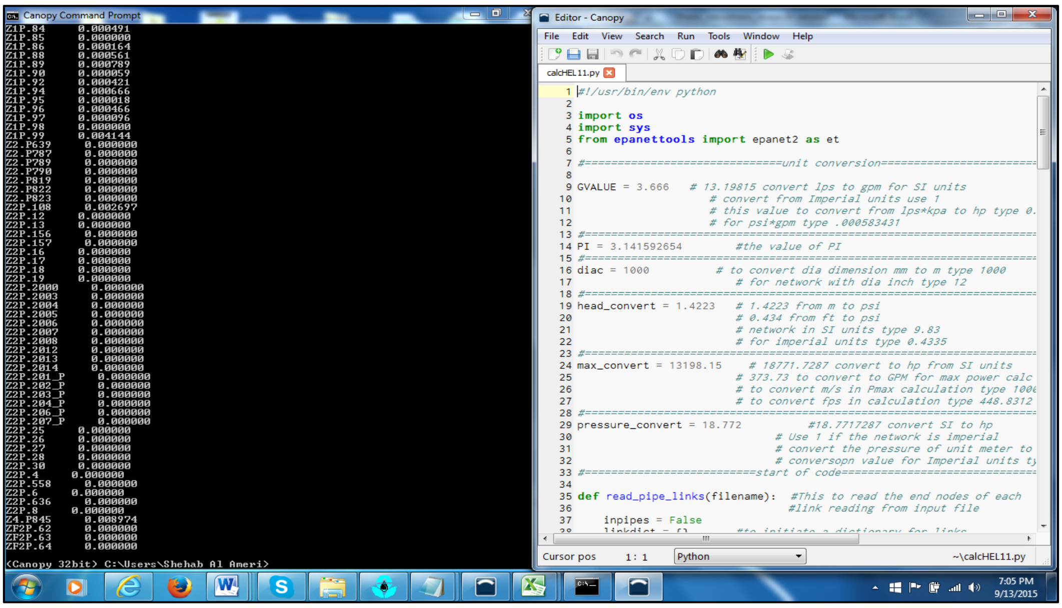
EPANET 2 - MasterPlan_AD WTNet 14_Zone 1-CIPS Scenario Analysis (Aug 2014)_U1&U2 By-pass1 (ADDC Data & LDC Scen-C2).NET

Junctions
107014588
107014589
107014591
107014607
107014614
107014614A
107015585
107015890
107015894

Auto-Length Off | CMH | 100% | X,Y: 246046.01, 2697217.82

Figure 7-14: Abu Dhabi water distribution network model in EPANET

4. Run the Python code (calcHEL11.py) which uses EPANET to calculate flow and pressure from which to calculate the hydraulic edge load on each edge/pipe Appendix I. The code is executed on every time simulation step, to produce an output txt file.
5. Organise the output txt files to sort data over time series for the calculated hydraulic edge load on each pipe. Due to the size of the network used in this illustration (Abu Dhabi transmission network), the output produced is included in 0.
6. Calculate of the hydraulic betweenness index (β_H) to find the importance of each edge in supplying to nodes



```
Z1P.84     0.000491
Z1P.85     0.000000
Z1P.86     0.000164
Z1P.88     0.000561
Z1P.89     0.000789
Z1P.90     0.000059
Z1P.92     0.000421
Z1P.94     0.000666
Z1P.95     0.000018
Z1P.96     0.000466
Z1P.97     0.000096
Z1P.98     0.000000
Z1P.99     0.004144
Z2.P639     0.000000
Z2.P787     0.000000
Z2.P789     0.000000
Z2.P790     0.000000
Z2.P819     0.000000
Z2.P822     0.000000
Z2.P823     0.000000
Z2P.108     0.002697
Z2P.12     0.000000
Z2P.13     0.000000
Z2P.156     0.000000
Z2P.157     0.000000
Z2P.16     0.000000
Z2P.17     0.000000
Z2P.18     0.000000
Z2P.19     0.000000
Z2P.2000     0.000000
Z2P.2003     0.000000
Z2P.2004     0.000000
Z2P.2005     0.000000
Z2P.2006     0.000000
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Z2P.2014     0.000000
Z2P.201_P     0.000000
Z2P.202_P     0.000000
Z2P.203_P     0.000000
Z2P.204_P     0.000000
Z2P.206_P     0.000000
Z2P.207_P     0.000000
Z2P.25     0.000000
Z2P.26     0.000000
Z2P.27     0.000000
Z2P.28     0.000000
Z2P.30     0.000000
Z2P.4     0.000000
Z2P.558     0.000000
Z2P.6     0.000000
Z2P.636     0.000000
Z2P.8     0.000000
Z4.P845     0.008974
ZF2P.62     0.000000
ZF2P.63     0.000000
ZF2P.64     0.000000

(Canopy 32bit) C:\Users\Shehab Al Ameri>
```

```python
#!/usr/bin/env python

import os
import sys
from epanettools import epanet2 as et

#==============================unit conversion========================

GVALUE = 3.666   # 13.19815 convert lps to gpm for SI units
                   # convert from Imperial units use 1
                   # this value to convert from lps*kpa to hp type 0.
                   # for psi*gpm type .000583431
#=====================================================================
PI = 3.141592654        #the value of PI
#=====================================================================
diac = 1000           # to convert dia dimension mm to m type 1000
                        # for network with dia inch type 12
#=====================================================================
head_convert = 1.4223   # 1.4223 from m to psi
                        # 0.434 from ft to psi
                        # network in SI units type 9.83
                        # for imperial units type 0.4335
#=====================================================================
max_convert = 13198.15    # 18771.7287 convert to hp from SI units
                        # 373.73 to convert to GPM for max power calc
                        # to convert m/s in Pmax calculation type 100(
                        # to convert fps in calculation type 448.8312
#=====================================================================
pressure_convert = 18.772          #18.7717287 convert SI to hp
                              # Use 1 if the network is imperial
                              # convert the pressure of unit meter to
                              # conversopn value for Imperial units ty
#=========================start of code===============================

def read_pipe_links(filename):  #This to read the end nodes of each
                               #link reading from input file
    inpipes = False
```

Figure 7-15: Running of calcHEL11.py on Abu Dhabi Network to calculate HEL of all edges on all time steps

7.6.2 Flexibility and vulnerability findings from Abu Dhabi Transmission network

Calculation of Hydraulic betweenness index (β_H) is carried out to inspect the edges importance in supplying to nodes. The same execution of the Python code is done on Abu Dhabi water network. In this implementation, graph theory based python-package called “NetworkX” is used to produce all simple paths from source to every node, which is then filtered based on the hydraulic losses criterion to obtain only feasible hydraulic walks as mentioned earlier. This package utilises the direction supplied from EPANET software that is tracking the flow direction in each pipe.

It is noticed that the hydraulic load observed on the network is partially loaded on around 38% of the edges/pipes capacity. This behaviour can be attributed to the structure of a transmission network where edges near the sources experience the most loads in order to supply the rest of the network.

On the other hand, looking at the hydraulic betweenness in Figure 7-16, It is interesting to point that there are 302 edges contributes each above 1% up to 38% from all hydraulic walks available from all sources to nodes. Higher index edges are concentrated around UMN pump source and there are few that are located near to high source nodes characterised by highly interconnected edges such as (Z1P449). The standard deviation shows the edges experiencing fluctuation in supply as explained earlier and it shows somewhat similar fluctuation except for 27 edges that have standard deviation higher than the average $\beta_{H.}$ Inspecting those edges shows these edges can be characterised as edges in Unit III pumping station except for two edges that interlinks with nodes AD4 and AD 5. These indicate that Unit III pumping station does not operate continuously, the same for AD4 and AD5.

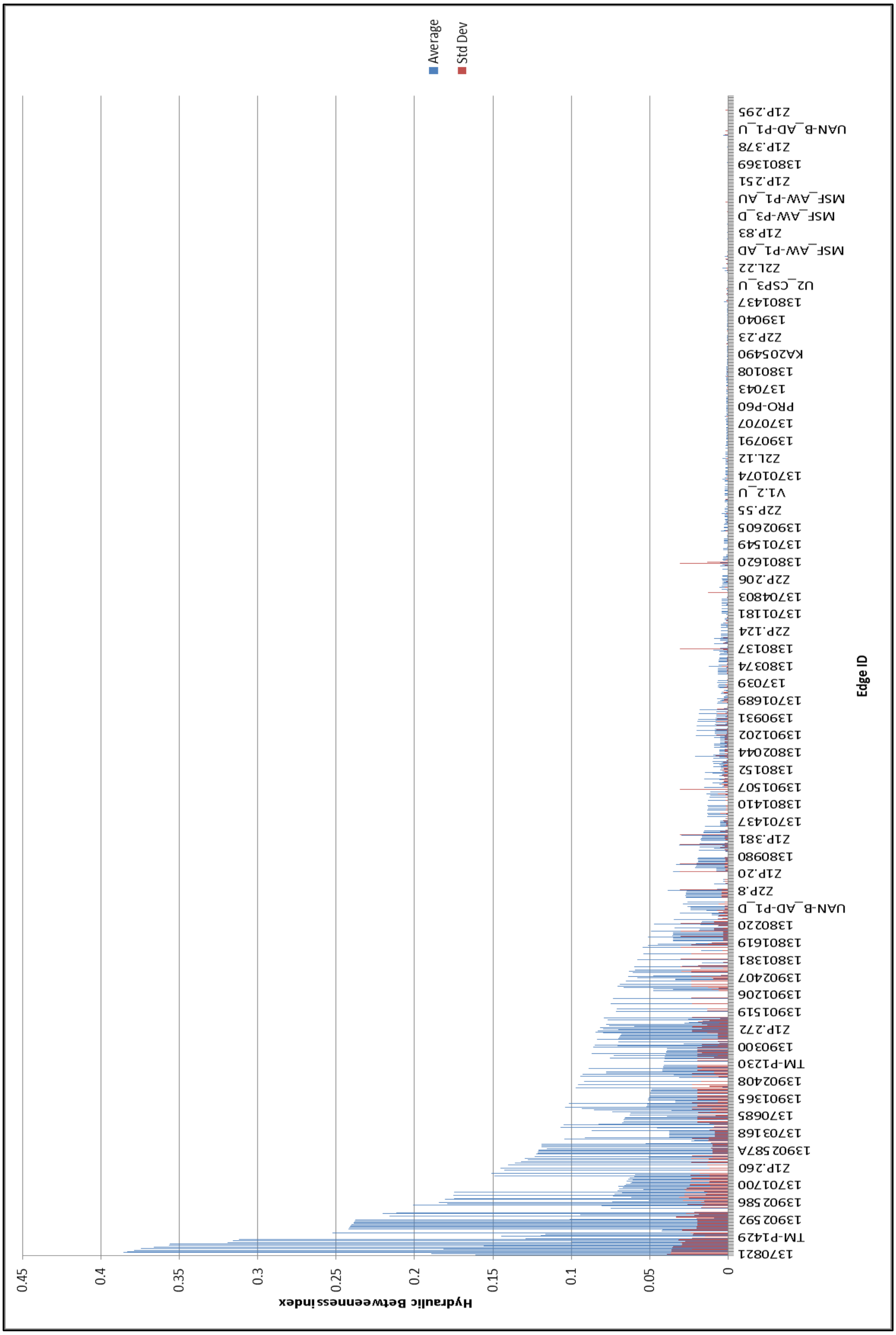


Figure 7-16: Average and Std Dev values of the hydraulic betweenness index for all pipes in the Abu Dhabi transmission water network

Hydraulic edge loads are shown to carry more priorities when placed near the network source (UMN) and few at the boundary of the network. These edges either are experiencing high velocity of flows such the ones closer to the source or the capacity of the physical pipes are limited such the ones at the boundary of the network. These edges detection can be used to look at or to inspect their condition to ensure their component supply dependability (reliability).

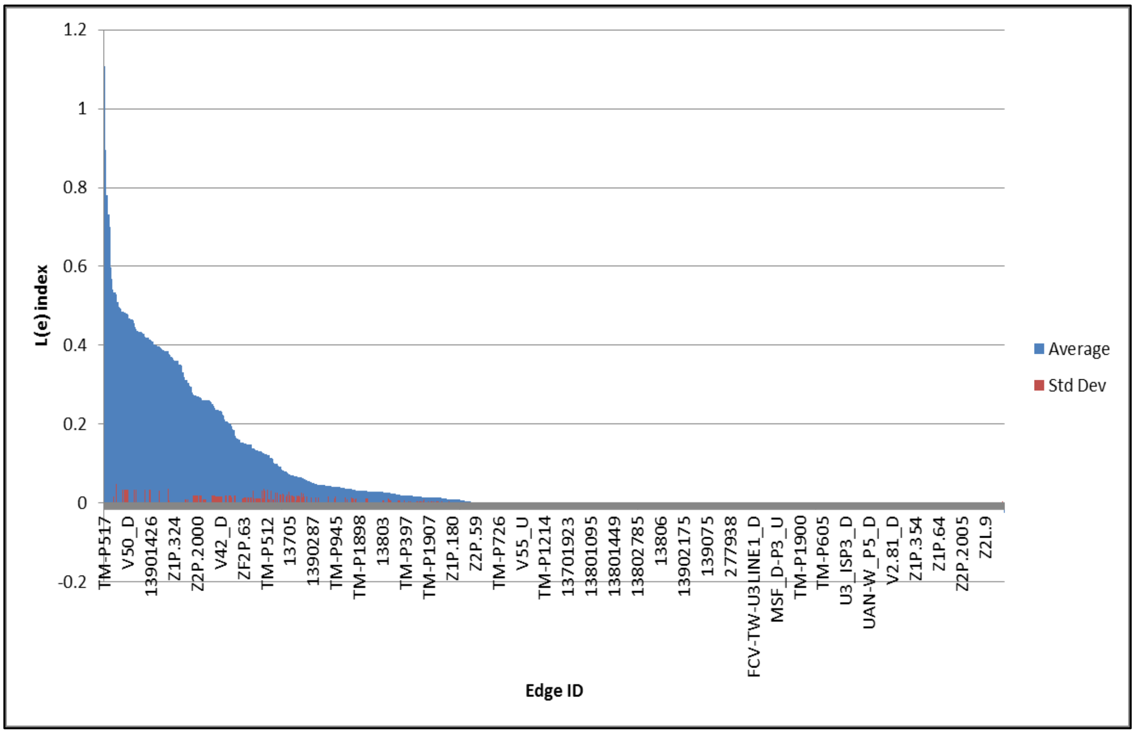


Figure 7-17: Average of L(e) metric for Abu Dhabi water network edges over all-time series run

There is only one edge scoring above 1 in L(e). When inspecting that edge, the system component is located upstream from pumping station in “Mussafah” location. These L(e) values detect velocity changes that can imply flow and pressures increases. For example reoccurring components from the network that are in the premises of pumping station can signify that this pumping station is loaded to supply the network. From Figure 7-17 shows there are around 8 edges that experience high standard deviations mostly located in Unit 3 pumping station, which is not experiencing a continuous supply operation. This depicts non-utilisation of capacity, which is exceeding demands during the day. Detailed calculation can be found in Appendix H and Appendix J.

For vulnerability assessment, Figure 7-18 shows average vulnerability and their relevant standard deviation scores for all nodes throughout the extended simulation time steps. Figure 7-18 shows the different pattern and shifting in vulnerability scores. The vulnerability assessment depicts vulnerability values in around 20% of the nodes, showing a more insensitivity to vulnerability changes

The pattern depicted in the network shows higher vulnerability scores near to UMN source and near to demand nodes AD4, AD5 and AD3. These nodes show high flows. The vulnerability in Abu Dhabi network shows segment of these nodes that express certain vulnerability even though their overall scores show low scores of maximum 0.004. This score gives an indication of the vulnerability scores to be compared against nodes. The remaining of the network shows less or no vulnerability due to lower flow or high redundancy routes to nodes. This can be inferred from transmission networks in general since nodes closer to sources carry the higher vulnerability criteria as per the definition used under this research. Standard deviation of vulnerability scores gives a different view, where the variation of scores vary from scenario to scenario and that nodes experience higher variations compared to the conditions of supply scenario it follows. Vulnerability of nodes can be described to be dependent on the supply scenario experiencing, thus there are scenarios that reduce vulnerability of nodes and it increases it somewhere else.

