Investigating Multidimensional Factors Affecting Water Supply Resilience to Disasters

Behrooz Balaei Langroudi

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Civil and Environmental Engineering

Field of Disaster Management

Supervised by:

Professor Suzanne Wilkinson
and
Professor Regan Potangaroa

Department of Civil and Environmental Engineering
The University of Auckland
New Zealand

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ABSTRACT

The supply of water following disasters has always been of significant concern to communities. Failure of water systems not only causes difficulties for residents and critical users but may also affect other hard and soft infrastructure and services. The dependency of communities and other infrastructure on the availability of safe and reliable water places even more emphasis on the resilience of water supply systems.

This thesis makes two major contributions. First, it proposes a framework for measuring the multifaceted resilience of water systems, focusing on the significance of the characteristics of different communities for the resilience of water supply systems. The proposed framework, known as the CARE framework, consists of eight principal activities: (1) developing a conceptual framework; (2) selecting appropriate indicators; (3) refining the indicators based on data availability; (4) correlation analysis; (5) scaling the indicators; (6) weighting the variables; (7) measuring the indicators; and (8) aggregating the indicators. This framework allows researchers to develop appropriate indicators in each dimension of resilience (i.e., technical, organisational, social, and economic), and enables decision makers to more easily participate in the process and follow the procedure for composite indicator development.

Second, it identifies the significant technical, social, organisational and economic factors, and the relevant indicators for measuring these factors. The factors and indicators were gathered through a comprehensive literature review. They were then verified and ranked through a series of interviews with water supply and resilience specialists, social scientists and economists. Vulnerability, redundancy and criticality were identified as the most significant technical factors affecting water supply system robustness, and consequently resilience. These factors were tested for a scenario earthquake of Mw 7.6 in Pukerua Bay in New Zealand.

Four social factors and seven indicators were identified in this study. The social factors are individual demands and capacities, individual involvement in the community, violence level in the community, and trust. The indicators are the Giving Index, homicide rate, assault rate, inverse trust in army, inverse trust in police, mean years of school, and perception of crime. These indicators were tested in Chile and New Zealand, which experienced earthquakes in 2010 and 2011 respectively. The social factors were also tested in Vanuatu following TC Pam, which hit the country in March 2015.

Interestingly, the organisational dimension contributed the largest number of factors and indicators for measuring water supply resilience to disasters. The study identified six organisational factors and 17 indicators that can affect water supply resilience to disasters. The factors are: disaster precaution; pre-disaster planning; data availability, data accessibility and information sharing; staff, parts, and equipment availability; pre-disaster maintenance; and governance. The identified factors and their indicators were tested for the case of Christchurch, New Zealand, to understand how organisational capacity affected water supply resilience following the earthquake in February 2011. Governance and availability of critical staff following the earthquake were the strongest organisational factors for the Christchurch City Council, while the lack of early warning systems and emergency response planning were identified as areas that needed to be addressed.

Economic capacity and quick access to finance were found to be the main economic factors influencing the resilience of water systems. Quick access to finance is most important in the early stages following a disaster for response and restoration, but its importance declines over time. In contrast, the economic capacity of the disaster struck area and the water sector play a vital role in the subsequent reconstruction phase rather than in the response and restoration period. Indicators for these factors were tested for the case of the February 2011 earthquake in Christchurch, New Zealand.

Finally, a new approach to measuring water supply resilience is proposed. This approach measures the resilience of the water supply system based on actual water demand following an earthquake. The demand-based method calculates resilience based on the difference between water demand and system capacity by measuring actual water shortage (i.e., the difference between water availability and demand) following an earthquake.

DEDICATION

To Maryam, the most amazing woman I have ever met in my entire life, for her constant support,

and to our daughter, Taraneh Aroha, who signifies a love song for us.

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When I was starting my PhD, I could not have imagined how it was going to change my life. This journey has been much more than an academic journey – it has made me grow and discover myself. I would like to take this opportunity to acknowledge everyone who has been a part of this journey.

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I am also very grateful to Carole Adamson for all the discussions we have had over the last few years on the social dimension of water supply resilience, which was completely a new concept for me. Her great guidance, advice, and comments helped me to understand how social capital can affect resilience.

Undoubtedly, researchers in a variety of subjects such as infrastructure, and social, organisational, or economic resilience have had a great impact on this study. Every single article and dissertation I read taught me something new and I owe a debt to their authors. In particular, I would like to acknowledge Craig Davis and Kevin Morley, whom I had conversations with and who shared their thoughts and materials.

Special recognition goes to Philip McFarlane from WSP Opus for his wise advice, patience, kindness, and constant support through this journey. I also would like to express my respect and appreciation to my colleagues at WSP Opus, especially Robert Gordon, Warren Bird, Brabhaharan Pathmanathan, Jasmin Callosa-Tarr, Michael Campin, Aaron Patterson, Wayne Griffith, and Sue Harrison – for all that I learned from them and their assistance during my PhD, either directly or indirectly.

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GLOSSARY

ADRA	Adventist Development and Relief Agency
AWWA	American Water Works Association
BCP	Business Continuity Plan
CARE	Comprehensive Aggregated Resilience Estimation
CAT	Catastrophe
CAT DDO	Catastrophe Deferred Drawdown Option
CCC	Christchurch City Council
CCTO	Council Controlled Trade Organisations
CDEM	Civil Defence and Emergency Management
DGMWR	Department of Geology, Mines and Water Resources
DMP	Disaster Mitigation Plan
DROP	Disaster Resilience of Place
DRR	Disaster Risk Reduction
ERP	Emergency Response Plan
EWS	Early Warning System
GIS	Geographic Information System
INGO	International Non-Governmental Organisation
LAPP	Authority Protection Programme Disaster Fund
LDC	Least Developed Country
LGNZ	Local Government New Zealand
MCDEM	Ministry of Civil Defence and Emergency Management
MDC	More Developed Country
MoH	Ministry of Health

NGO	Non-Governmental Organisation
PPE	Personal Protection Equipment
RWH	Rainwater Harvesting
SCIRT	Stronger Christchurch Infrastructure Rebuild Team
SIDS	Small Island Developing States
TC	Tropical Cyclone
UNDP	United Nations Development Program
UNICEF	United Nations Children’s Fund
UNISDR	United Nations for Disaster Risk Reduction
WASH Cluster	Water, Sanitation, Hygiene
WGI	World Governance Indicator
WHO	World Health Organisation
WNS	Water Network System
WSS	Water Supply System

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The University of Auckland
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Nature of contribution by PhD candidate	Lead author, conducted study and wrote the text.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and proofreading
Regan Potangaroa	Supervision and proofreading

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- that the candidate wrote all or the majority of the text.

Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019

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NEW ZEALAND

School of Graduate Studies
AskAuckland Central
Alfred Nathan House
The University of Auckland
Tel: +64 9 373 7599 ext 81321
Email: postgradinfo@auckland.ac.nz

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Nature of contribution by PhD candidate	Lead author, conducted study and wrote the text.
Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and advice for paper structure
Regan Potangaroa	Supervision and advice for paper structure
Nemat Hassani	Advice for methodology
Maryam Alavi-Shoshtari	Advice for methodology

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- that the candidate wrote all or the majority of the text.

Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019
Nemat Hassani	N. Hassani	6/03/2019
Maryam Alavi-Shoshtari	Maryam Alavi	8/03/2019

Last updated: 28 November 2017

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Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and advice for paper structure
Regan Potangaroa	Supervision and advice for paper structure
Philip McFarlane	Advice for methodology and proofreading

Certification by Co-Authors

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- that the candidate wrote all or the majority of the text.

Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019
Philip McFarlane		15/03/2019

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School of Graduate Studies
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Alfred Nathan House
The University of Auckland
Tel: +64 9 373 7599 ext 81321
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Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and advice for paper structure
Regan Potangaroa	Supervision and advice for paper structure
Carole Adamson	Advice for paper structure and methodology
Maryam Alavi-Shoshtari	Advice for methodology

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- that the candidate wrote all or the majority of the text.

Name	Signature	Date
Suzanne Wilkinson	[signature]	2/03/2019
Regan Potangaroa	[signature]	11/03/2019
Carole Adamson	C. R. Adamson	8/03/2019
Maryam Alavi-Shoshtari	Maryam Alavi	8/03/2019

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School of Graduate Studies
AskAuckland Central
Alfred Nathan House
The University of Auckland
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CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and advice for paper structure
Regan Potangaroa	Supervision and advice for paper structure and site visit

Certification by Co-Authors

The undersigned hereby certify that:

- ❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- ❖ that the candidate wrote all or the majority of the text.

Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019

Last updated: 28 November 2017

School of Graduate Studies
AskAuckland Central
Alfred Nathan House
The University of Auckland
Tel: +64 9 373 7599 ext 81321
Email: postgradinfo@auckland.ac.nz

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CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and advice for paper structure
Regan Potangaroa	Supervision and advice for paper structure
Mostafa Baghersad	Technical support

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and
- that the candidate wrote all or the majority of the text.

Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019
Mostafa Baghersad		5/03/2019

School of Graduate Studies
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Alfred Nathan House
The University of Auckland
Tel: +64 9 373 7599 ext 81321
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CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and advice for paper structure
Regan Potangaroa	Supervision and advice for paper structure

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Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019

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Extent of contribution by PhD candidate (%)	90%

CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and proofreading
Regan Potangaroa	Supervision and proofreading

Certification by Co-Authors

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- that the candidate wrote all or the majority of the text.

Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019

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CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and proofreading
Regan Potangaroa	Supervision and proofreading

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Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019

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CO-AUTHORS

Name	Nature of Contribution
Suzanne Wilkinson	Supervision and advice for paper structure
Regan Potangaroa	Supervision and advice for paper structure
Philip McFarlane	Advice for methodology and proofreading

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Name	Signature	Date
Suzanne Wilkinson		2/03/2019
Regan Potangaroa		11/03/2019
Philip McFarlane		15/03/2019

CHAPTER 1 – INTRODUCTION

1.1. Disasters - An Overview

The number of recorded natural disasters increased dramatically in the period between 1940 and 2000, although it has since showed a significant decline in the third millennium (Ritchie & Roser, 2019). Although a part of this increase is a result of improvements in recording of events, data from different sources shows that the actual number of disasters, especially climate related disasters, has increased over time (Figure 1-1).

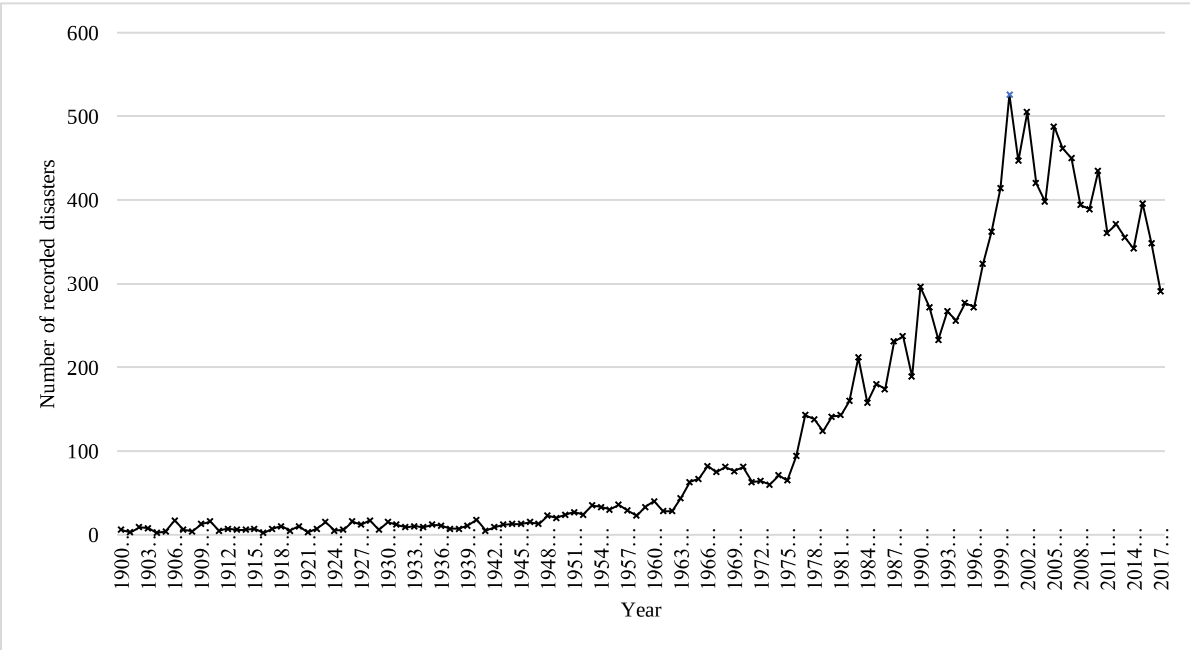

Figure 1-1: The Number of Global Reported Natural Disasters since 1900 (Ritchie & Roser, 2019)

Although making up less than 5% of disaster events, drought affected more than a billion people from 1994 to 2013. Low Developed Countries (LDCs) suffered the most despite early warning systems being in place. Flooding caused the majority of disasters over the same period, affecting approximately 2.5 billion people around the globe. Storm events, as the second most frequent disaster, killed over 244,000 people and caused US$936 billion in economic losses. Earthquakes and tsunamis, in contrast, caused the biggest death tolls, claiming about 750,000 people between 1994 and 2013 (CRED, 2015).

Despite the statistics showing a large number of people have been affected over the past 20 years, the impact of the most severe disasters on communities (e.g. the number of deaths per annum) has decreased (see Figure 1-2) as a result of a variety of factors, including increased awareness and improvements in early warning systems, preparedness and mitigation plans and measures (Alexander, 2017). International agencies have played a significant role in applying countermeasures to decrease the impact of disasters on hard and soft infrastructures. Countries have been encouraged by the United Nations to invest in mitigation and the development of early warning systems (UNISDR, 2005; UNISDR, 2015). When considering total disaster costs, around one third is spent in mitigation and preparedness and the rest is the direct and indirect economic losses imposed by disasters every year.

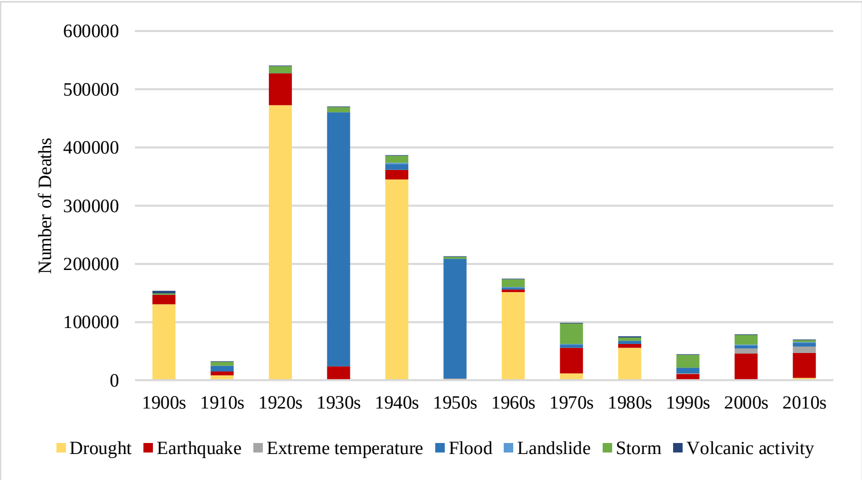

Figure 1-2: Number of Deaths from Natural Disasters by Decade (Ritchie & Roser, 2019)

Different types of disaster have contributed disproportionately to the overall number of deaths over the last decades. Drought has been responsible for slightly over half the deaths caused by external shocks (e.g. disasters) over time, while floods and earthquakes have caused 30% and

12% of deaths respectively. All other types of disaster combined have caused less than 7% of deaths. Figure 1-3 shows the number of deaths caused by disasters from 1990 to 2017.

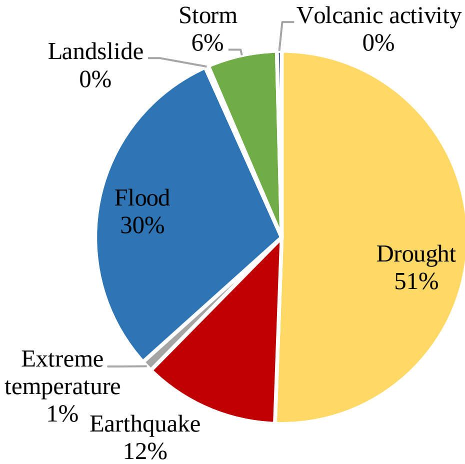

Figure 1-3: Number of Deaths Caused by Major Disasters from 1990 until 2017 (Ritchie & Roser, 2019)

However, the decrease in the number of deaths per annum has not resulted in a decrease in disaster-related economic costs (Figure 1-4). The increased number of assets being used by local authorities to provide people with a better quality of service is a major factor in increased disaster costs (Ritchie & Roser, 2019).

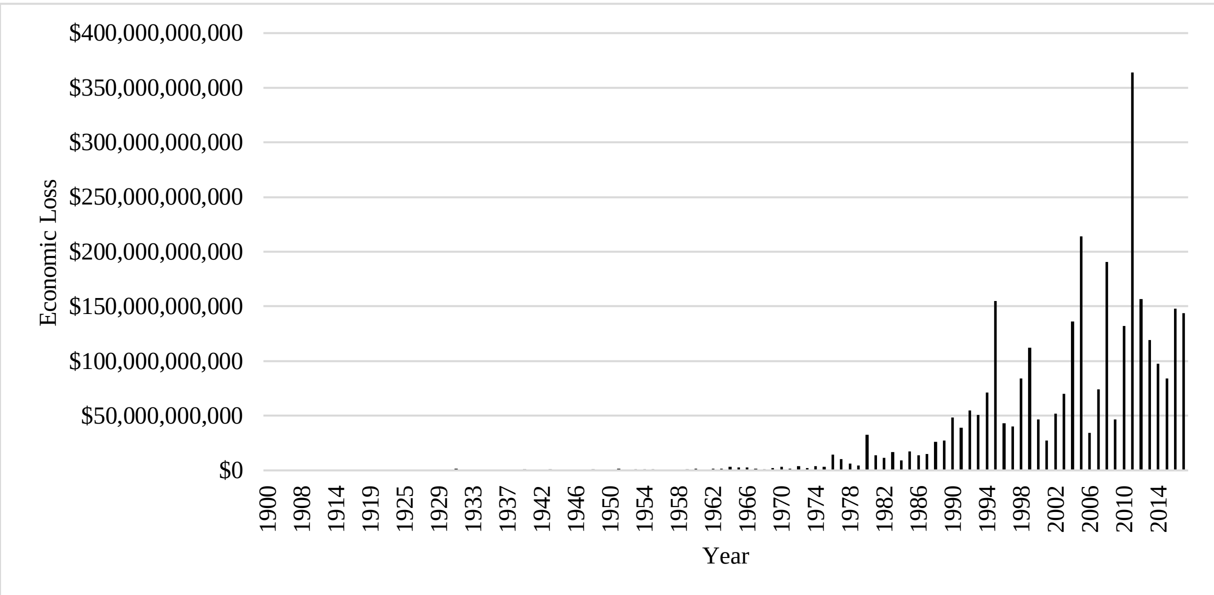

Figure 1-4. Total Economic Loss from Disasters (Ritchie & Roser, 2019)

1.2. Response to Disasters – Changing Perspectives over Time

General understanding of disasters has changed significantly over time. Natural hazards such as earthquakes and floods were once seen as “Acts of God” outside human control, and for which nobody could be held responsible. From this perspective, disasters were celestial punishment for moral misbehaviour. There was a general acceptance of disasters as external, inevitable, and uncontrolled events, however in some cases people started to avoid frequently flooded sites to minimise the impact on their lives.

Eventually, communities learned to manage some of the damaging effects of disasters by applying engineering measures. Engineering solutions to natural disasters began more than 4,000 years ago when the first river dam was constructed in the Middle East to protect property from frequent flood events. Applying mitigative measures to protect buildings against earthquake dates back over 2,000 years. Improvements in engineering and environmental science, such as earth science and weather forecasting, by the end of nineteenth century resulted in more effective structural responses to manage the adverse consequences of disasters. These developments resulted in improved short-term warning systems and long-term planning to avoid disaster-prone sites and decrease deaths and economic losses in more developed countries (MDC) in the mid- to late twentieth century.

Least developed countries (LDC) lagged behind for a number of reasons, including their lack of economic and social capacity. However, they did start increasing public awareness and building capacities to minimise the impact of disasters. By the end of twentieth century, human vulnerability had become an important notion in measuring the scale of disasters. The International Decade for Natural Disasters (IDNDR) programme, led by the United Nations in the final decade of the twentieth century, reflected global concern with controlling the impact of disasters on the rapidly growing populations of LDCs (Smith, K. & Petley, 2008).

At the same time, the interaction between different infrastructures as well as nature and society were attracting research attention. Complex interaction studies were conducted to improve long-term disaster management to address local needs and support sustainable development. The resilience paradigm was established early in the twenty-first century to address the multi-dimensionality and interdependency of soft and hard infrastructures, and the significance of community/system recovery time in managing disaster impact on societies. Table 1-1 outlines the evolution of disaster paradigms over time.

Table 1-1: The Evolution of Disaster Paradigms - Adopted from Smith and Petley (2008)

Period	Paradigm Name	Main Issue	Main Responses
Pre-1950	Engineering	What are the physical causes for magnitude and frequency of disasters? How can structures be protected against the most damaging consequences?	Scientific weather forecasting and environmental science developments helped communities to defend against disasters, especially those of hydro-meteorological origin
1950-70	Behavioural	Why do disasters create deaths and economic losses in MDCs? How can human behaviour minimise disaster risks?	Improved early warning and better long-term land use planning led to avoiding disaster-prone sites
1970-90	Development	What historical and socio-economic factors make people in LDC countries suffer severely in disasters?	Greater awareness of human vulnerability and understanding of social and economic capacities in LDCs
1990-2000	Complexity	How can disasters' adverse impacts be mitigated in a sustainable way?	More emphasis on the complex interactions between different infrastructures as well as nature and society
2000-	Resilience	What dimensions of communities affect their functionality? How does a system's functionality change over time when a disaster happens?	A more comprehensive understanding of systems' multifaceted behaviour and functionality over time when a disaster happens

1.3. Resilience

Disaster paradigm has evolved to the concept of resilience in recent decades. The notion of resilience has captured the attention of a wide range of scholars in diverse disciplines. The concept of community resilience to disasters was proposed in the 21st century (Klein et al., 2003), however it had been introduced earlier by Holling in relation to ecology (Holling, 1973).

Klein et al. (2003) explored the concept in relation to weather-related hazards as an example of natural disasters in coastal megacities, defining resilience as a desirable property of natural and human systems in the face of potential stresses. As a result of their study, Klein et al. (2003) recommended resilience be used in a "restricted sense" to describe specific system characteristics, namely: (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system's self-organisation capability. Other researchers also adapted the concept of resilience in engineering, environmental science, social science, etc. Table 1-2 outlines a number of definitions of resilience in different disciplines.

Table 1-2: Resilience Definition in Different Disciplines

Author (year)	**Subject Area**	**Definition**
Godschalk (2003)	Engineering	Sustainability of network of physical infrastructure and communities
Bruneau (2003)	Engineering-Infrastructure	The ability of an infrastructure (e.g. water, electricity, hospital, etc.) to withstand an external shock and bounce back to a normal level in a timely manner.
Wildavsky (1988)	Safety Engineering	The capacity to cope with unpredicted situations and understand how to bounce back
Home and Orr (1997)	Organisational	The ability of people, systems, and organisations as a whole to resist ‘environmental loading’
Ernstson et al. (2010)	Environmental science; Social sciences	The ability to sustain a particular dynamic regime
Campanella (2006)	Social sciences	The ability of a city to recover from destruction
Ahern (2006)	Environmental science	The ability of systems to rearrange and recover from disturbance without changing to other states
Leichenko (2011)	Environmental science; Social sciences	The capacity to withstand a diverse range of stresses
Liao (2012)	Environmental science	The ability of the city to withstand flooding and reorganise to prevent deaths and injuries and preserve current socioeconomic specification
Brown et al. (2012)	Environmental science; Social sciences	The ability to “dynamically and effectively” respond to changing climate while functioning at an acceptable level.

Author (year)	**Subject Area**	**Definition**
UNISDR (2015)	Multidisciplinary; Community	The ability of a system or community to adapt to obtain and maintain an acceptable level of functioning. Resilience is measured by the degree to which the social system increases this capacity to learn from past disasters for better future protection and to improve risk reduction measures.
Pelling (2003)	Social	The ability of an agent to cope with or adjust to a hazard’s adverse impact
Carpenter and Westley (2005)	Socio-ecology	A resilient ecosystem tolerates disturbance without falling into a different qualitative state and rebuilds itself when necessary.
Holling (1973)	Ecology	Resilience of an ecosystem is the ability of an ecosystem to absorb changes and still persist.
Pimm (1984)	Ecology	Resilience is the speed with which a system returns to its original state following a perturbation.

1.4. Water Supply Systems Resilience

Water needs to be available, without interruption, in sufficient quantity and quality to meet people's primary need for safe drinking water. Over 7.6 billion people around the globe depend on access to water, and this demand for safe and reliable water is ever increasing. Humans can live for a substantial period of time without many essential goods but will survive only a few days without safe drinking water.

The performance of the water supply system can change over time. While normal fluctuations occur during periods of business-as-usual, disasters can cause abrupt changes in the performance of the water supply system, leading to complete failure or at least a partial reduction in performance. Depending on the disaster-struck community's capacities and the resources employed, in general these abrupt changes are followed by restoration of the water system to normal level of performance.

Disasters cause water supply disruption by affecting water supply system's hard and soft assets. For instance, earthquakes can cause widespread pipe breakages, personnel shortages, and damage to water wells or other structures. Further, ensuing floods can threaten water quality and water extraction and conveyance through obstruction to intakes, treatment plants, or transmission systems. Table 1-3 shows the impact of earthquake, flood, volcanic eruption, hurricane, and drought on water supply systems.

Table 1-3: Disasters' Impact on Water Supply Systems (AWWA, 2001, WHO, 2002, Karamouz. M. et al., 2010)

Effect on Water supply	Earthquake	Flood	Volcanic Eruption	Hurricane	Drought
Personnel shortage	●	●	●	●	●
Water quality	●	●	●	●	●
Air contamination	●	●	●	●	●

Water-well damage	Severe	Severe	Moderate	Minimal	Minimal
Pipe breakage	Severe	Severe	Moderate	Moderate	Minimal
Obstruction in intakes, treatment plants or transmission systems	Minimal	Severe	Severe	Moderate	Minimal
Structural damage	Severe	Severe	Minimal	Severe	Minimal
Other utilities failure (e.g. power, communication, transport)	Severe	Severe	Minimal	Severe	Minimal

Severe Impact Moderate Impact Minimal Impact

The wellbeing of communities as a whole, and their infrastructure including health systems and firefighting capacity, depend on water serviceability after disasters. Prior to the Haiti earthquake in 2010, only 10% of people had access to potable tap water. The earthquake caused a number of water main breaks. These water mains were repaired within two weeks of the earthquake (DesRoches et al., 2011). However, nine months following the earthquake in Haiti (which affected over 3.5 million people), cholera broke out and quickly spread across the country which was partly due to sub-standard water (Delva, 2010). The Haitian Ministry of Public Health and Pollution reported 8,534 deaths and just under 700,000 cholera cases (Ministère de la Santé Publique et de la Population, 2014).

While the water supply system's physical vulnerability plays a significant role in the availability of safe water following disasters, it is not the only important factor in the overall water challenges faced by communities. Water system serviceability over time is what local authorities and governments try to maximise following disasters. Improving post-disaster water serviceability will decrease the number of people without water over time and can be achieved by increasing system robustness and decreasing service downtime. Following disasters, water system serviceability over time is usually referred to as water supply resilience. Harnessing concepts from a variety of disciplines, this study defines water supply resilience in conjunction with community as "the physical status of water supply system and social, organisational, and economic capacity of the community to withstand the disaster and recover to a normal level of serviceability in a timely manner". This definition enables us to develop a multidimensional approach to identifying the agents that affect water supply resilience.

1.5. Problem statement

The most significant challenge of measuring resilience is understanding resilience and its underlying factors. In other words, measuring resilience of water systems can provide decision makers with appropriate information about the most vulnerable components of the system and the community, as well as the duration of recovery in the event of disaster. In addition, exploring the concept of resilience will demonstrate the interdependencies between technical perspectives and other attributes of the community. Previous disasters have shown that even the most robust water system can fail due to an external shock. Recovery of water systems following complete or partial failure due to disaster is dependent on communities' economic, social and organisational capacities. These factors, however, are usually neglected in research on water supply resilience. The lack of multifaceted research envisaging the impact of physical attributes and community characteristics (also known as soft infrastructure) on water supply system serviceability following a disaster is a significant challenge in water resilience studies.

A considerable amount of research is available that considers the impact of disasters on each single dimension of hard urban (e.g. water supply systems) as well as soft infrastructure. For instance, Cimellaro et al. (2011), Yazdani & Jeffry (2012), and Giovinazzi et al. (2011) studied the impact of earthquakes on water supply system robustness. In another example, Carter (2005) studied the impact of hurricane on urban infrastructure. Rose (2004; 2007; 2009) and Chang (2012) looked at the impact of disasters in terms of the economy and economic recovery following disasters. In others studies, Pelling (2012) and Adger et al. (2005) considered the impact of disasters on social capital, Finally, Kachali et al. (2012) and Zachary et al. (2014)

considered the impact of disasters in relation to organisational resilience. These researches address a tangential issue, which is relevant but not exactly similar, to the aim of this study; we shift our focus from assessment of the impact of disasters on water supply system to identification of the factors that impact water supply system resilience to disasters.

Dimensions of community resilience to disasters have been assessed in previous works, such as Bruneau et al. (2003) and Cutter et al. (2008). Risk analysis has historically been the typical method employed to understand a water system's performance in particular circumstances (Hosseini & Moshirvaziri, 2008; Karamouz. M. et al., 2010; Sharma et al., 2014). Although risk analysis models are ideal for studying the water system's single-component behaviour, they may not be the best tool to understand the system's behaviour as a whole in disasters due to the complexity of the system (Davies, 2015; Gay & Sinha, 2012; UNISDR, 2014). In studying resilience of water supply to disasters, the physical characteristics of the system is not the only dimension that can affect/be affected by the disaster. Economic state of the community, organisational well-being and preparedness, and social capacities of the community can affect water supply resilience significantly.

Lessons learnt from previous disasters reveal that societies with higher social capital recover more quickly following a disaster (Aldrich, 2012a). In 2004, the Indian Ocean tsunami destroyed hundreds of villages in a number of countries and caused over 200,000 fatalities (Srinivas & Nakagawa, 2008). Despite heavy damage, some villages were able to rebuild with support from domestic and international organisations (Aldrich, 2012a). Thus, while some communities continued to suffer from the tsunami and its adverse consequences, others recovered quickly and restarted their businesses. When a 6.9 M_w earthquake hit Kobe in Japan in January 1995, the disaster response teams mobilised within the city slowly (Aldrich, 2011). As a result, the residents were first on the scene and had to deal with the fires following the earthquake (Shaw & Goda, 2004; Tsuji, 2001). They self-organised into civilian corps to fight the fires that commonly follow earthquakes as a result of gas release and explosion (Murosaki, 2007). Without this social capacity of communities to organise themselves, the level of damage will be higher, and recovery of the urban area may take longer than expected.

Water supply resilience and the economic capacity of communities are interdependent. Water supply shortage is a significant barrier to businesses re-opening after a disaster (Chang & Rose, 2012; Lam et al., 2009), while at the same time repairing a damaged water network and post-disaster recovery are costly for communities. The economic capacity of communities is also important in relation to the water sector adopting mitigation measures to help the system to withstand disaster, and planning for post-disaster restoration to return the system to a normal level of functionality in a timely manner.

Community resilience also depends on the resilience of its organisations and lifelines when a disaster happens (Bruneau et al., 2003). The organisational dimension refers to the capacity of water companies and other organisations responsible for managing disaster-related functions to effectively play their roles, both before and after disaster happens (Zobel, 2011). To increase a water system's technical resilience, best practices need to be applied throughout the institutional infrastructure.

A broad understanding of all of the factors affecting water supply system resilience provides a building block for overcoming water supply challenges following disasters. Neglecting the impact of the social, organisational, and economic capacities of communities on water supply resilience can lead to inappropriate or unbalanced investment of time, money, and effort in addressing the potential unserviceability of post-disaster water supply systems. This thesis builds upon previous research in this area by suggesting guidelines for developing a metric to measure water supply resilience that includes multiple dimensions of community resilience.

1.6. Research Overarching Aim and Objectives

The overarching aim of this research is to identify the significant factors affecting water supply resilience to disasters. To achieve the overarching aim, the following questions – representing research objectives – will be answered:

1. How can water supply resilience be measured?

The very first issue in measuring water supply resilience is to find/develop a conceptual framework that provides a big picture of the problem and enables us to formulate it. The conceptual framework should draw a road map showing the steps to achieving the overarching goal, which is measuring the resilience of water supply to disasters.

2. What dimensions of communities can impact water supply resilience?

The second issue is to understand what dimensions of communities, social, economic, environmental, etc., can impact water supply resilience to a disaster. A community is a complex unit that cannot be studied as a whole. Although many facets of communities may affect water supply resilience, the least effective dimensions, or the dimensions that are not within our control, should remain out of consideration. This leaves enough space for the most important dimensions to be considered.

3. What factors in each dimension affect water supply resilience?

The third issue is to identify the appropriate factors affecting water supply resilience. These factors fall under the different dimensions and impact water supply robustness and/or restoration rapidity.

4. What indicators are appropriate to measure the respective factors?

These factors may or may not be measured directly. Whatever the case, appropriate indicators are required to measure the various factors.

5. How can indicators be combined to measure resilience?

The last issue is to find out how to combine indicators of different types (i.e., qualitative and quantitative) and scale to achieve a multifaceted indicator for measuring resilience.

1.7. Structure of the Thesis

This thesis has been structured as 10 chapters to address the research questions and achieve the overarching aim of this research. Figure 1-5 shows a schematic of the thesis structure.

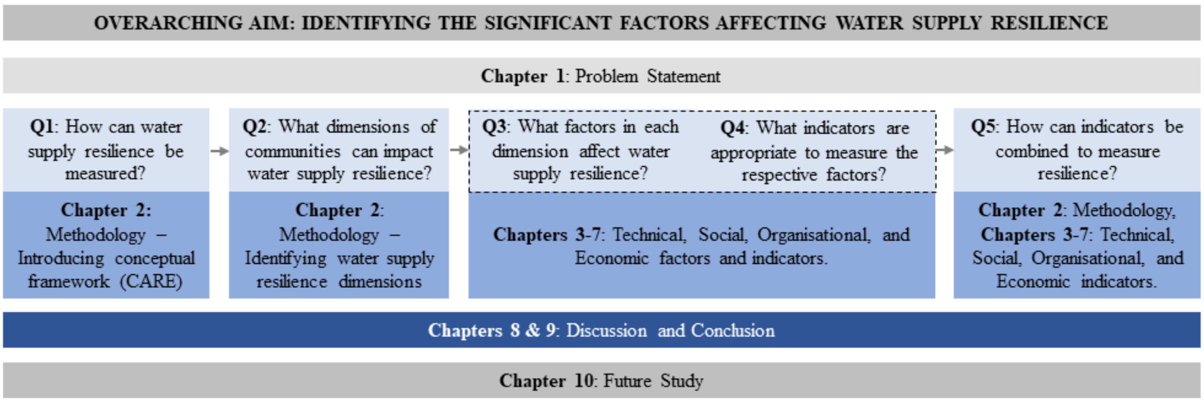

Figure 1-5: Schematic Showing the Thesis Structure as Organised Around the Research Questions

A brief description of the topic is outlined in Chapter 1, the introductory chapter. The main problem and overarching research aim, objectives and research questions are stated and the thesis structure described.

The research methodology is explained in Chapter 2. This chapter provides a comprehensive review of the water supply resilience literature, determines the resilience dimensions, and introduces a theoretical framework to measure water supply resilience to disasters. The theoretical framework provides a road map for finding and finalising significant factors affecting water supply resilience, and for how to identify indicators to measure relevant factors. A hypothetical case is investigated to show how the framework works in reality.

Chapter 3 discusses the technical dimensions of water supply resilience. The various impacts of disasters on water supply systems are explained. Further, the impact of changes in robustness on the rapidity of system recovery is also envisaged. The most significant technical factors for general water supply resilience to disasters are introduced, and then the technical factors of water supply resilience to earthquake (and more specifically to ground failure) measured for a case study (Pukerua Bay, New Zealand).

Social factors affecting water supply resilience to disasters are envisaged in Chapter 4. The role of social capital in disaster resilience is discussed and an indicator-based tool developed to enable the measurement of social factors that impact water supply resilience. The collected indicators and sub-indicators are analysed to minimise correlation between them and so increase the accuracy of the proposed model. The factors, indicators and sub-indicators are then tested for the Christchurch (22 February 2011) and Chile (27 February 2010) earthquakes respectively. The results are then used to justify the impact of the social factors identified on water supply resilience.

Chapter 5 describes an investigation of the impact of social capital on water system resilience during and following Tropical Cyclone Pam (March 2015) in Vanuatu. Port Vila, the capital, and several villages in Vanuatu were visited by the author in June-July 2015 and a number of interviews conducted with locals, NGO representatives and experts. The chapter, however, focuses on the impact of TC Pam in Laonkarai, a small village on Efate Island, and the social capacities and capabilities for coping with the disaster and bouncing back to a normal level. It also describes the social complexities and comes up with a recommendation for fostering water supply resilience in Vanuatu, and possibly other Pacific islands.

The organisational dimension of water supply resilience is discussed in Chapter 6. Institutional factors collected through a comprehensive literature review and interviews with social scientists, economists, and resilience experts are introduced, and their impact on water supply resilience outlined. This chapter also tests and verifies the significance of the organisational factors and measures their indicators for the case of the Christchurch earthquake in February 2011.

Chapter 7 discusses the economic factors that affect water supply resilience in communities. This chapter takes into account the impact of disasters on the economic capacity of communities, and shows how GDP per capita is affected in disaster-struck countries. The economic factors affecting water supply resilience are introduced, followed by an analysis of the Christchurch earthquake of 22 February 2011 to understand how these factors affected water supply resilience.

Chapter 8 outlines a discussion on how the key challenges were addressed in this study. It also describes how this study can be improved.

Chapter 9 provides conclusions on the factors and indicators gathered through this research. The conclusions chapter also addresses the research questions introduced in Chapter 1 and explains how the research objectives were achieved.

The last chapter, Chapter 10, outlines directions for future research to improve the concept of water supply resilience. The chapter outlines an innovative approach for measuring water supply resilience based on post-disaster water demand. This definition – which comes from the author’s academic and industry experience – has potential to improve the accuracy of water supply resilience measurement.

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CHAPTER 2 – METHODOLOGY

The current chapter is based on the following article:

Balaei, B., Wilkinson, S., Potangaroa, R., Hassani, N., & Alavi-Shoshtari, M. (2018) "Developing a Framework for Measuring Water Supply Resilience". *Natural Hazards Review,* 19(4), DOI: 10.1061/(ASCE)NH.1527-6996.0000292.

2.1. Introduction

The serviceability of infrastructures is subject to disruption when earthquakes occur. Urban societies have historically suffered from loss of infrastructure serviceability in the aftermath of disasters (Chang et al., 2002; Ghobarah et al., 2006). Due to numerous pull factors, urban areas around the world are absorbing people and growing in size and population. The coincidence of earthquakes and densely populated cities creates the potential for increased direct and indirect consequences of seismic events, such as loss of life, economic costs, infrastructure disruption, and so on. (Burby et al., 2000). The intensity of the adverse consequences of disasters is strongly influenced by the physical, social, economic, and organisational vulnerabilities of communities and their infrastructures. These vulnerabilities can in turn result in subsequent loss of the capacities of communities and longer recovery times for these various components and infrastructures.

The resilience of communities to disasters is a function of the performance of infrastructures and, specifically, water supply systems in the aftermath of the disaster, and their serviceability during recovery time. Water supply systems provide crucial services to enable, preserve and improve living conditions (Fulmer, 2009) and any disruption in these systems will cause inconvenience and difficulties for the community. Loss, or contamination, of water in previous earthquakes has led to epidemics such as cholera (Piarroux et al., 2011), or conflagrations and significant losses (Chung et al., 1996; Scawthorn, 1996; Scawthorn et al., 2005), which then shift priorities from activities directed towards recovery, to responding to the epidemics and conflagrations. As such, providing enough water at acceptable levels of service in disasters is crucial.

Identifying current levels of resilience to earthquake in water supply systems is becoming more important (Frazier et al., 2013). The most significant goals and functions of measuring resilience are understanding resilience and its underlying factors. In other words, measuring resilience of water systems can provide decision makers with appropriate information about the most vulnerable components of the system and the community, as well as the duration of recovery in the event of disaster. In addition, exploring the concept of resilience will demonstrate the interdependencies between technical perspectives and other attributes of the community.

As with other phenomena, gauging resilience requires indicators to be identified and then measured. Resilience indicators will enable different levels of administration to integrate resilience fostering strategies into mitigation and preparedness planning (Queste et al., 2006). Due to the unavailability of comprehensive quantifying indicators, it is difficult to estimate the resilience of water supply systems to earthquakes. In addition, the qualitative nature of indicators, if any, makes it difficult to assess the impact of different factors on water systems resilience. However, to enable evaluation of water systems resilience, the concept of resilience needs to be clearly defined and made quantifiable.

Although several researchers have assessed dimensions of community resilience (Cutter et al., 2008; International Strategy for Disaster Reduction, 2007; Paton, 2006; Renschler et al., 2010), challenges remain in the development of multi-dimensional indicators to estimate water supply system resilience to earthquakes. This paper proposes a comprehensive framework to measure water supply system resilience. The proposed framework aims to standardize the measuring process so that it can be adapted to various temporal and spatial conditions, with slight changes. In addition, the proposed framework is applied to a hypothetical case to show how it will work.

2.2. Importance of measuring resilience

Although measuring resilience to earthquakes has been discussed in recent literature (Béné, 2013; Chang & Shinozuka, 2004; Francis & Bekera, 2014; Winderl, 2015), a comprehensive and unanimously accepted methodology for measuring the resilience of communities is lacking. Domain-specific resilience concepts range from ecological systems (Holling, 1973), to economic systems (Brock et al., 2002; Rose, Adam, 2007), to organisational systems (McManus et al., 2008). To date, however, multi-dimensional measures of community and infrastructure resilience have attracted the most research attention.

In recent years, the resilience of communities has been investigated in several studies by academic researchers and local and international institutes. From a geographical perspective, disaster resilience measurement frameworks are categorized into four levels: global, national, community and household/individual (Winderl, 2015). Although global level measurements will ideally be the most comprehensive for some types of disaster (e.g. climate change), in the case of other disasters (e.g. seismic events) they cannot be utilised effectively. In addition, it is quite difficult, if not impossible, to provide metrics which take into account all the global variables. As such, there is currently no detailed global level measurement, although more precise methods might make it possible for researchers to develop such models.

The highest current resilience measurement is national level. The type of data typically used at this level, for example Gross Domestic Product (GDP), cannot be broken down to community level. Hyogo Framework for Action Monitor, the WorldRiskIndex (Birkmann, J. et al., 2011), the Global Focus Model by UN-OCHA, the Prevalent Vulnerability Index (Birkmann, Joern, 2007), the Risk Reduction Index (Schaub et al., 2013), the Country Resilience Rating (Winderl, 2015), and the OECD-DAC methodology for measuring resilient systems (Pouligny, 2010) are the most significant efforts in national level measurements around the globe.

The most common level of seismic resilience measurement is at the community level. Geographically, the community level involves political boundaries such as counties, districts, cities and/or rural areas. The Resilience Capacity Index (Building Resilience Regions, 2011), the Baseline Resilience Indicators for Communities (Cutter et al., 2008), and ResilUS (Miles & Chang, 2011) are some relevant resilience measurement models at the community level.

The household level is the smallest scale at which resilience is measured. It is rarely utilised in the case of seismic events, although individual variables affect community and even infrastructure resilience. The DRLA/UEH Evaluation Resilience Framework for Haiti and the Community Based Resilience Analysis (CoBRA) (Venton, 2014) are examples of household-level resilience measurement frameworks.

In the case of infrastructure resilience, however, the physical vulnerability of these systems was the dominant concern in estimating post-earthquake status for decades (Hashimoto et al., 1982; Hwang, Howard HM et al., 1998; Little, 2002). Most of these studies focused on estimating damage to lifelines when an earthquake happens, rather than system performance as a whole, or recovery phase required for the system to be bounced back to an acceptable level of service. In addition, they take the physical dimension of infrastructures into account in measuring outages after earthquakes.

Despite the importance of social, economic, and organisational factors, Bruneau et al. (2003) were the first disaster management researchers to propose a methodology for measuring resilience which considered technical, organisational, social, and economic dimensions of the system and community. Additionally, the authors suggested robustness and rapidity of reconstruction as two key properties in measuring infrastructures' resilience to seismic events.

Apart from a few papers which used real disaster data to measure resilience after the event (Aldrich, 2012a; Jacques et al., 2014), two main methodologies have been applied to estimate resilience for future disasters. In one approach, mathematical modelling is used to measure robustness and recovery for the purpose of estimating resilience (Baroud et al., 2014; Cimellaro et al., 2010; Zobel, 2011). Although these methods offer a new perspective on the problem of measuring resilience, they mostly consider the technical dimension of infrastructure resilience.

The second approach taken by researchers from various disciplines focuses on finding the variables of system resilience. In their seminal research on resilience indicators, Hahn et al. (2003) proposed an indicator-based methodology to mitigate and manage disaster risks among communities. Their focus was developing a set of criteria for selecting appropriate indicators for disaster resilience. Cutter et al. (2010) also proposed a methodology and a set of resilience indicators for communities that can be used to measure the effectiveness of programmes, policies, strategies, and interventions which are designed to improve resilience. Morley (2012) proposed operational and financial indicators to measure water supply system resilience. Although the terminology used in this study differs from the other studies, the concept of resilience remained intact.

The current paper proposes a measuring framework for water supply system resilience based on multi-dimensional indicators. In this approach, the water supply system is regarded as an integrated system rather than one made up of separate components, and the water system's resilience calculated based on the values of its elements. The result of this measurement will be a non-dimensional number between zero and one, showing the ability of the water supply system to withstand a disaster and bounce back in a timely manner.

2.3. Framework Development

As mentioned earlier, this study intends to develop a measuring framework for water supply system resilience on the basis of constructing and validating composite indicators. An overall approach to quantifying resilience has long been the subject of discussion. Inductive and deductive approaches have been the most common methods used for measuring resilience across various disciplines. The inductive approach, or bottom-up method, primarily rooted in practical experience on the basis of generic understanding of the concept of resilience, can be simply adapted to various geographical areas (Bryman, 2012). However, the outcomes of this approach are not easily generalizable and resilience indicators will vary in various locations.

In contrast to the inductive approach, and to overcome the problem of circular logic, this paper utilises independent measurements. Such measurements are independent from the characteristics of any specific area and community and can be used to test and validate an inductive method. The most important requirement of this approach is that the set of indicators to be tested are not directly derived from the attributes of a specific system, or community (Béné, 2013).

The literature on developing composite indicators includes various methodological approaches, however most studies having a process of indicators construction in common (Birkmann, Jorn, 2006a; Cutter et al., 2010). The current study proposes a framework to measure the resilience of water supply systems, precisely and in a straightforward manner (Figure 2-1). This framework consists of eight fundamental activities: (1) developing a conceptual framework, (2) selecting appropriate indicators, (3) refining the indicators based on data availability, (4) correlation analysis, (5) scaling the indicators, (6) weighting the variables, (7) measuring the indicators, and (8) aggregating the indicators.

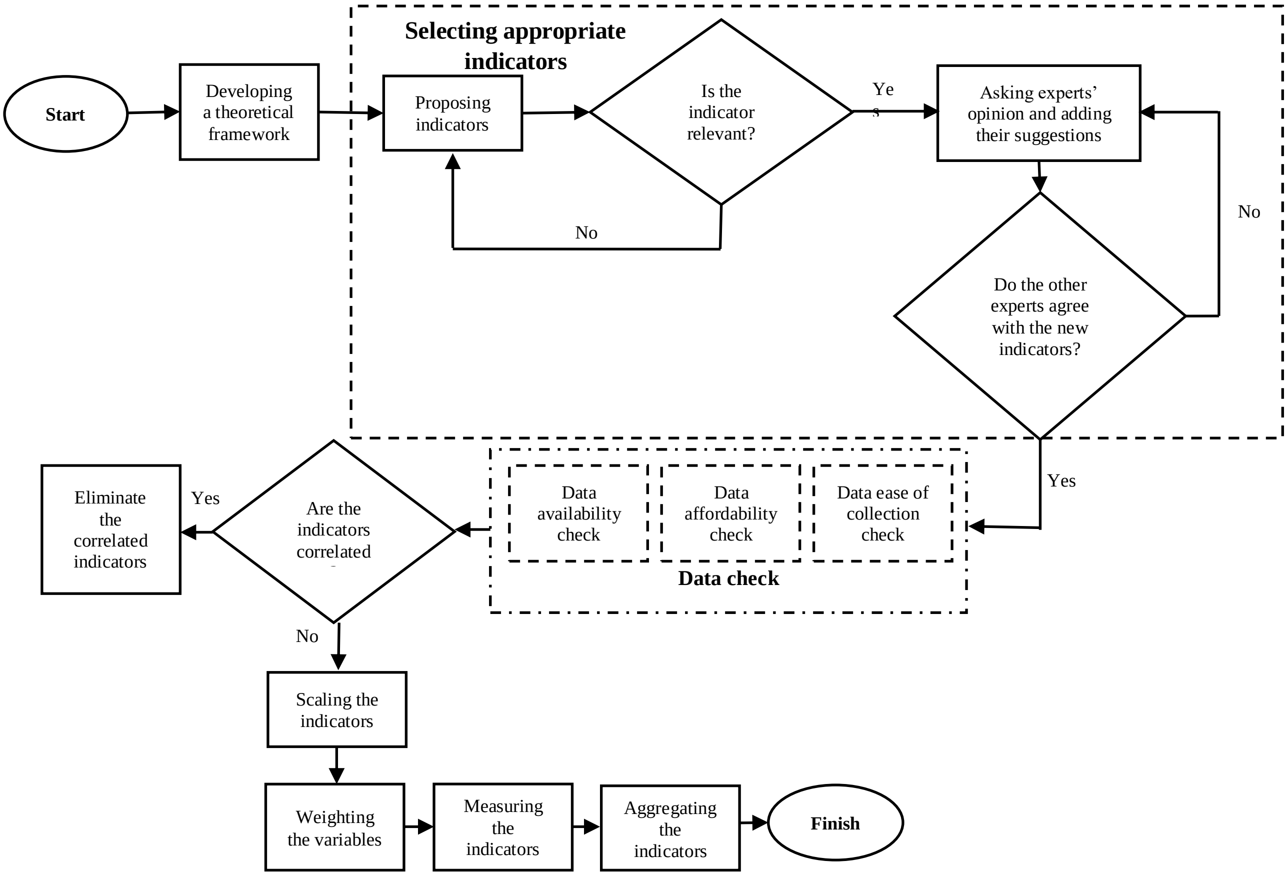

Figure 2-1: Water supply system resilience composite indicator development process

2.3.1. Developing a conceptual framework

The very first step involves the development of a theoretical framework to demonstrate the definition of resilience and its building blocks. This paper proposes the Comprehensive Aggregated Resilience Estimation (CARE) model as the conceptual basis.

2.3.1.1. Developing the resilience model

The concept of resilience has been developed and utilised in fields as diverse as ecology, economics, environmental science, and engineering research. Some studies have defined resilience as the characteristics of a system that make it strong in the face of any disturbance, such as natural hazards (Birkmann, Jorn, 2006b; Marburger, 2005). These definitions, which are mostly proposed by engineers, are quite similar to definitions of the concept of vulnerability. In contrast, other researchers have concentrated on the coping capacity and restorability of the system when an unexpected event happens (Gallopín, Gilberto C., 2006;

Wildavsky, 1988). These studies mainly emphasise bouncing back processes and concentrate on temporal problems after the event.

It is worth noting, however, that natural hazards are not the only consideration in terms of resilience. Man-made disasters, which are purposefully designed to harm human-beings and/or infrastructures, can also cause disruption to water supply. Further, technological events have adverse consequences for water supply systems. However, they are beyond the scope of this study as their consequences on water supply systems may be different from natural hazards.

Regardless of the discipline, the concept of resilience is generally acknowledged as containing attributes of both strength and restorability. Bruneau et al. (2003) proposed the first and most comprehensive definition of seismic resilience in urban systems. It has been modified in this paper to address water supply system resilience to earthquakes:

“Water supply system resilience to earthquakes is defined as its ability to remain functional when an earthquake happens (coping capacity) and carry out recovery activities as quickly as possible if the earthquake exceeds the coping capacities.”

Water supply system resilience depends greatly on the system’s serviceability during an earthquake. In this study, the ratio of the number of units (households, emergency agencies, etc.) receiving water services of an acceptable quality to the total number of units that received water services before the earthquake is defined as the serviceability of the water supply system (Davis, 2008). Generally, the term “acceptable quality” refers to a certain level of water quality (hygiene) and pressure that should be defined on the basis of local criteria.

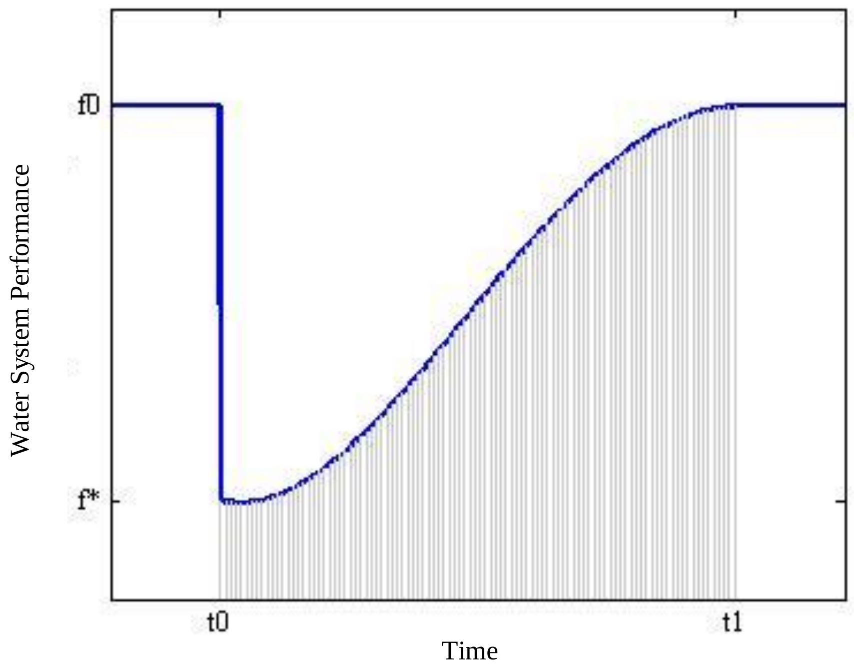

Figure 2-2: Schematic definition of the concept of resilience (adapted from Bruneau et al., 2003)

Figure 2-2 depicts the schematic definition of the concept of resilience proposed by Bruneau et al. (2003), as adapted to the water supply system. In the diagram, pre-earthquake water supply system serviceability (f_0) drops to its minimum level, called system robustness (f^*), at the event time (t_0). As reported in the literature (Bruneau et al., 2003; Chang & Shinozuka, 2004; McDaniels et al., 2008), water companies and other organisations as well as community members begin recovery processes to level up the system serviceability to an acceptable level in $[t_0 - t_1]$ time period.

With regard to the diagram, water supply system resilience is defined as the proportion of the area of the region bounded by the line tracking serviceability (f) and the x axis between t_0 (the time that an earthquake happens) and t_1 (the time that recovery finishes), to the rectangle of [pre-earthquake serviceability * recovery time $(t_1 - t_0)$]. Mathematically, it can be defined by:

$$Resilience = \frac{\int_{t_0}^{t_1} f(t)dt}{(pre\text{-}earthquake\ serviceability).(t_1 - t_0)} \quad (1)$$

2.3.1.2. The dimensions

The CARE conceptual model is designed to further understanding of water supply system resilience. The concept of resilience in the water supply system tracks the serviceability of the system from the time an earthquake happens until the system's level of service is recovered to an acceptable level (Figure 2-3).

Resilience in general and specifically in water systems is a complex concept that cannot be measured on a single scale. In this model, water supply system resilience consists of five dimensions, referred to as the resilience pentagon. Vulnerability and recovery of physical components of water supply systems, such as pipelines, pumps, reservoirs, treatment plants, etc. is a core concept in water supply system resilience, and is known as the technical dimension.

However, the resilience of a water supply system is not solely dependent on the system's physical vulnerability and, therefore, recovery is not achieved by only building back the technical elements. Other attributes of the community in the earthquake-struck area will affect the restoration and recovery time of the system, as well as its vulnerability to the geotechnical event. The social dimensions of the community, such as sense of community and people's skills and knowledge, can severely influence the water system's resilience. Many recovery activities are dependent on the social capital of that community and without taking this dimension into account, post-disaster recovery models will, at best, be hypothetical and so fail in providing an accurate expected recovery time.

The organisational dimension emphasises the influence of the community's institutional conditions on the resilience of the water system. These conditions can involve a variety of attributes from construction regulations, which can affect the construction quality, to the quality of emergency response plans, if there are any. The organisational dimension of resilience is not confined to the water companies, but includes all those in the public and private sector whose performance can affect the water system’s serviceability after an earthquake.

Resilience of water systems can be also affected by economic factors. The economic dimension encompasses both the country’s general economic situation and average economic status at the individual level. On the one hand, the water company’s budget as well as its access to quick finance, can affect recovery time after an earthquake. On the other hand, factors such as households with higher than average income or a low rate of unemployment in the community can result in a shorter recovery time after an earthquake.

Lastly, since the resilience of water supply system varies based on different temporal and spatial conditions, the environment that the earthquake happens in is of significance. Although temporal and spatial (geographical latitude) conditions may not impact on earthquake occurrence, they can actively determine post-earthquake needs. For instance, a dry, hot climate increases the need for water, both for general sanitation and/or firefighting purposes.

2.3.1.3. Resilience capacities

Resilience of the water supply system is a function of the capacity of the system as well as the community for dealing with potential events (Chang & Shinozuka, 2004). In general, three capacities or properties of the system and community help to minimize the costs, including loss of serviceability and time to recovery, which the community suffers in the event of an earthquake. These properties are: 1) absorptive capacity, 2) adaptive capacity, and 3) restorative capacity (Cutter et al., 2008; Vugrin et al., 2010).

Absorptive capacity is the ability of the system/community (SYSCO) to absorb and minimize the consequences of the shock with an acceptable amount of effort. Activities that lead to increasing absorptive capacity in the SYSCO are categorized in the disaster management cycle as the pre-disaster activities. These activities encompass mitigation activities that mostly lead to increased robustness of the SYSCO. Retrofitting water system infrastructure and increasing redundancy in water systems are examples of activities that increase absorptive capacity. However, any level of absorptive capacity can be exceeded if the event is so large and/or if the existing coping capacities are inadequate to handle the consequences of the disaster.

Adaptive capacity is defined as the ability of the SYSCO to adjust to the undesirable consequences of the external shock. When the absorptive capacity is exceeded, adaptive capacity acts to minimize the adverse consequences of the event. Adaptive capacity is increased mostly by means of preparedness activities, although it starts working immediately after the disaster during response and restoration activities. Increasing water saving capacity is an activity that elevates the adaptive capacity of the community in the post-disaster response phase. Restorative capacity is described by rapidity of the system's return to an acceptable level of serviceability. Restorative capacity, like adaptive capacity, is formed before the disaster by means of preparedness activities and will be activated during the recovery time.

The rapidity factor can vary from low to high depending on resilience capacities. If the absorptive capacity is not exceeded, a very quick recovery will occur without losing the level of service and the system's resilience will remain at its maximum level. If the absorptive capacity is exceeded, but the adaptive capacity is not exceeded, a mid-term recovery is expected. In this case, level of service will be lost in the aftermath of the disaster and resilience will decrease but it will still be at an acceptable level. If the absorptive and adaptive capacities are both exceeded, the recovery will be long term and, as such, system's resilience will drop dramatically. In the event that the disaster exceeds all capacities, not only is a long-term recovery expected, but international aid will be required to respond to the disaster.

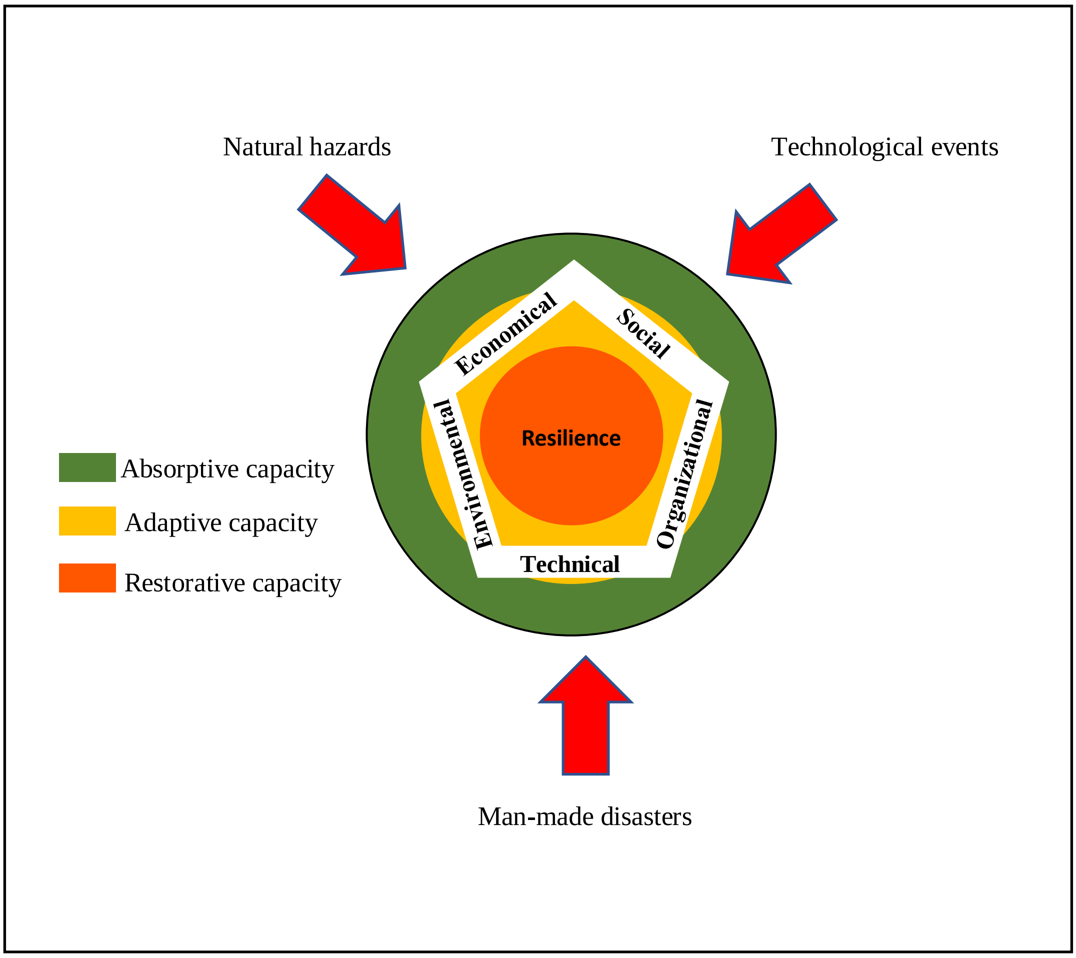

Figure 2-3: Schematic presentation of CARE model

2.3.2. Selecting appropriate indicators

The concept of "measuring resilience" includes not only quantitative approaches, but also seeks to find and develop various other methods to replicate the concept of resilience in practical tools to be applied in this field. These approaches include qualitative criteria as well as broader assessment procedures, such as endeavours for capturing organisational and environmental dimensions of resilience.