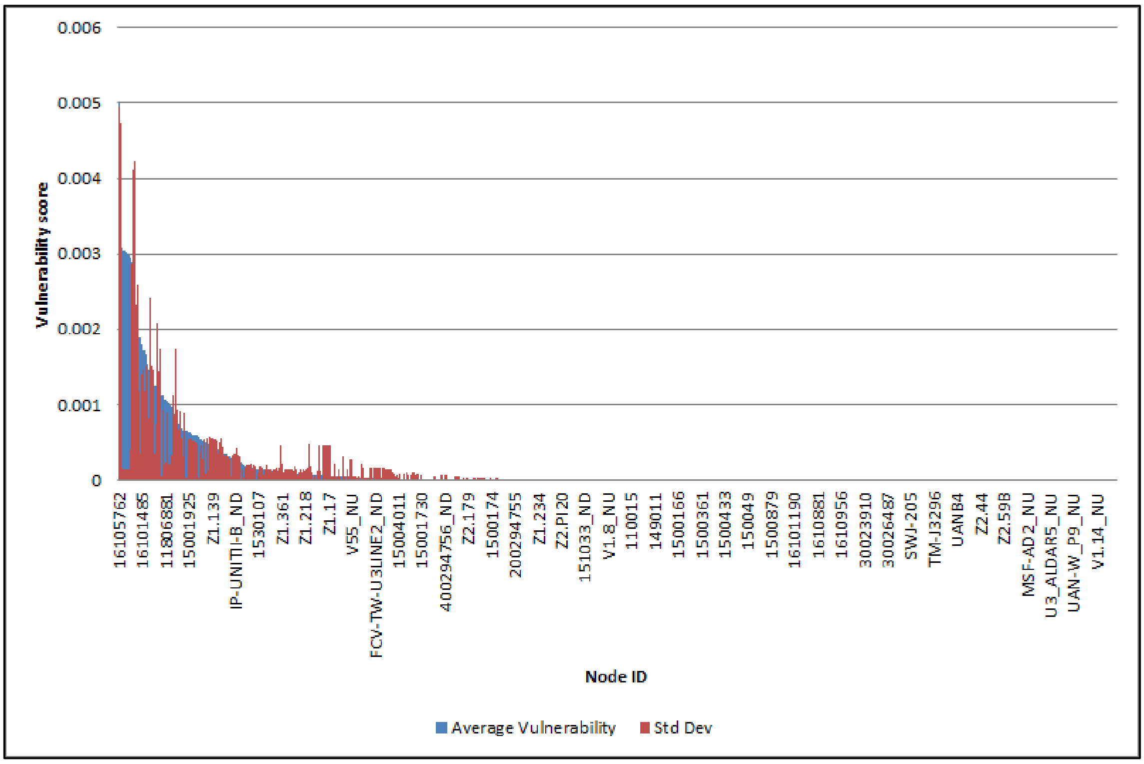


Figure 7-18: Averages and Std Dev of Vulnerability index for nodes in Abu Dhabi Transmission network reflecting all hydraulic scenarios

Results obtained from the model were cross referenced with expert opinion from practitioners in the sector to validate the results and understanding obtained. The results were analysed and cross checked with professionals to assess validity of the result outcome. It is interesting to show that UMN pumping station source is an important source in the network. The results obtained from the approach detected high scores for edges downstream or near that source. Also it is highlighted by the O&M staff that flexibility is much higher in the middle of the network rather than in near sources, implying that the higher the score of hydraulic betweenness index the more important that edge to the whole network to be operational. The hydraulic load where highlighted by the experts that it may indicate capacity, however edges should operate under two criteria of feasible supply separately. These are pointing toward the flow and pressure where the operation of the edge should be below the maximum of both these hydraulic criteria. The edges highlighted show criticality to O&M as highlighted which pointing to area of reinforcement to levitate the load from some of these edges in the network. For example it was highlighted that TM517 should be considered for a higher capacity, but it was noted that the enforcement will be extended to cover the whole header since construction wise is easier to change the rest rather than only one segment. It is highlighted that the segments considered in the network is arbitrary and should reflect the actual segment in site. This is can be referred back to the way the model in EPANET was built-up with different nodes and edges that dependent on software limitations.

Chapter 8 Discussion and conclusion

This chapter discusses the results of the quantitative assessment of flexibility and vulnerability, the contribution to knowledge, the limitations of the research and suggestions for further work.

This research set out to develop an advanced design framework for industrial practitioners to take robustness into consideration as part of the capacity water network expansion planning. The final robustness model is shown in Figure 8-1 presenting the overall factors to construct robust performance behaviour in water distribution networks. This research focused on the prospect of resiliency from network robustness perspective as discussed earlier in Section 5.5.2. The study develops a quantitative metrics and indices to assess the highlighted blocks of the overall framework. An important refinement is the ability to carry out an automated assessment for the network of interest, enabling hydraulic and topological navigation in the network operation.

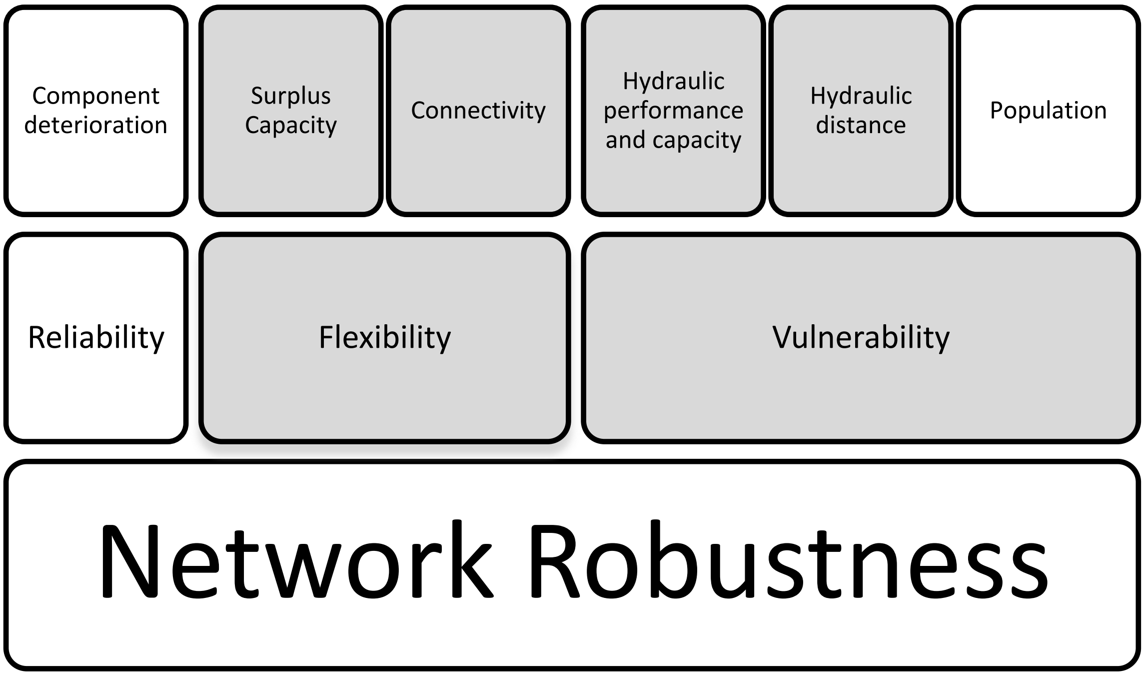


Figure 8-1: Overall robustness model for water distribution networks showing the factors and parameters. Shaded blocks represent metrics developed in the research

8.1 Discussion

Following the models constructed for flexibility and vulnerability in sections 6.3 and 5.5.2, the research proposes that resiliency draws its attributes from flexibility and vulnerability. This drives resiliency to consider both node centric and edge centric views. Having these two views, it brings the findings of edge reachability to nodes and how each edge (pipe) is hydraulically able to supply water. At the same time, vulnerability assesses sensitivity and exposure of impact on these nodes highlighting parts of network that are important. Todini (2000) structured resiliency to account for only one element hydraulically, which captures the spare pressure available within the network, missing other parameters of connectivity and node sensitivity to incident exposure. This research proposes the following definition of resiliency capturing the different pieces of information collated from literature and practice, allowing for a more defined way of looking at the overall concepts of robustness and resiliency carefully. The research highlight that resiliency is identified as manipulating the network by utilising the reachability and surplus capacity (flexibility) to serve users, highlighting network sensitivity to incidents (represented by its vulnerabilities).

Resiliency ($\mathcal{R}$) needs the two aspects mentioned to extract an insight of the network performance. The more vulnerable the network is, the less resilient it is as proposed in Section 5.5.2. On the other hand flexibility is a form of reachability of sources to nodes, where the more reachable edges, the more resilient the network it becomes. Therefore, resiliency can be formulated from:

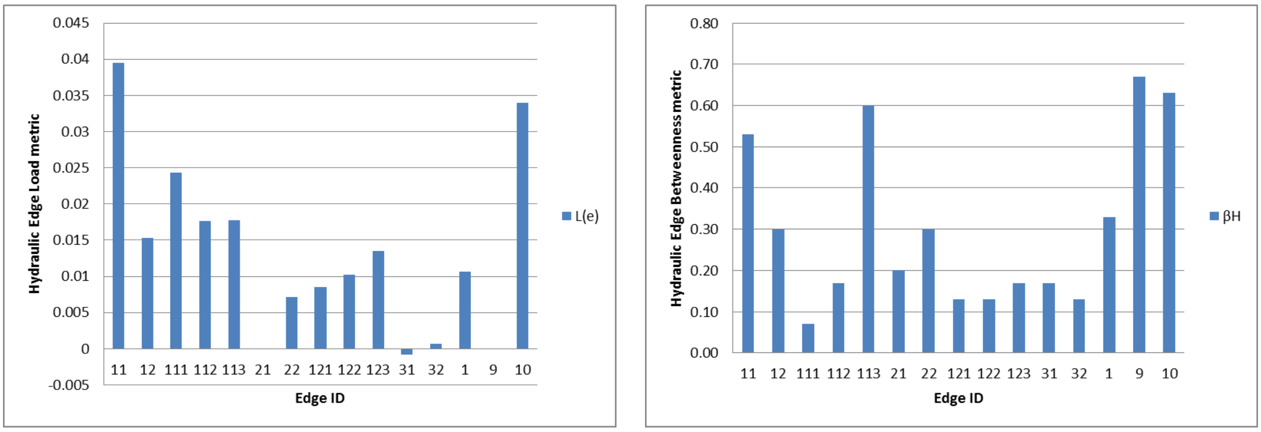
$$\mathcal{R} = \mathfrak{f}(\mathcal{F}, \mathcal{V}) \tag{19}$$

This formulation allow for a better understanding of the relation between flexibility and vulnerability to explore the different centric views, which can be integrated to assess resilience. This is one area that can be investigated further in future works. In the current stage of the research both of these parameters are treated discretely to compare and infer findings against resilience.

This section will review previous results from literature on the benchmark networks that are used in testing the quantitative assessment and compare results to show advantages and disadvantages in the devised assessment.

8.1.1 Literature networks

Two-source network has been studied by Ang & Jowitt (2006) to investigate modelling pressure deficient water network using an iterating algorithm to resemble a deficient supply. Although the focus of their study is to find a good approximation of deficient pressure system modelling, there are two points the current resiliency approach can provide additional information on; the condition of each edge/pipe during hydraulic performance and the role of edges toward supplying the network via the hydraulic betweenness metric. Two-source network is used as single case hydraulic scenario. This network was used to show an initial implementation of the devised assessment of flexibility and vulnerability.



a) Hydraulic edge load for Two-Source network

b) Hydraulic edge betweenness for Two-Source network

Figure 8-2: Results for flexibility assessment for two-source network a) HEL and b) β_H

The outcome of this assessment shows a pattern that contains a much closer grouping on edge and node performance; meaning the load are distributed on three groups reflecting the main supply from available sources. These three groups can indicate edges supplied from source, pipes distributing flow within the middle of the network and a third group of pipes that shows a low utilisation as depicted in Figure 8-2a. Interestingly, surplus capacity alone might overlook the source edges when considering HEL alone, for example Edge 9 scores 0 although it is downstream of the source in the network. Synthesising this outcome with $\beta_{H,}$ it captures the flow pattern in the network via relevant edges. It reflects 9, 10, 11 and 113 as major edges in supplying the network. Tracing the edges in correspondence to network topology and using the two metrics of flexibility; edges 10 and 11 shows a major contributor in flexibility definition, where these two edges carry to potential to increase security by increasing surplus capacity of these two.

Analysis of Two-source network results were compared with entropy definition by Tanyimboh & Templeman (2000). Using vulnerability definition used under this research, nodes of 13 and 23 are susceptible to changes. This is not reflected using entropy definitions, which shows in Table 8-1, these two nodes scores different ranking values.

Table 8-1: Comparison table on Two-source network between vulnerability and entropy scores

Node ID	Entropy score	Vulnerability score
11	10.20	0.0009
12	8.20	0.0019
13	4.61	0.0184
21	2.15	0.0032
22	2.33	0.0046
23	9.34	0.0145
31	0.10	0.0091
32	0.44	0.0089
33	1.14	0.0080
10	0.00	0.0006

This can be related to the definition of entropy, which needs to be maximised according to Tanyimboh & Setiadi (2008) in order to achieve optimal design against failures. Entropy sense the supply distribution by only capturing flows in the network and normalised against the total flow. The entropy score reflects the variance within the network to supply the network, where a homogenous flow supply indicates a more robustness in hydraulic performance. Entropy uses flow as a hydraulic measure to capture the robust performance. Meanwhile, vulnerability score, alternatively, reflects different hydraulic and topological features to assess its relevancy to the rest of the network. The metric developed in this research is normalised against the total power supplied by source to allow for comparison of the results within the network. The score enabled an in-depth analysis in the water networks by highlighting hydraulic performance and topological features individually or against the total network performance.

Anytown network, on the other hand, is used in several studies to investigate network reliability and robustness (Farmani et al. 2005; Raad et al. 2010; Fu et al. 2012). Farmani et al. (2005) investigated the trade-off of cost against hydraulic reliability. The study explored different designs versus the cost and performance. However, it did not highlight network component and where the overall reliability is impacted by. This study approach suggested evaluation of the overall resiliency index, taking into consideration the surplus hydraulic head. This definition of available hydraulic was incorporated in finding the hydraulic edge load that assesses surplus capacity, which is also reflected in scoring vulnerability of nodes.

Many studies on Anytown network pointed out the importance of the three downstream edges from the source as major components for optimisation. Fu et al. (2012) investigated sensitivity of pipe components on the overall global network performance to reduce the complexity of optimisation model. The study on Anytown network came to the conclusion the importance of the three downstream pipes from source, namely 2, 10 and 11, which agrees with $\mathcal{F}$ results produced in this research. On the other hand, the study highlighted edges 33, 34 and 7 as next sensitive network components but much less that the first three. In this research results, these edges score for L(e) are -0.0046, 0.0255 and -0.0242 respectively. But β_H for these edges are scoring 0.247, 0.247 and 0.081. The research partially agree with the findings from Fu et al. (2012) where both 33, 34 ranks third and fourth in terms of β_H. However from $\mathcal{F}$ perspective these edges flexibility do not show such importance.

Other studies deploying stochastic analysis to investigate damages are done on Anytown (Filion et al. 2007). This study suggested node 7 as a parameter to assess annual cost due to damages. The results obtained, even though it carries justification however it treats surplus pressure as a criteria separate from routing. Node 7 in this research when taking into account vulnerability parameters scored 0.0046 among G4 discussed in Section 7.4.2, where it is characterised as a boundary node in the network. The proposed approach under this research can enable the ranking of importance in each of the metrics from a specific hydro-topological aspect providing insight in the role each component play in impacting robustness of performance.in network.

In Ostfeld & Shamir (1993) highlighted in their study of the backup networks, where network loop consists of multiple tree structured networks laid on top of each other. The study acknowledges the importance of consumers on securing supply. The consumer's importance is addressed in this research as parameter to reflect level of tolerance under a real impact on users' perspective in assessing network vulnerability.

In the "Transmission example" network, the results from surplus capacity and connectivity shows the topological importance of edges/pipes in the middle region of the network underlining a bottleneck region that transfers the water from the different water sources to the other downstream network region as discussed in Section 7.5.1. The developed metrics provide a better way of navigating the importance of components under the definition of robustness parameters.

The approach used under this research to quantitatively assess resiliency have introduced a broader consideration of flexibility and vulnerability in terms of resiliency. This differs from some recent studies that accounted reachability as resiliency in a network. (Herrera et al. 2015) have considered K-shortest path method to address redundancy by detecting paths available to nodes from source while using hydraulic resistance as a proxy for reachability. However in water networks, water is supplied according to Bernoulli's rule, thus there are some similarities with resiliency definition adopted in this research, but also significant differences. For example, this research uses a simulation of hydraulics to account for energy required to supply water to nodes. This definition of hydraulic energy has been expanded to define feasible flow patterns that are available to nodes. The research proposes resiliency as function of both network flexibility and node vulnerability together.

8.1.2 Abu Dhabi transmission network

Abu Dhabi transmission network was used to provide a realistic application of the method developed to assess robustness. The network used a depiction of the transmission backbone of Abu Dhabi network. This network shows around 20% of the network experiences a comparatively high hydraulic load and betweenness. This is typical of a transmission network where the load is concentrated closer to the sources. It is noted that nodes experiencing higher flow passing or demanding nodes that are supplied from pumps are experiencing higher criticality in terms of vulnerability. For hydraulic loads it is shown that it may not link to criticality from O&M point of view as explained by O&M representative because some of these edges are peripheral in the network and placed a lower criticality from operational point of view.

The assessment needs to reflect the actual site segmentations to allow for more reliable results. Even though the results detected some of the actual criticality in the network, it still used the model segmentation to assess these different indices. But O&M acknowledge it provided a more insight into the performance of the network to focus on the higher critical indices and measures. The assessment can be further realigned with the model building to provide a more realistic segmentation to the model.

Results obtained from the model were cross referenced with expert opinion from practitioners in the sector to validate the results and understand them. The results were analysed and cross checked with professionals to assess validity of the result outcome.

It is interesting to show that UMN pumping station source is an important source in the network. The results obtained from the approach high scores are detected for edges that are located downstream or near this source. This coincide with the information provided by the O&M staff highlighting UMN importance in the overall system. It is worth noting that flexibility is to be able to supply to network nodes are higher in the middle of the network rather than near sources. This can be evident in case of having failure near sources or in the middle of the network which is interconnected. This is reflected on the metrics proposed implying that the higher the score of hydraulic betweenness index the more important that edge to the whole network to be operational.

On the other hand, the hydraulic load highlighted by water experts may indicate capacity; however edges should operate against two hydraulic supply criteria that are feasible separately. These are the flow and pressure where the operation of the edge should be below both of the maximum capacity for these two hydraulic parameters. The edges highlighted as critical to O&M is also highlighted by experts for the need of reinforcement to levitate the load from some of these edges in the network. For example it was highlighted that TM517 should be considered for a higher capacity, but it was noted that the enforcement will be extended to cover the whole header since construction wise is easier to change the rest rather than only one segment.

The industry experts highlighted that the segments considered in the network are arbitrary and should reflect the actual segments in site. This segmentation results from the way the model in EPANET was built-up with different nodes and edges. In practice, segments are created by valves: a fault requires a segment, which may contain multiple edges, to be isolated by closing valves. These create a more complex topology, to which the approach could be extended.

8.2 Contribution to knowledge

The research delivered the aim produced in Chapter 1:

> “to develop an assessment approach to incorporate robustness designs in water networks”

The research investigated different views of robustness from literature and practice. In the research, several contributions were made in two areas building a framework outlining the factors embodying robustness and the techniques used to quantify these factors. The research addressed both qualitative information and quantitative data to assess robustness viewpoint. The research developed a robustness framework that contains a two-layer concept, which is discussed in Section 5.5.2. The robustness framework gathers the different terms in industry and literature overarching the synthesis of their structured definitions. The research proceeded to describe resiliency while acknowledging reliability as foundation layer of robustness, to define network topological standing. The technique accommodates network's hydraulic information and topological aspect to quantitatively inform the assessment of resiliency. This illustrates the concept of resiliency by obtaining metrics for flexibility and vulnerability.

Reviewing the contributions in each of the set objectives of this research, the following is outlined against each of them:

Objective 1. Identified state-of-the-art literature in water network robustness

This objective was achieved by reviewing the up-to-date knowledge on the area of robust performance in water networks, which shown in Section 4.1 to extract related factors and parameters that deals with water networks to withstand adverse consequences from failures and also to deliver a spectrum of definitions adopted in other studies on robustness and their relevant features.

Objective 2. Identified the current practices in water network frameworks while aligning theoretical concepts with current practices

The current practices on robustness were captured through open and semi-structured interviews described in Chapter 5, highlighting similarities and differences with literature. This gives a specific view of definitions used for robustness to implement on water network planning schemes. An alignment exercise was conducted to show the mismatch between literature and practice factors and parameters. This is used as input to solidify the definitions used under this research and to inform the quantitative model for water network robustness identification.

Objective 3. Formed a water robustness planning framework incorporating relevant critical factors.

The outcome of the results obtained from literature and practice informed a conceptual framework that addresses robustness in water network shown in Section 5.5.2. The framework depicts the hierarchal layers to introduce robustness. This provides an overview of the relation between the critical factors and corresponding parameters. The framework orders the factors to achieve robust performance in water networks.

Objective 4. Developed an assessment model to utilise critical factors from the framework to assess robustness

The framework informed a mathematical approach integrating both topology and hydraulics to address different parameters of resiliency. The models described are covering portion of the robustness framework, illustrating the approach of quantifying robustness performance. The model is meant to provide insight to better navigate network components in terms of topology and hydraulics together. Theoretic formulisation and derivation is described in Chapter 6 under the premise of the created conceptual framework.

Objective 5. Verified the framework approach through literature and practical case studies

The mathematical models of flexibility and vulnerability were carried out on several water networks (literature networks/real case network) to assess output results and interpret findings in Chapter 7. The verification process shows that results are able to track topological and hydraulic features in water networks and can be used to navigate in the network to capture critical components. The research added value by conducting these proposed approaches from practical position and related results to literature to ensure applicability.

A further detailed contribution achieved under this research is listed below:

1. Defined factors and parameters that constitute robust behaviour in water networks
2. Cross referenced different terminologies between literature and practice to find cohesive definitions that describe robustness.

3. Produced a framework that structured component (reliability) and system levels (resiliency) factors into water distribution robustness framework
4. Quantified resiliency parameters by using an integrated hydro-topological approach to assess them.
    a. Modified a graph theoretical tool to consider connectivity in water networks using hydraulics information.
    b. Enabled an edge centric approach to evaluate surplus capacity in pipes rather than node centric in terms of flexibility.
    c. Defined vulnerability from user perspective using node centric in order to rank their tolerances

8.3 Limitation of the research

The nature of the design and implementation of the research programme gives rise to limitations that could affect the findings of this research. These limitations have been categorised as limitations of the research content ('what was found?') and limitations of the research process ('how was it found?').

8.3.1 Research content limitation

The limitations produced from "what was found" are linked to the information gathered synthesised to produce the robustness definitions and framework. These definitions are assimilated by highlighted factors and parameters providing two-level build-up. The research used the available definitions and measures from both literature and practice to bring up broader understanding of these different concepts via comparing them against each other. This may introduce a limitation due to a missed concept or a parameter that was overlooked. However the premise this research is founded on is the collective expertise available to the researcher most likely covered the essential parameters in enhancing robustness in water networks.

One of the shortcoming found in literature is inability to have a unified understanding of robust performance covering flexibility and vulnerability, and this might prevail as limitation to gain consensus, which might require time to reach the necessary buy in from experts in this field. The research carefully approached stating definitions and relevant parameters for factors framing them within available information from experts and literature. The information and data gathered are from restricted number of case studies as representative of the whole industry. This can be a limitation due to the large number of experts available in industry. However, the level of expertise sought to capture different concepts arguably are all entail sufficient seniority to sample the current understanding of robustness. Also, the research attempted to bring different experts view from different geographical area to cross check responses.

Mathematical technique proposed under this research to use heuristic techniques in modelling surrogates of water network robust performance can be a source for a limitation. This technique might lack precision and potential for optimisation, however it gives a relative measure to compare indices of network components against each other. The technique used as surrogate to validate the framework produced and analyse the potential to navigating components criticality of the network against the corresponding parameter.

8.3.2 Research process limitation

Reliability is considered under this research to cover the components of the network, whereas, resiliency covers the topology of it. The framework provides an insight into the structure of the factors, however quantitatively needs to be formulated with reliability in mind.

Reliability needs to be incorporated within the definition proposed of robustness under this research to investigate the effect of all the critical factors together. The current step taken to improve network enhancement is suggest a integrated definitions and measures relevant to their parameters. The research attempt in addressing blocks of robustness in conjunction with the quantitative methodology.

In the research, an assumption was considered on water network that each edge is standalone unit of analysis. Although this carries the merit to enable a more granular analysis of the network, real networks are segments. This is because isolation of one pipe in the network involves many neighbouring pipes (Walski 2011; Creaco et al. 2012). Therefore, network is more a connected segments rather than individual pipes. The research attempts to provide insights into this area of research, which can be further researched in future work considering segmentations.

Addressing deficient network scenario will help investigate the different behaviours related to the metrics developed for robustness factors and parameters. Therefore, incorporating a pressure-driven simulation will widen the context of the research to see different behaviours using the developed metrics.

Two simplifying assumptions were made in constructing the metrics, and two further limitations are presented in the implementation. Firstly, individual edges (pipes) were considered as the fundamental unit of networks. This is reasonable when considering hydraulic loading, but it may not be realistically representative of the disruption effects. This is because, a problem in practice with one edge would be isolated by closing valves, which could actually disrupt a larger section rather than an edge, as it would be rare to have isolation valves on every edge to achieve such effect. The methods could be extended to the more general case by considering the walks passing through each section instead of through single links, although combining this with the hydraulic edge load is not straightforward. Secondly, the assignment of demand in the calculation of the minimum power assumed it was proportional to the cross-section of the supplying pipes. In practice, other properties should be considered, but this is a reasonable first approximation with the available data. The formulations of resiliency parameters are based on the presumption that network are dealt in topological plan, although the use of valve can restructure the network segmentations and the concept of flexibility. The edges assumed can be isolated individually under this research.

Applying the assessment approach depends on the data available such as user types and strategic priority of nodes. This is because it will impact the population variable in (18). This can reflect strategic importance by approximating it to number of population. During the use of this approach, assumptions will be highlighted during generation of results and interpreting results accordingly in implementation chapter.

8.4 Future work

There is prospect for future work to explore the relation between the two different centric views to resiliency. Resiliency parameters will be assessed using the two metrics of flexibility and vulnerability to capture the network features on several benchmark networks from literature and case study to evaluate obtained results and drawing conclusion against resiliency behaviour.

The future work is inferred from the limitations highlighted that can provide a base for improvement in area of water network robustness. The following are highlighted areas that can be investigated further:

1. Introduce reliability aspect to resiliency and how change in network components can relate to its parameters.
2. Limitation in the research is the impact of cost. Commercial consideration was not addressed in this research. This is to enable the focus on robustness as a characteristic of behaviour in the attempt to build a meaning and understanding foundation before providing a commercial aspect to it. Therefore, cost-wise analysis can be a new research prospect incorporating it in relation to robustness factors underlined in this research.
3. The commercial aspect should introduce the cost in relation to improvement in a parameter of resiliency. This can provide an insight on the best efficiency improvement in network performance against the cost expensed.
4. User importance in vulnerability can be further developed to capture vulnerability of nodes. In this research have assumed a uniform reflection of users in network, a further development of users’ density at nodes into the definition of vulnerability can enable better streamlining of emergency planning.
5. Incorporation of node and edge centric view of the resiliency parameters, namely flexibility and vulnerability, needs more study. The definitions

derived under this research emphasise the different centric view of resiliency parameters. Bringing these two views together to form an integrated derivation to resiliency is believed needed.

6. Introducing reliability and further addressing the relation among all of robustness factors can illustrate which of these terms degrade or enhance robustness characteristics of water networks.

8.5 Concluding remarks

The principal research findings against the research aim, and discussed major contributions to knowledge is addressed. The limitations of the research have been identified and finally recommendations for future work suggested. It is hoped that the main contributions that this thesis has made to the body of knowledge will be relevant in theory and practice

Appendix A Theoretical research methodology evaluation

In order to provide theoretical basis and background on developing robustness framework, research methodology on such phenomenon can use different approaches: qualitative, quantitative, or mixed-method approach. An overview of these approaches is discussed to choose a suitable approach toward achieving the research aim.

Qualitative type research considers reality as constructed socially by means of the situation definitions (Easterby-Smith et al. 1999). Qualitative methods are designed to enable researchers to recognize cultural and social traits in research context. Eliciting phenomenon understanding require an approach that handles qualitative aspects of the problem, because quantifying textual data can compromise the integrity and could lead to missing data (Yin 2003). Qualitative research have detailed information which can lead to better understanding of the case study, but at the same time will reduce probability of generalisation. Table A-1 shows different research methods that filters the suitable research approaches (Yin 2003). Some of qualitative methods are; action research and case study.

This research propose on ‘how’ robust design is achieved in planning practices, consequently there are different candidates of research approaches as depicted from the table such as ‘Experiment’, ‘History’ and ‘Case study’. Since this research will be conducted in industrial setting, thus no behavioural control of the events are sought feasible, then ‘Experiment’ approach can be deducted. The focus of the examination is to be based on contemporary issues; therefore, ‘History’ is deducted from the suitable approaches to use and the access to interviewees are limited in this sector, thus ‘Survey’ can be difficult. Hereinafter, ‘Case study’ is chosen as research approach to investigate representative process in Development stage of this research.

On the other hand, the quantitative type research uses mechanisms to capture the varying perspectives and experiences of people into a limited number of predetermined response categories, to which numbers are assigned. Survey methods, laboratory experiments, formal methods and numerical methods are Examples of quantitative methods. Quantitative types assists in comparing and use statistical data to aggregate concepts to enable generalisation.

Table A-1 Different research methods[4]

Method	Form of Research Question	Requires Control of Behaviour?	Focusses on Contemporary?
Experiment	How, why?	yes	Yes
Survey	Who, what, where, how many, how much?	no	Yes
Archival Analysis	who, what, where, how many, how much	no	Yes/no
History	How, why?	no	No
Case Study	***How, why?***	***no***	***Yes***

Evidently, mixed method is a combination between the two methods seeking convergence across both methods. It is an attempt to use multiple techniques and multiple methods in answering research questions. The mixed method is not to replace any of the other approaches (namely either quantitative or qualitative), but rather to take advantage of the strengths and reduce the effects of the weaknesses of either. It is expected to create reliable explanation through triangulation. This has emphasised on “combining quantitative and qualitative research”. Therefore, to achieve the aim and objectives this research proposes, mixed method approach is adopted to capture the conceptual framework and construct a systematic approach for evaluating robustness.

A.1.1 Design stage

The relevant literature of robustness in water networks are described in three step sequence. First step is initiated by generating keywords that stems from the aim of this research to populate the research database. This research is then extended by using combination of the highlighted keywords. Finally, the

---

[4] Source (Yin 2003)

third step eliminates the papers that are not relevant of the field of interest through qualitative analysis of the abstract and the summary.

The method is highlighted in Figure A-4, outlining steps taking to filter relevant papers and studies in the context of water distribution networks. Using identified keywords presented and their combination, relevant literature filtered through qualitative evaluation to extract state-of-the-art. A list of papers describing the state-of-the-art of relevant factors and approaches in the water planning design are produced, summarising list of terms and factors shown in Appendix B.

A.1.2 Development stage: Industrial evaluation of robustness

The qualitative part uses case study to capture views from practice. Case study is defined as an “extensive study of a single situation such as individual, family or organization” (White, 2000). Literature have regarded case studies as one of the most influential techniques in operations management (Voss et al. 2002). However it is further commented that case study can be a difficult task to conduct due to time consuming as well as the requirement for proficient interviewers. A case study is believed to lead to new insights, structuring the foundation for new concepts while allowing high validity with practitioners. In this research context and the accessibility to expertise in the sector render case study as an appropriate strategy to support the understanding of robustness in water organizations. The target is to identify critical factors that impact robustness during the planning process. Case study selection is appropriate since the research is answering ‘how’ questions and there is no need for control over behavioural events while focusing on contemporary issues as described by (Yin 2003) and outlined in Figure A-1.

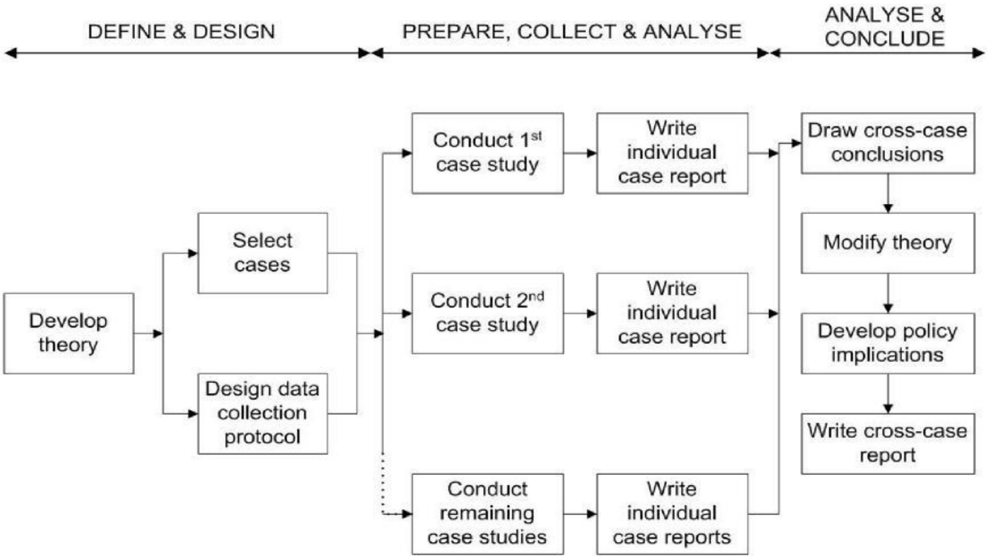


Figure A-1 Case study method

Bryan & Bell (2007) described research methodology merely as a data collection method. It may entail a special mechanism for instance, a self-completion questionnaire, a program of structured interviews or comments by participants where the researcher observes and views other parties. As this research will follow mixed-method approach, both types of data collected; i.e. qualitative and quantitative data. This represents the data collected by conducting semi-structured interviews to understand the perspective of robustness in water network.