Applying the complex concept of resilience of water supply systems to earthquakes requires the reduction of all potentially collectable data to a set of significant indicators, from regional to national level, to enable decision makers to assess the impact on the affected society. Due to the difficulty of quantifying resilience in absolute terms without utilising external references to validate the calculations, most existing resilience measurement techniques use indicators or variables to assess relative levels of resilience. Accordingly, relative levels of resilience are mostly being used to compare systems (e.g. water supply systems) in various places (spatial), or to analyse resilience trends for systems (e.g. water supply systems) in a certain place over time (Cutter et al., 2008; Schneiderbauer & Ehrlich, 2006).

Different researchers define indicators in different ways, as ambiguities and contradictions emerge when considering the general concept of indicators. Gallopin's (1997) comprehensive definition describes an indicator as a pointer that gives an outline of information relevant to a particular case. More precisely, indicators are variables –nominal, ordinal, or quantitative – which represent attributes –such as quality, quantity or a characteristic– of a system or phenomenon (Birkmann, Jorn, 2006a; Gallopín, Gilberto Carlos, 1997).

According to these definitions of indicators, resilience indicators are defined in this paper as follows:

Resilience indicators are variables which are operational representations of serviceability, quality or a characteristic of a system, either in technical, organisational, social, economic, or environmental aspects, which can potentially affect its resilience to natural disasters such as earthquakes.

The ability of indicators to show the characteristics of a system based on predefined goals reflects the quality of the indicators. The most important criteria for selecting indicators, and which are taken into account in this paper, include the following (Briguglio, Lino, 2003; Hahn, 2003):

- Validity, which determines if the indicator is a proxy for the targeted resilience dimension;
- Sensitivity, which shows whether or not the indicator is sensitive to changes in outcome;
- Objectivity, which demonstrates if the indicator can be utilised over time based on updated and reproduced data; and

- Simplicity, which represents ease of comprehension by decision makers and other users.

Although other criteria for selecting indicators have been described by other researchers, they are either data-relevant, or overlap with the above-mentioned principle criteria. Data-relevant criteria (e.g. data availability, affordability, etc.) are not considered here because the focus of this paper is gathering the most effective indicators for water supply systems, regardless of data concerns. However, the indicators can be localized and prioritised based on data availability and affordability over the spatial scale. The time scale in which resilience is measured is another significant consideration. Resilience indicators may vary over time due to data and information availability (Cutter et al., 2008).

2.3.3. Refining the indicators based on data availability

Data collection is one of the most challenging parts of constructing indicators. The most significant difficulties are due to:

- Lack, or deficiency of data;
- Data collection/generation costs;
- Difficulty of data collection;
- Lack of unity on definitions between countries;
- Reluctance of data holders to share; and
- Deliberate misrepresentation to progress the benefits to the country.

Lack, or deficiency, of data arises when data is not gathered during a certain event, or has a limited spatial and temporal scope. Data availability is a very significant concern in measuring phenomena because it can change the measuring method. In such cases the researcher should either gather/complete the required data or change the indicators to avoid massive errors in outcomes. In some cases, proxy variables may be appropriate if they do not impose huge uncertainties.

Although the availability of data is very important in developing indicators, data affordability can be of a major concern in any country, depending on its economic state. Gathering data can be a very expensive process, for instance measuring actual water leakage ex- and ante-earthquakes. In other instances, data is being gathered by several agencies and companies, but it may cost a lot to purchase whole data from them. The solutions to data unavailability can also be applied for data cost problems.

Difficulties in collecting data may not lead to permanent change of the indicators; however, it can result in temporary variable changes and postpone the finalization of measuring indicators. For example, when a water catchment is located in a hilly, wild, sylvan area, collecting data by aerial photography is not possible and it is difficult to gather the data manually. In these cases alternative variables can be quite helpful.

In general, data gathering processes and data units vary in different countries. In social sciences, such as economics and sociology, various agencies can be involved in gathering and representing the data across countries and regions. In these cases, every component of the final index should be accompanied by a detailed explanation of the intended measuring purpose to ensure the indicators are defined in an integrated way across the countries.

Sharing data and information is a common issue around the world. The institutions that gather or generate data are reluctant to share it due to the money and time they have spent, especially in the private sector. In addition, data can be a source of power and sharing data with others can be seen as giving up some power. Even when the data is coming from the country itself, cooperation between government and central statistical agencies is essential.

Both the public and private sector can choose to deliberately mis-represent data. Seeking more government funding can be a reason for exaggerating levels of vulnerability, while issues can be downplayed in the interests of international prestige. It is important to have procedures for checking the validity of gathered data.

2.3.4. Scaling the indicators

As various kinds of variables are utilised to measure resilience, they can come in different statistical units and scales. For example, some indicators may be measured in percentages while others can be per capita. A scaling process is vital to avoid problems when combining measurement units.

Having N indicators in total, the N-dimensional vector of the indicators can be considered as the impact vector on resilience. Then a natural definition of resilience would be the 2-norm, or 2-norm square, of the impact vector:

$$V = [i_1, i_2, i_3, \dots, i_N]^T \qquad (2)$$

$$Resilience = ||V||_2^2 = i_1^2 + i_2^2 + i_3^2 + \cdots + i_N^2 \qquad (3)$$

However, since the indicators are diverse in concept and magnitude, the numerical indicators (e.g. personnel) will dominate the Boolean or discrete ones. Scaling is required to make the indicator and, therefore, the resilience index bounded.

Min-Max scaling is proposed in this paper, as follows:

1) Booleans remain unchanged: $i \in \{0,1\}$
2) Discrete indicators are divided by $max\{i\}$. For example, $i \in \{0, 1, \dots, 5\}$ is transformed to $\bar{\imath} = \{0, \frac{1}{5}, \frac{2}{5}, \dots, 5/5\}$
3) Numerical indicators are calculated by percentage (e.g. per population) and transformed to a real number between zero and one.

We then define:

$$V = [\overline{\imath_1}, \overline{\imath_2}, \dots, \overline{\imath_N}] \;\; where\; \overline{\imath_j} \in [0, 1] \qquad (4)$$

$$Resilience = \frac{1}{N}||\bar{V}||_2^2 = \frac{1}{N}(\bar{\iota}_1^2 + \bar{\iota}_2^2 + \bar{\iota}_3^2 + \cdots + \bar{\iota}_N^2) \qquad (5)$$

Thus, resilience will be bounded between zero and one to make a resilience index with equal weights for the indicators.

2.3.5. Correlation analysis

The impact vector dimensionality may be reduced due to interconnection and correlation among the indicators. Cutter et al. (2010) used a correlation significance test between the indicators by normal approximation and employed Cronbach's alpha reliability/item analysis for variable selection. However, if normal approximation to the joint probability distribution of the indicators is severely violated, a correlation significance test may be rejected while the indicators are still highly dependent. In other words, measures such as Pearson's R and Cronbach's alpha can be suggestive, but not conclusive, in assessing the interconnectedness of the indicators. For effective dimensionality reduction, statistical routines such as Akaike's criterion can be employed in model selection in the context of linear and nonlinear regression, combined with hypothesis testing. One should however test whether tailored statistical methods for variable selection would significantly reduce the dimensionality of the resilience index in practice, compared to simple rule of thumb methods.

2.3.6. Weighting the variables

Assigning equal weights to the indicators (for example, all set to 1) will result in Boolean and discrete indicators dominating the definition of the resilience index. This is simply because, firstly, the Boolean and, secondly, the discrete indicators are more likely to reach the maximum (1) compared to the continuous numerical variables. Furthermore, some variables naturally have a higher impact on resilience than others. Thus, a weighted definition of the resilience index is required to realise the significance of each indicator. Importantly, the choice of weights $W_1, W_2, \ldots, W_N$ assigned to $i_1, i_2, \ldots, i_N$ respectively, is based on qualitative descriptions of the indicators and their impact on resilience. On the other hand, from a purely technical point of view, it is necessary that the weights satisfy the condition $W_1, W_2, \dots, W_N = N$ so that the resilience index will be still bounded between zero and one by the weighted definition.

2.3.7. Measuring the indicators

Once finalized and weighted, the indicators need to be measured in the Min-Max scaling scheme. Any indicator can, theoretically, range between zero, representing the worst condition of the indicator, and one, as the best status of the indicator.

Measuring the indicators can be carried out through a number of methods. While some variables can be quantified based on online statistical data, such as unemployment rate or the country's GDP, other data might be obtained by conducting interviews, such as detailed information on emergency response plans.

2.3.8. Aggregating the indicators

The final composite indicator of water supply system seismic resilience is derived from aggregating the weighted values of a indicators. Since the dimensions are not being weighted, the indicators will be aggregated regardless of which dimension (category) they are from. Not weighting (ranking) the dimensions prevents double-weighting of the indicators resulting in poor ranking. Otherwise, the most important variable of the second ranked dimension, for example, could be much more important than the least important variable of the first ranked dimension. The dimensions, therefore, are required to have equal weights.

The final water supply system seismic resilience indicator will be defined as:

$$Resilience = \frac{1}{\sum_{j=1}^{N} w_j} \left(W_1 \bar{\iota}_1^2 + W_2 \bar{\iota}_2^2 + \cdots + W_N \bar{\iota}_N^2 \right) \tag{6}$$

2.4. Applying the framework on a hypothetical case

The proposed framework was utilised to measure to water supply resilience in a hypothetical case without loss of generalizability, based on case studies in the southern hemisphere such as the 2011 earthquake in Christchurch, New Zealand. Twelve surveys had previously been conducted by experts in various fields, and 47 potential indicators of resilience collected. In this case study, nine indicators, ranging from technical, organisational, social and economic, were selected from among these 47 indicators, according to data availability and the weights assigned in the respective surveys. These indicators are given in Table 2-1.

Following interviews with the experts, the relevance of the indicators to resilience was assessed and, in some cases, they were replaced. For example, Domestic Violence was replaced by External Violence since social science experts found External Violence to be more relevant to resilience. Furthermore, the uncertainty of the Domestic Violence rate was higher than for External Violence since many domestic violence cases are not necessarily reported to Police. In addition, Median Household Income was removed as it was found in the surveys to be irrelevant to resilience. In general, the indicators were selected not only by relevance, but also after considering data availability and realistic means of estimation. Clearly, there is a trade-off in resilience estimation between the number of relevant indicators successfully assessed and the cost of reducing uncertainty.

In the next step, indicator correlation was assessed. As the suggested indicators are measuring both qualitative and quantitative parameters, the correlation analysis process has used a mixture of qualitative and quantitative methods. Volunteering rate was therefore removed due to its strong correlation with social participation rate, while emergency power was removed as it was found to be included in the Emergency Response Plan (ERP) during the interviews.

Six indicators remained for estimating the resilience in this hypothetical case study. As discussed in the previous section, the values of the indicators could be logical or qualitative, and they all need to be scaled and normalised to estimate resilience. The scaled measures are given in Table 2-2; the weights were determined according to the interviews with experts. The values of the indicators were determined as follows: It was assumed that the water supply system was fairly vulnerable (50%) to a specific type of disaster (earthquake). It was also assumed that Emergency Response Plan (ERP) was in place (value=2). Rates for social participation and external violence from the Christchurch case study, online at http://www.stats.govt.nz/, were used, as well as GDP per capita which was binned and indexed. Finally, the disaster struck country was assumed to have access to finance 25 to 48 hours after the disaster. These measures, partly hypothetical and partly inspired by a real case study, were scaled between zero to 1 as discussed in Section 2.3.4.

Table 2-1:The Initial Indicators of Water Supply Resilience

Dimension	Indicators	Relevance	Correlation	Replacement with/removed	Data check (data source)
Technical	[1] Water supply system's physical vulnerability	Yes	N/A	N/A	Water company
Organisational	[2] Emergency Response Plan (ERP)	Yes	N/A	N/A	Water company
	[3] Emergency power (electricity)	Yes	[2]	N/A	Water company
Social	[4] Social participation rate	Yes	N/A	N/A	NZ Statistics
	[5] Domestic violence	No	N/A	External violence	Police
	[6] Volunteering rate	Yes	[4]	N/A	NZ Statistics
Economic	[7] GDP per capita	Yes	N/A	N/A	MBIE
	[8] Quick access to finance	Yes	N/A	N/A	Water company

	[9] Median households' income	No	N/A	Removed

Based on the interview results, the unweighted estimate of Resilience by (1) would then give,

$$R_U = \frac{1}{6}(0.5^2 + 0.4^2 + 0.44^2 + 0.04^2 + 1^2 + 0.5^2) = 0.3092$$

As shown in Table 2, the same average weights were given to physical vulnerability and ERP; and these were quite similar to the weight for quick access to finance. The weights for the social and quick access to finance indicators were roughly same, at about 74% of the weights of the first two indicators. Considering that the sum of the weights should be equal to the total number of indicators (6), the following system of equations was formed:

$$W_1 + W_2 + W_3 + W_4 + W_5 + W_6 = 6$$

$$W_1 = W_2 = W_6$$

$$W_3 = W_5 = 0.74W_1$$

$$W_4 = 0.84W_1$$

Thus $W_1 = 1.13$, $W_3 = 0.83$, and $W_4 = 0.95$ and the weighted Resilience by (6) is given by,

$$R_w = \frac{1}{6}(1.13 \times 0.5^2 + 1.13 \times 0.4^2 + 0.83 \times 0.44^2 + 0.95 \times 0.04^2 + 0.83 \times 1^2 + 1.13 \times 0.5^2) = 0.2897$$

which is scaled by the importance of each indicator. The difference in the unweighted estimate $\boldsymbol{R_U}$ and the weighted estimate $\boldsymbol{R_W}$ reveal the importance of the indicators' weights to the reliability of resilience estimate. The weights may be dependent on the case studies.

There is, however, a possibility of estimating resilience by direct calculation from Figure 1, provided that at least $\boldsymbol{f}^*$ and $\boldsymbol{t_1}$ are available. Then the linear estimation of resilience (which is not necessarily the best unbiased estimate) would be the area of the triangle bounded by $\boldsymbol{t_1 - t_0}$ and $\boldsymbol{1 - f^*}$. However, these parameters are not always available and give no estimate for resilience prior to the disaster.

Table 2-2: Final indicators for measuring water supply resilience

Dimension	Indicator	Measurement Scale	Values (hypothetic Case Study)	Scaled values	Average Weights (W)
Technical	Water supply system's physical vulnerability	N/A	50%	0.5	4.875
Organisational	Emergency Response Plan (ERP)	"1- No ERP 2- ERP developed 3- Staff trained on ERP theoretically 4- Teams are defined and received instructions 5- Functional exercises are conducted on ERP"	2	0.4	4.875
Social	Social participation rate	N/A	44%	0.44	3.5
	External violence	No. of events per capita	4.44%	0.0444	4
Economic	GDP per capita	1- below 216 2- between 162 and 215 3- between 108 and 161 4- between 54 and 107 5- above 53	5	1	3.5
	Quick access to finance	1- Finance is accessible in more than 73 hours after the disaster 2- Finance is accessible between 49 and 72 hours after the disaster	2	0.5	4.593

	3- Finance is accessible between 25 and 48 hours after the disaster 4- Finance is accessible in less than 24 hours after the disaster	

In this hypothetical case study, assuming that the serviceability of the water network reduced to 50% immediately after the disaster, the estimated recovery time would be around 97 days if the estimated resilience is $\boldsymbol{R_W = 29}$%. This estimation method therefore provides a framework that not only links the technical, economic, social and organisational indicators, but also ties them to estimations of serviceability and recovery time post disaster.

Although in this case the results do not show much difference in the unweighted and weighted Resilience Index, they may show more variation in other cases when there are more variations in the values, or when all indicators are included in the model.

The results show that change in indicators with bigger weights can result in bigger variations in the Resilience Index. These indicators also can be used by the governments to plan for fostering resilience of water supply to disasters. The indicators with bigger weights have more influence on the water supply resilience and so should potentially be prioritised by governments and/or water companies. However, they need long-term programs and more investments, in general, which is of concern to the companies.

In contrast, the less weighted indicators have less impact on overall water supply resilience but can be modified and resolved more easily and quickly. This is relevant to planning for fostering water supply resilience based on a dynamic cost-effectiveness program to provide water companies and/or governments with a step-by-step plan, outlining the priorities and costs.

2.5. Conclusion

Measuring resilience of water supply system calls for a multifaceted conceptual framework. A resilience measuring framework should address all factors, including the technical, organisational, social, economic, and environmental elements that affect the resilience of water supply. A key challenge is finding how to measure resilience as precisely as possible based on information available from previous earthquakes.

Considering the concept of resilience in a different way is the most significant strength of this approach. It is an accepted fact that community's resilience depends on water supply resilience. However, the water supply resilience, in turn, significantly depend on the community's characteristics and capacities. Instead of considering the impacts of earthquake on various characteristics of the community, the CARE model proposed in this paper considers the influence of characteristics of the community on water supply system serviceability, from when an earthquake happens until the end of recovery phase. CARE model shows various dimensions of water supply resilience and how different capacities of the water supply system and community work to response a disaster.

This paper has presented a quantitative framework for measuring water supply systems resilience. This framework is proposed for community or sub-national level because cities generally have independent water supply systems, although several cities can be fed from one water source, or a number of cities may be located in one basin and use shared sources. Although this framework can be adapted for other urban infrastructures, and even different types of disasters, the adaptation process should be applied carefully and precisely to prevent unforeseen issues such as the infrastructure's recovery priority and its impact on society. The framework was also applied to a hypothetical case to show how it can be used to measure water supply resilience.

Despite the evident strengths of using indicators to measure resilience, there are a number of possible limitations. One issue that should be avoided is the subjective selection of indicators. This is not a particular issue for a resilience index, but could become so in more empirical work, especially multivariate analysis (Briguglio, Lino, 2003). Subjective selection of indicators could result in using redundant indicators. A clear understanding of the objectiveness of the indicators will minimise this problem.

A second concern goes back to the measurement problems outlined. Although data availability, affordability, and accessibility will be checked in this approach, measurement of the indicators will be carried out by different people with different sensitivities who may unwittingly introduce measurement errors. To overcome this issue, firstly knowledgeable and skilful people should be selected to collect data. Secondly, increasing redundancy in data sources and/or the people collecting data can help to increase data collection reliability.

Another difficulty may arise when data is being gathered from the public sector, which could mean it has been exaggerated or downplayed. In these cases, using composite indicators may cause political issues by pitting one community against another. For example, in the case of government aid, lower levels of political and financial support could result for communities who score lower on the index. In this case, the fostering of resilience planning in general or variable prioritisations will not be an issue as the indices in the index are relative. Planners can still use the framework to compare the conditions of different variables to those of other variables, even though the final resilience index may not be highly accurate.

2.6. References

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CHAPTER 3 – TECHNICAL DIMENSION

The current chapter is based on the following article:

Balaei, B., Wilkinson, S., Potangaroa, R., McFarlane, P. (2019) Investigating the Technical Dimension of Water Supply Resilience to Disasters

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3.1. Introduction

While uninterrupted access to safe water is crucial following a disaster, water supply systems are prone to interruption due to disasters. The characteristics of the disaster itself are important factors in the extent of the interruption risk; however, the system's behaviour in coping with the disaster is more significant in the system's functionality (Karamouz. M. et al., 2010).

Risk analysis has historically been the typical method employed to understand a water system's performance in particular circumstances (Hosseini & Moshirvaziri, 2008; Karamouz. M. et al., 2010; Sharma et al., 2014). Although risk analysis models are ideal for studying the water system's single-component behaviour, they may not be the best tool to understand the system's behaviour as a whole in disasters due to the complexity of the system (Davies, 2015; Gay & Sinha, 2012; UNISDR, 2014). Moreover, risk assessment tools often fail to take into account the system's performance over time. To address these issues, the concept of resilience was developed, and a shift took place from a risk assessment approach to one of resilience measurement.

Water supply resilience is defined as the ability of the system to keep functioning acceptably in the wake of a disaster and to recover to a normal level of functionality if decline was experienced due to the disaster (Balaei et al., 2018; Bruneau et al., 2003; Chang & Shinozuka, 2004). While response and restoration activities focus on minimising the system recovery time following a disaster, the mitigation measures aim to enhance the system's resilience by appreciating the ability of the system to withstand a disaster (i.e., system robustness). Increasing the system's robustness not only fosters the system resilience directly, it also impacts on the resilience by affecting system recovery time. In other words, the more robust a water supply system is, the shorter time will be spent on system restoration and recovery. However, Polyethylene (PE) pipe is an exception to the general rule. PE pipes are extremely robust for ground failure but repairing PE pipes takes a long time as they normally need to be fusion welded, which requires a lot of preparation and is time consuming.

Previous literature on the subject shows that a variety of factors affect a water supply system's resilience. These factors are mainly categorised as technical, social, organisational, and economic (Aldrich, 2012b; Bruneau et al., 2003). The technical dimension – which is the subject of this study – refers to the ability of physical components of the system to perform at an acceptable level following a disaster (Bruneau et al., 2003; Pagano et al., 2017). Although these characteristics may affect recovery time, their most significant impact is on the system's robustness (McDaniels et al., 2008).

The technical dimension of infrastructure resilience has been of interest of researchers who have developed a variety of frameworks and models to quantify resilience in systemic approaches (Menoni et al., 2002; Wang & Reed, 2017; Zobel, 2010). While some researchers have studied the dynamic behaviour of water supply systems by modelling it with system dynamics (Pagano et al., 2017; Simonovic, 2009), others have formulated the network-by-network theory focusing on system redundancy as a significant factor in water supply resilience (Di Nardo et al., 2013; Yazdani, A. & Jeffrey, 2011). Qualitative approaches such as expert judgments also have been adopted by researchers to quantify infrastructure resilience (Chang et al., 2014).

Although a considerable number of invaluable studies have already been carried out to measure resilience from the technical perspective, there is a gap in the literature in identifying the technical attributes of the water supply system that impact on the system's resilience. This paper proposes an innovative indicator-based resilience quantification model and utilises a novel framework to identify the technical variables affecting water supply robustness and, consequently, its resilience to disasters. The indicators were gathered through a comprehensive literature review, and then verified and ranked through a series of interviews with water supply and resilience specialists, social scientists and economists. To test the proposed model, the indicators were then measured for a hypothetical earthquake scenario in Pukerua Bay, New Zealand. Awareness of these indicators and their influence on public water supply resilience will enable local authorities to identify existing strengths and weaknesses, and to optimise investment to obtain best results.

3.2.Methodology

The Comprehensive Aggregated Resilience Estimation (CARE) model was utilised in this study to understand the building blocks of water supply system resilience to the impact of disasters (Balaei et al., 2018). The CARE model defines water supply resilience based on the physical attributes of the system and the characteristics of the community the water supply serves. These are organisational, social, and economic factors that can affect water supply robustness and/or restoration rapidity when a disaster happens. Figure 3-1 shows the process for measuring water supply resilience based on the CARE model.

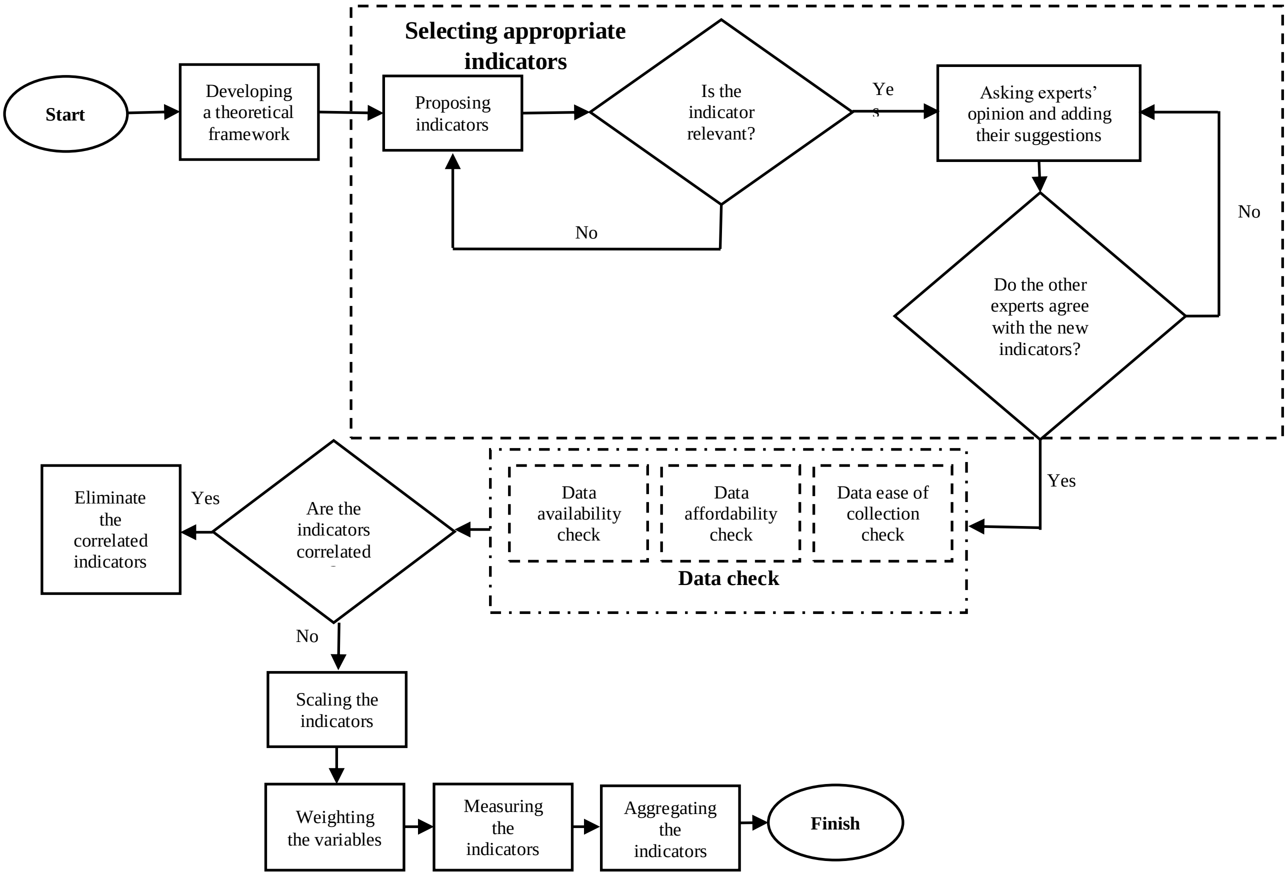

Figure 3-1: Water Supply Comprehensive Aggregated Resilience Measure (CARE) Model (Balaei et al., 2018)

The objective of this research was to identify the technical characteristics of the water system affecting its resilience to disasters. To select appropriate technical indicators to best measure resilience, a theoretical framework was utilised (Balaei et al., 2018). In the first step, potential indicators were identified through a literature review and canvassed in interviews with social science specialists to obtain the most effective social metrics. Next, data availability, affordability, and ease of collection were checked. Data checks help to avoid using indicators that are not cost-effective and, consequently, not feasible. Afterwards, correlation between the collected indicators was taken into account. As a result, the most relevant variables were kept, and highly correlated variables removed.

3.3. State of the art – Water Supply Resilience

Drinking water outage is not the only impact of disasters in urban areas; impacts can include conflagration, interruption to medical services, business continuity disruption, and other disruptions to daily life (AWWA, 2001). The fire following the Kanto earthquake of 1923, which killed ten thousands of people in Tokyo, grew because of a lack of water due to water main breaks and other environmental conditions like wind and high temperatures (Scawthorn et al., 2005). Therefore, availability of water in the aftermath of a disaster is a crucial concern for a variety of decision makers and authorities.

The 2010 Haiti earthquake also showed how challenging it is to provide enough, both quantity and quality of water in the aftermath of a disaster. Prior to this earthquake, only 10% of people had access to potable tap water. The earthquake caused a number of water main breaks. These water mains were repaired within 2 weeks of the earthquake (DesRoches et al., 2011). Nine months following the earthquake in Haiti (which affected over 3.5 million people), cholera broke out and quickly spread across the country (Delva, 2010). The Haitian Ministry of Public Health and Pollution reported 8,534 deaths and just under 700,000 cholera cases (Ministère de la Santé Publique et de la Population, 2014).

The impacts of different disasters on water supply systems are not all the same. While earthquakes can cause widespread pipe breaks, personnel shortages, water well or structural damage, floods threaten water quality and water extraction and conveyance through obstruction in intakes, treatment plants, or transmission systems. Table 3-1 shows the impact of earthquake, flood, volcanic eruption, hurricane, and drought on water supply systems.

Table 3-1: Disasters' Impact on Water Supply Systems (AWWA, 2001; Karamouz. M. et al., 2010; WHO, 2002)

Effect on Water supply	**Earthquake**	**Flood**	**Volcanic Eruption**	**Hurricane**	**Drought**
Personnel shortage	🔴	🟠	🟠	🟠	🟢
Water quality	🟢	🔴	🔴	🔴	🔴
Air contamination	🔴	🟢	🔴	🔴	🟢
Water-well damage	🔴	🔴	🟠	🟢	🟢
Pipe breakage	🔴	🔴	🟠	🟠	🟢
Obstruction in intakes, treatment plants or transmission systems	🟢	🔴	🔴	🟠	🟢
Structural damage	🔴	🔴	🟢	🔴	🟢
Other utilities failure (e.g. power, communication, transport)	🔴	🔴	🟢	🔴	🟢

🔴 Severe Impact 🟠 Moderate Impact 🟢 Minimal Impact

The notion of resilience has captured the attention of a wide range of scholars in diverse disciplines. The concept of community resilience to disasters was proposed in the 21st century although it was introduced by Holing in relation to ecology earlier, in 1973 (Holling, 1973). Klein et al. (2003) define resilience as a desirable property of natural and human systems in face of potential stresses and investigate the concept of resilience in relation to weather-related hazards as an example of natural disasters in coastal megacities. Through their study, Klein et al. (2003) recommend resilience be used in a "restricted sense: to present specific system characteristics that discuss: (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system's self-organisation capability.

A significant number of researchers have developed conceptual frameworks to measure community resilience from various perspectives. According to Norris (2008), resilience can be understood as a set of network adaptive capacities, namely economic development, resource equity, social capital, and information and communication. Similarly, Cutter et al. (2008) proposed the DROP framework and model — Disaster Resilience of Place — to conceptualise disaster resilience at the community level. The DROP model demonstrates how resilience capacities (coping, adaptive, and absorptive) influence the degree of recovery and resilience of the community. It also includes six groups of indicators: ecological, social, economic, institutional, infrastructure and community competence, to quantify a community's overall resilience.

Bruneau et al. (2003) were pioneers in adopting the concept of resilience in infrastructure systems. According to them, infrastructure resilience is a multidimensional concept, integrating technical, organisational, social, and economic dimension that show a system's ability to cope with an external shock and bounce back as quickly as possible. They also proposed a model to quantify resilience based on system performance over time. In their model, resilience is quantified by measuring the system performance from when a disaster happens until the time the system recovers to pre-disaster levels of performance. Built on the same theory, McDaniel et al. (2008) developed a framework to identify the decision types to foster infrastructure system resilience through mitigation and adaptation measures and using flow diagrams.

Another common approach in resilience studies has been through identifying the system's capacities in coping with disasters. Identifying the resilience capabilities (absorptive, adaptive, and restorative), Nan and Sansavini (2017) developed an integrated tool to quantify water system resilience and a hybrid multi-layer modelling to identify the failure behaviour of the lifeline. Cutter et al. (2008) also combined resilience capacities and system vulnerabilities to measure resilience.

Since Hurricane Katrina in 2005, a significant shift has been witnessed in the research literature from protecting lifelines to community's resilience, which is defined as the ability and preparedness of the community to respond to a disaster and recover to a sustainable level (O'Rourke, 2007). A number of studies have proposed metrics to measure water supply resilience to disasters (Cimellaro et al., 2015; Farahmandfar et al., 2016; Makropoulos et al., 2018; Morley, 2012). Some of these studies propose functional measures to quantify resilience in water networks and also propose frameworks to improve water supply network resilience (Farahmandfar et al., 2016; Matthews, 2015).

Recovery of a community is multifaceted, including, but not limited to, the recovery of lifeline systems. Water supply malfunctioning can cause a variety of challenges and increase the number of disaster victims and fatalities. During the 6.8 magnitude Northridge earthquake in the United States in 1994, for instance, approximately 45,000 people had no access to water services and it took 12 days to restore the utility for 99% of residents (Davis et al., 2012; Goltz, 1994; McReynolds & Simmons, 1995). Likewise, more than one million people in the Kobe earthquake in Japan in 1995 lost water services for up to 60 days in some regions (Chung et al., 1996). Table 3-2 shows a number of the impacts of the recent decades' major disasters on water supply systems.

Table 3-2: Disasters' Impact on Water Supply Systems

Disaster	Date	Water availability
Chile earthquake (Chile)	27 February 2010	In some parts of the country (e.g. Talcahuano), almost 100% of people lost water services. Water supply was recovered in 45 days (Eidinger & Tang, 2012).
Kobe earthquake (Japan)	17 January 1995	More than 95% of people lost water in some parts of the city. Water system took about 60 days to get recovered (Chung et al., 1996; Shimazu et al., 2003).
Christchurch earthquake (New Zealand)	22 February 2011	80% of people lost water in the aftermath. Water supply took approximately 35 days to recover (Ministry of Health, 2012).

Tohoku earthquake and tsunami (Japan)	11 March 2011	Approximately 50% of people lost water in the aftermath of the earthquake. 90% of water system was restored in 2 weeks' time and the water system restored completely in 3 weeks (Furumai, 2012).
Northridge Earthquake (United States)	17 January 1994	100% of people in some parts lost water and the water system was restored in 12 days (Davis et al., 2012; Goltz, 1994).
Hurricane Mitch (Latin America)	October 1998	In Honduras, more than 90% of the population were without access to water services in early November; 40% were without access by late November. In Nicaragua, 32% of water service infrastructure was damaged. In El Salvador, 32% of water service infrastructure damaged (WHO, 2002).

Although most of the water supply resilience indicators focus on technical dimensions of resilience (Gay & Sinha, 2012; Jeong et al., 2017; Piratla & Ariaratnam, 2013), a few researchers have broadened their research area to take the other dimensions of water supply resilience, into account. One of these multidimensional studies proposed a combined water supply resilience index to measure the performance of the water distribution network based on technical, environmental, and social dimensions of resilience (Cimellaro et al., 2015). The proposed metric combines three indices of functionality and recovery namely: the number of users who lost water service; the water quantity in tanks; and the water quality. The study also claims that the index can be used by urban planners to estimate water supply system functionality, including the delivery of an acceptable level of service, and post-event restoration processes.

The Sustainable Cities Water Index (SCWI) developed a measure to estimate water sustainability in urban areas and introduces the cities that are best placed to harness water for future success in terms of sustainability (Arcadis, 2016). The SCWI consists of three sub-indices including resiliency, efficiency, and quality. The resiliency sub-index addresses water resources' resilience, water-related disaster risks, and vulnerabilities. According to (Arcadis, 2016), most cities across the world require greater investment and prioritisation to improve their resilience to disasters and unforeseen water shortages.

Research and development is continuing. A City Water Resilience Framework (CWRF) is being developed by Arup Group (Arup, 2018) together with The Rockefeller Foundation to give cities of all sizes a guide to understanding and measuring the resilience of their water systems. The overarching aim of this framework is to create a global standard for water resilience assessment. Aligned with The City Resilience Index (CRI), this framework claims to develop an accessible, evidence-based and measurable way to inform planning, development and investment decisions. Cities from five continents have been selected to contribute to the development of a global framework for water resilience. Amman, Cape Town, Mexico City, Greater Miami and the Beaches, and Hull were selected due to their diversity in terms of size of population, geographic location and economic status to represent the range of water challenges facing cities around the world (Cities, 2018).

This paper measures the water supply resilience on the basis of system functionality over time. Although some researchers have proposed a variety of system attributes such as robustness, redundancy, rapidity, and resourcefulness (Bruneau et al., 2003), or robustness and redundancy (Hwang, Hwee et al., 2013), this study argues that only robustness and recovery rapidity are the fundamental system attributes that affect system functionality following a disaster (Balaei et al., 2018). Robustness shows the system's ability to withstand the disaster while recovery rapidity shows its ability to return to a new normal level, which can be different from a pre-disaster normal.

3.4. Defining Water Supply Robustness

Bruneau et al. (2003) first introduced robustness along with rapidity, resourcefulness, and redundancy as four elements of infrastructure resilience to seismic events. Although resourcefulness and redundancy are important factors, they have indirect impacts on system resilience by influencing on robustness or recovery rapidity and as such, they have been removed from the principle elements of system resilience by other researchers (Balaei et al., 2018; McDaniels et al., 2008). Defined as a topological quality of water supply system, structural robustness presents water system performance immediately after a disaster. In other words, robustness refers to the ability of the water supply system to withstand a disaster without losing considerable levels of system performance. Water system performance is not a solid concept and can be defined with reference to what characteristics of the water system are more significant for the researcher/decision maker. Functionality of the physical system (e.g., the number or percentage of customers served) and levels of service are the most common attributes of system performance being used to measure robustness and resilience.

Robustness and recovery rapidity need to be measured to be able to quantify resilience of the water supply system. Robustness and recovery are functions of a variety of factors with technical, organisational, social, and economic dimensions. These factors dictate a water system's capacity to cope in a disaster. To measure resilience, these factors need to be identified. This paper aims to identify the technical factors than can affect water system resilience. Although technical factors can potentially affect both robustness and rapidity, their influence on system robustness is significantly higher than the system's recovery rapidity. Therefore, this paper focuses on identifying the technical factors enabling us to measure the water system's robustness.

Water supply resilience is a function of numerous factors of different dimensions. Even the value of technical factors is dependent on organisational or economic variables such as disaster mitigation and emergency response plans or the country's state of economic development (WHO, 2002). However, technical factors have the most significant impact on water systems' resilience through affecting system robustness. Lack of water system robustness in disasters will mean loss of water downstream and can cause water contamination, reduction in firefighting capabilities, and flooding problems. Lack of robustness not only imposes economic pressure on the water companies, it can also cause social inconvenience and have environmental impacts (Berardi et al., 2008).

Community factors, such as organisational, social and economic variables, influence post-disaster recovery rapidity. In two hypothetical scenarios, in which the community factors are assumed to be similar, robustness has a direct impact on resilience; the scenario with the more robust network is more resilient since, between two scenarios with similar recovery rapidity rates, the one with higher offset (i.e., robustness) will reach the target performance faster. Figure 1 gives a schematic view of these hypothetical scenarios: In both scenarios, a disaster happens at t_0, where scenario 1 has robustness 1 < robustness 2 in scenario 2, and the recovery rates are assumed to be similar. Clearly, the time to restore full functionality of the network in scenario 2 is shorter than in scenario 1, and the resilience as the ratio of the shaded area to the total is higher in scenario 2. One should note in a more robust network, the community factors may have more positive effect on the recovery rapidity which can result in a more resilient system. In other words, the robustness and recovery rapidity may well be correlated. Figure 3-2 gives a linear approximation of resilience (the area under the recovery with respect to time) for a disaster at time t_0, under three different scenarios with recovery times t_1, t_2 and t_3. Note that the resilience with recovery times t_1 and t_2 has the same slope (i.e., recovery rate) with different offsets (i.e., different levels of robustness at time t_0). Scenario 3 has the same robustness as scenario 2 with a faster recovery rate.

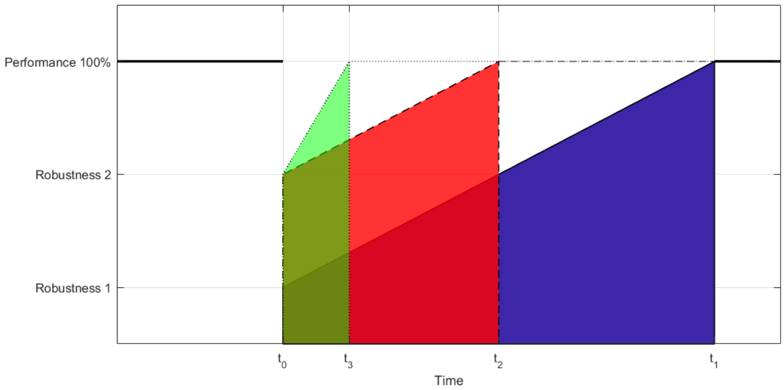

Figure 3-2: Linear Approximation of Resilience (the area under the recovery with respect to time) for a Disaster at Time t_0, under Three Different Scenarios

Although there is no agreed threshold for robustness, Shinozuka et al. (2003) claim that an ideal water supply system preserves 80% of its pre-disaster functionality immediately after a disaster. In other words, a water supply system is considered robust if it does not lose more than 20% of its performance following a disaster.

Identifying appropriate indicators to measure robustness is a key challenge in the area of resilience building. Indicators have been used to measure a variety of variables for eight decades. Generally, indicators are tricky as they measure only a limited number of parameters while other parameters can be neglected especially when the system is complicated. However, indicators give a tangible measure to the planning and investment decision makers to evaluate the current condition and enable them to understand the need for improvement action.

The following characteristics were tested for the indicators in order to select them (Birkmann, Jorn, 2006a; Mainz, 2003):

- Agreed definitions: the indicators need to be unique in terms of definition to avoid ambiguity.
- Precise: the indicators need to be precisely defined in clear terms.
- Specific and sensitive: the indicators need to describe clearly and exactly what is being measured. They also need to be sensitive enough to react when input data vary.
- Valid and reliable: need to be consistently measured over time and between data collectors.
- Discriminative: the indicators should not be correlated.
- Evidence-based: the indicators are collected based on the literature and lessons learnt from previous disasters.

Water system vulnerability, pipe redundancy, pipe criticality, and water infrastructure interdependency with other utilities such as power have been identified affecting the water supply system robustness. Power blackouts can stop water pumping through the pipes and serving residences with water. Water system recovery rapidity is also dependent on telecommunication system functionality and transport infrastructure connectivity (refer to Tang and Eidinger (2013) as an example). However, other utilities are considered as exogenous factors in this paper. Exogenous factors can be omitted as they cannot be controlled or manipulated. Therefore, the interdependencies between other infrastructures are not envisaged in this paper. The following sub-sections explain how system vulnerability, pipe redundancy, and system criticality can affect water supply robustness to disasters.

3.5. Vulnerability

Although water system vulnerability assessment tools have been widely used since 1970s (Hashimoto et al., 1982), researchers identified that vulnerability of systems is not the only important factor in understanding the system’s condition in coping with disasters. As a component, vulnerability has the most significant impact on water system’s robustness insofar as some researchers have defined robustness as the system’s invulnerability (Wang & Reed, 2017).

Infrastructures' vulnerability to disasters were significantly developed in the 1990s (Menoni et al., 2002). A number of water system vulnerability assessment methods were developed by institutes. The Applied Technology Council (ATC) was a pioneer in developing a seismic model in 1991 (ATC, 1991). Funded by the Federal Emergency Management Agency (FEMA), ATC-25 utilised Damage Probability Metrics (PDMs) based on Modified Mercalli Intensity scale (MMI) as the earthquake index (instead of magnitude) to estimate the number of pipe breaks per kilometre.

The other model developed to evaluate water system vulnerability to disasters is Hazard HAZUS. HAZUS was developed by FEMA, co-founded with the National Institute of Building Sciences (NIBS), to estimate damage due to earthquake, flood, or hurricane in the United States (Kircher et al., 2006; Scawthorn et al., 2006; Vickery et al., 2006). HAZUS has a GIS platform to apply the vulnerability assessment methodology to water systems and other structures and lifelines and enables the user to overlay the required GIS layers and conduct a complex analysis. The software contains the United States' base-maps that makes it difficult to utilise in other countries. Several European teams and seven European cities also combined their knowledge and experience and developed a methodology called RISK-UE to estimate seismic damage to buildings and lifelines, including water systems, which are designed and constructed within Europe (Milutinovic & Trendafiloski, 2003).

Apart from the methodologies and tools created by organisations, individual researchers have also conducted studies on water supply vulnerability assessment (Schiff & Buckle, 1995). A number of researchers have developed systemic approach to lifelines (Menoni et al., 2002), while others have focused on single components (Shinozuka, Masanobu, 1986). Among all water supply components, most studies were dedicated to water pipes (Kettler & Goulter, 1985; Yazdani, A. & Jeffrey, 2011); although other components (e.g., pumps and treatment plants) have been of particular concern for researchers over the last three decades (Kawamura, 2000; Lindell & Perry, 1997).

When a water pipe runs out of functionality – either due to breakage or blockage – the downstream user may lose water as their connectivity to the water source can be destroyed. Using the percentage of users receiving water services following a disaster as a metric for resilience and robustness, damaged water pipes can cause users to be without water. As the number (and percentage) of the households losing water increases, robustness, and subsequently resilience, declines.

3.6. Redundancy

Traditionally, water networks are designed to minimise construction and operation costs. In addition to the economic constraints, the area's geography and other circumstances can determine the network configuration (Swamee & Sharma, 2008). Water supply systems can be configured as branch, gridiron, or ring and radial networks. Branch networks are not desirable because of water distribution reliability and water quality considerations. In contrast, gridiron, ring and radial configurations are preferred by water network designers and water companies as the inherent redundancy in these configurations provide higher water provision reliability and resilience.

Graph theory has been the most common tool in analysing water network redundancy (Kleiner, 1997; Ostfeld & Shamir, 1996; Ostfeld, 2005). Topological redundancy in water distribution networks is defined as the existence of alternative paths to provide water to a particular node (Di Nardo et al., 2017) that can be used to address water demand when the main path is disrupted (Goulter, 1987). In addition to the topological redundancy, energy redundancy is a significant factor in water supply systems. A number of hydraulic characteristics of the network such as flow and head are essential to design and manage the water system in compliance with the water supply level of service. In the aftermath of a disaster, water companies try to pump water into the pipes to build positive pressure to avoid water contamination due to backflow. Water backflow, especially in the aftermath of a disaster, imposes serious risk of water resource contamination. The contamination can enter water pipes through the cracks and breaks where other sources of pollution (such as broken sewerage pipes) are in the vicinity of the broken water pipe. Therefore, this study focuses on topological redundancy to simplify the model and assuming constant positive pressure within the water pipes.

3.7. Criticality

A variety of definitions have been provided for the concept of criticality based on the requirements of each lifeline. Representing the greatest risk to the system, criticality can be defined based on different factors such as financial, loss of levels of service or functionality, environmental impact, and safety, etc. While some researchers have defined criticality as the dependency of communities' daily activities on specific utilities (Oh et al., 2012; Smith, R. & Mobley, 2011), others have defined it as the importance level of a utility's component (e.g., a pipe) in terms of cost and energy expenditure for repairs (Piratla & Ariaratnam, 2011). Taking the relevant definitions into account, this paper defines the criticality of each component of the water system by the number of users losing water services following a disaster.

Criticality analysis allows water companies to identify the consequence of water asset and severity of asset failure when a disaster happens. To assess water system components' criticality, all assets should be compared against the same set of criteria. The severity of asset failure can be measured on a qualitative or a quantitative scale. Extracted through interviews or questionnaires, the qualitative approach usually focuses on asset operators and technicians' observations and opinions (Márquez, 2007). In contrast, quantitative water asset criticality assessment can be made by measuring the number of users losing water service when the asset fails. The more users losing water, the more critical will the asset be.

Estimating Robustness

Hazard and water supply system information are required to assess the vulnerability of the water system. Pipe criticality is calculated based on water system and demographic information. Redundancy is evaluated based on water system information. Figure 3-3 shows the water supply system robustness evaluation framework.

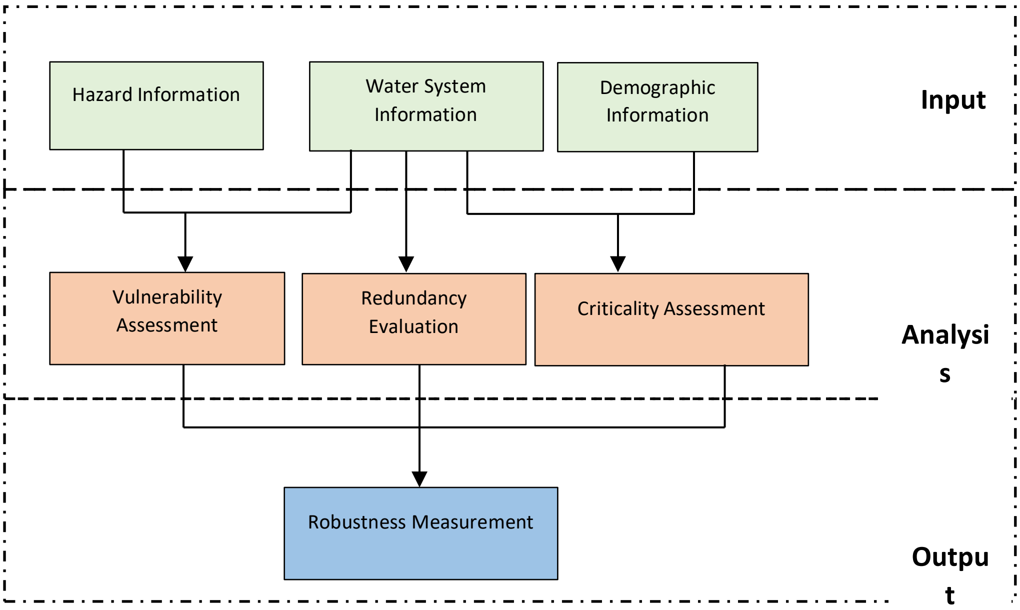

Figure 3-3: Water System Robustness Evaluation Framework

Although most researchers and consultants assess asset criticality based on either of the qualitative or quantitative approaches, a mixed approach can give the most accurate results. In reality, water companies suffer from a lack of accurate data in their GIS systems for a variety of reasons such as lack of metadata standard, data gathering or entrance mistakes, etc. The preferred approach in this study is to quantitatively assess asset criticality and then reviewing the criticality ranking by an experienced field operator or technician.

A water supply network can be partitioned to *N* subsectors. In that case, we assume that the vulnerability, criticality, and redundancy of each pipe can be estimated as a constant on average. Then, the robustness of the subsector *i, i=1, …, N* is defined as:

$$R_i = 1 - \frac{V_i.C_i}{\rho_i} \qquad (1)$$

Where R_i is robustness, V_i is vulnerability, C_i is criticality and ρ_i is the redundancy estimates for the subsector ***i***. the robustness of the water system network is defined as a weighted average of:

$$R = \frac{\sum_i^N R_i.Length_i}{\sum_i^N Length_i} \qquad (2)$$

3.8. Case study – Pukerua Bay

The Wellington region is located in an earthquake-hazard-prone area with active faults and ground failure susceptibility. Among all faults under and around the Wellington region, the Wellington Fault is considered to be the most devastating one with M_w 7.6 and a probable intensity of MM10 for Wellington City and Hut City and MM9 for the remaining urban areas such as Upper Hutt and Porirua City (Cousins et al., 2012). The Wellington region consists of 4 cities: Wellington City, Upper Hutt, Hutt City, and Porirua City.

Although the rainfall averages 1205 mm per annum in Porirua City (including Pukerua Bay), water restrictions are considered serious. As an example, Porirua City Council encourages residents to find ways to use less water during dry periods (Porirua City, 2018b). Wellington Water also encourages people to store 20 litres of water per person per day for at least 7 days as an individual capacity to cope in the first days following disasters. People are also encouraged to purchase 200 litre water tanks from the Porirua City Council. It has been decided to install two drinking water tanks on the west and east side of the Ohariu Fault which is considered as a potential for earthquake as it runs through the middle of the Porirua region.

The water tank proposed for the east side will provide 11.3 million litre capacity while the tank proposed for the west side will provide approximately 3-5 million litre capacity and service Takapūwāhia and wider Titahi Bay areas (Scoop Independent News, 2018).

The population as of June 2017 was 55,900 (Stats NZ, 2018) including 2000 residents of Pukerua Bay (CensusPorirua, 2014). Wellington Water is responsible for supplying water to Porirua City. Porirua has no water source of its own and a single transmission water pipe supplies water to the City from Hutt Valley. Approximately, 88% of people had access to centralised drinking water as of 2017. Although almost 80% of Pasifikas have no complaint, only 63% of Maoris appear satisfied with water management and the overall water management performance is 71% (Porirua City, 2018a).

Figure 3-4 shows water pipes diameter and material in Pukerua Bay. Pukerua Bay contains 18 km of drinking water pipes varying in material, diameter and age. Approximately 64% of Pukerua water pipes are Asbestos Cement (AC) while 22% are PVC and 6% are polyethylene (PE). As expected, the majority of water pipes (82%) have a diameter of 150 mm or less.

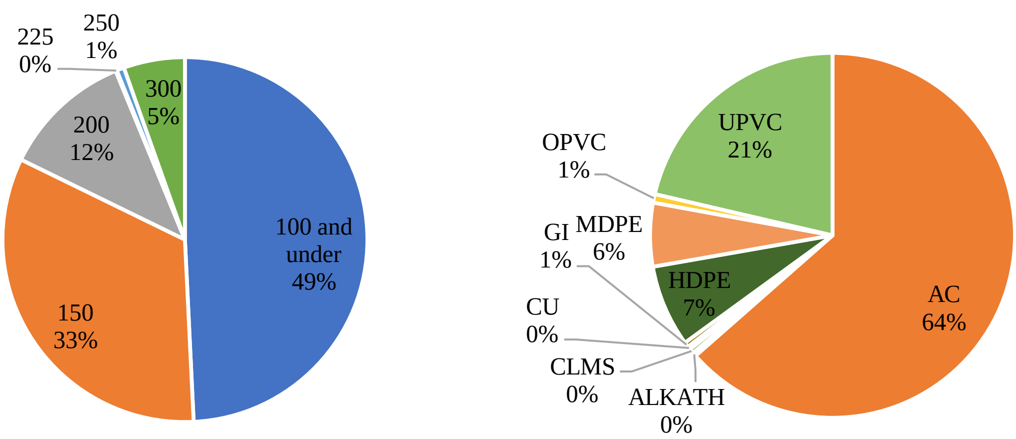

Figure 3-4: Pipe Material and Diameter Distribution in Pukerua Bay

A Wellington fault M7.6 earthquake with an epicentre in Thorndon is considered as the base scenario (Cousins et al., 2012). An earthquake of this magnitude will cause fault ruptures, earthquake-induced landslides, liquefaction and lateral spread. This scenario has a typical return period of 800 years to 1,100 years. Rupture of the fault is expected to cause a surface rupture with 4-5 m horizontal displacement and 1-2 m in vertical displacement (Begg & Johnston, 2000). Apart from the Wellington Fault which can cause severe ground failures, the rupture of the Ohariu Fault which crosses through Pukerua Bay could cause very severe pipe breaks in the region. Therefore, the Ohariu Fault and potential impacts on the water system have also been identified.

Earthquakes could also cause slope failures in Pukerua Bay such as that observed in the 2016 Kaikōura earthquake and the 2010-2011 Canterbury earthquakes in the Port Hills of Christchurch in New Zealand. Information on the earthquake-induced slope failure hazards for the Wellington Region were obtained from Brabhaharan (2000) which is the most up-to-date study in the Wellington region. Brabhaharan (2000) assessed the susceptibility of the slopes on a regional scale for a magnitude 7.5 earthquake on the Wellington Fault.

Although above-ground water supply facilities may suffer from ground shaking, buried pipelines are mostly affected by ground failure induced by an earthquake such as liquefaction, slope failure, or fault rupture (Zohra et al., 2012). Water infrastructure located within the areas susceptible to slope failure or fault rupture (Ohariu Fault) will be prone to damage. Generally, Pukerua Bay is not prone to liquefaction except for a small area between Pukerua Bay and Porirua City. Water pipes ground failure damage is measured based on Table 3-3.

Table 3-3: Ground Failure Impact on Water Pipelines

Ground Damage	Grade	Fault Rupture	Slope Failure	Liquefaction
No damage	0	-	No slope failure induced damage.	No liquefaction induced damage.
Low	1	-	Minor / rare slope failure damage.	Minor subsidence with low pipe damage.

Moderate	2	-	Moderate slope failure damage.	Moderate subsidence with deeper liquefaction, with enhanced pipe damage.
Significant	3	-	Slope deformation leading to localised deformation or damage to pipeline.	Large subsidence with shallow liquefaction leading to significant damage and potential intrusion of sand silt into pipeline.
Severe	4	Adjacent deformation zone with extensive ground deformation, leading to severe pipe damage. (20 m to 50 m of fault trace)	Failure of slope in sections with metres of displacement, leading to loss of some sections of pipeline.	Lateral spreading with tens to hundreds of millimetres of displacement with severe damage to pipeline.
Very Severe	5	Rupture zone with metres of displacement leading to complete damage of pipeline. (5 m to 20 m of fault trace)	Failure of slope with metres of displacement, leading to complete damage to pipeline.	Extensive lateral spreading leading to metres of displacements leading to complete damage to pipeline.

A water supply criticality criteria matrix was designed specifically for Pukerua Bay reflecting the population of the Bay to identify each link's importance in terms of the number of users being served with (Table 3-4).

Table 3-4: Pukerua Bay Criticality Criteria

Grade	Description	Population Bands
1	Very low	Very low (0-50 people)
2	low	Low (51-200 people)
3	Medium	Moderate (201-500 people)
4	High	High (501-1,000 people)
5	Very high	Very high (>1,000 people)

Water system redundancy is defined from no redundancy (grade=5) to very redundant (grade=1). Table 3-5 shows water system redundancy grading defined in this study. Robustness bands are also defined following Shinozuka et al. (2003) as per Table 3-6.

Table 3-5: Water System Redundancy Grading

Grade	Description
1	Very Redundant
2	Redundant
3	some Redundancy
4	Low Redundancy
5	No Redundancy

Table 3-6: Water System Robustness Bands

Description	Population Bands
Robust	Robustness ≥ 80%
Significant Robustness	61 ≤ Robustness < 80
Moderate Robustness	41 ≤ Robustness < 60
Low Robustness	21 ≤ Robustness < 40
Very Low Robustness	Robustness ≤ 20

Due to the topography of Pukerua Bay, the water network is a configured branch. As such, redundancy is relatively low in the Bay's water network. In summary, 4.8 km and 5.0 km of water pipes in Pukerua Bay are prone to slope failure and fault rupture, respectively. Robustness of Pukerua Bay water pipes is analysed as per equations 1 and 2:

$$R = \frac{\sum_i^N R_i.Length_i}{\sum_i^N Length_i} = 82.7\%$$

Estimations show that Pukerua Bay's water supply system is robust. However, disruption of the water transmission pipe (Southeast of the Bay) which provides Pukerua Bay with reliable water can cause serious problems for the bay. The transmission pipe is not only vulnerable to slope failure, it is the most critical pipe for the bay with no redundant pipe that can replace it while it is being repaired following an earthquake. Furthermore, the bigger the pipe is in terms of diameter, the longer its restoration will take and subsequently, the lower its resilience will be. As such, extra attention needs to be paid to the Bay's water transmission pipe. When investing to foster the pipe's resilience, it should be noted that decreasing vulnerability is not necessarily the key to increase resilience. Other options such as increasing transmission pipe's redundancy may be a more efficient and cost-effective approach, depending on the case. Table 3-7 shows a sample of water network robustness analysis in Pukerua Bay.

Table 3-7: A sample of Pukerua Bay Water System Robustness Analysis

FID	Dia	Age	Pipe Length	Pipe Type	Unit Type	Buffer Distance	LQ Severity	SF Severity	FR Severity	C	ρ	Robustness (1-100)
145	100	35	395	AC	WATER	0	3	5	0	1	5	80.0
202	100	35	208	HDPE	WATER	0	3	5	0	1	5	80.0
283	100	35	182	AC	WATER	0	3	5	0	1	5	80.0
303	450	35	450	AC	TRUNK	0	0	6	0	5	5	0.0
54	150	36	12	AC	WATER	0	2	4	0	1	1	96.8
61	200	38	0.5	AC	TRUNK	0	2	4	0	1	1	96.8
62	300	38	4.4	AC	TRUNK	0	2	4	0	1	1	96.8
72	150	35	25	AC	WATER	0	2	4	0	2	5	68.0
76	150	36	3	AC	WATER	0	2	4	0	1	1	96.8
77	150	36	223	AC	WATER	0	2	4	0	2	5	68.0
80	100	35	1	CLMS	WATER	0	2	4	5	2	5	60.0
0	50	38	18	HDPE	RIDER	50	0	0	0	1	1	100.0
1	100	38	19	UPVC	WATER	50	0	0	5	1	5	80.0

Although the system is defined significant robust based on table 6, it is falling in the left tail of the band (61%-80%). This means that Pukerua Bay water system needs further attempts to become robust and subsequently, resilient to earthquake. Figure 3-5 shows water network robustness in Pukerua Bay.

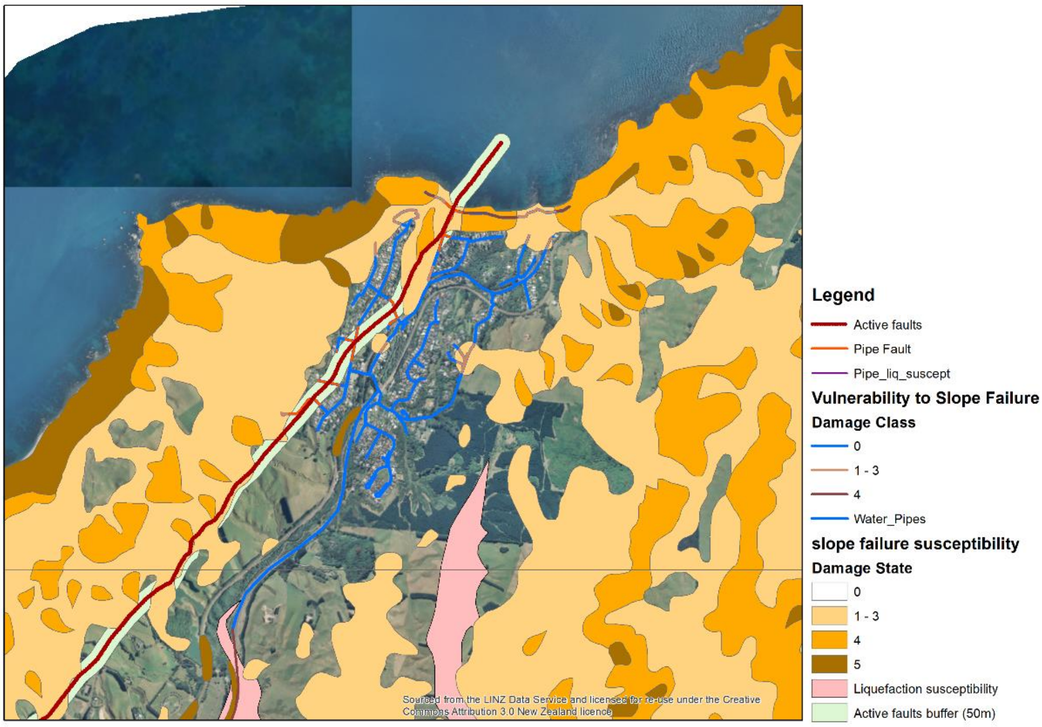

Figure 3-5: Pukerua Bay Water System Robustness

3.9. Conclusion

Water supply resilience is a significant challenge for communities prone to disasters. This paper introduced an innovative framework in analysing water supply resilience and its dependency for the community it is functioning in.

The CARE model was utilised to develop a multidimensional approach in measuring water supply resilience. This model brings technical, organisational, social, and economic dimensions together to identify which factors and variables affect water supply resilience. The indicators were gathered through a comprehensive literature review, verified and weighed through a series of interviews with water supply personnel, resilience, social science specialists, and economists. Finally, the model was applied to Pukerua Bay in Porirua, Wellington, New Zealand as a case study to verify the model.