Case studies as highlights by Yin (2003) used to derive analytical generalisation. Two or more case studies hence support reproduction and the empirical results are considered more compelling. thus the case studies is needed to be tested in similar context but differ enough to avoid the argument that the model is too specific to the problem in hand and hence analytical generalisation cannot be made. Selection of the research process and cases to be used is highlighted along with the data collection protocol. The cases are then executed with subsequent cross case analysis summarising the industrial evaluation on robust design of water networks. Development stage is to enhance the current robust design process and incorporate all factors that are represented by a new developed framework. There is, however, risk of making too specific decision selection in the study cases used from the industrial cases.

Therefore, changes and modifications will need to be carried in a manner that diminishes biases to the cases to enable reviewing the shortcomings successively.
The research utilises an exploratory pilot study on practice and probe the experts view in an open-ended settings clarifying the role of robustness in water sector. The pilot provides a first look of the different terms and themes to act as a priori-theme for the case study preparation and analysis. This considers identification of external influences where the model can be affected by. The framework incorporates the information collated from the case studies by themes that are compared via cross-case analysis with the theoretical perspective. A priori-thematic analysis is utilised to generalise definitions and understanding informing the framework, which will guide the quantitative validation of the models. These themes are the areas the case study attempts to cover in order to involve all relevant information and create a bigger picture of robustness in water networks.

The type of the interviews used for the case studies is semi-structured interviews. Semi-structure interviews are flexible and help to explore issues that may emerge when conducting the interviews, but at the same time keeping focus on the issue under study. Based on the literature review and the industrial pilot study findings, the research constructs a generic understanding of the main critical factors. Semi-structure interviews are used as a technique in order to cover different insights from literature to the mind of interviewee.

A.1.3 Validation stage: Robust design assessment model: development and testing

Validation stage inspiration is to conduct case studies through developing process of evaluating the new model and comparing it to old one as well as to promote the development of the new model. Selecting case studies is an important part in this. This stage promoted by building a quantitative assessment approach to inspect robustness characteristics in networks. Several case study water networks are tested against to ensure comparability with previous results.

Kolkman et al. (2005) outlined stages in linking decision making into water management to scientific model illustrating the different considerations to formulise a representative model on design policy decisions. This study attempted to produce a methodology to link between knowledge, system and society and how frameworks can distorts the depiction of system due to limitations imposed by set objectives or coverage of factors. This study suggest concept mapping carry potential of mitigating misrepresentations of linking different factors. It have produced a stage

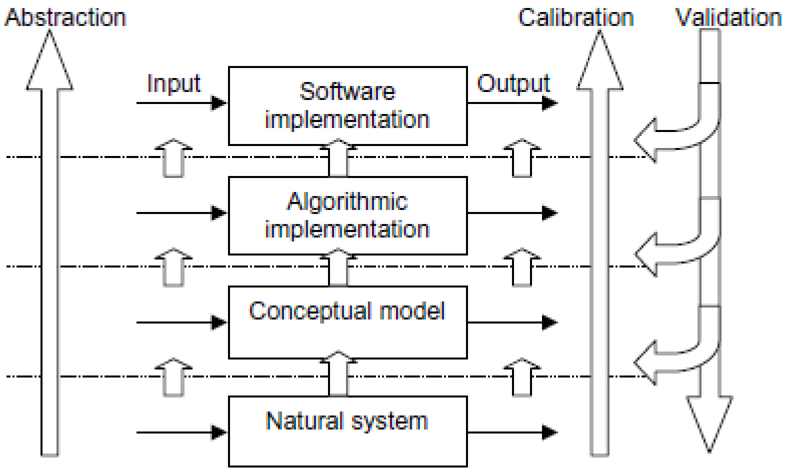


Figure A-2 Validation of complex system concept model build-up as shown Kolkman et al. (2005)

The conceptual model allows for inclusion of perceptions and theories to represent a real complex system such as water networks. Figure A-2 shows the different stages to construct a model that can be later formulised and implemented on scientifically. The calibration and validation are dependent on the data produced from such model; assessing the reflection of the results obtained.

In this part of the research, the task is to verify the framework developed and enable interpretation of concepts in water networks, hence achieving the aim of this research. Validation of the framework which is the basis of the model needs to be aligned with the verification process of models. Therefore, defining how inferences are made in case study based approach presents itself to two different theories. (Yin 2003) discusses deriving inferences from different approaches of ‘Survey’, ‘Experiment’ and ‘Case study’ strategies.

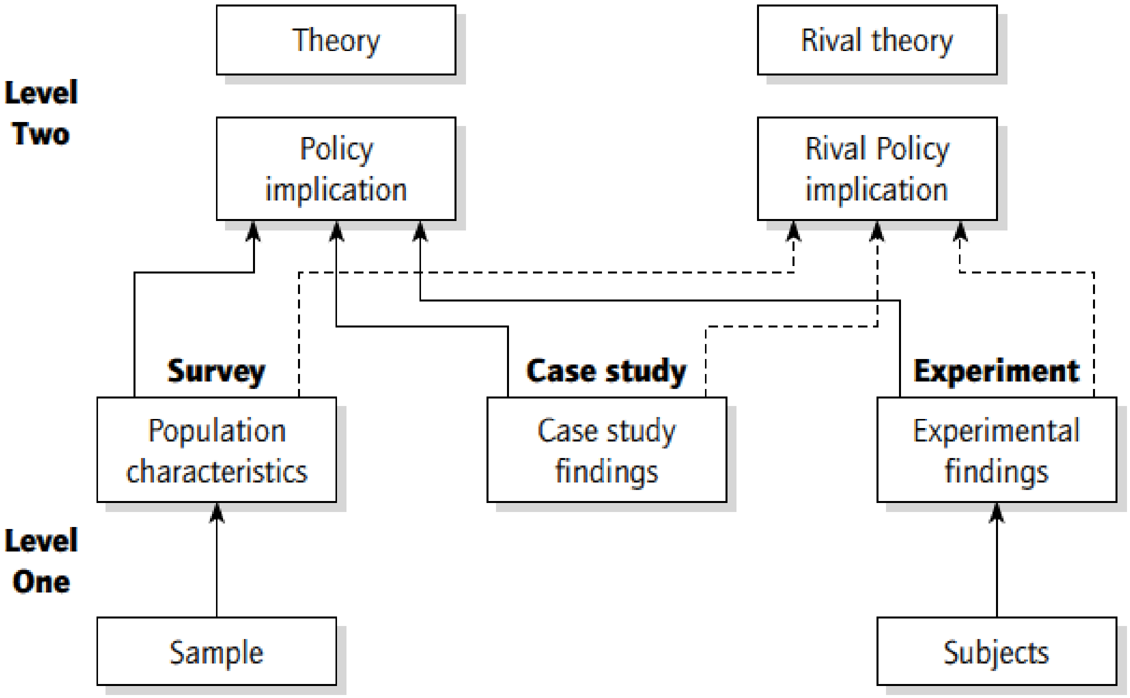
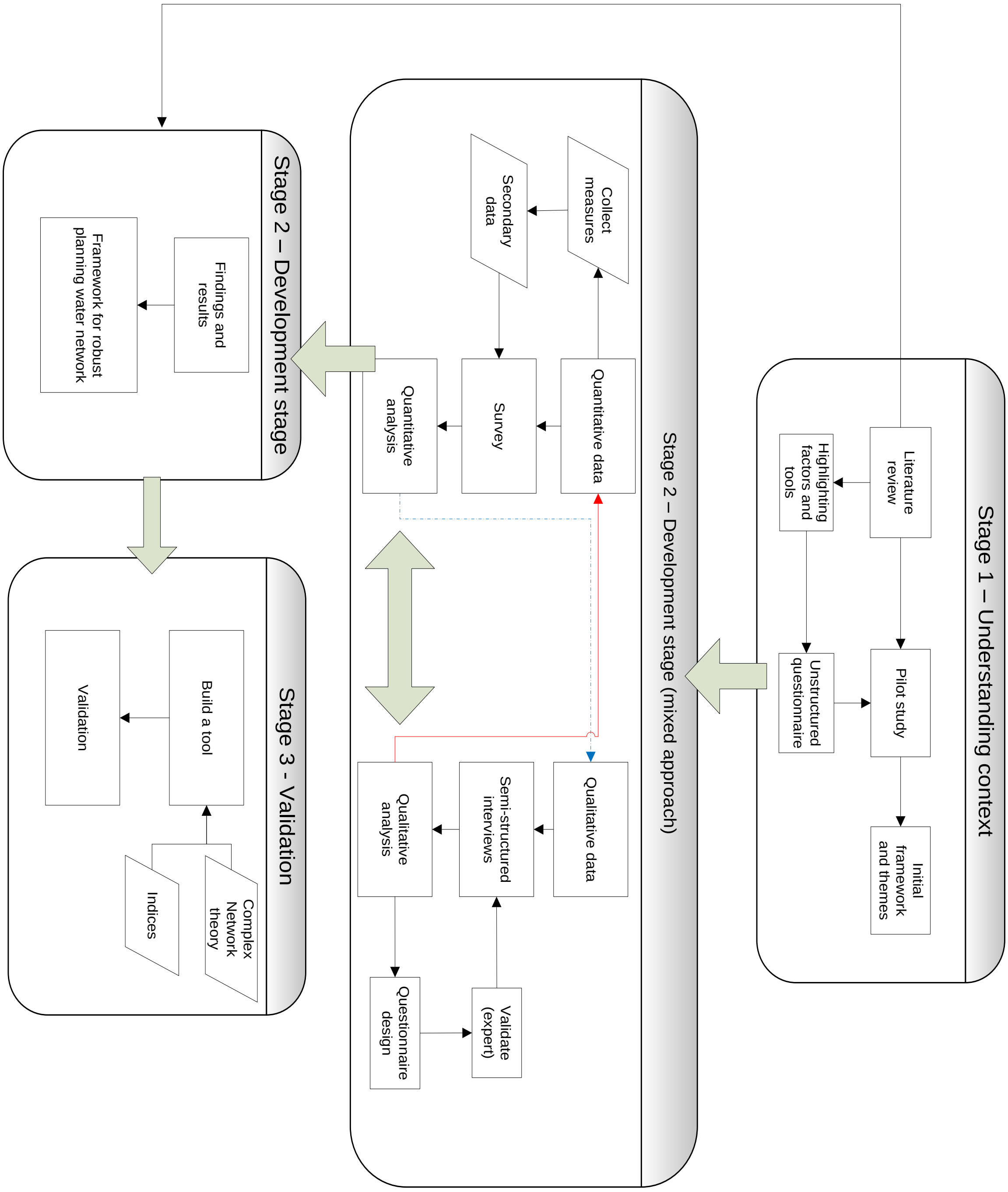


Figure A-3 Two level: Making inferences

Motivation of this stage is to apply the newly introduced concepts and their relevant model to case studies; hence evaluating the new model compared to the old one, promoting the development of the new model. As pointed by Yin (2003), case studies can be used to derive analytical generalisation, where two or more case studies support reproduction and empirical results. Therefore, Refinement and final model

This is to gather collective knowledge formed from previous stages to identify any limitations and suggest refinements.


Stage 1 – Understanding context
Literature review
Highlighting factors and tools
Unstructured questionnaire
Pilot study
Initial framework and themes
Stage 2 – Development stage (mixed approach)
Collect measures
Secondary data
Quantitative data
Survey
Quantitative analysis
Qualitative data
Semi-structured interviews
Qualitative analysis
Questionnaire design
Validate (expert)
Stage 2 – Development stage
Findings and results
Framework for robust planning water network
Stage 3 - Validation
Build a tool
Validation
Complex Network theory
Indices

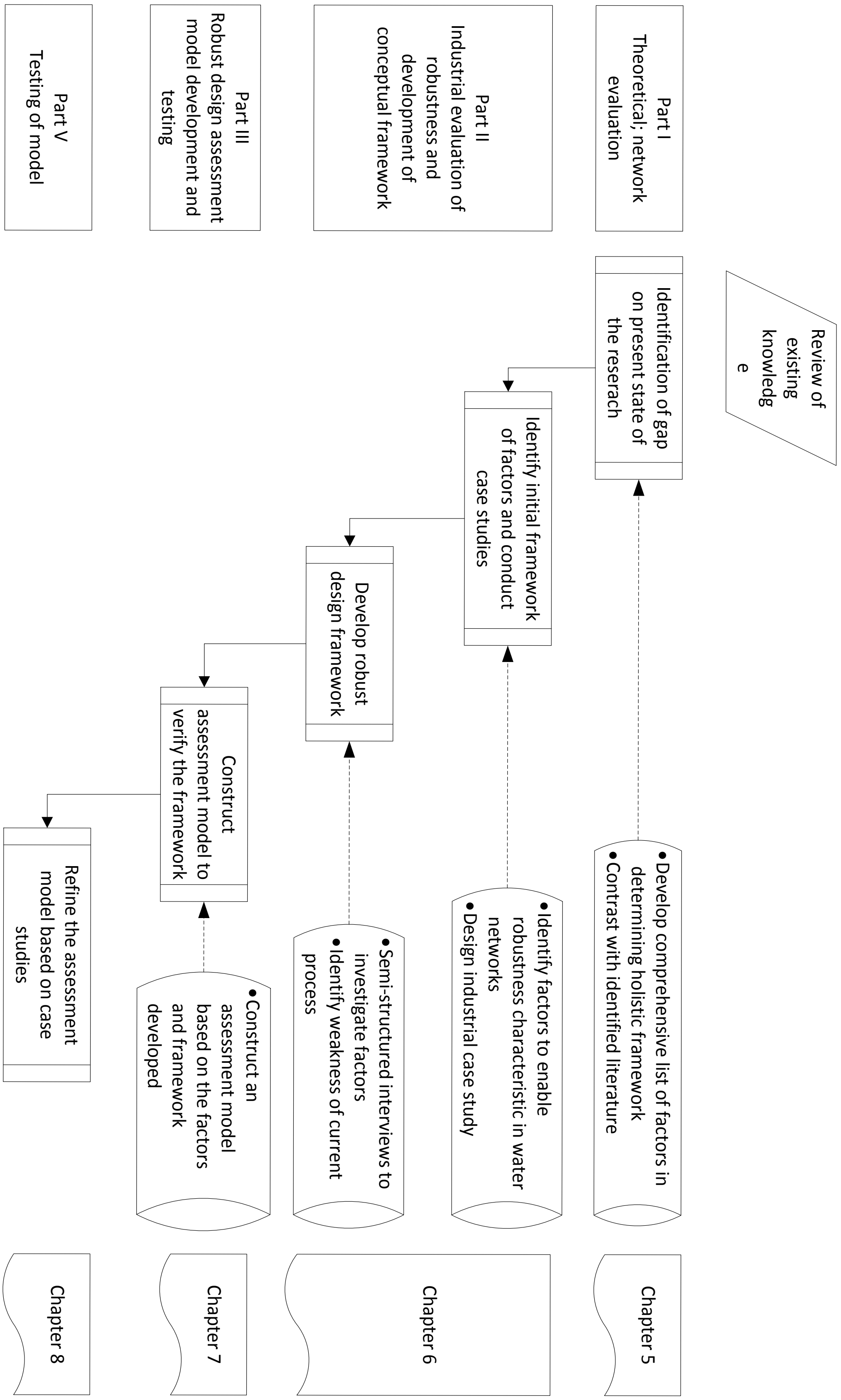


Figure A-4 Research program

Appendix B Definitions and summary of concepts from literature

The following table provides spectrum of definitions of variable terms discussed or used to address system robustness:

Table B-1 Overview of different terms and concepts on robustness in literature

References /Factors	Resiliency	Vulnerability	Surplus capacity	Flexibility	Reliability
(Hashimoto , Stedinger, et al. 1982)	Quickness of the system to recover after an occurrence of failure	The likely magnitude of failure			Probability of maintaining performance
(Walski 1993)					Derived from redundancy within the system to compensate for any failure and to minimize the impact
(Todini 2000)	Intrinsic capability of a system to overcome degradation Ratio of power input to the system to the power loss, measuring the excess pressure at the node				

References /Factors	Resiliency	Vulnerability	Surplus capacity	Flexibility	Reliability
(Kjeldsen & Rosbjerg 2004)	Measure of system reaction to compensate for failure	Measures the likely damage caused by failure			Failure duration and demand deficit as elements in categorizing system reliability
(Adger & Vincent 2005)		Vulnerability is function of risk exposure, sensitivity and surplus capacity			
(Hawick, 2011)				Anticipates a design that accommodates different future scenarios	
(Prasad and Park, 2004)				Flexibility was considered as sub-factor in reliability	
(Ostfeld & Shamir 1993)					Links between connectivity and reachability of water network as definitions of reliability the probability that the system meets consumers' demands for flow and pressure

References /Factors	Resiliency	Vulnerability	Surplus capacity	Flexibility	Reliability
(Gallopín 2006)	Surplus capacity where it was a component in resiliency; Systems' ability to cope with disturbances,	Characteristic of system that is prone to fail	Ability to cope with disturbances, where it was a component in resiliency		
Duan *et. al.*					Probability of failure, cycle time between failures, expected duration of failure and expected un-served demand
(Bruneau et al., 2003)	Characteristics of a resilient system as (a) reduced failure probabilities, (b) reduced failure consequence and (c) reduced recovery time				
(Bentes et al. 2011)		Measures of total hours of failure, total water lost and total number of users affected			Ability to provide adequate performance for end-users under abnormal conditions

References /Factors	Resiliency	Vulnerability	Surplus capacity	Flexibility	Reliability
(Farmani et al. 2005)		Components of exposure to perturbations or external stresses, sensitivity to perturbation, and the capacity to adapt.	Surplus capacity is considered as part of vulnerability		

Table B-2 Overview of the tools and approaches to address robustness in water networks

Robustness	Resiliency	Vulnerability	Failure	Adaptive capacity
Potentia of cost variance between actual cost of a project and the least cost design to meet future demans	[49] defined the resiliency index as the ratio of power input to the system to the power loss.	theory of vulnerability of water pipe networks (TVWPN	[53] investigated the application of fuzzy logic to model the uncertainly as non-probabilistic problem, since the details of deciding the magnitude of demand can relate to pressure behaviour	[24] devised a discrete formulation using a stochastic algorithm in order to visualize network optimization
	Cross entropy theory	[42] assessed the connectivity to node routes and how an impact on one part of the network could affect the service		
redundancy allocation within an expansion plan requires researching to minimize costs, or maximize robustness, or do both and satisfy connectivity among the nodes while keeping costs low	graph theory can apply to water networks. Node connectivity and topological features in water networks were found to be some of the parameters affecting reliability and resiliency to failures [54].	Vulnerability measures the likely damage caused by failure		
	resiliency was a measure of system reaction to compensate for failure			
[20] devised a heuristic design support methodology to define locations of district metering compatible with system hydraulic performance. They used	Modelling water distribution networks using graph theory			
	Characterizing the network structural properties, such as redundancy and optimal connectivity			
[25] who adopted a harmony search algorithm. This method was tested and found to have the ability to consider discrete solutions able to locate global optimum flow velocity constraint	The study addressed the characteristics of water network to graph, and how indices and measures [54]			

Appendix C Complex network theory

Table C-1 Some Complex network theory measures on water network topology

Measure	Attribute	Description
Geodesic path length $\boldsymbol{d_{ij}}$	Network efficiency	(d_{ij}) number of edges has to traverse to reach from any node to other (Yasdani & Jeffrey 2011) n = number of nodes in a graph
Graph diameter	Network efficiency	measure of maximum graph eccentricity represented as the maximum value of the shortest geodesic paths that relates to efficiency (Najjar & Gaudiot 1990)
Characteristic path-length	Network efficiency	Average of the shortest path-lengths in graph Defined as: $l = \frac{1}{n(n-1)} \sum_{i \neq j} d_{ij}$ (Diestel & Sprüssel 2011)
Central-point dominance $\boldsymbol{C_b}$	Network efficiency	Measure of structural network organisation indicating dominance of central points defined as average difference in betweenness centrality $$C_b = \frac{\sum_{i=1}^{n} [C_b(n_k^*) - C_b(n_i)]}{n-1}$$ $C_b(n_k^*)$ is the maximum relative betweenness centrality around central node k $C_b(n_i)$is the relative betweenness centrality for any node i where n is total of nodes (Yakowits et al. 1993)
Betweenness centrality	Connectivity	$C_b(k) = \sum_{s \neq k \neq t \in V} \frac{\sigma_{st}(k)}{\sigma_{st}}$, where $\sigma_{st}$is the total number of shortest paths from node s to node t and $\sigma_{st}(k)$ is the number of paths going through node k (Narayanan et al. 2014).

Algebraic connectivity $\boldsymbol{\lambda_2}$	Connectivity	This is a measure of graph failure tolerance through its connectivity, where a large value indicates higher resistance in decoupling the network It defined by second smallest eigenvalue of normalised Laplacian network matrix. Laplacian matrix G is n square matrix $L = D - A$, $D = diag(d_i)$, $A = \left(a_{ij}\right)$ is the adjacency matrix of graph where $a_{ij} = 1$ if there is a link between nodes i and j otherwise 0 (de Abreu 2007; Jamakovic & Uhlig 2007)
Meshdness coefficient $(\boldsymbol{r_m})$	Connectivity	This measure pertain to particular scenario where the number of independent cycles in network represented by $f = m - n + 1$ for single source networks and $f = m - n$ for multi-source networks; hence the coefficient defined to be (de Graaf & der Brugge 2010; Di Nardo & Di Natale 2011; Yasdani & Jeffrey 2011): $$r_m = \frac{f}{2n - 5}$$ That $r_m$is the ratio of actual cycle number to the maximum possible numbers in network, quantifying density of cycles

Appendix D List of surveyed documents for the Case study

Table D-1 Surveyed documents from water sector

Document	Description
Resilience – outcomes (focused regulation) by Ofwat	Principles for resilience planning – May 2012 (Ofwat 2012)
Seven year water planning statement (2012 – 2019)	• Inform the Users of the system of its expansion plans and development • Strategies covering a successive period of seven years into the future (e.g. 2013-2019 in this case) • Identify and evaluate the opportunities available when planning to connect and make use of the system.
Network access security strategy	Assess security and counter actions – May 2012
Contingency planning	Regulatory body – March 2004
Security standard report	• Regulatory body – March 2004
Water distribution code document – March 2010	• specifies the criteria and procedures to be applied by a DISCO in planning and development
Maintenance record 2006 ~ 2012	• Corrective and planned maintenance record

Appendix E Pilot Study interview questionnaires

Please state your name and position

How long you’ve been in this position?

1. Could you go through the planning process steps in the organization?
    - Who is responsible of each step?
2. What are the roles of water network planning? What does it achieve?
3. Where would challenges occur in water planning?
    - Classifying the different challenges that needs to be addressed
4. What desired characteristics/functions would you seek from water network?
    - From organisational and regulation point of view
    - How these characteristics are beneficial?
5. What are the factors considered when planning for water network?
    - *Do you consider resiliency, reliability, vulnerability, and surplus capacity flexibility, connectivity in water planning?*
6. What are the available techniques used to enhance success of water networks?
7. What are the problems inhibiting water network to be robust?
8. What is the strategy in generating water network design alternatives?
9. What can be done to improve the water network planning process?
10. Are there guidelines or regulation for water planning in the organization?

Appendix F Case study questionnaires

Standard

Name:

Position:

Organization:

Experience

Theme

Sub-factor Flexibility:

No.	Questions	Target	Aim
1	What does flexibility of system means to you	Definition	Explore reason for flexibility
2	Are there elements in the water network that exhibit flexibility behaviour	Initiation point	Stage of work, flexibility is considered explicitly
3	Is flexibility is measurable attribute in network design	Context	Where does it show
4	How do you manage such factors to enhance flexibility or to reduce it	How to Manage	Show how such parameters are controlled or used
5	What are the limitations in adding flexibility in networks	Limitation	Define constraint in introducing flexibility
6	Who are the stakeholder interested in flexible network and champion it	Driven by who	Stakeholder who are interested and pushing for flexibility
7	Is flexibility considered in design processes or in design guidelines	Perception	Illustrate if flexibility is qualitative or quantitative sub-factor
8	Who take the decision on flexibility	Decision maker	Stakeholder who takes decision technically

Interview Questionnaire

Name:

Position:

Organization:

Experience

Theme **Definition**

Sub-factor Vulnerability:

No	**Questions**	**Target**	**Aim**
1	What are the criteria to measure vulnerable node	Definition	Explore reason for vulnerability
2	Are there means of controlling vulnerable nodes	Context	Where does it show
3	What are the prioritization criteria for a vulnerable nodes	Current	Check status quo
4	What are the threshold to consider points as vulnerable points	Specific tool	Technical tools to use
5	How do you tackle vulnerable nodes to strengthen supplies to these nodes	Attributes	Investigate parameters that contribute to vulnerability
6	What are the limitations of enforcements	How to Manage	Show how such parameters are controlled or used
7	Who are the stakeholder that guides or point the vulnerable nodes	Limitation	Recognize decision maker in this factor
8	When do you initiate a corrective action for these vulnerabilities? Are there premeasures to minimize impact on vulnerable nodes?	Measure	Detection measures available in organization
9	Do you have insights of these vulnerable nodes during planning stage	Perception	Illustrate if vulnerability considered during planning stage

What does resiliency means to you

Name:

Organization:

Experience:

Theme

Sub-factor

No.		**Questions**	**Target**
1	How can you decide on resiliency of a system/node	Attributes	Investigate design standard used to include resilient performance
2	What are the technical parameters that highlight resilient performance	Attributes	Investigate parameters that contribute to resiliency
3	Are there tools to use to increase resilient performance	Tools	Investigate the tools available
4	in what part of the planning process you identify resiliency	Who's designer	Highlight how far design is considering resiliency
5	What are the constraints that prohibit maximising resiliency	Limitation	Define constraints technically
6	Who take the decision on related issues with resiliency of the system	Decision maker	Stakeholder who takes decision technically
7	How to assess water performance after construction	performance	Post evaluation

Appendix G Synthesis of the Case study responses

This presents the depiction of the responses for the three factors used in the Case study. The depiction shows the summary of the responses and the thematic segregation produced and analysed against.