Application of the model in the Pukerua Bay water network shows that the Bay suffers from lack of robustness in 3 general areas: transmission line to the Bay; pipelines alongside the Ohariu Fault; and the pipeline serving people in the north of the Bay. The water system is identified robust; however, the water transmission pipe feeding the bay is highly vulnerable to slope failure. High criticality and lack of redundancy make the transmission pipe extremely low robust. As such, applying appropriate measures to increase the Bay water transmission pipe’s robustness and subsequently resilience is recommended.

Although the model is tested for earthquakes in this paper, it can be applied for any other disaster as long as the water system’s vulnerability to that disaster is identified.

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3.11. References

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CHAPTER 4 – SOCIAL DIMENSION

The current chapter is based on the following article:

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4.1. Introduction

Post-disaster water supply has always been of crucial concern for decision makers and governments in disaster-prone countries (Makropoulos et al., 2018). The resilience of communities as a whole, and their infrastructure including health systems and firefighting capacity, depends on water serviceability after disasters. However, the common strategy following disasters has been to strengthen the physical infrastructure (by renewing water pipes, reinforcing facilities, etc.), without reference to the social, economic and organisational factors that can influence post-disaster recovery.

While community resilience is defined as the aggregated ability of a geographically defined area to handle an external shock and subsequently resume everyday life (Aldrich & Meyer, 2015), water supply resilience in conjunction with community is defined as the physical status of water supply system and social, organisational, and economic capacity of the community to withstand the disaster and recover to a normal level of functionality in a timely manner (Balaei et al., 2018). In studying resilience of water supply to disasters, the physical characteristics of the system is not the only dimension that can affect/be affected by the disaster. Economic state of the community, organisational well-being and preparedness, and social capacities of the community can affect water supply resilience significantly.

While physical strengthening fosters water supply resilience to disasters by increasing system robustness, the role of social capital in bouncing back after disasters is often neglected. In addition, despite its benefits, physical strengthening has a number of drawbacks when undertaken without considering social capital. First, it cannot eliminate the vulnerability of infrastructure to all disasters and, regardless, it is never sufficient without consideration of the social variables. Second, budgetary, construction, and transport constraints make physical strengthening of water supply ineffective in a variety of geographical conditions (e.g. remote rural areas). Finally, national expenditure on disaster mitigation measures varies with political cycles, not according to criticality or necessity (Healy & Malhotra, 2009).

Lessons learnt from previous disasters reveal that societies with higher social capital recover more quickly after disaster regardless of the extent of damage or their economic resources (Aldrich, 2012a). In 2004, the Indian Ocean tsunami destroyed hundreds of villages in a number of countries and caused over 200,000 fatalities (Srinivas & Nakagawa, 2008). Despite heavy damage, some villages were able to rebuild with support from domestic and international organisations (Aldrich, 2012a). Thus, while some communities continued to suffer from the tsunami and its adverse consequences, others recovered quickly and restarted their businesses. When a 6.9 M_w earthquake hit Kobe in Japan in January 1995, the disaster response teams mobilized within the city only slowly (Aldrich, 2011). As a result, the residents were first on the incident scene and had to deal with the fires following the earthquake (Shaw & Goda, 2004; Tsuji, 2001). They self-organised into civilian corps to fight the fires that commonly follow earthquakes as a result of gas release and explosion (Murosaki, 2007).

Although one can reasonably argue that the recovery of the water supply system is different to the recovery of living spaces and businesses, this view cannot be generalized to all societies and circumstances. Water supply in most countries is subject to specific standards and regulations and lay people are not allowed to intervene to install or repair water systems.

However, in the case of disaster, governments are generally willing to utilise capable people living in the locality to facilitate water system recovery for a number of reasons, including lack of recovery crews, remoteness of the areas affected, or inaccessibility due to road closures. Involving local people in the reconstruction of water supply can also contribute to strengthening sense of efficacy and purpose, thus capitalising on the community spirit and collective actions commonly observed following disasters (Dionisio & Pawson, 2016).

Restoration and recovery personnel are often neglected in disaster resilience studies, even though having an adequate number of recovery personnel in the aftermath of disaster is crucial for a rapid recovery (Davis, 2008). However, the more devastating the disaster is, the fewer trained and knowledgeable personnel will be available in the aftermath. Recovery crew are reluctant to leave their families when they feel it is not safe to do so. In Concepción City in Chile, water supply restoration personnel did not want to work due to the chaos following the earthquake in 2010, and the need to mobilize restoration crews from other cities delayed the recovery process for a few days (ASCE) (Tang & Eidinger, 2013). After the Christchurch earthquakes, Canterbury's contribution to Small and Medium Enterprise (SME) employment in New Zealand fell to its lowest levels in 2011 (when the earthquake happened) and in 2012, at 12.3% and 12.4% respectively. A portion of this decline (including in the water sector) was because of the numbers of employees moving to other cities for safety reasons (IRD, 2015).

This paper proposes a framework to identify the social variables affecting water supply resilience to disasters. The indicators were gathered through a comprehensive literature review, and then verified and ranked through a series of interviews with water supply and resilience specialists, social scientists and economists. The identified variables have been analysed qualitatively and quantitively considering their nature, availability, and metrics. The indicators were then measured in two case studies namely Christchurch (New Zealand) and Concepción (Chile) and the cases compared. Awareness of these indicators and their influence on water supply resilience in society will enable local authorities to identify existing strengths and weaknesses, and to optimise investment to obtain best results.

4.2.Literature Review

4.2.1. Water Supply Resilience

Drinking water outage is not the only impact of seismic events in urban areas; impacts can include conflagration, interruption to emergency and medical services and business continuity, and other disruptions to daily life (AWWA, 2001). For example, following the 1923 Kanto earthquake, which killed tens of thousands of people in Tokyo, fires developed because of a lack of water due to water main breaks and other environmental conditions like wind and high temperature (Scawthorn et al., 2005). Therefore, availability of water in the aftermath of a disaster is a crucial concern for a variety of decision makers and authorities.

The notion of resilience has captured the attention of a wide range of scholars in diverse disciplines. The concept of community resilience to disasters was first proposed in the 21st century, although it was introduced earlier by Holling in relation to ecology (Holling, 1973). Klein et al. (2003) define resilience as a desirable property of natural and human systems in the face of potential stresses. They investigated resilience in relation to weather-related natural disasters in coastal megacities, and recommended that resilience be used in a "restricted sense" to describe specific system characteristics concerning (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system's self-organisation capability (Klein et al., 2003).

A significant number of researchers have developed conceptual frameworks to measure community resilience from various perspectives. According to Norris, Stevens, Pfefferbaum, Wyche, and Pfefferbaum (2008), resilience can be understood as a set of network adaptive capacities, namely economic development, resource equity, social capital, and information and communication. Similarly, Cutter et al. (2008) proposed the DROP framework and model – Disaster Resilience of Place – to conceptualize disaster resilience at the community level. The DROP model demonstrates how resilience capacities (coping, adaptive, and absorptive) influence the resilience and degree of recovery of a community. It also includes six groups of indicators: ecological, social, economic, institutional, infrastructure and community competence, to quantify a community's overall resilience.

Recovery of a community is multifaceted, including but not limited to the recovery of lifeline systems. Water supply malfunction can cause a variety of challenges and increase the number of disaster victims and fatalities. During the 6.8 magnitude Northridge earthquake in the United States in 1994, for instance, approximately 45,000 people lost access to water services and it took 12 days to restore the utility for 99% of these residents (Davis et al., 2012; Goltz, 1994; McReynolds & Simmons, 1995). Likewise, following the Kobe earthquake in Japan in 1995, more than one million people lost water services, for up to 60 days in some regions (Chung et al., 1996). Table 3-2 shows a number of the impacts of major disasters on water supply systems in recent decades.

Table 4-1: Disaster impacts on water supply systems

Disaster	Date	Country	Water availability	Reference
Chile earthquake	27 February 2010	Chile	In some areas (Talcahuano), almost 100% of people lost water services. Water supply was recovered in 45 days.	(Eidinger & Tang, 2012)
Kobe earthquake	17 January 1995	Japan	More than 95% of people lost water in some parts of the city. Water systems took about 60 days to restore.	(Chung et al., 1996; Shimazu et al., 2003)
Katrina Hurricane	23rd August 2005	U. S. A.	More than a million people lost water following the hurricane. Approximately 85% of water system was restored in 47 days following the disaster. After 97 days, 95% of drinking water system was operational.	(Copeland, 2005)
Christchurch earthquake	22 February 2011	New Zealand	80% of people lost water in the aftermath. Water supply took approximately 35 days to recover.	(Ministry of Health, 2012)

Disaster	Date	Country	Water availability	Reference
Tohoku earthquake and tsunami	11 March 2011	Japan	Approximately 50% of people lost water in the aftermath of the earthquake; 90% of the water system was restored by 2 weeks, and the water system was completely restored by 3 weeks.	(Furumai, 2012)
Northridge earthquake	17 January 1994	U.S.A.	100% of people in some areas lost water and the water system took 12 days to recover.	(Davis et al., 2012; Goltz, 1994)
Hurricane Mitch	October 1998	Honduras	>90% of the population were without access to water services in early November; 40% were without access by late November	(WHO, 2002)
		Nicaragua	32% of water service infrastructure damaged	
		El Salvador	32% of water service infrastructure damaged	

Since Hurricane Katrina in 2005, there has been a significant shift in focus in the research literature from protecting lifelines to community resilience, which has been defined as the ability and preparedness of the community to respond to a disaster and recover to a sustainable level (O'Rourke, 2007). A number of studies have proposed metrics to measure water supply resilience to disasters (Cimellaro et al., 2015; Farahmandfar et al., 2016; Makropoulos et al., 2018; Morley, 2012). These include functional measures to quantify resilience in water networks and also frameworks to improve water supply network resilience (Farahmandfar et al., 2016; Matthews, 2015).

Although most water supply resilience indicators focus on technical dimensions of resilience (Gay & Sinha, 2012; Jeong et al., 2017; Piratla & Ariaratnam, 2013), a few researchers have broadened their approach to take other dimensions of water supply resilience into account. One multidimensional study proposed a combined water supply resilience index to measure the performance of the water distribution network based on technical, environmental, and social dimensions of resilience (Cimellaro et al., 2015). The proposed metric combines three indices of functionality and recovery, namely: the number of users who have lost water service, the quantity of water in tanks, and the water quality. The authors claim that the index can be used by urban planners to estimate water supply system functionality, including the delivery of an acceptable level of service, and post-event restoration processes.

Pagano et al. (2018) developed a multifaceted approach to measure resilience of hard (physical systems such as water) and soft infrastructure (such as social capital) and their interaction by means of graph theory and social network analysis and applied their model to assess infrastructure resilience during L'Aquila earthquake in 2009. In another study, Labaka et al. (2016) developed an integrated framework on the basis of empirical findings and expert judgments to measure critical infrastructure resilience. The framework consists of three phases as identification of resilience policies, development of the influence table and development of methodology for applying the resilience policies in critical infrastructure. This study benefits from ac predecessor empirical study that applied the framework in a nuclear plant to improve its resilience (Labaka et al., 2015).

The Sustainable Cities Water Index (SCWI) is a measure to estimate water sustainability in urban areas and has been used as the basis to identify global cities that are best placed to harness water for future success in terms of sustainability (Arcadis, 2016; Arcanjo, 2018). The SCWI consists of the three sub-indices of resiliency, efficiency, and quality, which impact water-related disaster risk and vulnerability as well as overall sustainability. According to Arcadis (2016), most cities across the world require greater investment and prioritisation to improve their resilience to disasters and unforeseen water shortages.

A City Water Resilience Framework (CWRF) is being developed by the Arup Group (Arup, 2018) together with the Rockefeller Foundation to give cities of all sizes a guide to understanding and measuring the resilience of their water systems. The overarching aim of this framework is to create a global standard for water resilience assessment. Aligned with the City

Resilience Index (CRI), the intention is to provide an accessible, evidence-based and measurable way to inform planning, development and investment decisions. In a further development, cities from five continents are being used as the basis for a global framework for water resilience. Due to their diversity in terms of size of population, geographic location and economic status, Amman, Cape Town, Mexico City, Greater Miami and the Beaches, and Hull were selected to represent the range of water challenges facing cities around the world (Cities, 2018).

The study reported in this paper measured water supply resilience on the basis of system functionality over time. Although other researchers have proposed a variety of system attributes, such as robustness, redundancy, rapidity, and resourcefulness (Bruneau et al., 2003), or robustness and redundancy (Hwang, Hwee et al., 2013), we argue that robustness and recovery rapidity are the fundamental system attributes affecting system functionality following a disaster (Balaei et al., 2018). Robustness shows the system’s ability to withstand the disaster and recovery rapidity demonstrates its ability to return to a new normal level that can be different from pre-disaster normal.

4.2.2. The Role of Social Capital in Disaster Resilience

Social capital is defined as the resources rooted in one’s social networks that can be accessed or deployed through bonds and connections in these networks (Lin, 2001). It also refers to the aspects of social structure of value to social actors that can be mobilized to address their needs and interests (Dynes, 2005). As a concept, social capital illustrates *investment* in specific types of resources of value in each society. As a theory, it is regarded as a factor in surplus value (Marx, 1942) and as depicting the *process* by which capital is obtained and regenerated for returns (Lin, 2000).

In recent years, researchers have linked rapidity of disaster recovery to the resources available in social networks (Aldrich, 2011; Lin, 2008). Aldrich investigated the role of social capital in community recovery after the Kobe earthquake in 1995 (Aldrich, 2011; Aldrich & Meyer, 2015). In their study of the aftermath of the Kobe and Gujarat earthquakes, Nakagawa and Shaw claim that social capital is a crucial link in disaster recovery, especially in challenging situations (Nakagawa & Shaw, 2004). Further, Dynes argues for social capital as the primary basis for resilience and outlines specific suggestions for empowering social capital to foster post-disaster recovery (Dynes, 2005).

Two mechanisms allow communities to speed up the post-disaster recovery process. First, better-connected communities can express their demands and thereby evoke the required resources from the authorities (Olson, 2009). They can also better share water resources within society and neighbourhood. Effective resource sharing can lead to a less chaotic community and subsequently less time and energy is needed to calm down the residents and maintain safety. A safe community also ensures that recovery crew and contractors feel safe to leave their families and get back to work in the aftermath of the disaster. Otherwise, mobilization of restoration personnel from other places can adversely affect the restoration time as it is dependent on other lifelines such as transport and telecommunication and these may be damaged in a disaster.

The general chaos that developed within eight hours in the Concepción area in Chile after the earthquake in 2010 obliged the military to step in as the local police could not maintain safety. The military took three days to arrive as travel by road was almost impossible due to severe bridge damage. “The need for safety for Essbió [Chile water company] staff and contractors” resulted in a delay of several days for water system restoration (Tang & Eidinger, 2013).

Second, societies with higher capacities and capabilities prioritise water network restoration more appropriately. In communities with capabilities such as self-sufficiency and ability to repair water systems, especially in rural and remote areas, local people restore water networks and thus lift this responsibility from recovery personnel. As such, the need for mobilization of restoration crews will be minimized and less time will be spent accessing different parts of the disaster-affected area, especially in the first days after the disaster when infrastructure (e.g. telecommunication systems, roads and bridges) is damaged and regional traffic is at maximum busyness. Capable societies also allow more time for systematic restoration that avoids expenditure on (extremely) quick restoration that potentially leaves pipes vulnerable to the next disaster (or aftershocks in the case of earthquake), and which needs to be redone, again and again.

Tropical Cyclone Pam hit Vanuatu in March 2015, devastating more than two thirds of houses. Due to damage to roofs, people lost their primary water source: rainwater harvesting systems (Government of Vanuatu, 2015b). Although damage to rainwater harvesting systems was severe, the consequences were delayed as people had saved water before the cyclone. Some villages are also equipped with secondary water sources such as semi-networked water systems. These water systems include water catchments (often located in a mountainous area), from which a narrow water pipe transmits water to the village and a water tank to reserve water for emergencies. As the majority of villages are remote, the public sector could not assist rural residents with repairs to their rainwater harvesting systems or water pipes. Locals in capable rural communities were able to restore the rainwater harvesting and secondary water systems with basic equipment. Although the restoration was not perfect and they did not receive the same quantity and quality of water as pre-disaster, it solved their immediate water shortages and helped restoration crews prioritise water system recovery rather than rushing to apply extremely quick restoration techniques, which are often vulnerable to future disasters of the same magnitude.

As another example, after the Christchurch earthquake in New Zealand in September 2010, most pipe damage was repaired by the quickest possible methods, including installation of pipe clamps or short lengths of new pipe (2–4 metres). This is a common strategy among water companies around the world. Although the repaired pipes were serviceable after the first earthquake, they remained as fragile as the pre-earthquake pipes. A few months later when the second earthquake hit Christchurch in February 2011, the repaired pipes broke and caused severe water problems (Eidinger & Tang, 2012).

Most of the studies considering the role of social capital in the post-disaster recovery phase are impressionistic and based on qualitative views of community recovery (Aldrich, 2011). Accordingly, applying psychosocial concepts of social capital to develop indicators for water supply resilience is open to challenge. Conceptually, this is due to the tensions between models for psychosocial recovery, characterized by attempts to integrate multiple and dynamic influences in complex environments, and models from engineering science, which utilise technical knowledge to address and solve specific problems. Nevertheless, we argue that social factors and community capacity are variables affecting the resilience of water supply systems, and therefore we now turn to the development of an indicator-based model in order to provide a quantifiable method for measuring water supply resilience. The following section addresses this issue by defining quantitative indicators to measure the social factors that affect recovery time following a disaster.

4.3.Methodology

4.3.1. Developing an Indicator-based Tool

The ability to measure resilience is a prerequisite for increasing the ability of the water supply system to function when disaster happens and decreasing water supply recovery time in the post-disaster period. “Measuring resilience” does not demand quantitative approaches per se but requires a method for translating the abstract concept of resilience into a practical tool. To be useful, this tool needs to simplify and reduce the amount of potentially collectable data, information, and measurements to a number of manageable indicators to assist with measuring resilience (Birkmann, Jorn, 2006a).

Identifying appropriate indicators to measure resilience is a key challenge in the area of building resilience. Various indicators have been used to measure a range of variables over the past eight decades. Economic indicators emerged first in the early 1940s (Birkmann, Jorn, 2006a). Generally, these indicators are flawed as they only measure a limited number of parameters and other parameters can be neglected, especially when the system is complicated. However, indicators do provide tangible measures that planning, and investment decision makers can use to evaluate the current condition and implement action to improve it.

In order to measure resilience accurately, indicators need to possess the following characteristics (Birkmann, Jorn, 2006a; Briguglio, Lino, 2003; Hahn, 2003; Mainz, 2003):

- Agreed definitions: the indicators need to be unique in terms of definition to avoid ambiguity.
- Precise: the indicators need to be precisely defined in clear terms.
- Specific and sensitive: the indicators are required to describe clearly and exactly what is being measured. They also need to be sensitive enough to react when input data varies.
- Valid and reliable: consistently measured over time and by data collectors.
- Discriminative: the indicators should not be correlated.
- Evidence-based: the indicators are collected based on research from previous disasters.

Apart from the above-mentioned criteria, this paper adds a criterion called *data collectability* to ensure an indicator can be utilised in measuring water supply resilience to achieve an applicable tool. Data collectability considers availability, collection cost and ease of collection. In lack of appropriate data, the indicator with readily available data should be replaced with the indicator that is not practical to be measured in quantitative studies although the metrics may not be optimised.

The Comprehensive Aggregated Resilience Estimation (CARE) model was utilised in this study to understand the building blocks of water supply system resilience to the impact of disasters (Balaei et al., 2018). The CARE model defines water supply resilience based on the physical attributes of the system and the characteristics of the community the water supply serves. These are organisational, social, and economic factors that can affect water supply robustness and/or restoration rapidity when a disaster happens. Figure 4-1 shows the process for measuring water supply resilience based on the CARE model.

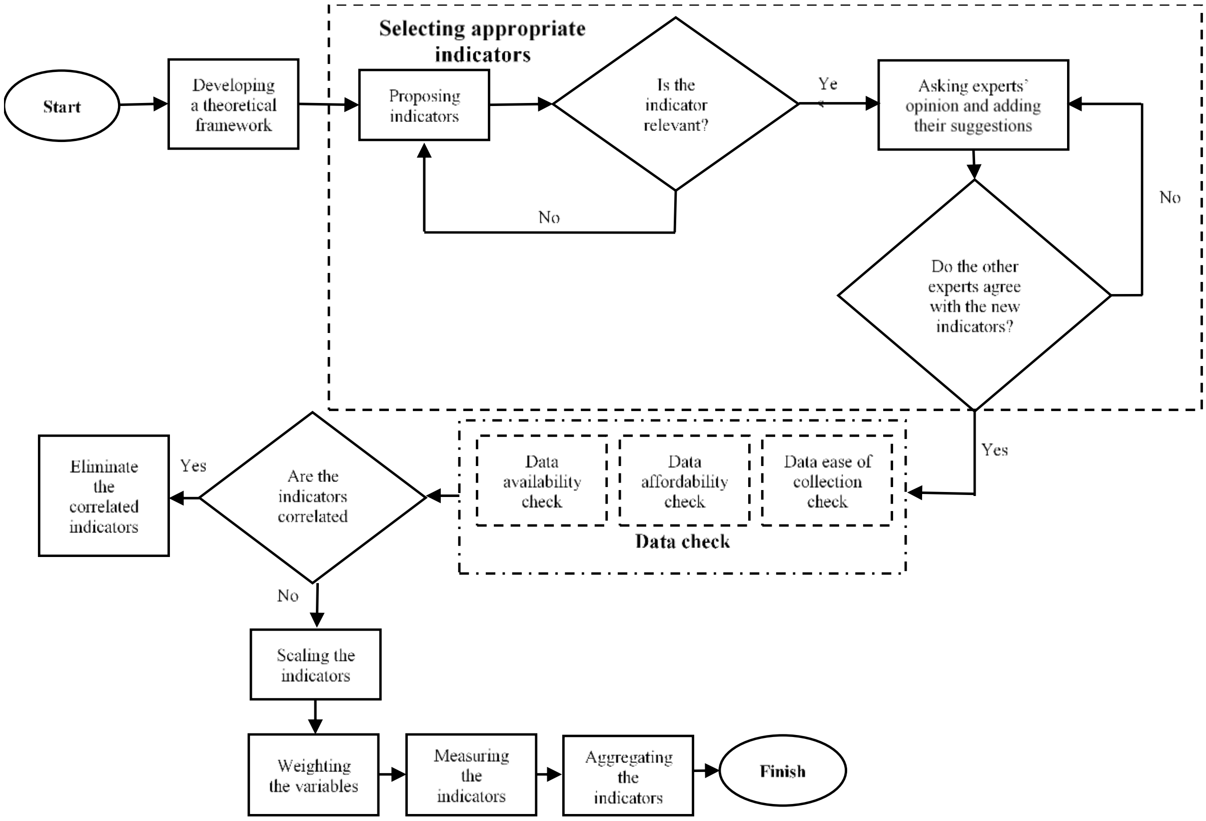

Figure 4-1: Water Supply Comprehensive Aggregated Resilience Measure (CARE) model (Balaei et al., 2018)

The objective of this research was to identify social characteristics and community factors affecting water supply resilience to disasters. The research process involved the following phases:

4.3.2. Resilience Measurement Framework

To select appropriate social indicators to best measure resilience, a theoretical framework was utilised (Balaei et al., 2018). In the first step, potential indicators were identified through a literature review and canvassed in interviews with social science specialists to obtain the most effective social metrics. Next, data availability, affordability, and ease of collection were checked. Data checks help to avoid using indicators that are not cost-effective, and consequently not feasible. Afterwards, correlation between the collected indicators was taken into account. As a result, the most relevant variables were kept and highly correlated variables removed.

4.3.3. Collecting Social Indicators Data

Data gathering for this study encompassed two parts: identifying the social indicators and gathering case study information and statistics to which to apply the indicators. A set of primary social indicators was collected through a literature review.

According to Kvale (1992), the research interview is the best tool to address social research problems. Key informant interviews have several benefits over other data gathering methods, including eliminating the need to use additional screening to understand facts that are not easy to grasp. The data gathered through this method is considered reliable as the respondents are competent (Dorussen et al., 2005). As such, a series of recursive interviews was designed and conducted with 23 specialists, deemed competent by virtue of their expertise in the field, to summarize the indicators. The experts were selected in early stages of the study from a variety of disciplines and backgrounds namely resilience, water engineering, social science and economists. The interviewees were selected from consultants (WSP-Opus, Jacobs, Market Economics), local authorities (Auckland Council, Christchurch City Council, Vanuatu Water Department, and Tehran Water and Wastewater Company), Universities (University of Auckland and University of Tehran), International agencies (United Nation WASH Cluster), charities working in disasters (ADRA New Zealand and Vanuatu), and independent experts. Semi-structured questionnaire was used to overcome biases and heuristics that can affect the results. The experts were asked about the factors and indicators found through literature review as well as an option for adding new factors and/or indicators they thought could affect water supply resilience. Twelve of experts were interviewed for the second time to give their judgement about the factors and/or indicators which were introduced through interviewing the other experts.

The indicators and sub-indicators' data were then collected for 20 sub-indicators from 22 countries through online databases. Not all sub-indicators were available for all countries so there are missing data points. The research selected countries with a wide range of social factors, and all countries had experienced forms of natural disaster in the last few decades. The collected data is provided in Appendix A.

3-4- Statistical Analysis

The discriminative characteristic among the collected indicators should be considered to derive a measure their impact on water supply resilience. Correlation coefficients have been traditionally used to study linear relationship between two sub-indicators (Preston & O'bannon, 1997). However, the significance of correlation coefficients is highly sensitive to the sample size. In addition, they only provide pairwise comparison between two indicators whilst the mutual correlation is often the result of the overall dynamics and interconnectedness among all variables. Therefore, when the collected data is limited, correlation coefficients may result in ambiguous conclusions (Boos & Stefanski, 2013).

The Principal Component Analysis (PCA) was used to study the interconnections among the sub-indicators. PCA considers all variables in a multivariate framework and reduces high-dimensional data into a few dimensions for principal components that are independent from one another. This dimension reduction is based on the maximum variations among the variables, and each variable is transformed into new low-dimensional coordinates (Boos & Stefanski, 2013).Appropriate transformation and scaling were employed as part of data pre-processing to meet PCA assumptions (Boos & Stefanski, 2013). Some PCA algorithms set default values (usually zero), or try to interpolate the gaps of missing data based on the available data. Neither of these approaches was ideal for this study since the aim was to discover the inter-dynamics between the variables. For this reason, we removed the countries with missing data from the general study.

4.4.Results and Discussion

4.4.1. Social Factors Affecting Water Supply Resilience

The social infrastructure of communities can affect water supply resilience. Fostering social capabilities for dealing with disasters (for instance, by means of improving preparedness, awareness, and skills) will increase a society’s coping, adaptive, and absorptive capacities, enabling communities and their assets to return to a normal level of functionality in a timely manner.

The results of literature review, the interviews, and surveys are summarized in Table 4-2 where the social factors and relevant indicators and sub-indicators used to measure them are introduced. Please refer to Appendix A for further details on the value of the indicators for countries. The description of the factors is discussed in this section.

Table 4-2: List of Social Factors, Indicators, and Sub-indicators

Social Factor	Indicator	Sub-indicator	Source
Individual demands and capacities	Households' reservoir capacity	N/A	Field survey
	Average knowledge and skill level of the community	Level of education	Human Development Index Report (2015)
	Giving Index	Helping stranger	

Individual Involvement in the community		Donating money	Charities Aid Foundation (2015)
		Volunteering time	
Violence level in the community	Crime rate	Burglaries, robberies, assaults, murders	Numbeo (2018)
	Social perception of crime	Perception of crime level, being rubbed, physically attacked, dealing with drugs, corruption	
	Social perception of safety	Feeling safe walking during day and night	
Trust	Most people can be trusted		World Value Survey (2018)
	Trust your neighbourhood		
	Trust people you know personally		
	Inverse trust in army		
	Inverse trust in Police		

4.4.1.1. Individual Capacities

In disaster prone areas, water companies encourage people to store the minimum water required per person for seven days or more (personal water reservoir). The logic behind this idea is to reduce pressure during system restoration to minimize faults (occurring due to peripheral pressure) and avoid quick but inadequate repairs that impose expenses and extra effort in the long run. In addition to water self-sufficiency, improving the average knowledge and skill level in communities can support overall restoration, especially in remote and/or rural areas. Access to remote areas after a disaster can be affected by landslides or debris generated due to the disaster, so skilled locals can have restored the water supply by the time restoration crews reach the affected area.

4.4.1.2. Individual Involvement in the Community

The more people are involved in the community, the higher the sense of community generated. A sense of community (SoC) is “a feeling that members have of belonging, a feeling that members matter to one another and to the group, and a shared faith that members’ needs will be met through their commitment to be together” (McMillan & Chavis, 1986). This “sense that one [is] part of a readily supportive network of relationships upon which one [can] depend” (Sarason, 1974) is a core component of social capital. These bonding processes work to support community connectedness and resourcefulness and can provide a continuation of resilience-focused behavior from pre-disaster resources into response and recovery phases of a disaster (Sadri et al., 2017). In stating this, it is also acknowledged that bonding between individuals within their own community can be strained by the differential impact imposed by disaster, and by intersecting tensions within the bridging and linking processes inherent in the delivery of water supply to whole communities.

Individual involvement of residents in the community can potentially affect water supply restoration. Community members may often forget that the restoration and recovery personnel and their families are also part of the disaster struck area and they need to mentally recover and feel safe in order to be able to leave their families and go back to work. Lower sense of community can affect the disaster response and recovery workers’ ability and willingness to return to work.

In this study, the World Giving Index (WGI) was utilised to measure people’s involvement in communities. The Index gives an insight into generosity around the world (Charities Aid Foundation, 2015). WGI is measured based on three sub-indicators, namely rates of helping strangers, donating money, and volunteering time. They were averaged to give the Giving Index.

4.4.1.3. Violence Level in the Community

High levels of violence in a community mean insecurity for both citizens and the water authority personnel who are in the field to restore the network. In such cases, the water restoration personnel will be reluctant to leave their families unattended and start working. All incentives, including money and social recognition lose their meaning if personnel do not feel they or their safe families are safe. The following indicators measure community violence and crime levels.

There are two approaches to measuring violence: using formal reports of violence, and/or using people's perception of crime based on surveys of people living in the community (Ferraro & Grange, 1987; Monahan, 1992). Recorded violence – the number of cases recorded by police – is subject to certain definitions of crime in different countries. Cultural barriers that prevent people reporting violence such as rape or domestic violence, lack of trust in police, and community structure are other reasons that can mean official reports not fully indicative. On the other hand, the accuracy of studies into people's perception of violence and crime in the community is subject to sample selection and sample size. Although societal perceptions of violence and safety are highly correlated with official police statistics, they are not necessarily equivalent. However, we argue that in the context of resilience, people act based on their perception of violence rather than statistics and reports. In this paper, we consider both formal reports and societal perception of crime. From a social capital perspective, we consider that high levels of perceived and reported violence within communities are pre-disposing factors for reducing the effectiveness of formal institutional (local, regional or national) interventions to support restoration of water supply, as these indicate the potential for weakened linking and bridging processes between local communities and water supply management. Furthermore, in acknowledgement that disasters will exacerbate pre-existing inequities in communities (Jha et al., 2015) the heightened stress of disasters has the potential to generate higher levels of violence, as resource allocation becomes fractured along lines of power and privilege in social functioning. Stark and Ager (2011), for instance, address issues of gender-based violence occurring both within the home and in communities affected by complex emergencies.

A variety of indicators have been used to measure crime levels. However, due to the nature of crime and lack of globally-agreed definitions for different crimes, extra care should be taken when working with relevant indicators. For instance, rape and domestic violence are two well-known indicators of violence levels within communities but neither were utilised in this study. Rape was rejected as definitions of rape vary significantly. While marital rape is not recorded in most countries, it is considered a crime in countries such as Sweden. Domestic violence was not used either as the number of domestic violence incidents reported to police is far less than the actual number of incidents in the home, and so there are no accurate statistics.