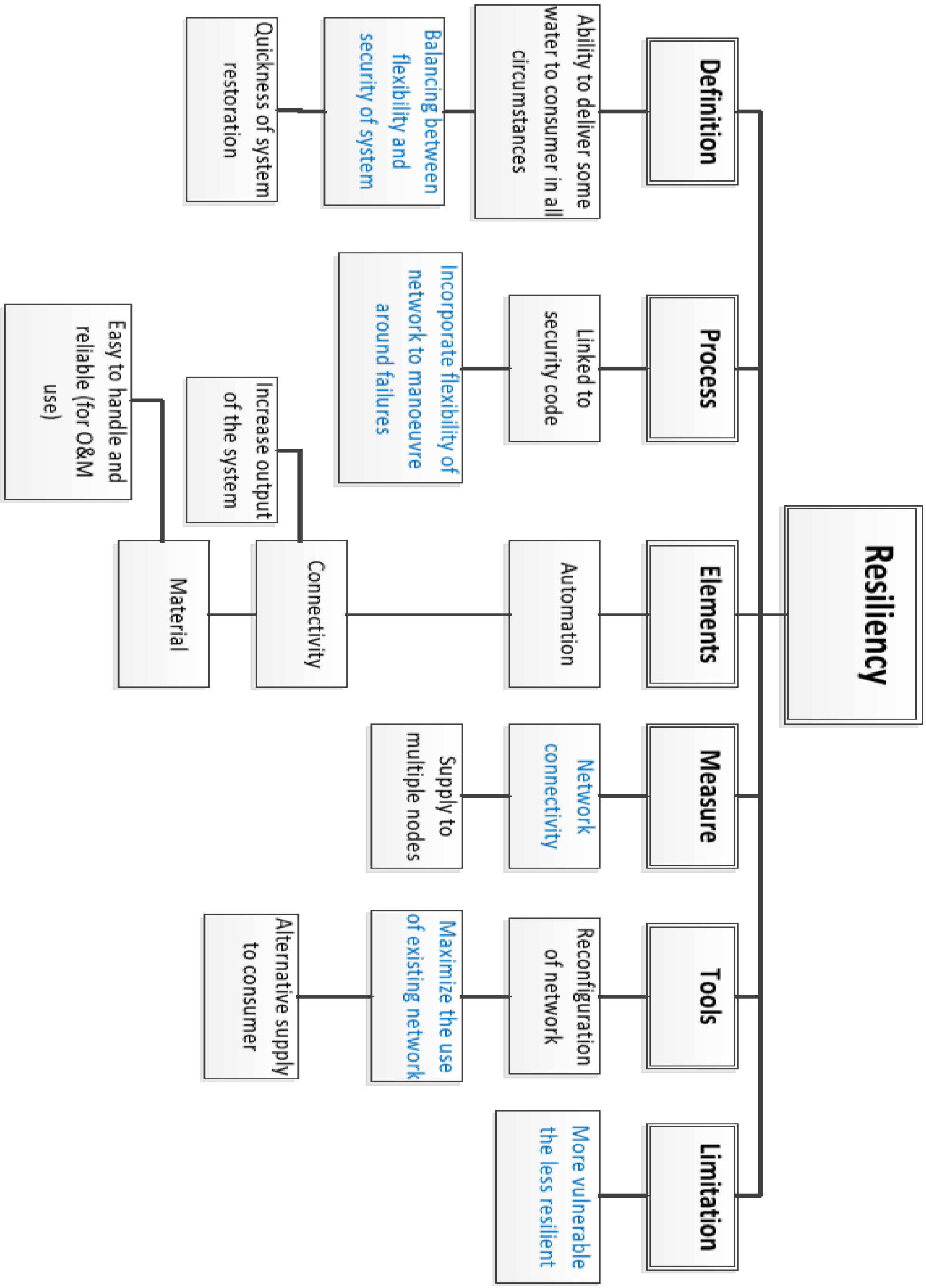


Figure G-1 Summary of interview responses on resiliency

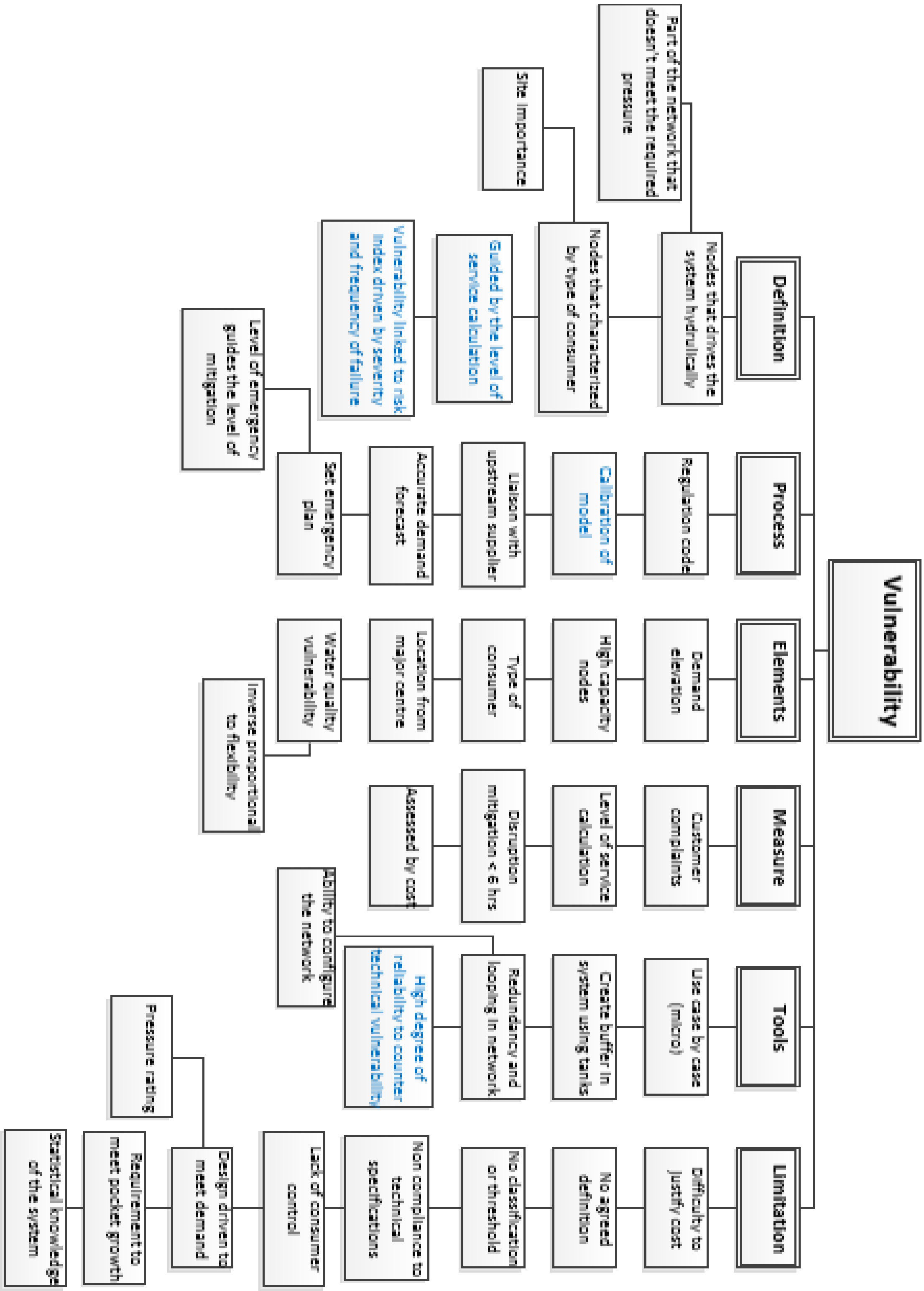


Figure G-2 Summary of interview responses on Vulnerability

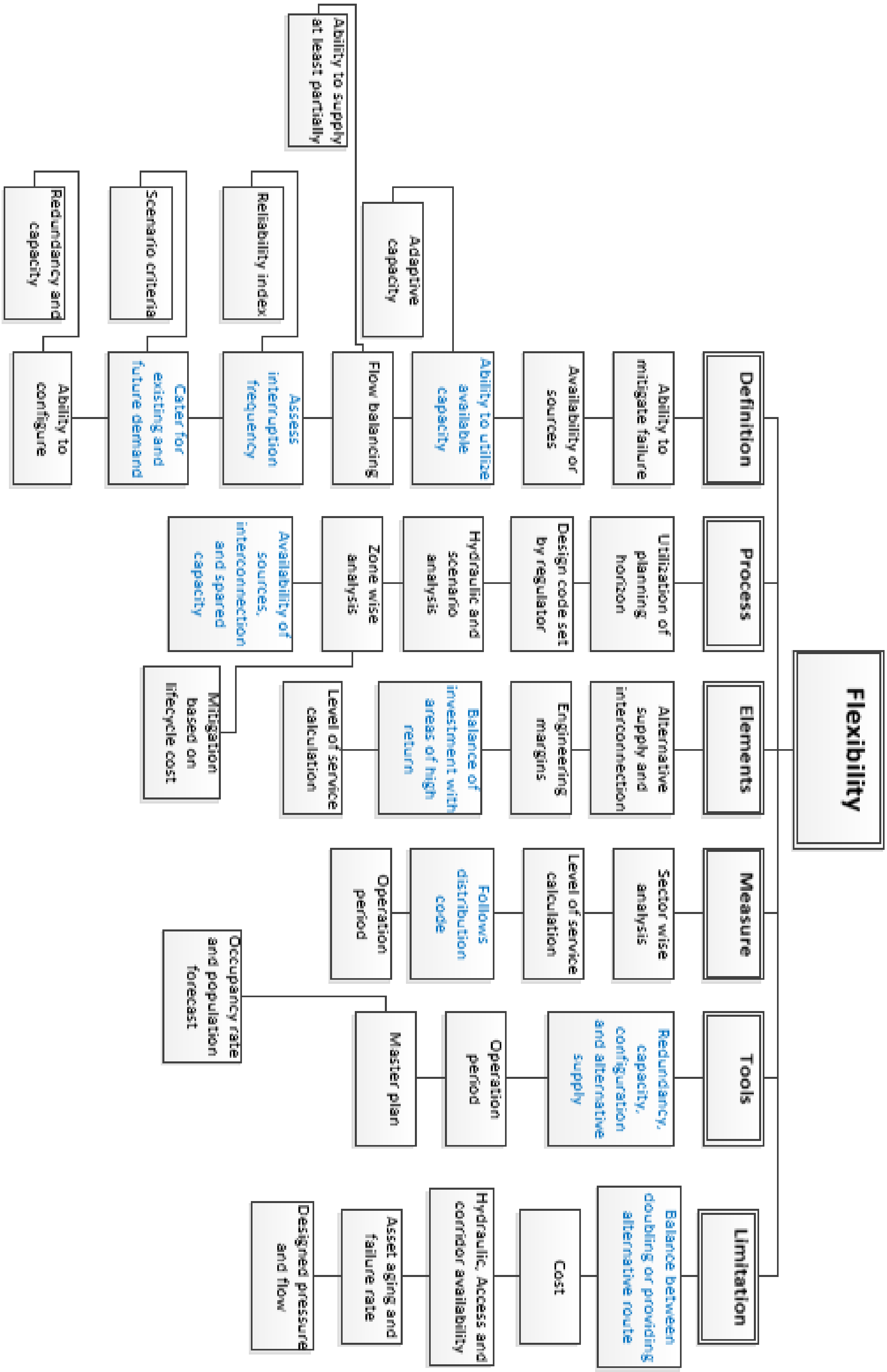


Figure G-3 Summary of interview responses on flexibility

Appendix H Files on enclosed in attached CD

Due to page size limitations and big amount of data available, an attached CD is included with this thesis to provide supplementary information and data. The information is to provide evidence of the conclusions and findings reached in this research. The below list of files and documents with brief description

File title	Description
Literature Map.xls	Mapping of the literature concepts
Anytown Extended Simu HEL and B.xls	Output of “Anytown” water network HEL and B. Output is for the Extended Period simulation
anytownVulCalc1.xls	Output of “Anytown” water network Vulnerability. Output is for the Extended Period simulation
AUH_HEL.xls	Extended Period simulation output of “Abu Dhabi” real case water network HEL.
AUH_PATH.xls	Extended Period simulation output of “Abu Dhabi” real case water network B.
AUH_TRANS_VUL.xls	Extended Period simulation output of “Abu Dhabi” real case water network Vulnerability V
ExampHEL1.xls	Extended Period simulation output of “Transmission network” literature network Hydraulic edge load HEL.
ExampVul1.xls	Extended Period simulation output of “Transmission network” literature network Vulnerability V.
PathExamp1.xls	Extended Period simulation output of “Transmission network” literature network Hydraulic Betweenness.
TwoSource HEL B.xls	Output of “TwoSource” literature network Hydraulic edge load HEL and Hydraulic Betweenness. Output is only for single time step
Anytown3.inp	EPANET input file for network of “anytown”
Examp.inp	EPANET input file for network of “Transmission network”
TwoSource.inp	EPANET input file for network of “TwoSource”

Appendix I Computer Program (Python)

This program is to calculate Hydraulic edge load of each edge. The program name is CalcHEL11.py

```
#!/usr/bin/env python

import os
import sys
from epanettools import epanet2 as et

#==============================unit
conversion=====================================

GVALUE = 13.2142#3.666 # 13.19815 convert lps to gpm for SI units
# convert from Imperial units use 1
# this value to convert from lps*kpa to hp type 0.0003047
# for psi*gpm type .000583431
#======================================================================
============
PI = 3.141592654 #the value of PI
#======================================================================
============
diac = 1000 # to convert dia dimension mm to m type 1000
# for network with dia inch type 12
#======================================================================
============
head_convert = 1.4223 # 1.4223 from m to psi
# 0.434 from ft to psi
# network in SI units type 9.83
# for imperial units type 0.4335
#======================================================================
============
max_convert = 13198.15 # 18771.7287 convert to hp from SI units
# 373.73 to convert to GPM for max power calc
# to convert m/s in Pmax calculation type 1000
# to convert fps in calculation type 448.8312
#======================================================================
============
pressure_convert = 18.772 #18.7717287 convert SI to hp
# Use 1 if the network is imperial
# convert the pressure of unit meter to kpa type 9.83
# conversopn value for Imperial units type 1
#==========================start of
code===========================================
```

```
def read_pipe_links(filename): #This to read the end nodes of each
#link reading from input file
inpipes = False
linkdict = {} #to initiate a dictionary for links
try:
with open(filename, 'r') as f: #read network input file name
for line in f:
if line.startswith(';'):
continue
if inpipes is False:
if line.startswith('[PIPES]'):
inpipes = True
else:
continue
else:
if line.startswith('['):
break
cols = line.split()
if len(cols) < 3:
break
ident, start, end = cols[:3]
linkdict[ident] = (start, end)
except Exception as e:
print e
return linkdict
print linkdict


def main():
if len(sys.argv) < 3:
print >>sys.stderr, 'Usage: %s <inp-file> <maximum-file>' % sys.argv[0]
sys.exit(-1)

if not os.path.isfile(sys.argv[1]):
print >>sys.stderr, 'File %s not found' % sys.argv[1]
sys.exit(-1)

if not os.path.isfile(sys.argv[2]):
print >>sys.stderr, 'File %s not found' % sys.argv[2]
sys.exit(-1)

inp_file = sys.argv[1]
rpt_file = '%s.rpt' % inp_file.rsplit('.', 1)[0]
max_file = sys.argv[2]
```

```
print inp_file
ret = et.ENopen(inp_file, rpt_file, '')
if ret != 0:
print >>sys.stderr, 'Failed to open File %s' % inp_file
sys.exit(-1)

# read maximum file
vp_max = {}
with open(max_file, 'r') as f:
for line in f:
if line.startswith(';'):
continue

cols = line.split()
if len(cols) < 3:
break
linkid, velocity, pressure = cols[:3]
ret, _ = et.ENgetlinkindex(linkid)
if ret != 0:
print >>sys.stderr, ('Link %s in %s not found in %s' %
(linkid, max_file, inp_file))
sys.exit(-1)
vp_max[linkid] = (float(velocity), float(pressure))

# read pipe data
_, n_links = et.ENgetcount(et.EN_LINKCOUNT)
pipes = []
pipe_diameters2 = {}
for it in range(1, n_links + 1):
#print it
_, linktype = et.ENgetlinktype(it)
if linktype != et.EN_PIPE:
continue
_, linkid = et.ENgetlinkid(it)
if linkid not in vp_max:
print >>sys.stderr, ('Link %s in %s not found in %s' %
(linkid, inp_file, max_file))
sys.exit(-1)
pipes.append(linkid)
_, pipe_diameters2[linkid] = et.ENgetlinkvalue(it, et.EN_DIAMETER)
pipe_diameters2[linkid] = ((pipe_diameters2[linkid])/diac)** 2
pipe_links = read_pipe_links(inp_file)

timestamps = []
rates = {}
```

```
et.ENopenH()
et.ENinitH(0)
while True:
_, t = et.ENrunH()
print '======== time:%d ========' % t
timestamps.append(t)
print >>sys.stderr, '======== time:%d ========' % t
endnode = {}
startnode={}
# caculate sum of diameter square
node_sum_d2 = {}
for it in pipes:
#print it
_, linkindex = et.ENgetlinkindex(it)
_, flow = et.ENgetlinkvalue(linkindex, et.EN_FLOW)
if flow < 0:
endnode[it] = pipe_links[it][0]
startnode[it] = pipe_links[it][1]
else:
endnode[it] = pipe_links[it][1]
startnode[it] = pipe_links[it][0]

if endnode[it] not in node_sum_d2:
#print "pipe dia", pipe_diameters2[it]
#print "endnode", endnode[it]
node_sum_d2[endnode[it]] = pipe_diameters2[it]
else:
node_sum_d2[endnode[it]] += pipe_diameters2[it]
#print node_sum_d2

# caculate rate
for it in pipes:
_, linkindex = et.ENgetlinkindex(it)
_, linkid = et.ENgetlinkid(linkindex)
_, nodeindex = et.ENgetnodeindex(endnode[it])
_, startindex= et.ENgetnodeindex(startnode[it])
_, elevation = et.ENgetnodevalue(nodeindex, et.EN_ELEVATION)
elevation+=3
#print "elevation",it, elevation
elevation = elevation * head_convert
_, demand = et.ENgetnodevalue(nodeindex, et.EN_BASEDEMAND)
#print "demand",it, demand
minpower = (GVALUE * elevation * demand)/1714
#print "minpower",it, minpower
minpower *= pipe_diameters2[it] / node_sum_d2[endnode[it]]
```

```
maxpower = (max_convert * PI * vp_max[it][0] * vp_max[it][1] * (pipe_diameters2[it] /
4))/1714
#print "max Power", it, maxpower
_, flow = et.ENgetlinkvalue(linkindex, et.EN_FLOW)
flow = abs(flow)
#print "flow:",flow

_, pressure = et.ENgetnodevalue(nodeindex, et.EN_PRESSURE)
#print "pressure", pressure
actualpower = (pressure_convert * flow * pressure)/1714 #* GVALUE
#print "edge power", actualpower
rate = (actualpower - minpower) / (maxpower - minpower)
#print rate
print '%s %f' % (linkid,rate) #"HEL",linkindex, it,
if it not in rates:
rates[it] = []
rates[it].append(rate)
_, ts = et.ENnextH()
if ts <= 0:
break
et.ENcloseH()
#print rates['1']
#print rates['11']


if __name__ == '__main__':
main()
```

This program to calculate Hydraulic betweenness index of each edge

The program called “pav.py”

```
#!/usr/bin/env python

import networkx as nx
import os
import sys
from epanettools import epanet2 as et


def read_pipe_links(filename):
inpipes = False
linkdict = {}
nodepair = {}
try:
with open(filename, 'r') as f:
for line in f:
if line.startswith(';'):
continue
if inpipes is False:
if (line.startswith('[PIPES]') or
line.startswith('[VALVES]')):
inpipes = True
else:
continue
else:
if line.startswith('['):
if not (line.startswith('[PIPES]') or
line.startswith('[VALVES]')):
inpipes = False
continue
cols = line.split()
if len(cols) < 3:
break
ident, start, end = cols[:3]
linkdict[ident] = (start, end)
nodepair[(start, end)] = ident
nodepair[(end, start)] = ident
except Exception as e:
print e
return linkdict, nodepair
```

```
def read_pump_links(filename):
inpumps = False
linkdict = {}
try:
with open(filename, 'r') as f:
for line in f:
if line.startswith(';'):
continue
if inpumps is False:
if line.startswith('[PUMPS]'):
inpumps = True
else:
continue
else:
if line.startswith('['):
break
cols = line.split()
if len(cols) < 3:
break
ident, start, end = cols[:3]
linkdict[ident] = (start, end)
except Exception as e:
print e
return linkdict


def main():
if len(sys.argv) < 2:
print >>sys.stderr, 'Usage: %s <inp-file>' % sys.argv[0]
sys.exit(-1)

if not os.path.isfile(sys.argv[1]):
print >>sys.stderr, 'File %s not found' % sys.argv[1]
sys.exit(-1)

inp_file = sys.argv[1]
rpt_file = '%s.rpt' % inp_file.rsplit('.', 1)[0]

ret = et.ENopen(inp_file, rpt_file, '')
if ret != 0:
print >>sys.stderr, 'Failed to open File %s' % inp_file
sys.exit(-1)

# read pipe data
```

```
pipe_links, node_pairs = read_pipe_links(inp_file)
pump_links = read_pump_links(inp_file)

timestamps = []
et.ENopenH()
et.ENinitH(0)
while True:
_, t = et.ENrunH()
print '======== time: %d ========' % t
timestamps.append(t)
print >>sys.stderr, '======== time: %d ========' % t
sources = []

# make a graph
graph = nx.DiGraph()
_, n_links = et.ENgetcount(et.EN_LINKCOUNT)
for it in range(1, n_links + 1):
_, linktype = et.ENgetlinktype(it)
if linktype not in [et.EN_PIPE, et.EN_PUMP, et.EN_FCV, et.EN_GPV,
et.EN_PBV, et.EN_PRV, et.EN_PSV, et.EN_TCV]:
continue
_, linkid = et.ENgetlinkid(it)
_, flow = et.ENgetlinkvalue(it, et.EN_FLOW)
if linktype in [et.EN_PIPE, et.EN_FCV, et.EN_GPV, et.EN_PBV,
et.EN_PRV, et.EN_PSV, et.EN_TCV]:
if flow < 0:
graph.add_edge(*pipe_links[linkid])
else:
graph.add_edge(*pipe_links[linkid])
else:
if flow < 0:
endnode = pump_links[linkid][0]
else:
endnode = pump_links[linkid][1]
if endnode not in sources:
sources.append(endnode)
demand_id = []
_, n_nodes = et.ENgetcount(et.EN_NODECOUNT)
for it in range(1, n_nodes + 1):
_, nodeid = et.ENgetnodeid(it)
_, demand = et.ENgetnodevalue(it, et.EN_DEMAND)
if demand < 0 and nodeid not in sources:
sources.append(nodeid)
if demand > 0:
demand_id.append(nodeid)
```

```
all_paths = []
for s in sources:
for n in demand_id:
try:
targets = nx.all_simple_paths(graph, s, n)
except:
continue
#targets = targets.keys()
#targets.remove(s)
# for t in targets:
all_paths.extend(targets)

filtered_paths = []
for path in all_paths:
# _, headloss = et.ENgetlinkvalue(it, et.EN_HEADLOSS)
# print s, head
_, nodeindex = et.ENgetnodeindex(path[0])
_, head = et.ENgetnodevalue(nodeindex, et.EN_HEAD)
pipelinks = ([node_pairs[it] for it in zip(path[:-1], path[1:])])
headlosses = []
for pipe in pipelinks:
_, linkindex = et.ENgetlinkindex(pipe)
_, headloss = et.ENgetlinkvalue(linkindex, et.EN_HEADLOSS)
headlosses.append(headloss)
if head >= sum(headlosses):
filtered_paths.append(path)
print len(filtered_paths)

# for path in filtered_paths:
# print '%s to %s' % (path[0], path[-1])
# for i in range(len(path)):
# print path[i],
# if i != len(path) - 1:
# print '-%s->' % node_pairs[(path[i], path[i+1])],
# print

link_count = {}
for path in filtered_paths:
pipelinks = ([node_pairs[it] for it in zip(path[:-1], path[1:])])
for pipe in pipelinks:
link_count[pipe] = link_count.get(pipe, 0) + 1
for k, v in link_count.items():
print k, v * 1.0 / len(filtered_paths)
```

```
_, ts = et.ENnextH()
break
if ts <= 0:
break
et.ENcloseH()


if __name__ == '__main__':
main()
```

The following program calculates vulnerability metric for nodes in water network. The program called “vavs.py”

```
#!/usr/bin/env python


import networkx as nx
import os
import sys
from epanettools import epanet2 as et

#==============================unit
conversion=====================================

GVALUE = 1 # 13.19815 convert lps to gpm for SI units
# convert from Imperial units use 1
# this value to convert from lps*kpa to hp type 0.0003047
# for psi*gpm type .000583431
#============================================================================
=============
PI = 3.141592654 #the value of PI
#============================================================================
=============
diac = 12 # to convert dia dimension mm to m type 1000
# for network with dia inch type 12
#============================================================================
=============
head_convert = .434 # 1.4223 from m to psi
# 0.434 from ft to psi
# network in SI units type 9.83
# for imperial units type 0.4335
#============================================================================
=============
max_convert = 373.73 # 13198.15 convert from m3/s to gpm
# 373.73 ft3/s to convert to GPM for max power calc
# to convert m/s in Pmax calculation type 1000
# to convert fps in calculation type 448.8312
#============================================================================
=============
pressure_convert = 1 #18.7717287 convert SI to hp
# Use 1 if the network is imperial
# convert the pressure of unit meter to kpa type 9.83
# conversopn value for Imperial units type 1
#============================start of
code==============================================
```

```
ZERO_HEADLOSS_THRESHOLD = 0.0
source_convert = 1 # 1 for imperial network to convert pressure of psi to psi
# 1.4223 to convert SI network from meter pressure to psi


def read_pipe_links(filename):
inpipes = False
linkdict = {}
nodepair = {}
try:
with open(filename, 'r') as f:
for line in f:
if line.startswith(';'):
continue
if inpipes is False:
if (line.startswith('[PIPES]') or
line.startswith('[VALVES]')):
inpipes = True
else:
continue
else:
if line.startswith('['):
if not (line.startswith('[PIPES]') or
line.startswith('[VALVES]')):
inpipes = False
continue
cols = line.split()
if len(cols) < 3:
continue
ident, start, end = cols[:3]
linkdict[ident] = (start, end)
nodepair[(start, end)] = ident
nodepair[(end, start)] = ident
except Exception as e:
print e
return linkdict, nodepair


def read_pump_links(filename):
inpumps = False
linkdict = {}
try:
with open(filename, 'r') as f:
for line in f:
if line.startswith(';'):
```

```
continue
if inpumps is False:
if line.startswith('[PUMPS]'):
inpumps = True
else:
continue
else:
if line.startswith('['):
break
cols = line.split()
if len(cols) < 3:
break
ident, start, end = cols[:3]
linkdict[ident] = (start, end)
except Exception as e:
print e
return linkdict


def main():
if len(sys.argv) < 3:
print >>sys.stderr, 'Usage: %s <inp-file> <maximum-file>' % sys.argv[0]
sys.exit(-1)

if not os.path.isfile(sys.argv[1]):
print >>sys.stderr, 'File %s not found' % sys.argv[1]
sys.exit(-1)

if not os.path.isfile(sys.argv[2]):
print >>sys.stderr, 'File %s not found' % sys.argv[2]
sys.exit(-1)

inp_file = sys.argv[1]
rpt_file = '%s.rpt' % inp_file.rsplit('.', 1)[0]
max_file = sys.argv[2]

ret = et.ENopen(inp_file, rpt_file, '')
if ret != 0:
print >>sys.stderr, 'Failed to open File %s' % inp_file
sys.exit(-1)

# read maximum file
vp_max = {}
with open(max_file, 'r') as f:
for line in f:
```

```
if line.startswith(';'):
continue

cols = line.split()
if len(cols) < 3:
break
linkid, velocity, pressure = cols[:3]
ret, _ = et.ENgetlinkindex(linkid)
if ret != 0:
print >>sys.stderr, ('Link %s in %s not found in %s' %
(linkid, max_file, inp_file))
sys.exit(-1)
vp_max[linkid] = (float(velocity), float(pressure))

# read pipe data
_, n_links = et.ENgetcount(et.EN_LINKCOUNT)
pipes = []
pipe_diameters2 = {}
for it in range(1, n_links + 1):
_, linktype = et.ENgetlinktype(it)
if linktype not in [et.EN_PIPE, et.EN_FCV, et.EN_GPV, et.EN_PBV,
et.EN_PRV, et.EN_PSV, et.EN_TCV]:
continue
_, linkid = et.ENgetlinkid(it)
if linkid not in vp_max:
print >>sys.stderr, ('Link %s in %s not found in %s' %
(linkid, inp_file, max_file))
sys.exit(-1)
pipes.append(linkid)
_, pipe_diameters2[linkid] = et.ENgetlinkvalue(it, et.EN_DIAMETER)
pipe_diameters2[linkid]=(pipe_diameters2[linkid]/diac)**2

pipe_links, node_pairs = read_pipe_links(inp_file)
pump_links = read_pump_links(inp_file)

timestamps = []
rates = {}
et.ENopenH()
et.ENinitH(0)
while True:
_, t = et.ENrunH()
print '======== time: %d ========' % t
timestamps.append(t)
print >>sys.stderr, '======== time: %d ========' % t
```

```
endnode = {}
sources = []
source_pressure = {}
total_source_power = 0
total_supply={}
total_flow = {}
heads = {}

# make a graph
graph = nx.DiGraph()
_, n_links = et.ENgetcount(et.EN_LINKCOUNT)
for it in range(1, n_links + 1):
_, linktype = et.ENgetlinktype(it)
if linktype not in [et.EN_PIPE, et.EN_PUMP, et.EN_FCV, et.EN_GPV,
et.EN_PBV, et.EN_PRV, et.EN_PSV, et.EN_TCV]:
continue
_, linkid = et.ENgetlinkid(it)
_, flow = et.ENgetlinkvalue(it, et.EN_FLOW)
if linktype in [et.EN_PIPE, et.EN_FCV, et.EN_GPV, et.EN_PBV,
et.EN_PRV, et.EN_PSV, et.EN_TCV]:
if flow < 0:
graph.add_edge(*pipe_links[linkid][::-1])
startnode = pipe_links[linkid][1]
enode = pipe_links[linkid][0]
else:
graph.add_edge(*pipe_links[linkid])
startnode = pipe_links[linkid][0]
enode = pipe_links[linkid][1]
if enode not in total_flow:
total_flow[enode] = 0
total_flow[enode] = abs(flow)*GVALUE #gpm
_, nodeid = et.ENgetnodeindex(startnode)
_, demand = et.ENgetnodevalue(nodeid, et.EN_DEMAND)
if demand < 0:
_, head = et.ENgetnodevalue(nodeid, et.EN_HEAD)
_, pressure = et.ENgetnodevalue(nodeid, et.EN_PRESSURE)
if enode not in total_supply:
total_supply[enode] = 0
total_supply[enode] += abs(flow)*GVALUE #gpm
#print "total flow", enode, total_supply
heads[startnode] = head
total_source_power += abs(flow) * pressure * source_convert
source_pressure[startnode] = pressure
else:
if flow < 0:
```

```
end_node = pump_links[linkid][1]
else:
end_node = pump_links[linkid][1]
if end_node not in sources:
sources.append(end_node)
_, nodeid = et.ENgetnodeindex(end_node)
_, head = et.ENgetnodevalue(nodeid, et.EN_HEAD)
_, pressure = et.ENgetnodevalue(nodeid, et.EN_PRESSURE)
heads[end_node] = head
total_source_power += abs(flow) * pressure * source_convert
#print "total_source_power", total_source_power
source_pressure[end_node] = pressure


_, n_nodes = et.ENgetcount(et.EN_NODECOUNT)
for it in range(1, n_nodes + 1):
_, nodeid = et.ENgetnodeid(it)
_, demand = et.ENgetnodevalue(it, et.EN_DEMAND)
#_, base_demand = et.ENgetnodevalue(it, et.EN_BASEDEMAND)
if demand < 0 and nodeid not in sources:
sources.append(nodeid)

all_paths = []
for s in sources:
try:
targets = nx.single_source_shortest_path_length(graph, s)
except:
continue
targets = targets.keys()
targets.remove(s)
for t in targets:
all_paths.extend(nx.all_simple_paths(graph, s, t))
filtered_paths = []
for path in all_paths:
#_, headloss = et.ENgetlinkvalue(it, et.EN_HEADLOSS)#
#print s, head#
_, nodeindex = et.ENgetnodeindex(path[0])
head = heads[path[0]]
pipelinks = ([node_pairs[it] for it in zip(path[:-1], path[1:])])
#print pipelinks
flows = []
headlosses = []
zero_headloss = False
for pipe in pipelinks:
_, linkindex = et.ENgetlinkindex(pipe)
```

```
_, flow = et.ENgetlinkvalue(linkindex, et.EN_FLOW)
_, headloss = et.ENgetlinkvalue(linkindex, et.EN_HEADLOSS)
#print "headloss", pipe,headloss
if headloss < ZERO_HEADLOSS_THRESHOLD:
zero_headloss = True
break
flows.append(flow)
headlosses.append(headloss)
if zero_headloss:
continue
if head >= sum(headlosses):
filtered_paths.append((path, sum(flows), sum(headlosses)))

# caculate sum of diameter square
node_sum_d2 = {}
for it in pipes:
_, linkindex = et.ENgetlinkindex(it)
_, flow = et.ENgetlinkvalue(linkindex, et.EN_FLOW)
if flow < 0:
endnode[it] = pipe_links[it][0]
else:
endnode[it] = pipe_links[it][1]
if endnode[it] not in node_sum_d2:
node_sum_d2[endnode[it]] = pipe_diameters2[it]
else:
node_sum_d2[endnode[it]] += pipe_diameters2[it]

hel = {}
nel = {}
rc = {}
# caculate rate
for it in pipes:
_, linkindex = et.ENgetlinkindex(it)
_, nodeindex = et.ENgetnodeindex(endnode[it])
_, elevation = et.ENgetnodevalue(nodeindex, et.EN_ELEVATION)
elevation+=3
elevation = elevation * head_convert
_, demand = et.ENgetnodevalue(nodeindex, et.EN_BASEDEMAND)
minpower = (GVALUE * elevation * demand)/1714
minpower *= pipe_diameters2[it] / node_sum_d2[endnode[it]]
#print it, minpower

maxpower = (head_convert*max_convert * PI * vp_max[it][0] * vp_max[it][1] *
(pipe_diameters2[it] / 4))/1714
```

```
_, flow = et.ENgetlinkvalue(linkindex, et.EN_FLOW)
flow = abs(flow)
_, pressure = et.ENgetnodevalue(nodeindex, et.EN_PRESSURE)
#print pressure
actualpower = (pressure_convert*flow * pressure)/1714
rate = (actualpower - minpower) / (maxpower - minpower)
hel[it] = rate
#print maxpower
#print actualpower
if total_source_power == 0:
rc[it] = 0
else:
#print "actualpower", actualpower
#print "total_source_power", total_source_power
##################################################
rc[it]= (maxpower - actualpower)/total_source_power
#nel[it] = actualpower / total_source_power
if actualpower>maxpower:
rc[it]=0
#print "nel:", it, nel
#if hel[it] == 0:
# rc[it] = 0
#elif hel[it] > 1:
# rc[it] = 0
#elif hel[it] < 0:
# rc[it] = 1
#else:
# rc[it] = (maxpower - actualpower)/total_source_power
#rc[it] = (1 - hel[it]) #* nel[it] / hel[it]
#print "rc: ", rc
# HEL = rate
# NEL = actual-power/source-total-power
# remaining capacity = (1 - HEL) * NEL / HEL
# find min of RC on each path
if it not in rates:
rates[it] = []
rates[it].append(rate)
for it in range(len(filtered_paths)):
path = filtered_paths[it][0]
min_rc = rc[node_pairs[(path[0], path[1])]]
#print "min_rc: ",min_rc
for i in range(1, len(path)):
if i == len(path) - 1:
break
min_rc = min(min_rc, rc[node_pairs[(path[i], path[i+1])]])
```

```
filtered_paths[it] = tuple(list(filtered_paths[it]) + [min_rc])
#print "filtered_paths", filtered_paths
# for path, _, _, min_rc in filtered_paths:
# print '%s to %s' % (path[0], path[-1])
# for i in range(len(path)):
# print path[i],
# if i != len(path) - 1:
# print '-%s->' % node_pairs[(path[i], path[i+1])],
# print
# print 'Min RC: %f' % min_rc
#print 'Vul:'
_, n_nodes = et.ENgetcount(et.EN_NODECOUNT)
for it in range(1, n_nodes + 1):
_, nodeid = et.ENgetnodeid(it)
if nodeid in sources:
continue
_, pressure = et.ENgetnodevalue(it, et.EN_PRESSURE)

max_source_pressure = 0
sum_min_rc = 0
headlosses_to_node = []
for path, _, headlosses, min_rc in filtered_paths:
if path[-1] != nodeid:
continue
#print "max source pressure, source pressure of path[0]", max_source_pressure,
source_pressure[path[0]]
max_source_pressure = source_pressure[path[0]]
#print "max pressure used in calc of vul", max_source_pressure
sum_min_rc += min_rc
headlosses_to_node.append(headlosses)

if not headlosses_to_node:
metric = 0
elif any([it == 0 for it in headlosses_to_node]):
metric = 0
else:
min_headlosses = min(headlosses_to_node)
metric = sum([min_headlosses / it
for it in headlosses_to_node])
#print "metric: ",metric

#for it in headlosses_to_node:
#print "headlosses_to_node", type(max_source_pressure)
if not headlosses_to_node:
vul = 0
```

```
else:
vul =
head_convert*(sum(headlosses_to_node)/len(headlosses_to_node))#max_source_pre
ssure - pressure
#print max_source_pressure
if sum(total_supply.values()) == 0:
vul = 0
#print "vul",vul
#print "min_rc", sum_min_rc
#print "headloss vul value: ", vul
getflow = total_flow.get(nodeid, 0)
#print "total flow: ", getflow
try:
vul *= total_flow.get(nodeid, 0) / (1 + sum_min_rc)**metric
except:
continue
#print "after multi flow", vul
#print "total source supply: ", sum(total_supply.values())
#print "max_source_pressure: ", max_source_pressure
#print total_supply, max_source_pressure, vul
if max_source_pressure == 0:
vul = 0
else:
vul /= sum(total_supply.values())*max_source_pressure#total_source_power
#print vul

#print vul
#vul *= metric
#print "max_source_pressure - pressure", max_source_pressure, pressure
#print "total_flow", total_flow
print '%s %f %f %f %f %f ' % (nodeid, vul, getflow, sum_min_rc, metric,
max_source_pressure)
# if A->B->C and A->D->C
# then the min between A->C will be
# min(A->B, B->C) + min(A->D, D->C)
# vul = ((max source pressure - node pressure) * total flow to node) / (1 + RC)
_, ts = et.ENnextH()
#break
if ts <= 0:
break
et.ENcloseH()


if __name__ == '__main__':
main()
```

Appendix J Output graphs using the new conceptual framework

This appendix shows different graphs produced for Transmission network (Pathirana 2006) used and real case of Abu Dhabi network from the program.