Four sub-indicators were therefore chosen to measure reported crime levels: burglaries, robberies, assaults, and murders. Concern over being robbed, concern over being physically attacked, the problem of people using and dealing drugs, and feelings of corruption were used as sub-indicators to measure social perceptions of crime. Perception of safety can be measured by means of feeling safe walking during day and night. This data was obtained from Numbeo. Numbeo surveys these sub-indicators to measure perceptions of crime and safety in more than 4700 cities worldwide (Numbeo, 2018).

4.4.1.4. Trust

Trust is a gauge of the quality of relationships, and involves a number of factors at the cognitive, emotional, and behavioral levels. Trust is closely connected to the norms, values, and beliefs of a community’s culture. It is also the outcome of communication behaviors by local authorities, including clear communication about decision-making and openness and transparency.

Trust is not only a characteristic of the community during times of business-as-usual, as it can also be built or undermined in the post-disaster period. When people trust government institutions such as water companies, they are more likely to take part in necessary processes. Therefore, although some steps in building trust (e.g. appropriate communication for making decisions) require a commitment of time from the water companies, time is saved during the response and survival phases when decisions are being applied to the community, as people are more accepting of what is being undertaken. Higher levels of trust in a community also lead to lower levels of chaos and violence in post-disaster conditions. As a result, water company personnel will be able to deliver the planned services without significant delays.

Trust was measured by means of four major indicators: public trust, trust in neighbourhood, inverse trust in police, and inverse trust in army, as measured in surveys collected by the World Values Survey (World Value Survey, 2018).

We argue that level of violence in society, as indicated by both police statistics and perceptions of violence, is reflected in public levels of trust, as well as trust in the police. Similarly, one can argue that the level of individual involvement in society is affected by trust and perception of safety. It is also expected that the sub-indicators of each category will relate to one another.

4.4.2. Discriminative study of the sub-indicators

There were only seven countries out 22 with data available for all sub-indicators. Figure 4-2 shows the two-dimensional space of PC1-PC2 for the 20 social sub-indicators. Their contribution to PCA is indicated by colours and the loadings are given in the Appendix B.

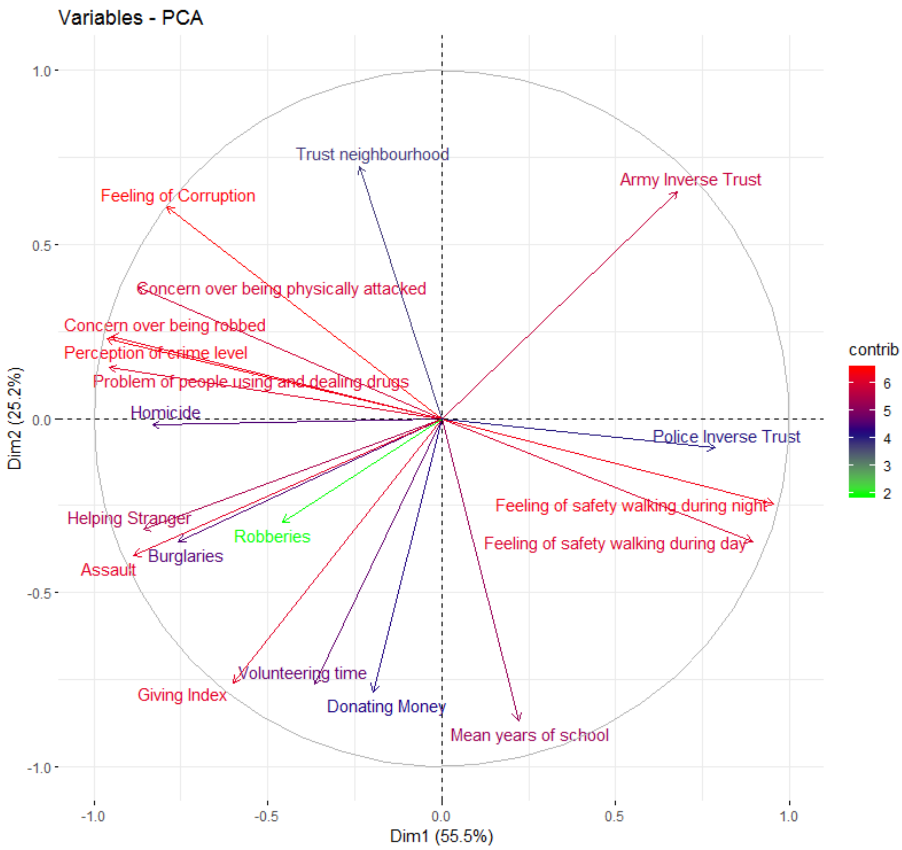

Figure 4-2: The two-dimensional space of PC1-PC2 for the 20 social sub-indicators

As expected, some sub-indicators, especially the ones in the same category, are highly correlated with one another. For example, the police-recorded assault, burglaries, robberies and homicide rates are positively correlated with each other and negatively correlated with feelings of safety, such as walking during the day or night (see the direction of each sub-indicator vector in the new coordinates). While the sub-indicators for perceptions of safety are also highly correlated (perceptions of corruption, concerns over being physically attacked, robbed or people dealing drugs), they are relative, but not equal, to recorded crime rates.

Inverse trust in police rightfully seems to have a highly positive relationship with feelings of safety for walking during the day and night, whilst this correlation is lower for inverse trust in army. Interestingly, level of education and trust in neighbourhood seem to have an opposing impact on one another. As expected, the sub-indicators of individual involvement are highly correlated with one another, and it is interesting to observe that money donation rate is almost orthogonal (i.e., has no relation) to perception of corruption in society. Figure 4-2 also shows the location of each of the seven countries in this two-dimensional diagram.

Although Figure 4-2 gives the overall picture of the variations and interdependencies of the sub-indicators, due to missing data either collection of a larger dataset was required, or fewer observations to deal with (in our case, seven countries only). We used the information provided by Figure 4-2 to omit some sub-indicators from the analysis. The omitted sub-indicators are the ones highly correlated with others so, from a theoretical viewpoint, they would not provide extra information for the analysis. The advantage of this dimension reduction was not only to simplify the analysis and interpretation of results, but also to reduce the amount of missing data and include more countries in the analysis. Figure 4-3 shows the summarized social sub-indicators used to measure factors affecting water supply resilience. As a result of summarization, the amount of violence explained by the first component reduced to 45%. On the other hand, the sub-indicators now tended to be more independent from one another. In the following section, we consider the impact of these sub-indicators on the two case studies in detail.

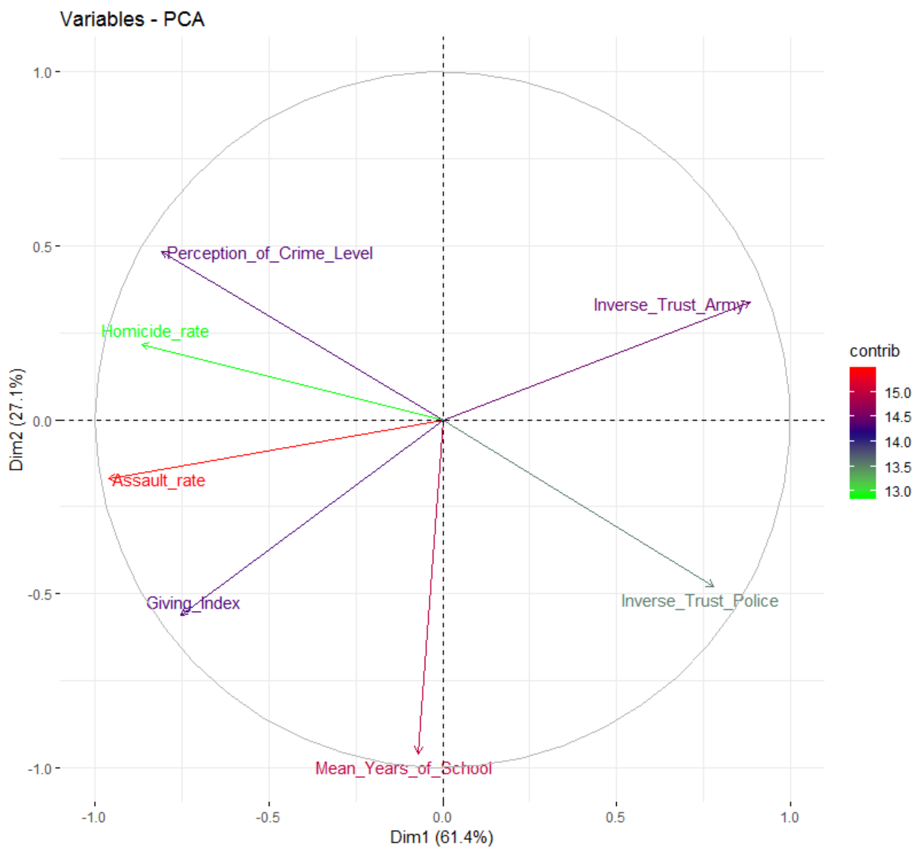

Figure 4-3: Two-dimensional Space of PC1-PC2 of 7 Social Sub-indicators (the contribution of each sub-indicator is shown in colours)

4.5. Case Study: Comparing Social Factors in New Zealand and Chile

4.5.1. Disasters and Water Restoration Processes

On 27 February 2010, a subduction M_w 8.8 earthquake hit the west coast of the Maule Region of Chile, followed by 200 aftershocks of magnitude 6 or higher in the week after the first disruption. The epicentre of the earthquake was located offshore about 105 km NNE of Concepción, at a depth of 35 km. The rupture zone was approximately 150 km by 500 km. Figure 4-4 shows the earthquake epicentre and its location in relation to Concepción and Santiago, the capital city.

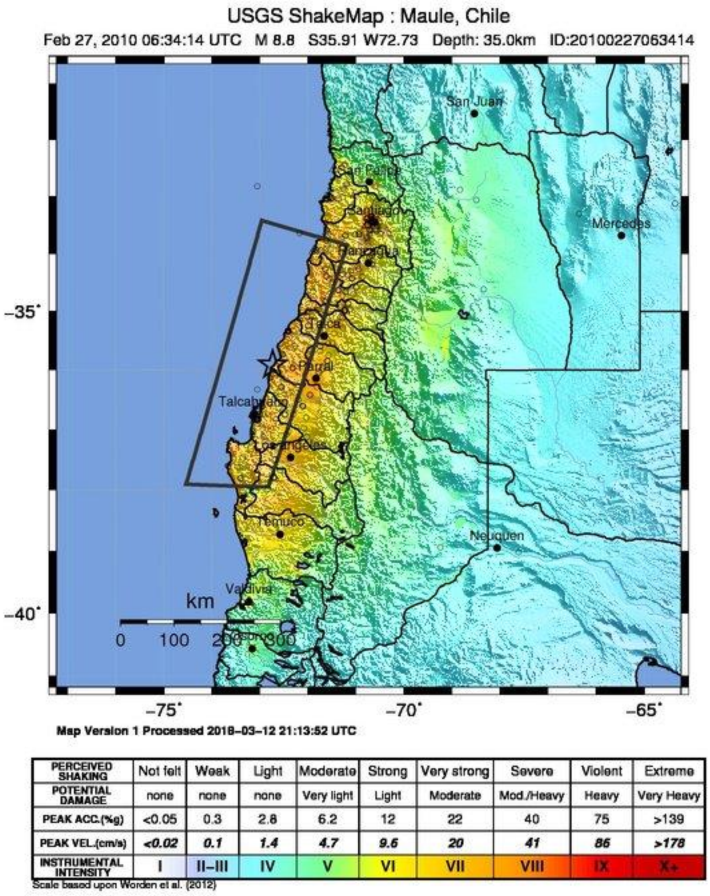

Figure 4-4: Chile Earthquake ShakeMap (USGS, 2018)

As this area has a long history of earthquakes of magnitude 8 or higher, the Chilean government promotes earthquake mitigation and preparedness in infrastructure. These mitigation measures worked appropriately during the earthquake and proved their effectiveness, as the damage was small in relation to the magnitude of this disaster. However, the water system in Concepción experienced relatively heavy damage. More than 3,000 pipe repairs and damage to the water treatment facilities were recorded after the earthquake (Tang & Eidinger, 2013).

Two water companies serve most of the cities in the strong shake area. Aguas Andina delivers water to the Santiago, and Essbió serves Rancagua, Curico, Talca, Chillan, Concepción, Talcahuano, Coronel, Los Angeles, and Temuco. In addition, the government's Ministry of Public Works (MOP) has developed hundreds of small water systems to supply water to the rural areas.

In the aftermath of the February 2010 earthquake, 17% of Essbió's customers in Region VIII (the region in which Concepción and Talcahuano are located) had water service. Forty-four days from the earthquake, 97% of people in that region had access to drinking water.

On the other side of the Pacific Ocean and over a period of nine months, a sequence of three earthquakes hit Christchurch in New Zealand: the first on 4 September 2010, the second on 22 February 2011, and the third on 13 June 2011. The second earthquake was the most devastating in the sequence, with 181 fatalities and economic losses totalling $US 11.1 billion. This study focuses on the second earthquake, which is referred to as the Christchurch earthquake (Eidinger & Tang, 2012).

The water supply system was damaged, mainly due to broken water pipes because of lateral spreading and liquefaction. Slope failure also caused pipe damage. In the aftermath of the earthquake, more than 80% of people lost their drinking water service (Ministry of Health, 2012). Two days after the earthquake, service had been restored to 50% of people, although all residents were reminded to boil or to add bleach to water prior to drinking it (NZHerald, 2011).

As expected, the values for social indicators are different for the two countries. Interestingly, assault and homicide rates are not in agreement with each other. While the reported assault rate in New Zealand is twice the assault rate in Chile, reports show lower numbers of homicides in New Zealand. However, the perception of crime in New Zealand is significantly higher than in Chile.

With regard to individual involvement in community, New Zealand shows a high Giving Index (58) score compared to Chile, which scores in the mid-range (36) of Giving Index values globally. The mean years of school indicator was used to measure average level of education in the two countries. New Zealanders, on average, spend 12.5 years in the school education system compared to Chileans who spend 9.8 years in school.

New Zealand showed higher scores for both trust indicators compared to Chile. Approximately 78.5% of New Zealanders report inverse trust in police compared with 63.9% of Chileans. The difference between two countries for inverse trust in army is higher, at 76.1% of New Zealanders to 55.2% of Chileans. Figure 4-5 compares social sub-indicators for Chile and New Zealand.

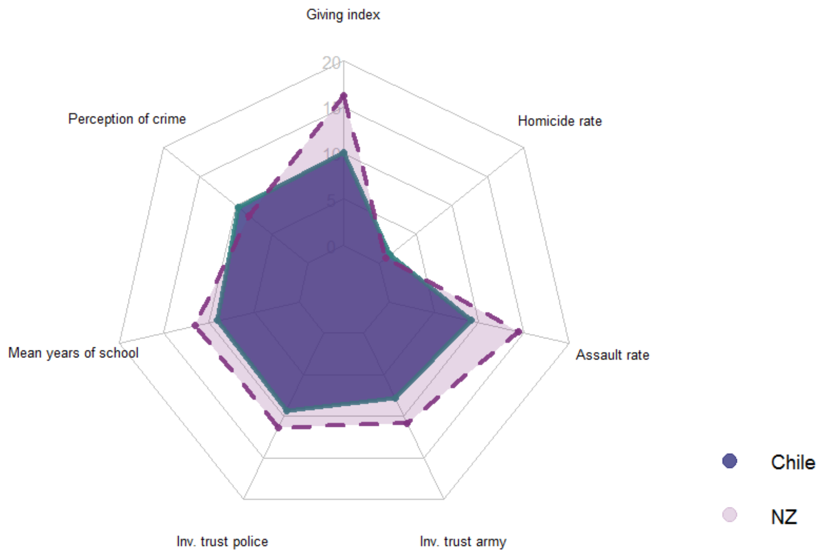

Figure 4-5: Comparison of Social Sub-indicators in Chile and New Zealand

Mesoscale studies show that water supply restoration process can vary from one city to another in the country. Although water system restoration in both Concepción and Talcahuano took longer than Christchurch, the restoration pattern in these two cities were different. While both Concepción and Talcahuano water supply system were restored in about 45 days, Concepción water restoration showed a considerably quicker restoration in the first two weeks. Figure 4-6 compares the water supply restoration process following the Chile earthquake in February 2010 with Christchurch following the earthquake in February 2011.

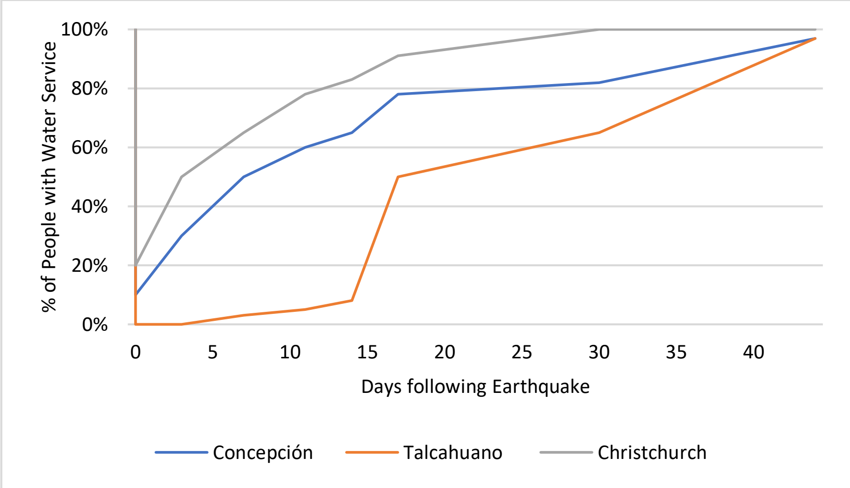

Figure 4-6: Drinking Water Service Following Chile Earthquake (2010) (Evans & McGhie, 2011; Tang & Eidinger, 2013) vs Christchurch Earthquake (2011) (Ministry of Health, 2012)

4.5.2. Impact of Social Factors on Water Supply Resilience to Disasters

Although both New Zealand and Chile's public and private sectors have asked residents to store sufficient water in case of disaster, people do not generally keep water for this purpose. Following both earthquakes, a lack of stored water put excessive pressure on water companies and restoration crews to restore water systems as quickly as possible, thus undermining their resilience. In Christchurch, for example, a significant number of pipes repaired quickly after the September 2010 earthquake broke in the next earthquake in February 2011.

Outbreaks of community violence following the Chile earthquake caused significant delays in water supply restoration. According to the BBC, Talcahuano – a city close to Concepción – was left to cope by itself mainly because of a lack of local police personnel and difficulties in bringing in back-up support due to the damaged transport system. In Concepción, military police reportedly arrested 160 people in the first two days following the earthquake for burglaries and general chaos, including looting stores and setting fires. The local police failed to maintain safety in Concepción and the military stepped in to control the crowds, often at gunpoint, on the third day following the earthquake. Lack of safety for Essbió staff and contractors as well as other factors such as lost communication systems resulted in a slower recovery time (Tang & Eidinger, 2013).

Following the Christchurch earthquakes, a student movement called the “Student Volunteer Army” was initiated. The student volunteers facilitated community action through engagement, disaster preparedness and providing clean-up services (Student Volunteer Army, 2018). Although volunteers such as the Student Volunteer Army were not involved directly in the water supply restoration process, their assistance in cleaning up the roads allowed quicker dispatch of restoration crews and spare parts and equipment to where they were required.

Social factors, alongside other economic and organisational factors, caused a longer recovery time in Chile compared to New Zealand. It is notable that even on a local scale, social factors make a considerable contribution to water supply restoration. As can be seen in Figure 4-6, although at the country level values for social indicators are the same for Concepción and Talcahuano, the local social conditions made a significant difference in these two cities which are located next to each other. Although the water supply system was restored to over 90% of the population in both cities by the end after 45 days, the rate of system restoration was significantly different over the first two weeks.

4.6. Conclusion

This paper identifies the important social factors in communities affecting water supply resilience to disasters. Although this paper focuses on the social dimension of communities as a soft infrastructure, it should be noted that water supply resilience is a multifaceted time-base measure of water system’s performance when a disaster happens. Social factors are not the only measure of water supply resilience. Technical, organisational, and economic dimensions should also be considered measuring water supply resilience to disaster. In the first step, the CARE framework was utilised by the authors to obtain an overall perspective of water supply resilience to disasters. Four fundamental social factors were extracted from the literature review and confirmed by interviewing field and academic experts. The social factor identified in this paper are individual capacities, individual involvement in the community, violence level in the community, and trust. A set of indicators and sub-indicators were introduced to measure the respective social factors.

The inter-dynamics and mutual relationships between the sub-indicators were investigated using Principal Component Analysis (PCA). As the sub-indicators were highly correlated to one another, we were able to choose seven social sub-indicators based on data availability and discriminant analysis. Data for these seven social sub-indicators was then considered in detail for the New Zealand and Chile case studies.

We gave equal weights to the sub-indicators in this paper. In other words, we assumed that all of the social factors had equal contribution to resilience. In the next research step, however, an appropriate weight for each factor could be assigned to achieve a more accurate impact assessment of the social capacity of communities on water supply resilience to disasters. In addition, the interaction between social, organisational, technical, and economic dimensions need to be addressed to understand the dimensions' relationship and potential overlaps.

4.7. Acknowledgement

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CHAPTER 5 – SOCIAL DIMENSION CASE STUDY

The current chapter is based on the following article:

Balaei, B., Wilkinson, S., Potangaroa, R. (2019) "Social Capacities in Fostering Water Supply Resilience in Vanuatu"

Submitted to "*Disaster Prevention and Management: An International Journal*"

5.1.Introduction

Access to safe drinking water is a human right, as stated explicitly by the United Nations General Assembly (UN, 2010). Water supply systems are one of the most significant services in relation to public health, general welfare, and sustainable development. Planners and decision makers are responsible for ensuring provision of safe, clean, accessible and affordable potable water, taking into account projected habitat expansion and population growth (Rosenberg et al., 2016). Inadequate water services or water quality increase the transmission of disease generated through contact with contaminated water and can have broader, long-term consequences on public health and wellbeing.

These consequences are more severe for poor and struggling developing countries where post-disaster survival is challenging (UNISDR, 2005). Receiving official recognition at the United Nations Conference on Environment and Development in June 1992, Small Island Developing States (SIDS) started working together as a distinct group of developing countries. Among the top 25 countries severely affected by natural disasters in the 1970s and 1980s, 13 were small islands developing states, including Pacific, Caribbean and Indian Ocean islands that share similar sustainable development challenges, namely limited resources, remoteness, susceptibility and vulnerability to natural disasters.

Located in the Pacific cyclone belt, Vanuatu experiences an annual season of cyclones, some of which are destructive. In February 1987, Port Vila was struck by TC Uma. The category 4 cyclone damaged 95% of the building stock, causing losses estimated at US$150 million over a period of seven hours (UN, 2010). More recently, in January 2011, TC Vania passed through the Tafea province of Vanuatu. Winds of 140 km/hr caused damage amounting to US$742,000 and affected over 10,000 households, destroying water systems and other infrastructure (NDMO, 2011).

The high risk of natural disasters in Vanuatu (Birkmann, J. et al., 2011; Heintze et al., 2018) combined with changing demographics, unplanned habitation in high-risk zones, competition for resources, environmental degradation, and climate change have made communities vulnerable to disasters. In addition, the islands of Vanuatu stretch over such a long distance and some are isolated, making it is difficult to access some communities both before and after disasters. Less access means less opportunity for the government and international NGOs to reach them and provide health, education and basic facilities to cater for their needs in the event of a disaster.

As it passed over the country on 13 March 2015, TC Pam caused severe damage to water supply systems; across the country approximately 68% of rainwater harvesting (RWH) structures were broken and 70% of wells contaminated. Strong winds and debris devastated rainwater catchment intakes and gutters, while fallen trees and landslides damaged pipelines and blocked spring water intakes. In addition, power blackouts and mechanical damage affected water pumping which caused more water outages around the country. In the period immediately following the cyclone, more than half of the country's population claimed to have access to less than three litres of potable water per person per day. This figure varied among the islands, depending on their remoteness, proximity to the cyclone's eye and the level of destruction.

Despite the endeavours of the public and private sectors, setting up emergency water supply and recovery of the water system was complicated, and the majority of people had limited access to water. In many cases, people's lack of access to water of appropriate quality and quantity was exacerbated following the cyclone, however SPHERE minimum standards were not being met even prior to the event. In rural areas, locals had to address water system damage and people had to go long distances to access water resources. The limited quantity and poor quality of water available were major issues in post-disaster water supply.

While the overall economic status of Vanuatu had a significant influence on the resilience of water supply, the focus of this paper is identifying the effect of social capital at the community level in addressing the water challenges following the cyclone. After (i) describing and discussing water supply in Vanuatu and outlining damage to water resources and systems based on site visits following the cyclone, we next (ii) consider the challenges of water supply and local solutions to these, and then (iii) investigate social factors in the resilience of water supply in rural areas of Vanuatu following TC Pam.

5.2. Literature Review

5.2.1. Water Supply Resilience

The notion of resilience has captured the attention of a wide range of scholars in diverse disciplines. The concept of community resilience to disasters was proposed this century (Klein et al., 2003), but had been introduced earlier by Holling in relation to ecology in 1973 (Holling, 1973). Klein et al. (2003) define resilience as a desirable property of natural and human systems in the face of potential stresses in their investigation of resilience to weather related hazards in coastal megacities. As a result of their study, Klein et al. (2003) recommend that resilience be used in a "restricted sense" to describe specific system characteristics, namely: (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system's self-organisation capability.

A significant number of researchers have developed conceptual frameworks to measure community resilience from various perspectives. According to Norris et al. (2008), resilience can be understood as a set of network adaptive capacities, comprising economic development, resource equity, social capital, and information and communication. Similarly, Cutter et al. (2008) proposed the DROP framework and model—Disaster Resilience of Place — to conceptualise disaster resilience at the community level. The DROP model demonstrates how resilience capacities (coping, adaptive, and absorptive) influence the degree of recovery and resilience of the community. It also includes six groups of indicators: ecological, social, economic, institutional, infrastructure and community competence, to quantify a community's overall resilience.

Recovery in a community is multifaceted, including but not limited to the recovery of lifeline systems. Water supply malfunction can cause a variety of challenges and increase the number of disaster victims and fatalities. During the 6.8 magnitude Northridge earthquake in the United States in 1994, for instance, approximately 45,000 people had no access to water services and it took 12 days to restore the utility for 99% of residents (Davis et al., 2012; Goltz, 1994; McReynolds & Simmons, 1995). Likewise, in the Kobe earthquake in Japan in 1995, more than one million people lost water services for up to 60 days in some regions (Chung et al., 1996).

Since Hurricane Katrina in 2005, a significant shift in focus has been apparent from protecting lifelines to community resilience, which is defined as the ability and preparedness of the community to respond to a disaster and recover to a sustainable level (O'Rourke, 2007). A number of studies have proposed metrics to measure water supply resilience to disasters (Cimellaro et al., 2015; Farahmandfar et al., 2016; Makropoulos et al., 2018; Morley, 2012).

Some of these studies propose functional measures to quantify resilience in water networks, along with frameworks to improve water supply network resilience (Farahmandfar et al., 2016; Matthews, 2015).

The resilience of small islands to disasters has captured research attention. The vulnerability of SIDS and their economies to natural disasters was recognised early on by Briguglio (1995). Pelling and Uitto (2001) described the root causes of SIDS' vulnerability to natural disasters and the impact of globalisation. Marto et al. (2018) discussed the resources required by SIDS' governments to recover infrastructure and how to invest cost-effectively in mitigating the impact of future disasters on lifelines. They applied their model to Vanuatu, concluding that donors would need to provide a further 50% of pre-cyclone GDP in grants to be spent over the next 15 years to ensure the country remains resilient to economic challenges following TC Pam. Despite invaluable research investigating the impact of climate change on SIDS in general (Barnett & Waters, 2016; e.g. Robinson, 2017), and the South Pacific region in particular (e.g. Janif et al., 2016; Mimura, 1999; Singh et al., 2001), the resilience of water supply systems in South Pacific Islands has not been taken into account.

5.2.2. The Role of Social Capital in Disaster Resilience

Social capital is defined as resources rooted in one's social networks that can be accessed or deployed through bonds and connections in the networks (Lin, 2001). It also refers to the valuable aspects of social structure for social actors that can be mobilised to address their needs and interests (Dynes, 2005). As a concept, social capital illustrates investment in specific types of resources of value in each society. As a theory, it is regarded as a component of surplus value (Marx, 1942) and depicts the process by which capital is obtained and regenerated for returns (Lin, 2000).

In recent years, researchers have linked rapidity of recovery to the resources available in social networks (Aldrich, 2011; Lin, 2008). Aldrich investigated the role of social capital in community recovery after the Kobe earthquake in 1995 (Aldrich, 2011; Aldrich & Meyer, 2015). In their study of the Kobe and Gujarat earthquakes, Nakagawa and Shaw claim that social capital is crucial to disaster recovery, especially in challenging situations (Nakagawa & Shaw, 2004). Dynes argues for social capital as the primary basis for resilience and outlines specific suggestions for promoting social capital to foster post-disaster recovery (Dynes, 2005).

Two mechanisms allow communities to speed up the post-disaster recovery process. First, better connected communities can express their demands and evoke the required resources from the authorities (Olson, 2009). Field research has shown that these communities can better share water resources within the society and the neighbourhood. For example, Jackson et al. (2017) used qualitative data from Emae Island, Vanuatu, including community perceptions of exposure to different hazards, and applied it to their multifaceted framework for identifying factors affecting disaster vulnerability and resilience. They found family networks/support and sharing information and resources to be significant social factors influencing community resilience in Emae. Vachette et al. (2017) also found that bonding, bridging and linking social networks helped in developing the response system in Vanuatu following TC Pam. Rey et al. (2017) found that pre-existing vulnerabilities were exacerbated following TC Pam. They also claimed that urbanism increased the adverse effects of disasters on communities in Vanuatu.

Effective resource sharing can lead to a less chaotic community and subsequently, less time and energy is needed to calm down the residents and maintain safety. A safe community also makes the recovery crew and contractors feel safe to leave their families and get back to work in the aftermath of the disaster. Delays in mobilisation of restoration personnel can adversely affect the restoration time as it is dependent on other lifelines such as transport and telecommunication and they may be damaged in a disaster.

General chaos occurred in the Concepción area in Chile within 8 hours following the earthquake in 2010, obliging the military to step in as the local police could not maintain safety.

However, the military took three days to arrive as travel by road was almost impossible due to severe bridge damage: “The need for safety for Essbió [Chile water company] staff and contractors” resulted in a delay to water system restoration of several days (Tang & Eidinger, 2013).

Second, societies with greater capacities and capabilities manage water network restoration more appropriately. In capable communities, especially in rural and remote areas, local people are able to restore water networks and so lift water restoration pressure from recovery personnel. As such, mobilisation of restoration crews will be minimised, and less time will be wasted commuting to different parts of the disaster struck area, especially in the first days after the disaster when infrastructure (e.g. telecommunication system, roads and bridges) is damaged and regional traffic is at its maximum level. Capable societies also allow more time for systematic restoration that avoids wasting money on (super) quick restoration that leaves pipes vulnerable to the next disaster (or aftershocks in the case of earthquake) and needs to be redone, again and again.

Recently, Balaei et al. (2019) introduced four social factors affecting water supply resilience to disasters and tested them for the cases of the Christchurch (2011) and Concepción (2010) earthquakes, in New Zealand and Chile respectively. These factors are: individual demands and capacities, individuals’ involvement in the community, and societal level of violence and level of trust. Individual demands and capacities encompass the local water reservoir capacity and locals’ average level of knowledge and skills. Individuals’ involvement in the community reflects the level of cooperation in the community, and violence level reflects perceptions of safety within a society, and has implications for restoration crews feeling secure about leaving their families at home and working to provide needed water without fear of being attacked. Connected to the norms, values, and beliefs of a community’s culture, trust is a gauge of the quality of relationships. It is also the outcome of communication behaviours by local authorities, including clear communication about decision-making and openness and transparency.

5.3.Methodology

The social factors and indicators affecting water supply resilience were collected by Balaei et al. (2019) through literature review and a series of interviews with 18 specialists, deemed competent by virtue of their expertise in the field. The experts were selected from a variety of disciplines and backgrounds namely resilience, water engineering, social science and economists. The interviewees were selected from consultants (WSP-Opus, Jacobs, Market Economics), local authorities (Auckland Council, Christchurch City Council, and Tehran Water and Wastewater Company), Universities (University of Auckland and University of Tehran), and independent experts. Semi-structured questionnaire was used to overcome biases and heuristics that can affect the results. The experts were asked about the factors and indicators found through literature review as well as an option for adding new factors and/or indicators they thought could affect water supply resilience. Twelve of experts were interviewed for the second time to give their judgement about the factors and/or indicators which were introduced through interviewing the other experts.

This study tests impact of these social indicators on the resilience of water supply in rural responses to TC Pam through the following approaches:

1. Review of existing documents
2. A case study of a village
3. Interviews with locals and international NGO experts working in Vanuatu

There were two categories of documents. The first category had either been commissioned and/or published (or remain unpublished in some cases) by the Government of Vanuatu. The National Water Strategy (Government of Vanuatu, 2008) and post-cyclone plans (Esler, 2015; Government of Vanuatu, 2015a; Government of Vanuatu, 2015c) are examples. The second category of documents were pre- and post-cyclone reports on the complexities of water supply (Esler, 2015; Government of Vanuatu, 2015b; SOPAC, 2006; SOPAC, 2007). These documents were mostly based on assessments carried out in collaboration with international NGOs.

A site visit was made in June and July 2015 to the village of Laonkarai on Efate Island in Shefa Province. Laonkarai was selected based on anecdotal reports of the severity of damage to its water systems due to the cyclone. The authors' investigations in other villages on Efate and Tanna Islands confirmed that Laonkarai very well reflected the state of water system damage in Vanuatu.

In Laonkarai, the RWH systems were inspected and four locals interviewed, each for approximately 30 minutes, to gain an understanding of the existing situation and water-related issues in the village. The interviewees spoke in Bislami and translation was provided by a local person who knew both Bislami and English. Guided by three locals, we visited the water catchment and assessed it as an alternative water source. The water catchment was not easy to access without local assistance.

Apart from the site visit, six interviews were conducted with field experts to help measuring the social factors' impact on water supply following TC Pam. The experts were selected from the public sector (e.g. Water Department), UN clusters (Water, Sanitation and Hygiene (WASH) Cluster, United Nations Children's Fund (UNICEF), and Shelter Cluster), disaster charities (ADRA, New Zealand and Vanuatu) and also from among local people to build an understanding of the severity of damage and its consequences for the local people, as well as their social and cultural responses to the problem. In addition, the role of international NGOs in responding to the damage to the water system was investigated.

Ethical approval was obtained for this research, the main condition being that respondents were not to be identified in order to protect their credibility from negative reporting. The interviewees and survey respondents were identified primarily through discussions with individuals we met during the site visit. They included representatives of the local Ni-Vanuatu authorities, non-governmental organisations (NGOs) and members of the private sector who assisted in the response and recovery phases.

5.4. TC Pam and the Role of Social Capital in Water Supply Resilience in Rural Vanuatu – Case Study: Laonkarai

Tropical Cyclone (TC) Pam struck Vanuatu on the evening of March 13, 2015. The destructive category 5 cyclone caused widespread damage across 22 islands within five provinces of the archipelago – Shefa, Tafea, Malampa, Penama and Torba. The eye of the cyclone passed close to Efate Island in Shefa Province, where the capital Port Vila is located, with wind speeds of around 250 km per hour and gusts peaking at 320 km per hour. The emergency phase after the cyclone lasted for approximately three months, with the early recovery stage beginning on 12 June 2015. The recovery phase spanned from the end of June 2015 to December 2016 when the post-cyclone development period started. The field work missions (including 1,049 response activities) took place from 19 June to 8 July 2015, when most of the international aid was distributed (Rey et al., 2017).

Apart from Port Vila and Luganville, Vanuatu suffers from the lack of a centralised water supply system. Water in Vanuatu is captured by rainwater harvesting (Figure *5-1*a), and from surface water (e.g. creeks) (Figure *5-1*b) or groundwater. Approximately one third of Vanuatu's inhabitants collect water from roofs. In rural areas, this proportion increases to slightly less than 40 percent on average. In partnership with NGOs, the government supplies one water tank per every few houses in the villages. The people living in these houses are responsible for water collection and RWH system maintenance. The attractions of RWH systems are their low cost, accessibility and easy maintenance at the household level.

Figure 5-1: a. Rainwater harvesting system in Vanuatu; b. Lololima River on Efate Island, Vanuatu

Located on the northern side of Efate Island (Figure 5-2), approximately 48 km from Port Vila, the capital, Laonkarai is a relatively small village with eight families living in 11 houses. As in most rural areas of Vanuatu, the primary water source is rainwater, harvested and saved in tanks provided to the village by the government. Four of the 11 houses in Laonkarai have RWH systems and tanks, and the collected water is used by the whole village. The tanks are made of polyethylene and each tank has a capacity of 1000 litre (Figure 5-1a).

Figure 5-2: Location of Laonkarai and water catchment on Efate Island

As their houses and roofs were not designed to withstand cyclones, almost half of the houses in Laonkarai lost their roofs, either completely or partially, due to the strong winds during TC Pam. In some cases, gutters were broken and/or became detached from houses which also decreased RWH capacity. The village inhabitants partially repaired roofs with materials they had at hand, but even after repairs not all the rainfall could be collected due to a shortage of guttering to cover the whole of the roof area. In one case, only a quarter of the roof area was effective as a RWH area because of a lack of guttering to collect the water. The village water tanks, another main component of the RWH system, were undamaged, although tanks were out of order in other areas of the country.

After TC Pam, the quantity and quality of water deteriorated across the country in general, and in rural areas in particular, mostly due to debris falling onto roofs and into gutters. Prior to the cyclone, people had enough water for drinking and cooking purposes, basic hygiene, etc., although water quality rarely met SPHERE standards in rural areas. However, despite the efforts of various agencies and NGOs, water supply did not meet the minimum SPHERE standards in terms of quantity. People had much lower access to water in rural areas than required by the minimum standards. After the cyclone, the quality of the available water was difficult to gauge as it was not being systematically monitored. In addition, the villagers suffered from lack of equipment such as proper water containers, washing basins, and hygiene supplies. Table 5-1 compares the minimum water supply standards in SPHERE (Sphere, 2011) with the post-cyclone conditions found in Laonkarai.

Table 5-1: Comparison of the existing condition in rural areas and Sphere standards for water supply systems

Minimum standards in Sphere 2011 (Sphere, 2011)	**Current condition in Laonkarai**
Average water use in any household is at least 7.5–15 litres per person per day (including 2.5–3 litres for drinking and food, 2–6 litres for basic hygiene practices, and 3–6 litres for cooking, depending on social and cultural norms)	More than half of the country has access to less than 3 litres per day per person (this figure varies from province to province)

There are no faecal coliforms detected per 100ml of water at the point of delivery and use	This is not being monitored.
Any household-level water treatment options used are effective in improving microbiological water quality and are accompanied by appropriate training, promotion and monitoring	Majority of people in Vanuatu (and everybody in Laonkarai) are not using disinfection tablets. There is no appropriate training, promotion, and monitoring.
All affected people drink water from a protected or treated source in preference to other readily available water sources	Because of the decentralised water system, there are no controls on the water sources people are retrieving water from.
Each household has at least two clean water collecting containers of 10–20 litres, one for storage and one for transportation. Water collection and storage containers have narrow necks and/or covers for buckets or other safe means of storage, and for safe drawing and handling – and are demonstrably used	The existing water containers are not necessarily designed and built for storing and transporting water safely.
There is at least one washing basin per 100 people and private laundering and bathing areas available for women. Enough water is made available for bathing and laundry	There is insufficient water for hygienic practices.
All people are satisfied with the adequacy of facilities they have for water collection, storage, bathing, hand washing and laundry	People are not satisfied because of the lack of water-related facilities.

Although damage to RWH systems was severe, the consequences were delayed as people had saved water before the cyclone. However, the inhabitants' refusal to use disinfection tablets caused health issues for people in the village, especially for children. People did not purify rainwater, either before or after the cyclone, as they claimed that the purifying, disinfecting and treatment tablets provided by the Government and NGOs changed the water's taste. When roofs are not being cleaned regularly, the collected water becomes contaminated with all the sediment on the roof, both chemical and biological, including bird droppings. As a result, a number of infections, flus, and cases of fever were observed after the cyclone mainly due to water contamination, and fighting disease was made more difficult due to the lack of water for hygiene purposes (Government of Vanuatu, 2015c). The Government, in partnership with international agencies such as UNICEF, visited people and distributed medications to try and control the epidemics (Health Cluster, 2015).

Rainwater harvesting, however, is not the only source of water for the village as the collected rainwater is not sufficient to cover domestic usage as well as agriculture, especially during dry seasons. Like most rural communities in Vanuatu, Laonkarai enjoys a secondary water source that is used in summer when rainfall is low. The alternative water resource in Laonkarai is a water catchment fed by a creek, and located approximately 2 km from the village and around 450 metres above sea level (Figure 5-2 and Figure 5-3). The catchment has a naturally irregular shape and its volume is less than 3000 litres. A transmission system fed by two polyethylene tanks, each with a capacity of 6000 litres, ensures the consistency of water flow. The transmitted water is mainly used for agricultural purposes, but it also meets hygiene, cooking, and washing needs.

Figure 5-3: Water catchment in Laonkarai village

The cyclone washed soil and other contamination from around the creek and discharged them into the water catchment. The debris then clogged the water intake, filled the catchment and subsequently decreased the water catchment's volume, causing water outage for the inhabitants of the village. Moreover, falling objects and residue from the cyclone almost blocked the creek and disrupted the water flow to the catchment. Fallen trees broke the transmission water pipe at a number of points and blocked and/or changed the water catchment's access routes. The resulting dramatic drop in water discharge created major problems for the villagers who used the water on a small garden built to grow vegetables and herbs. In addition, water in the taps was full of sediment and of poor quality.

5.5. Discussion

What happened during TC Pam showed poor pre-disaster mitigation across all types of water supply systems in Vanuatu. The RWH systems were not designed to withstand cyclones, so the majority of them were easily damaged. Guttering systems, even in public places such as schools, were not installed appropriately. In most cases, the water transmission pipes had already exceeded their design life and were suffering from the effects of age, and there was a lack of anchoring and appropriate supports in mountainous areas such as Laonkarai. Water pipes were also exposed to falling objects. When water pipes are exposed, falling debris affects water quality and blocks the water intakes during cyclones and thunderstorms. Debris kept blocking water catchments for a few weeks following the cyclone. Preparedness had also been neglected within the majority of communities, especially in the rural areas.

Although early warning of the category 5 cyclone was broadcast on 12 March, the majority of people had no idea what a category 5 cyclone meant. Further, in remote villages and islands, even if the locals knew the meaning of a category 5 cyclone, they could not do much without appropriate equipment and effective training. However, as seen in Laonkarai, the cohesiveness of rural communities compensated for these shortcomings and helped to some extent in the recovery process.

People in Vanuatu's rural areas live like a family. They have a strong sense of community and significant levels of social participation. The involvement of individuals in the community, as well as embedded cultural responses to difficult situations, prevented chaos and sped up the recovery process after TC Pam.

Although the Government has not developed comprehensive enforcement laws to prohibit violence (World Health Organization, 2014), the level of violence in Vanuatu is low compared to other countries around the globe. Based on Numbeo statistics, the crime rate and social perceptions of crime in Vanuatu are low. In parallel, community perceptions of safety are significantly high (Numbeo, 2018). The homicide rate has been decreasing over the last 20 years. INGOs are educating Ni-Vanuatu with the aim of decreasing violence against women and girls by challenging negative assumptions and teaching people to make good relationship choices. About 7% of women in Vanuatu have reported suffering from non-partner sexual violence at some point in their lives (World Health Organization, 2017).

Trust in general includes community trust (trust in each other) and trust in the public sector. Although there is no recorded data, the authors found through the site visit and interviews that trust levels in Vanuatu are high in the sense that most people trust each other and their neighbours. Levels of trust seem to be higher in rural areas where people know each other personally. However, trust in the public sector is not very high, mainly due to political instability within the country. According to statistics, political stability was at its lowest level in 2015 when TC Pam hit the country (The Global Economy, 2019).

Locals' level of knowledge and skills to help in water system restoration are highly dependent on INGO training within communities. In general, the level of education in Vanuatu is lower than the global average. Ni-Vanuatu spend 6.8 years in school on average. However, in communities where international agencies have been active in the last few years, people showed an acceptable level of skill for restoring the water system without external assistance. Laonkarai was one of the villages that enjoyed the benefits of having a skilled person with some field experience in water supply systems, who provided leadership to young members of the village in restoring roofs, gutters, and pipes.

As part of developing sustainability, the NGOs have set up committees for water supply and water management in the villages to look after the water supply systems. The NGOs provide the committees with training and manuals, and involve the committees in the construction work, etc. The NGOs also leave the communities with the means for fundraising. The committees collect money from the community on a regular basis for different purposes, such as water supply recovery in the case of pipes bursting or breaking due to a disaster. The money can be spent for purchasing spare parts and materials, either from the Department of Water within the Department of Geology, Mines, and Water Resources (DGMWR) in the Ministry of Lands, or other suppliers.

Despite the overall low level of knowledge and skills at the village level, many recovery tasks were carried out by locals, especially in rural and remote areas. Inhabitants cleaned the water catchments and removed debris and sedimentation from the catchment inputs, reservoirs, and intakes. The younger generation in Vanuatu showed an enormous capacity to assist in this aspect of the response and recovery phase. Locals also fixed leaking and broken pipelines by means of basic equipment such as rubbers. All these factors plus the community’s calmness in a difficult situation and the people’s trust in each other provided a strong basis for a quicker and smoother recovery.

Ni-Vanuatu involvement in their communities was a factor that supported the water supply restoration process. Rural areas in Vanuatu are difficult to be reach. In addition, the Department of Water within the Department of Geology, Mines, and Water Resources (DGMWR) in the Ministry of Lands, which is responsible for both rural and urban water supply, does not have sufficient numbers of restoration crews. In the aftermath of TC Pam, local people repaired roofs and gutters with the materials and equipment they had available in the village, although the quality and quantity of harvested water was adversely affected due to imperfect repairs. Young people in Laonkarai cleaned the water catchment, removed obstacles and fixed water transmission pipes to restore the secondary water resource. Similar to the roof and gutter repairs, repairs to the pipeline were undertaken with materials and equipment at hand. Figure 5-4 shows the pipeline transmitting water from the catchment to Laonkarai.

Figure 5-4: Transmission pipeline from water catchment to Laonkarai

While not all rural communities over the whole country showed the same degree of cohesion during the emergency phase following the cyclone, their similarities were more marked than their differences. In Laonkarai, their responses as a community enabled the villagers to deal with the water problems after the cyclone. Their foresight in saving water before the cyclone and ability, and acceptance in coping with inadequate water supply after the cyclone, were great strengths. The relatively young average age of households was another advantage. Conversely, their relatively low level of knowledge and skills in relation to fixing the water supply problems can be considered a weak point.

5.6. Conclusion

The water supply system in Vanuatu suffered severely from TC Pam due to a variety of factors, ranging from technical to organisational. The damage was mostly to the RWH systems, pipelines, and pumping systems. None of the Sphere standards and criteria for providing people with at least a minimum quantity and quality of water were met in a timely manner, despite the hard work of a variety of NGOs.

This study aimed to identify how social capital impacts water supply resilience in Vanuatu. Consisting of over 80 islands and lacking a central water supply system, Vanuatu presents geographical and organisational challenges for water supply recovery following disasters. Four social factors were identified in Laonkarai on Efate Island as representative of rural Vanuatu: individual demands and capacities, individuals' involvement in the community, and societal levels of violence and trust. At the village or community level in Vanuatu, people's reaction to the cyclone and its consequences was impressive. Ni-Vanuatu resilience is best understood as an acceptance that this is how it is. Despite severe shortages of water in some areas, the communities dealt with the issue calmly and the country did not experience any chaos due to water shortages. This fatalism and associated willingness to improvise helped camouflage deeper organisational issues. People remained patient during the response and recovery process and started repairing their RWH systems (regardless of repair quality), helping the agencies as much as they could. Such behaviour reflects a healthy level of social capital and raises the question: How do we link the overall resilience with the social satisfaction from the situation?

As RWH is a major water supply solution in the rural areas of Vanuatu, and because of its high vulnerability to cyclones, the locals should be trained and encouraged to maintain roofs and gutters regularly, and repair secondary water resources such as water catchments and pipes in the aftermath of cyclones. Maintenance should take the form of cleaning and repair activities to ensure the greatest amount and cleanest water possible is being collected. In addition, disinfection tablets that are more palatable to the locals need to be distributed, and information provided on the disadvantages of using untreated water to minimise resistance to using tablets.

Vanuatu suffers from lack of reliable data. The data released by Vanuatu's government is fairly reliable, but the data gathered by international organisations suffers from a lack of reliability – or is completely lacking. For instance, Giving Index or Trust indicators do not exist for Vanuatu. Collecting more social data from Vanuatu would help improve research in the future.

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CHAPTER 6 – ORGANISATIONAL DIMENSION

The current chapter is based on the following article:

Balaei, B., Wilkinson, S., Potangaroa, R., Baghersad, M. (2019) "How the Organisational Factors of Communities Affect Water Supply Resilience to Disasters"

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6.1. Introduction

Natural disasters can interrupt the supply of sufficient quantity and quality of water to households. Previous disasters have shown that providing residents and disaster response personnel with sufficient quantities of safe water is always a challenge for authorities (Goltz, 1994; Ministry of Health, 2012; Tang & Eidinger, 2013). In New Zealand, approximately 80 per cent of people lost water services in the aftermath of the Christchurch earthquake on 22 February 2011. The water system took 35 days to recover to a normal level (Ministry of Health, 2012). In October 1998, Hurricane Mitch passed through Latin America, devastating buildings and infrastructure in a number of countries. More than 90 per cent of people in Honduras were still without access to water services in early November, and only 60 per cent had access by the end of November. In Nicaragua and El Salvador, 32% of people lost water services in the aftermath of the hurricane (WHO, 2002).

A functioning water system following a disaster is dependent on a set of activities that need to be undertaken prior to the disaster. Water companies apply a variety of measures to foster water supply resilience to disasters. The most cost-effective ones, identified by Muller (2007), are mitigation measures to minimise disaster impacts on water supply systems. In disaster-prone countries such as New Zealand, the United States, or Japan, mitigation is fundamental to their disaster management, and specifically to utility organisations (Godschalk, 2003). Preparedness is another measure applied by water companies to facilitate response activities and quicker restoration following disasters (Paton, 2003; Russell et al., 1995). Similar to mitigation measures, preparedness activities to reduce potential damage and loss of the system vary in nature and scope.

Appropriate infrastructure is required to provide the platform for application of mitigation and preparedness measures, as well as coordinating post-disaster response and restoration activities (King, 2007). Although mitigation and preparedness activities are mostly planned and implemented by the water companies responsible for supplying residents with safe drinking water, not all organisational factors are limited to water companies. Post-disaster water supply is affected by a variety of factors, many of which are not under the control of water companies. As such, the term "organisation" should be considered at the regional and even national level.

Community resilience depends on the resilience of its organisations and lifelines when a disaster happens (Bruneau et al., 2003). An organisation is considered *resilient* if it withstands the disaster and recovers pre-disaster functionality within a short time period (Sundström & Hollnagel, 2006). Institutional resilience has been addressed by researchers to identify how different organisations function and bounce back following disaster. However, findings are highly dependent on the case studied. For instance, following the Darfield earthquake in New Zealand in September 2010, Whitman et al. (2014) identified wellbeing of staff, cash flow and losing customers as the main concerns in relation to organisational resilience. Moreover, they found that the main factors for reducing the impact of disaster were staff members' relationships, building design and type, and continuity of critical services. In another case, Zaato and Ohemeng (2015) claimed that adaptive capacity, employees, leadership, and organisational design are the most significant factors for the successful recovery of an organisation.

Although there is some research investigating aspects of organisational impact on post-disaster recovery (McManus et al., 2008; Zaato & Ohemeng, 2015) or measuring the capacity of organisations to accomplish their duties (Otley, 1999), the impact of organisational wellbeing and development as a whole on the resilience of the community lifelines such as water supply systems has been largely neglected. Organisations as structured entities coordinate disaster-related activities within communities and infrastructure systems. Coupled with other characteristics of communities such as social capital and economic capacity, organisational capacity is the main driver in system restoration and disaster recovery. All social and economic capacities need to be directed through organisations to be effective in responding to disaster. As such, organisational wellbeing plays a centric role in resilience of utilities such as water systems to disasters.

This paper proposes a framework to identify the organisational variables affecting water supply resilience to disasters. The indicators were gathered through a comprehensive literature review, and then verified and ranked through a series of interviews with water supply and resilience specialists, social scientists and economists. The identified variables have been analysed qualitatively and quantitively considering their nature, availability, and metrics. The indicators were then measured in Christchurch earthquake in February 2011. Awareness of these indicators and their influence on water supply resilience in society will enable local and national authorities to identify existing strengths and weaknesses, and to optimise investment to obtain best results.

6.2. Water Supply Resilience

Drinking water outage is not the only impact of seismic events in urban areas. Impacts can include conflagration, interruption to medical services, business continuity, and other disruptions to daily life (AWWA, 2001). For example, the fire which killed tens of thousands of people in Tokyo following the Kanto earthquake of 1923 spread because of wind and high temperature, compounded by the lack of water due to water main breaks (Scawthorn et al., 2005). Therefore, availability of water in the aftermath of a disaster is a crucial concern for a variety of decision makers and authorities.

The notion of resilience has captured the attention of a wide range of scholars in diverse disciplines. The concept of community resilience to disasters was proposed in the 21st century, although it had been introduced earlier by Holing (1973) in relation to ecology. Klein et al. (2003) investigated the concept of resilience in relation to weather-related hazards as an example of natural disaster in coastal megacities. They define resilience as a desirable property of natural and human systems in the face of potential stresses, and recommend that resilience be used in a "restricted sense" to present specific system characteristics: (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system's self-organisation capability.

A significant number of researchers have developed conceptual frameworks to measure community resilience from various perspectives. According to Norris (2008), resilience can be understood as a set of network adaptive capacities, namely economic development, resource equity, social capital, and information and communication. Similarly, Cutter et al. (2008) proposed the DROP framework and model — Disaster Resilience of Place — to conceptualise disaster resilience at the community level. The DROP model demonstrates how resilience capacities (coping, adaptive, and absorptive) influence the degree of recovery and resilience of the community. It also includes six groups of indicators: ecological, social, economic, institutional, infrastructure and community competence, to quantify a community's overall resilience.

Recovery of a community is multifaceted, including but not limited to recovery of lifeline systems. Water supply malfunction can cause a variety of challenges and increase the number of disaster victims and fatalities. During the 6.8 magnitude Northridge earthquake in the United States in 1994, for instance, approximately 45,000 people lost access to water services and it took 12 days to restore the utility for 99% of residents (Davis et al., 2012; Goltz, 1994; McReynolds & Simmons, 1995). Likewise, more than one million people lost water services after the Kobe earthquake in Japan in 1995, for up to 60 days in some regions (Chung et al., 1996).

Since Hurricane Katrina in 2005, a significant shift in focus has been witnessed in the research literature from protecting lifelines to community resilience, which is defined as the ability and preparedness of the community to respond to a disaster and recover to a sustainable level (O'Rourke, 2007). A number of studies have proposed metrics to measure water supply resilience to disasters (Cimellaro et al., 2015; Farahmandfar et al., 2016; Makropoulos et al., 2018; Morley, 2012). As well as proposing functional measures, some researchers have also introduced frameworks to improve water supply network resilience (Farahmandfar et al., 2016; Matthews, 2015).

Although most water supply resilience indicators focus on technical dimensions (Gay & Sinha, 2012; Jeong et al., 2017; Piratla & Ariaratnam, 2013), a few researchers have broadened their focus to take other dimensions of water supply resilience into account. One multidimensional study proposed a combined index to measure the performance of the water distribution network based on technical, environmental, and social dimensions of water supply resilience (Cimellaro et al., 2015). The proposed metric combines three indices of functionality and recovery, namely: the number of users who have lost water service, quantity of water in the tank, and water quality. The authors also claim that the index can be used by urban planners to estimate water supply system functionality, including the delivery of an acceptable level of service and post-event restoration processes.

The Sustainable Cities Water Index (SCWI) assesses the cities best placed worldwide to harness water for future success in terms of sustainability (Arcadis, 2016). The SCWI consists of three sub-indices: resiliency, efficiency, and quality. The resiliency sub-index addresses water resource resilience, water related disaster risks, and vulnerabilities. According to Arcadis (Arcadis, 2016), most cities across the world require greater investment and prioritisation to improve their resilience to disasters and unforeseen water shortages.

Research and Development is ongoing. A City Water Resilience Framework (CWRF) is being developed by the Arup Group (Arup, 2018) together with The Rockefeller Foundation to give cities of all sizes a guide to understanding and measuring the resilience of their water systems. The overarching aim of this framework is to create a global standard for water resilience assessment. Aligned with the City Resilience Index (CRI), this framework is promoted as an accessible, evidence-based and measurable way to inform planning, development and investment decisions. In another project, cities from five continents have been selected to contribute to the development of a global framework for water resilience. Amman, Cape Town, Mexico City, Greater Miami and the Beaches, and Hull were selected to represent the range of water challenges facing cities around the world due to their diversity in terms of size of population, geographic location and economic status (Cities, 2018).

This paper measures water supply resilience on the basis of system performance over time. Researchers have proposed a variety of system attributes such as robustness, redundancy, recovery rapidity, and resourcefulness (Bruneau et al., 2003), however we consider robustness and recovery rapidity as the two fundamental attributes affecting system functionality following a disaster (Balaei et al., 2018). Accordingly, the organisational variables affecting water system robustness and restoration are explored in this paper.

6.3.Methodology

The ability to measure resilience is a prerequisite for increasing the ability of the water supply system to function when disaster happens and decreasing water supply recovery time in the post-disaster period. “Measuring resilience” does not demand quantitative approaches per se but requires a method for translating the abstract concept of resilience into a practical tool. To be useful, this tool needs to simplify and reduce the amount of potentially collectable data, information, and measurements to a number of manageable indicators to assist with measuring resilience (Birkmann, Jorn, 2006a).

Identifying appropriate indicators to measure resilience is a key challenge in the area of building resilience. Various indicators have been used to measure a range of variables over the past eight decades. Economic indicators emerged first in the early 1940s (Birkmann, Jorn, 2006a). Generally, these indicators are flawed as they only measure a limited number of parameters and other parameters can be neglected, especially when the system is complicated. However, indicators do provide tangible measures that planning, and investment decision makers can use to evaluate the current condition and implement action to improve it.

In order to measure resilience accurately, indicators need to possess the following characteristics (Birkmann, Jorn, 2006a; Briguglio, Lino, 2003; Hahn, 2003; Mainz, 2003):

- Agreed definitions: the indicators need to be unique in terms of definition to avoid ambiguity.
- Precise: the indicators need to be precisely defined in clear terms.
- Specific and sensitive: the indicators are required to describe clearly and exactly what is being measured. They also need to be sensitive enough to react when input data varies.
- Valid and reliable: consistently measured over time and by data collectors.
- Discriminative: the indicators should not be correlated.

- Evidence-based: the indicators are collected based on research from previous disasters.

Apart from the above-mentioned criteria, this paper adds a criterion called data collectability to ensure an indicator can be utilised in measuring water supply resilience to achieve an applicable tool. Data collectability considers availability, collection cost and ease of collection. In lack of appropriate data, the indicator with readily available data should be replaced with the indicator that is not practical to be measured in quantitative studies although the metrics may not be optimised.

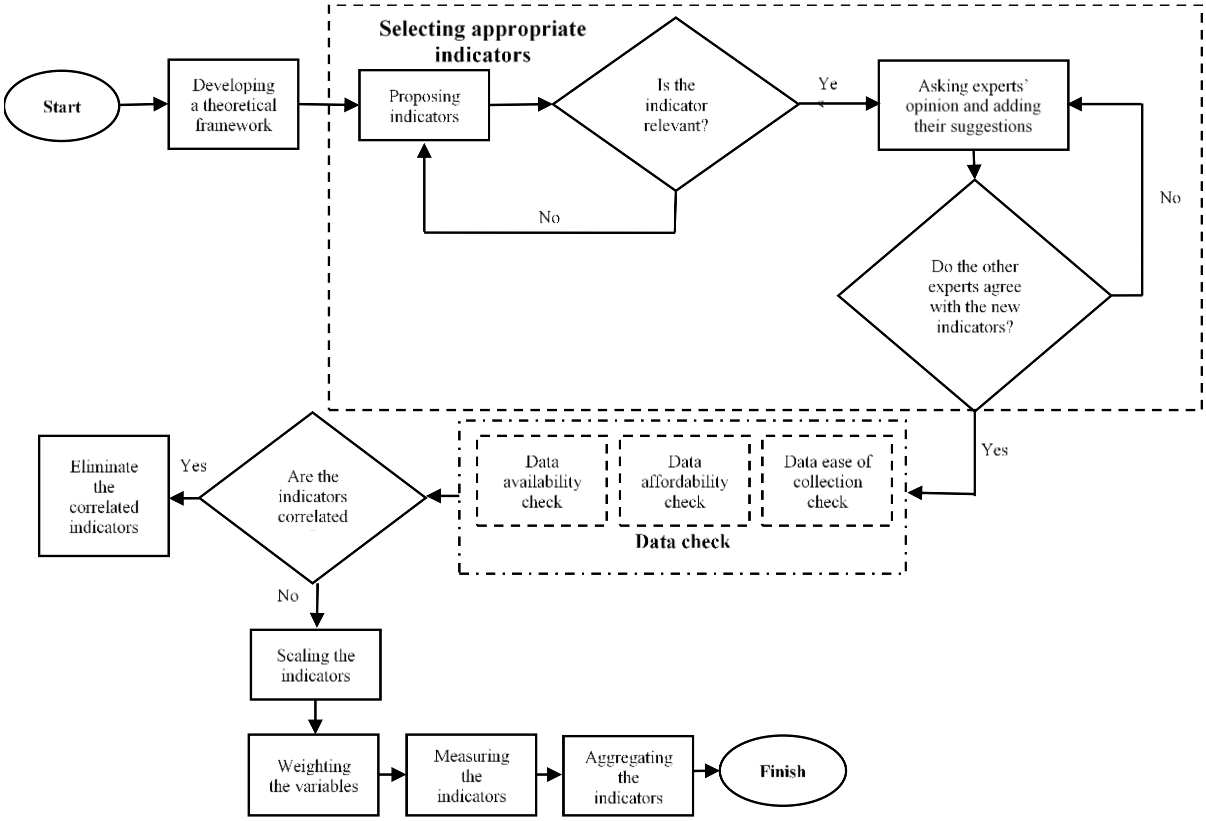

Figure 6-1: Water Supply Comprehensive Aggregated Resilience Measure (CARE) model (Balaei et al., 2018)

The Comprehensive Aggregated Resilience Estimation (CARE) model (Figure 6-1) was utilised in this study to understand the building blocks of water supply system resilience to the impact of disasters (Balaei et al., 2018). The CARE model defines water supply resilience based on the physical attributes of the system and the characteristics of the community the water supply is serving. These characteristics are organisational, social, and economic factors that can affect water supply robustness and/or restoration rapidity when a disaster happens. Figure 6-1 shows the process of measuring water supply resilience based on the CARE model.

The objective of this research was to identify the institutional characteristics and factors of the community affecting water supply resilience to disasters. The research process involved the following phases:

6.3.1. Resilience Measurement Framework

To select appropriate social indicators to best measure resilience, a theoretical framework was utilised (Balaei et al., 2018). In the first step, potential indicators were identified through a literature review and canvassed in interviews with resilience and social science specialists as well as experts working in water industry to obtain the most effective social metrics. Next, data availability, affordability, and ease of collection were checked. Data checks help to avoid using indicators that are not cost-effective, and consequently not feasible. Afterwards, correlation between the collected indicators was taken into account. As a result, the most relevant variables were kept, and highly correlated variables removed.