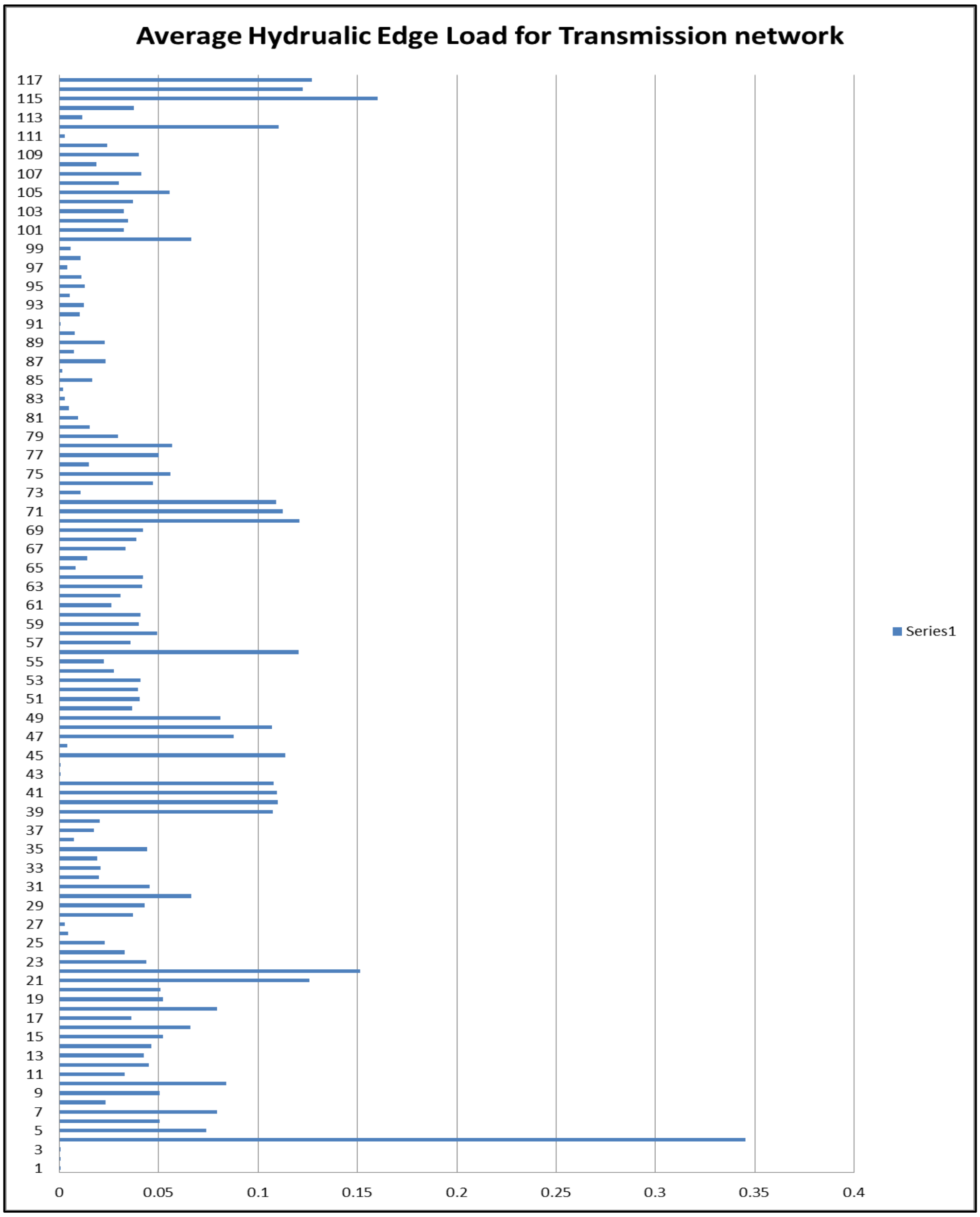


Figure 8-3: Average Hydraulic edge load for edges in literature Transmission network with Y-axis as edge ID and X-axis L(e)

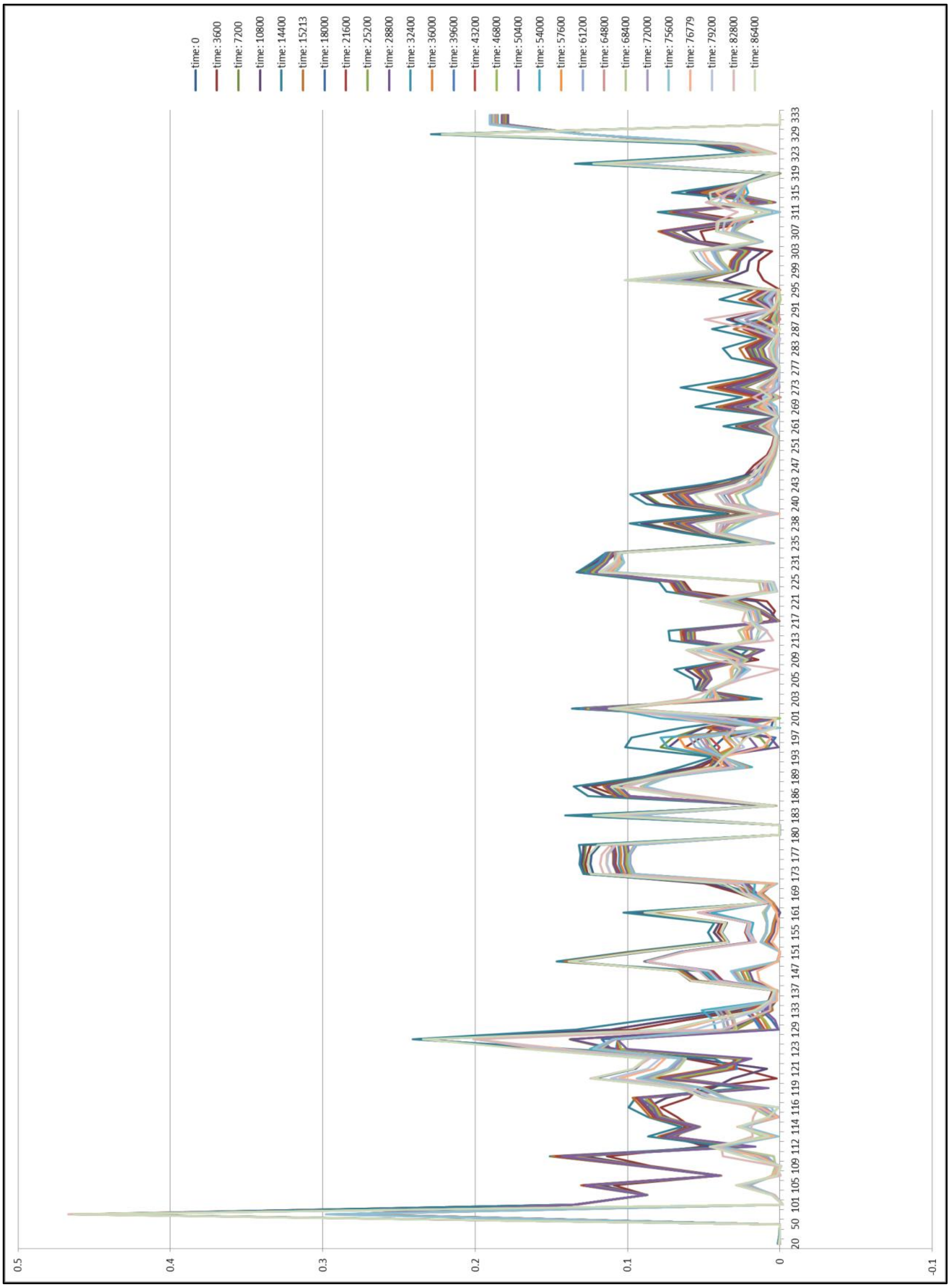


Figure 8-4: Hydraulic Edge Load for extended simulation of Transmission network example for all-time series

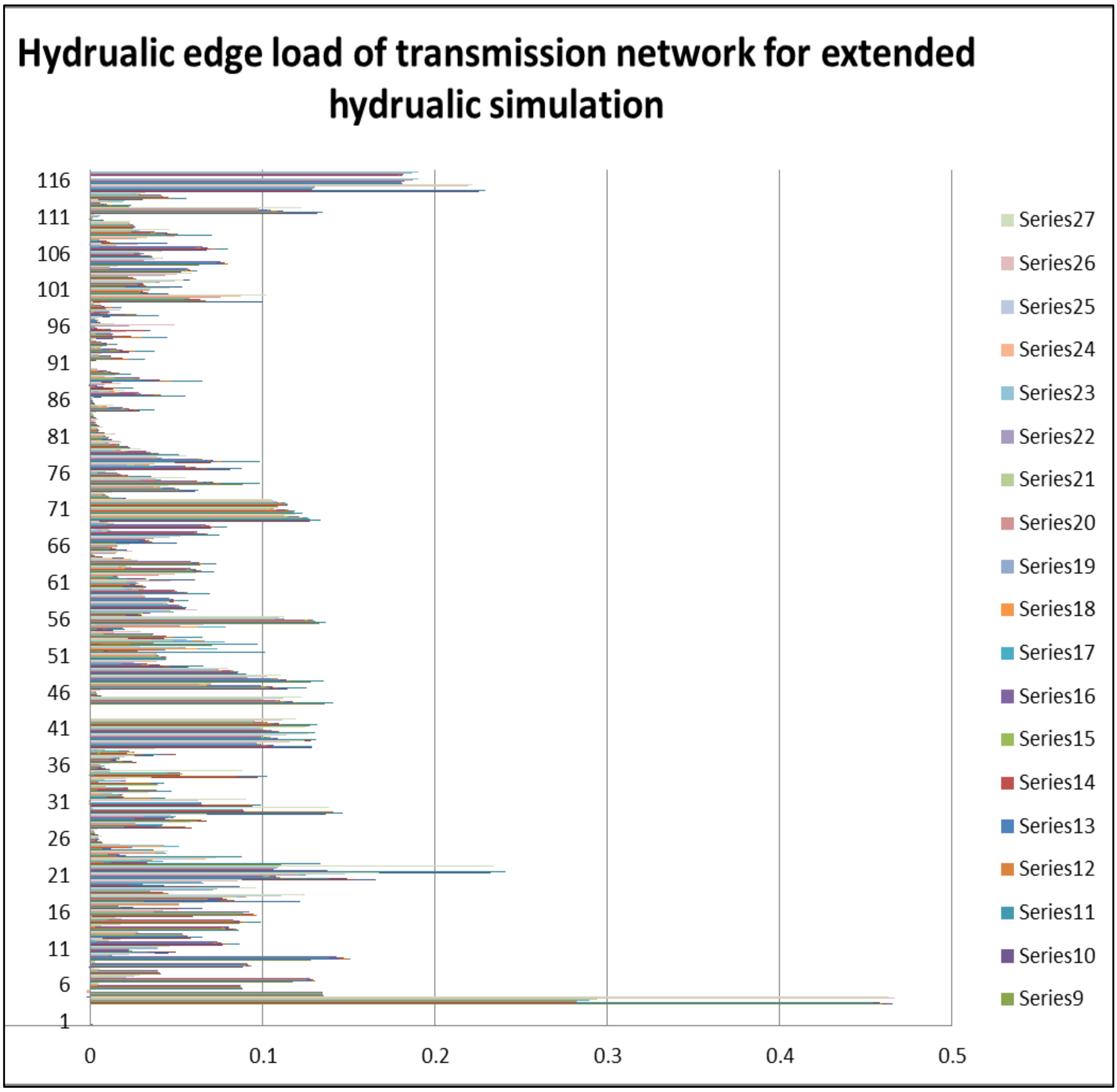


Figure 8-5: Hydraulic edge load for all edges of the network in extended hydraulic simulation

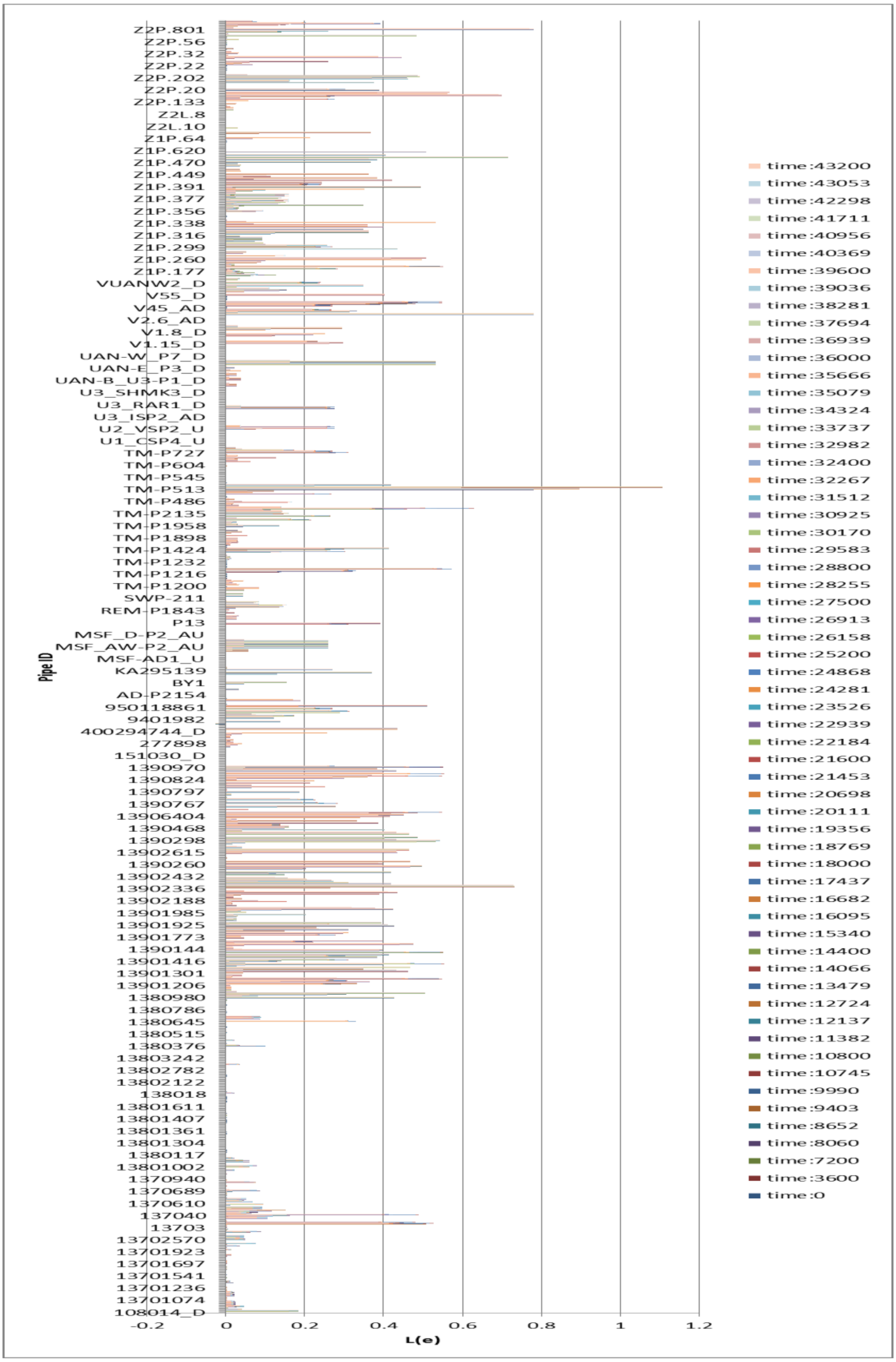


Figure J-1 Hydraulic edge load of Abu Dhabi network for all time steps

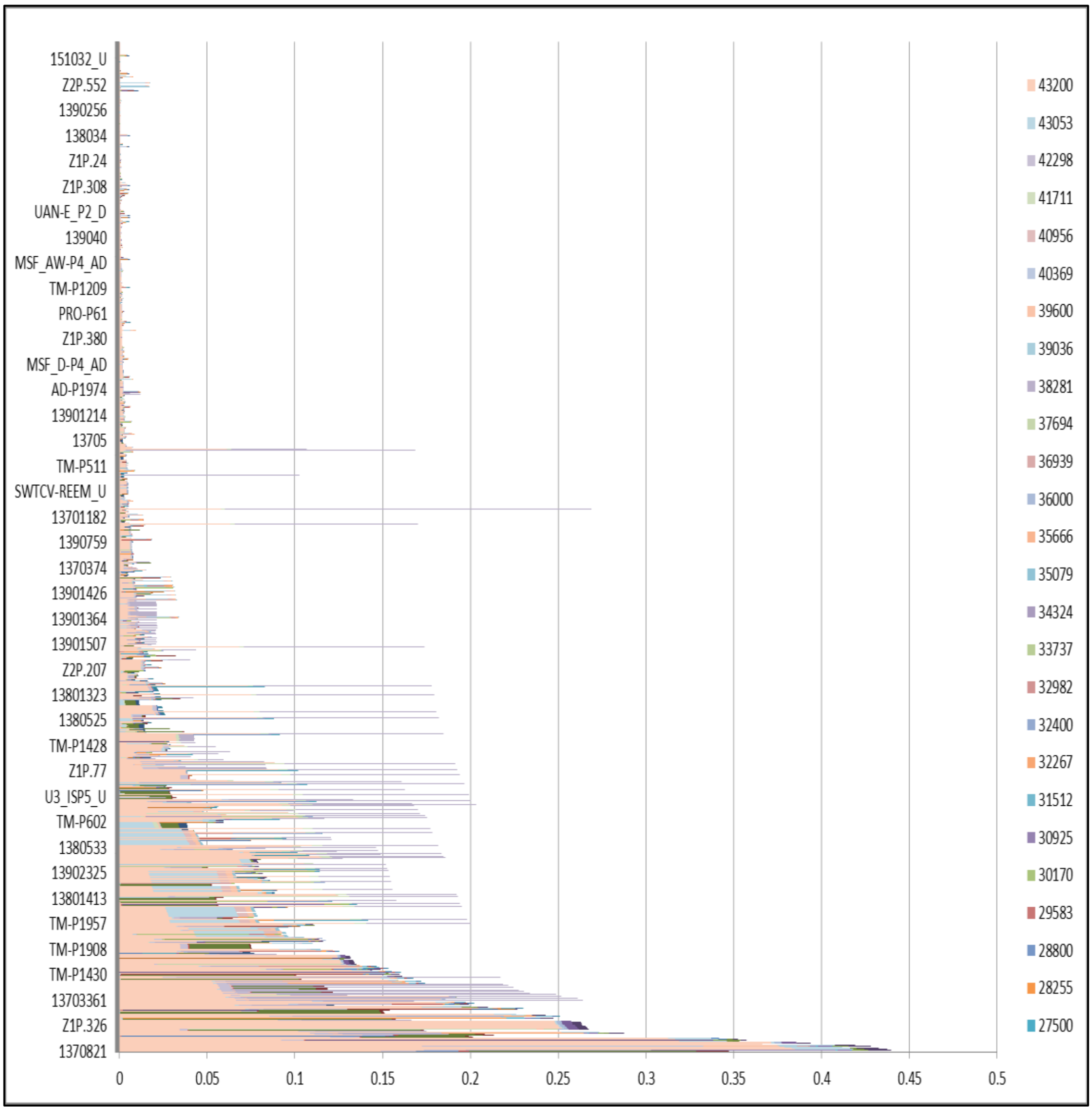


Figure J-2 Hydraulic betweenness for all nodes in Abu Dhabi Transmission network depicting all scores during the extended simulation

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