6.3.2. Collecting Organisational Indicators data

Data gathering for this study encompassed two parts: identifying the social indicators and gathering case study information and statistics to which to apply the indicators. A set of primary organisational indicators was collected through a literature review. a series of recursive interviews was designed and conducted with 23 specialists, deemed competent by virtue of their expertise in the field, to summarise the indicators.

The experts were selected in early stages of the study from a variety of disciplines and backgrounds namely resilience, water engineering, social science and economists. The interviewees were selected from consultants (WSP-Opus, Jacobs, Market Economics), local authorities (Auckland Council, Christchurch City Council, Vanuatu Water Department, and

Tehran Water and Wastewater Company), Universities (University of Auckland and University of Tehran), International agencies (United Nation WASH Cluster), charities working in disasters (ADRA New Zealand and Vanuatu), and independent experts. Semi-structured questionnaire was used to overcome biases and heuristics that can affect the results. The experts were asked about the factors and indicators found through literature review as well as an option for adding new factors and/or indicators they thought could affect water supply resilience. Twelve of experts were interviewed for the second time to give their judgement about the factors and/or indicators which were introduced through interviewing the other experts.

6.4. Organisational Capacity Factors and Indicators

In total, six factors were identified to measure organisational capacity in relation to water supply system resilience to disasters: disaster precaution, pre-disaster planning, data availability and accessibility and information sharing, staff and parts and equipment availability, pre-disaster maintenance, and governance. In addition, 17 indicators were identified or developed to measure these organisational factors and enable decision makers to evaluate each factor's impact on water supply resilience. The factors and relevant indicators are explained in the following section.

6.4.1. Disaster Precaution

Predicting the location and magnitude of disasters prior to their occurrence can help the water sector to mitigate adverse consequences. The prediction of slow-paced hazards (such as droughts) and medium-paced disasters (such as floods) has been developed to an acceptable level of uncertainty (Basha & Rus, 2007; Collins & Kapucu, 2008; Lohani & Loganathan, 1997). However, earthquakes remain one of the most challenging types of disaster in terms of prediction. While not predictive, earthquake early warning systems (EWSs) are able to determine the earthquake's source parameters and provide an estimation of the shaking intensity distribution (Kanamori, 2007). The output information can be distributed to a variety of users such as water systems to reduce the effect of earthquake on the system's components and the system as a whole.

Earthquake early warning systems usually work based on the timing difference between primary (P) compressional waves and secondary (S) shear waves. The P waves travel through the interior of the earth longitudinally at 5km to 7km a second while S waves travel transversely and more slowly, at around 2–3km/s a second. Depending on the depth of the earthquake hypocentre, P waves arrive at the destination (the accelerometer) earlier than S waves (Wu & Zhao, 2006). This timing difference between P and S waves can be used to mitigate damage to the water system by, for instance, shutting off water reservoir valves or shutting down water pumps. However, data processing and information transmission need to be undertaken rapidly so that the key sites receive the data and respond prior to the start of shaking at the site (Allen & Kanamori, 2003).

Early warning systems for other types of disaster can be used to mitigate adverse consequences on water system elements which are vulnerable to that specific disaster. As a rule of thumb, the earlier the disaster is predicted, the more easily it can be mitigated. For instance, the drinking water contamination that caused four deaths and affected over 5000 of the 14,000 residents of Havelock North in New Zealand in August 2016 could have been mitigated if the pumping of contaminated water was stopped prior to the flooding (Watson et al., 2018).

6.4.2. Roles and Responsibilities

Although water companies are the primary organisations responsible for water supply system mitigation, response, and recovery, there is crossover with other sectors. To minimise the water supply restoration time, the roles and responsibilities of all of the organisations involved in the disaster response and recovery need to be clearly identified and the overlaps and gaps between responsibilities need to be minimised.

Confusion occurs when roles and responsibilities are not defined clearly among the organisations who are in charge of supplying water to residents. Both duplication and neglect can be expected, especially in the system restoration period when different organisations need to carry out their responsibilities in a timely manner. In Vanuatu, for example, a variety of organisations from the national to the village level have responsibility for water supply. Following TC Pam in March 2015, unclear responsibilities between agencies and organisations delayed water system restoration and several rural areas were left without safe water to meet basic needs.

6.4.3. Pre-disaster Planning

Appropriate disaster planning can significantly improve the effectiveness and efficiency of institutional response to disaster. Disaster planning needs to be prepared based on systematic knowledge rather than relying solely on common sense. However, although some researchers claim that bad planning is worse than no planning in disaster management (Quarantelli, 1985), we argue that even having a poor disaster plan can improve the water system's ability to withstand disaster and speed up system restoration. Although poor disaster planning in water supply systems can be economically inefficient, it still can improve the water system's robustness and prepare the organisation(s) and their personnel to cope with disaster to some extent. Moreover, if reviewed, tested, and revised periodically, disaster plans can improve water sector preparedness for disaster.

6.4.3.1. Hazard Identification

Hazard identification is a crucial factor for coping with disasters. Hazard identification means not only understanding the potential hazard(s) that can hit an area but also the quality of this impact, such as the probable hazard's magnitude. Japan is a good example with both successful and unsuccessful experiences in hazard identification. Although the risk of earthquake was recognised in Kobe, seismologists failed to gauge the magnitude of the devastating 1995 earthquake which hit Kobe (Katayama, 2004). In the more recent earthquake and tsunami in east of Japan in 2011, the risk of tsunami was predicted, and sea walls had already been constructed. However, the intensity of tsunami meant the region was washed out by waves that passed over the levees (Goto et al., 2011). In both cases, the disaster exceeded expectations and caused unexpected damage to communities and utilities.

It is important to note that there is no automatic link between hazard identification and resilience enhancement. However, an organisation's knowledge and perception of hazard characteristics helps them to identify a system's vulnerability and provides a basis for planning the intensity of reaction and the support required.

6.4.3.2. Business Continuity Plan (BCP)

Disasters can cause interruption to business. The longer a business is closed following a disaster, the more likely that it will never reopen. One study reported that more than 40 per cent of companies never reopen following a disaster, and about 30% of the businesses that do reopen crash within two years (Schut, 1990). BCPs are not limited to private sector businesses; infrastructure companies also need to develop BCPs. A BCP indicates a utility's dedication to supporting their operations by introducing risk management principles into the management culture, and mitigates the adverse consequences of a disaster prior to it happening (Cerullo & Cerullo, 2004).

A BCP can outline how to avoid risks, what contingencies to apply, and how to restore business. Although BCPs and other mitigation and preparedness may have some factors in common, their overarching aims are different. BCPs usually focus on the financial dimension of the business to ensure the company regains a normal level of revenue and remains stable following a disaster. In the case where the water organisation is a private company, a BCP can decrease post-disaster financial issues. A 2012 study in the United States revealed that only

40% of the utilities had implemented a BCP, although an equal number claimed that their utilities were in the process of developing one (Morley, 2012).

6.4.3.3. Disaster Mitigation Plan (DMP)

Comprehensive long-term disaster mitigation plans (DMPs), also known as hazard mitigation plans, aim to reduce loss of life, physical damage and economic loss by balancing safety and risk reduction with maintaining post-disaster levels of service (Hosseini & Moshirvaziri, 2008). DMPs increase awareness of hazards and vulnerabilities, identify long-term risk reduction strategies, build partnerships between key stakeholders for risk reduction, identify implementation approaches, and establish priorities for absorbing and assigning the appropriate source of funding (FEMA, 2018).

Disaster mitigation has been emphasised as a strategic goal by the Hyogo Framework for Action (UNISDR, 2005). Applying mitigation measures not only improves the capacity of the emergency response, but also contributes to maintaining routine operations and increasing system reliability (Pan American Health Organization, 1998). Some countries encourage local utilities to get involved in hazard mitigation planning. Apart from helping their communities become more resilient, becoming involved in a disaster mitigation planning can make the local utilities eligible for external funding opportunities (EPA, 2016). With regard to water system vulnerability, following assessment a DMP prioritises areas for renewal, flexibilisation approaches, and structural retrofitting measures (Pan American Health Organization, 1998).

The time required for water system restoration is decreased by mitigating the known vulnerabilities to disaster (Davis, 2008). In the water supply system, a disaster mitigation plan can reduce the response and recovery phases in a cost-effective manner. Mitigation plans for water supply systems can be categorised into three levels. First is filling in for missing assets, such as providing a spare generator to cover loss of power. Next is replacing assets or their belongings that are not in good condition or cannot perform their function, such as pipes, valves, pumps, etc. Finally, repairing assets systematically to preserve their functionality in the aftermath of a disaster (Pan American Health Organization, 1998).

Moreover, different mitigation measures should be considered for different disasters. For instance, mitigation measures for drought can be classified as follows: increasing water supply, reducing water demand and minimising drought impact. Each measure can encompass short- and long-term approaches. With regard to increasing water supply, adding sources of water is a short-term activity, while reinforcing existing resources by reusing treated wastewater, for example, happens over the longer term. For reducing water demand, the short-term activity can be regulation of crop irrigation, with replacing irrigated crops with dry crops occurring long term. For minimising the impact of drought, water resources can be temporarily relocated in the short term and early warning systems developed in the long term (Rossi, 2000).

Mitigation measures for water systems include but are not limited to replacing or retrofitting the pipes. A systematic approach is needed to identify the most vulnerable elements of the system and prioritise them for mitigation. When water sector personnel turned up to their offices following the Christchurch earthquake in February 2011, they found the computer screens collapsed and broken in some cases, with papers and documents strewn on the floor. In this case, a retro-fit of non-structural elements could have saved time and decreased the water system restoration period.

6.4.3.4. Emergency Response Plan (ERP)

An emergency response plan (ERP) is also an outcome of a water system vulnerability assessment. Water system ERPs include the procedures and information required to effectively prepare and mobilise the water company's resources (such as spare parts and equipment as well as human resources) in the case of emergency (Davis, 2008). Increasing damage assessment capabilities can reduce water system recovery time and subsequently increase the system's resilience. ERPs should be designed to realistically, not ideally, respond to disasters with the available resources. Water system ERPs should be reviewed and revised continuously and kept up-to-date based on the mitigation measures applied to the system and new technologies and equipment adopted (Pan American Health Organization, 1998). The plans also need to be available for use at any time by personnel involved in the emergency response.

The following is the basic information an ERP should contain (WHO, 2002):

1. Legislation and regulations pertaining to disasters at the local and the national level
2. Information on hazards, including: earthquakes, hurricanes, floods, slope failures, etc.
3. Land use planning
4. Information on response and restoration projects:
    - Consultants and contractors, equipment and material suppliers
    - Water truck owners, private drinking water wells, and fuel suppliers
    - Information on critical users, including:
        - Hospitals, health centres, emergency services, firefighters, the police, etc.
        - Shelters, prisons, markets, schools, etc.
5. Technical information
    - Up-to-date information on the systems
    - Official register of water supply networks and up-to-date technical files
    - Operational procedures
    - Roles and responsibilities of maintenance and other teams
    - Previous disaster experiences, water mains breaks, major maintenance jobs, etc.
    - Improvement projects.
6. Administrative information
    - Description of human, material, and financial resources of the company
    - Organisation of the company and its objectives, goals and strategies
    - Legal framework
    - Personnel training programmes
7. Operational and logistical support information
    - Availability of heavy machinery
    - Vehicles' condition and track record
    - Inventory of facilities (e.g. pumps, compressors, etc.)
    - Personal protection equipment (PPE)
    - Stock of spare parts and chemical products

6.4.3.5. Personnel Training and Exercise

The pre-disaster planning approaches discussed above cannot be achieved without training and exercises, which are a vital part of preparedness activities (Perry, 2004).

Simulation exercises and drills can be used by organisation(s) to evaluate and test plans, and also enhance the skills and knowledge of personnel before a disaster occurs. Simulations comprise table-top exercises in which partners need to respond to the information received based on a hypothetical scenario. A drill includes practical exercises in which participants need to react based on simulated damage and injuries. In contrast to simulation exercises, actual mobilisation of human and material resources is needed for drill exercises. Preparedness drills include three types: partial or full scale, pre-announced or surprise, and simple or complex drills.

A study by Peterson and Perry (1999) revealed that training can boost the preparedness of personnel by building teamwork, training sufficiency, the effectiveness of response activities, recognition of risks and sufficiency of equipment. Further, doing drills provides opportunities to examine protocols and equipment during training. Alongside periodical training, plans can be reviewed, gaps identified, and revisions made. Exercises vary and can include firefighting, emergency evacuation, and dealing with chlorine gas emissions in water treatment plants, etc. To increase efficiency, water companies can accomplish repairs and renewals during periodical exercises. This has two benefits: first, the operation (or restoration) crew will face a real issue in the network; and second, new fixings and renewals can increase water system resilience to disasters.

6.4.4. Mutual Aid Agreements

Mutual aid agreements are binding contracts between two or more authorities and are negotiated and signed in collaborative meetings. In general, it is either impossible or less cost-effective for an organisation like a water company to possess all the equipment needed to cope with a disaster (McEntire & Myers, 2004). Lack of specialised personnel, spare parts or equipment can lead to chaos in response and longer restoration times. Mutual aid agreements are crucial to increasing the water sector's capability to cope with disasters by resolving challenges arising from resource and personnel shortages that can overwhelm the organisation during disaster.

Mutual aid and assistance needs to be agreed/contracted prior to the disaster to be effective. For example, a mutual aid agreement can be signed between water and power companies since these systems interact with each other. Muller (2007) estimated that hydropower provides 19 per cent of the world's electricity. On the other hand, water supply systems are dependent on power to run pump stations and water treatment plants for example. Therefore, failure in one system can result in failure or reduced efficiency in the other.

6.4.5. Data Availability, Accessibility, and Information Sharing

According to Comfort et al. (2010), decision-makers need two types of information to make effective decisions following disaster. They need information that gives them an idea of the scale of social and physical damage in an area, and they need to know about the level of resources, personnel and capacity provided by organisations. Coordination and performance of response activities by organisations will be enhanced by good availability and accessibility of information (2004). Further, estimating and recording details of damage in any given disaster is crucial to evaluating the scope of demands in the response phase and providing services such as housing, sanitation, etc.

As with other lifelines, lack of data in water companies reduces the effectiveness of disaster response operations in the organisation. Decision makers in water companies, for example, need to be informed about the volumes of water required for the affected population and the duration of support because the demand ratio for water varies over time. However, there are high levels of uncertainty immediately after disasters when accurate and reliable data is needed. Therefore, data need to be updated and revised on a regular basis so that it becomes more accurate from the time of the event onwards.

Moreover, empirical and theoretical studies reveal that flow of information is just as important as capturing it (Comfort et al., 2004). All authorised personnel in an organisation need to have access to the information and know where to find it when required. In general access to information should not be restricted to a limited number of individuals as the knowledge and information will disappear when the organisation is missing some personnel for any reason. This problem is highlighted when disaster occurs as the organisation is more likely to be missing critical staff.

6.4.6. Staff, Parts, and Equipment Availability

Availability of human resources as well as continuous training reduces the potential for problems when operational staff become unavailable following disasters (Turner, 1994). It is crucial to have spare staff who are practiced in simulated response activities to assure the effectiveness of operations in the event of disaster.

Damage to any part of the water system, especially critical parts necessary for producing, distributing or treating of water, can cause delays in the response and recovery phases after disasters (Morley, 2012). The organisation(s) needs to prepare spare parts to replace those that fail due to damage. Checking equipment availability is a routine aspect of preparedness plans. Spare equipment needs to be stored in an easy to access and safe place that is known to staff.

6.4.7. Pre-disaster Maintenance

Pre-disaster maintenance, known as planned maintenance (preventive), is a set of regular maintenance activities carried out to ensure the water system reliability and safety during business-as-usual. The primary objective of maintenance is to reduce the rate of deterioration and failure risk in water assets (IPWEA, 2015). Regular pre-disaster maintenance can reveal the weak points and so mitigate the adverse consequence of disasters. In New Orleans, poor maintenance of flood protection structures resulted in failure of the levee and canal systems, which caused extensive damage to the city (Oh et al., 2012).

In case of emergency, acceptable amounts of water, water pressure (especially for firefighting) and water quality are crucial. Extending the life of equipment and structures, high performance, enhancing the reliability of the system, reducing costs and providing safe water for drinking are the objectives of system maintenance (Ministry of Health, 2010). By means of maintenance, decision makers ensure that the system continuously performs its predesignated function. In the water supply system, these activities can include adjustment of components, tidying, greasing, repairing and replacing deteriorated equipment.

The simple way to identify any failure of the asset is regular observations. For instance, in pump stations, this will involve checking vibration of pumps, condition of oil and efficiency of the asset (Ministry of Health, 2010). So, it is essential to specify a plan for checking and carrying out maintenance systematically and periodically. This plan should include paper or electronic documents which formalise the planning and scheduling. Each maintenance plan should have at least four components: “asset inventory and asset record cards” which list of maintenance tasks to be done, “task description cards” for recording a summary of activities, “maintenance schedule and checklist” for arranging dates in the calendar and a “maintenance tracking tool” to follow the maintenance activities.

6.4.8. Governance

The concept of governance has long been the subject of discussion among scholars and decision makers. Some definitions are broad and cover rules, enforcement mechanisms and organisations (World Bank, 2001), while other definitions focus on public sector management matters (Kaufmann, D. et al., 2006). This study understands governance as the traditions and institutions by which authority in a country is operated (Kaufmann, Daniel et al., 2011).

There is no governance indicator specific to water sectors. Therefore, national level governance indicators are the best instruments to use. This study uses the Worldwide Governance Indicators (WGI) developed by the World Bank and covering over 200 countries since 1996. Although WGI indicators do not directly assess governance of water sectors, they are assumed to appropriately represent different sectors, including the water sector.

WGI consists of six indicators, namely voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption. These indicators are measured based on several hundred variables obtained from over 30 different data sources. The indicators assess governance based on perceptions in the public sector, commercial business data and information provided by NGOs and other individual and business respondents across the globe (Kaufmann, Daniel et al., 2011). Among these indicators, voice and accountability has been identified as irrelevant to the water sector as it captures citizens' ability to participate in selecting their government, freedom of expression, freedom of association, and a free media.

6.4.8.1. Political Stability

Political stability and absence of violence (terrorism) measures perceptions of the risk of political instability and/or politically motivated violence. Political instability can potentially cause (and emerge because of) violence such as protests and riots, terrorism, and civil war. By disrupting normal activities and business operations, protests and riots, terrorism, or civil war can cause damage to people and/or water supply assets (Kaufmann, Daniel et al., 2011).

6.4.8.2. Government effectiveness

Government effectiveness assesses perceptions about the quality of public services such as water supply and their degree of independence from political pressure, the quality of policy development and execution, and the reliability of the government's commitment to policies.

6.4.8.3. Regulatory quality

Regulatory quality captures perceptions about the government's formulation and execution of appropriate policies, strategies, and regulation to encourage private sector development. Normal business operations can become overpriced as a result of low regulatory quality, including but not limited to regulatory compliance or bureaucratic inefficiency.

6.4.8.4. Rule of law

Rule of law measures perceptions of the extent to which community members trust and comply with the rules of society. It also shows the quality of commitment to implementation, the police, and the likelihood of crime and violence.

6.4.8.5. Control of corruption

Corruption occurs when bribery or other corrupt practices are involved in securing contracts, importing/exporting goods and other business activity. Corruption threatens the operation of both the private and public sector. Control of corruption captures perceptions of the extent to which public authorities are utilised for private benefit and includes minor and major forms of corruption and undue influence on government by elites.

6.5. Case study: Christchurch Earthquake (February 2011)

A sequence of three earthquakes hit Christchurch, New Zealand; the first on 4 September 2010, the second on 22 February 2011, and the third on 13 June 2011. The February 2011 earthquake was the most devastating with 181 fatalities and economic losses totalling $NZ11.1 billion. This study focused on this second earthquake, which is referred to as the Christchurch earthquake (Eidinger & Tang, 2012).

The main damage to the water supply system was broken water pipes due to lateral spreading and liquefaction. Slope failure also caused pipe damage. In the aftermath of the earthquake, more than 80% of people lost drinking water service (Ministry of Health, 2012). Two days after the earthquake, 50% of people were receiving water service although all residents were reminded to boil or add bleach to water prior to drinking (NZHerald, 2011). As expected, the Canterbury rebuild profile clearly shows that the maximum level of infrastructure rebuild happened immediately after the earthquake and decreased over time, while recovery of other sectors (residential and commercial) increased over the same period of time (New Zealand Parliament, 2011). The first priority of local authorities was to provide the residents with basic hygiene services such as water supply, wastewater, and transport to facilitate community recovery following the earthquake. Figure 6-2 shows drinking water service after the 22 February 2011 earthquake in Christchurch.

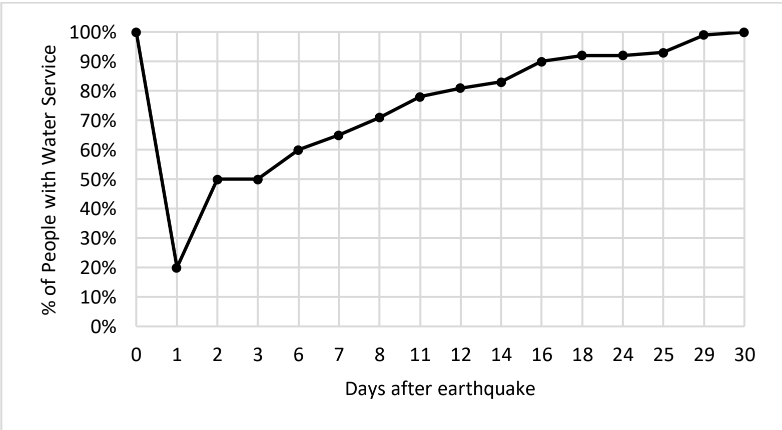

Figure 6-2: Drinking Water Service after 22 February 2011 Earthquake in Christchurch (Ministry of Health, 2012)

Governance has a crucial role in enabling organisations to cope with disasters; however, there is no recorded evidence for governance quality in the Christchurch water sector. However, overall governance in New Zealand can be applied to the water sector with an acceptable level of confidence. In this study, 2010 WGI data was utilised to increase accuracy when envisaging governance for the Christchurch earthquake in 2011.

Over the last two decades, New Zealand has consistently been ranked among the top 10 countries on all dimensions of the WGI. As described earlier, WGI uses over 30 individual data sources to measure governance quality worldwide. Table 6-1 shows the Worldwide Governance Indicators for New Zealand.

Similar to other sectors in New Zealand, Christchurch City Council (CCC) and its units – including the three water and waste units responsible for providing water to residents – is a transparent organisational system with minimum corruption. The Council comprises a mayor and 16 councillors. Christchurch residents elect the mayor. The councillors are elected by residents from the ward they represent. Christchurch also has seven community boards representing their individual areas. Consisting of six to nine members and covering two to three wards, community boards are elected by residents from the area they represent. Councillors are also members of the community board covering their ward. Community boards make decisions on local issues, activities and facilities.

Table 6-1: New Zealand Governance Indicators as of 2010 (The World Bank, 2018b)

Indicator	Number of Sources	Governance Score (-2.5 to +2.5)	Percentile Rank (0 to 100)	Standard Error	Rank in the World
Political Stability	8	1.24	91.47	0.24	3
Governance Effectiveness	7	1.82	96.65	0.23	4
Regulatory Quality	7	1.81	98.56	0.24	2
Rule of Law	11	1.87	98.10	0.16	4
Control of Corruption	9	1.34	99.52	0.17	2

CCC had made some improvements since 1990 (recommended by Lifeline Group) to make the water system more resilient, including using motorised valves in reservoirs, improving the safety of non-structural elements (e.g. switchboards are tied to the wall and vertical pumps are tied so they don't fall over), the use of flexible joints at reservoirs to cope with differential settlement, and so on. However, Christchurch did not have the benefit of a systematic early warning system prior to the February 2011 earthquake, although some response teams such as Civil Defence crew were using a prototype warning system which gave rescuers a 3-second warning for aftershocks on their mobile phones (Davison, 2011). The only automated system the Christchurch water sector had prior to the earthquake was motorised shut-off valves installed at water reservoirs. When motorised valves detect movement in the ground, they shut off water flow to preserve water in the reservoir for firefighting and domestic use.

In general, CCC had adequate understanding of the hazard(s) threats the region prior the earthquake. Apart from local studies on planning for disaster (for instance refer to Forsyth (2006) or Becker (2010)), the September 2010 earthquake provided some preparation for the next two earthquakes. However, it depreciated resources and may have created a false sense of security among local authorities that they would not experience another devastating earthquake for a few years. Previously, all planning undertaken in the Canterbury region had been based on predictions of a large movement of the Alpine Fault (Intensity IX in Modified Mercalli) and Alpine Fault ruptures approximately every 300 years, and intensity VIII (significant damage and loss of life) events approximately every 55 years (Elder et al., 1991).

Christchurch City Council had developed pre-disaster plans including a business continuity plan (BCP) to increase water resilience to disasters. However, the interviewed experts now believe the BCP did not help or prepare them in any way to deal with the water supply issues. In the aftermath of the earthquake, key staff reacted to the earthquake based on their intuitive knowledge. Although technology can facilitate damage assessment following a disaster, technology failures can cause difficulties in post-disaster water management. For example, the Council thought one of the big reservoirs was still operating but the level sensor had fallen to the bottom of the reservoir and was submerged. To avoid this type of misleading information, damage assessment teams and restoration crew were subsequently sent out to key components of the water system in the first hours to assess the amount of damage and system operability.

The Council had also developed an emergency response plan (ERP). In particular, the September 2010 provided valuable lessons which were applied in the February 2011 earthquake. The September 2010 earthquake helped CCC in terms of applying contingencies to cope with the post-earthquake water shortage. The Council already had saw horses (stands with taps on them that people could plug into). When the pipe system failed, people could go and collect water from any of the 60 sites around the city.

The CCC model of successfully managing water supply restoration through a trusted contractor could be applied to other disaster-prone areas around the globe. Although there was no prior agreement covering the post-disaster situation, there was enough trust established that the Council was able to ask their main contractor to begin repairing water pipes once the damage had been assessed. The principal contractor had a number of sub-contractors to assist with repairs around the city. The good existing relationship between Council and the local power company also ensured power connectivity was prioritised in critical facilities such as pump stations. Further, approximately half of the pumping stations had standby generators and the rest were able to use portable (plug-in) generators. As water demand reduced in the aftermath of the earthquake, the generators provided good capacity for pumping water in the network until power was restored to the pump stations.

It should be noted that CCC established The Stronger Christchurch Infrastructure Rebuild Team (SCIRT) as a virtual organisation in 2011 to rebuild Christchurch's earthquake damaged lifelines. The main mission of SCIRT was to provide a cost-effective and efficient approach to recover and reconstruct Christchurch's lifelines in a timely manner. SCIRT was not involved in system restoration – which happened within a few weeks – but provided a strong means for Council to facilitate longer term system recovery. Funded by the New Zealand Government and Christchurch City Council, SCIRT developed a NZD 2.2 billion programme including over 700 projects to repair and rebuild three main water pipes, pump stations and the transport system.

At the time of the February earthquake, the main water contractor had access to GIS desktop and the water supply system maps and data were supposed to be updated annually. However, the GIS maps were not updated for the contractor after the 2010 earthquake. As such, the contractor did not have access to the most up-to-date repairs on an integrated GIS map. While the comprehensive GIS data from the water network was very helpful to Council in dealing with the February 2011 earthquake, the lack of up-to-date GIS data on the contractor side resulted in a number of failures in recording repair information following the earthquake. For instance, the restoration team would go out to repair a pipe only to find the pipe had already been replaced.

In general, availability of critical staff, parts or equipment was not an issue following the Christchurch earthquake. Although the February 2011 earthquake caused severe damage to buildings, houses, and the transport system, almost all key water personnel returned to work within the first few hours. Although it is not practical to stock all parts that may be required following a disaster due to variability in parts and materials used across the water supply system, the main contractor did have supplies of extremely critical parts (e.g. 600 mm water mains) and was able to quickly source smaller pipes from other suppliers in New Zealand and overseas following the earthquake.

CCC owns and is responsible for the maintenance of all water pipes, fittings, and connection boxes (including water valves). Christchurch loses millions of litres of water every year due to water leakage as maintenance is mainly reactive rather than proactive, and repairs are not applied before a leakage or breakage is detected. The reactive maintenance strategy results in higher expenditure in the long term and means CCC is not up to date in terms of network functionality information.

An acceptable level of proactive maintenance had been carried out at the pump stations as programmed, including testing switchboards, pumps, electrical systems, etc. However, some level of damage to the water system could have been mitigated if more proactive or predictive maintenance measures had been applied to the water network. Accordingly, CCC needs to shift from reactive to more proactive maintenance by using new technologies such as thermography for early detection of malfunctions in pipes and other facilities.

Overall, the Christchurch water supply system showed a medium level of resilience to the earthquake. Although organisational factors are not the only factors affecting water supply system resilience, they do play a crucial role. In summary, CCC demonstrated an impressive level of governance over time and critical staff were available following the earthquake. Availability of critical parts was achieved through its agreement with a main contractor, who was handed responsibility for restoring the water system to a normal level after the earthquake. Data availability, mutual aid and agreement, regular system maintenance and hazard identification were the organisational capacities that supported water system resilience to the earthquake.

On the other hand, establishing an earthquake early warning system and more emergency response planning are needed to foster water supply system resilience to earthquakes. An integrated system connected to an operational early warning system can preserve water capacity and minimise damage to water system facilities such as pumps prior to an earthquake happening. Practical emergency response planning also can help the water sector to foster water system restoration following a disaster. CCC was involved in exercises designed by Civil Defence and Emergency Management (CDEM) prior to the earthquake, but the training was general and designed to help residents to survive when an earthquake happens. Training and exercises tailored to the water sector for particular disasters would increase knowledge and awareness among personnel.

Figure 6-3 shows organisational indicators as measured for Christchurch earthquake in February 2011.

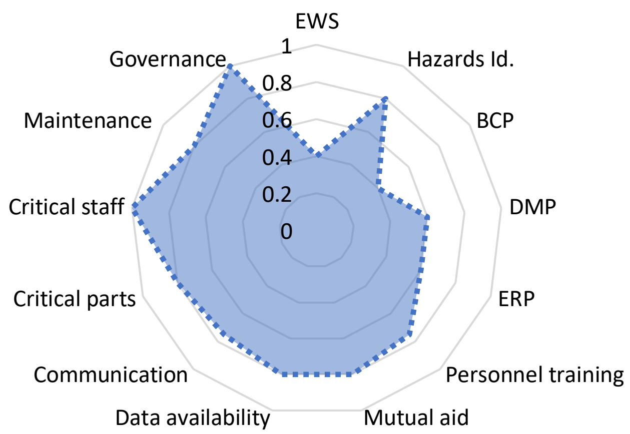

Figure 6-3: Organisational indicators of water system resilience in Christchurch

6.6. Conclusion

Having a functioning water system following a disaster is crucial to the wellbeing of residents and first responders. Water agencies are the platforms for delivery of water services to communities. The capacity and performance of water agencies and other interacting organisations can affect water supply resilience, including system robustness and recovery rapidity following a disaster. This study investigated the impact of organisational factors within communities on resilience of water supply to disasters using the CARE framework.

A literature review followed by interviews with water supply system experts identified six factors and 17 indicators for water supply resilience to disaster. The six factors are disaster precaution; pre-disaster planning; data availability, accessibility, and information sharing; staff, parts, and equipment availability; pre-disaster maintenance; and governance. The 17 indicators for these factors are early warning system (EWS), hazard identification, business continuity plan (BCP), disaster mitigation plan (DMP), emergency response plan (ERP), personnel training and exercises, mutual aid and assistance, availability and accessibility of databases, communication and information sharing, spare critical parts and equipment and their accessibility, availability of critical staff, regular maintenance, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption.

These factors and indicators were tested for the case of Christchurch to understand how organisational capacity affected water supply resilience following the earthquake in February 2011. Governance and availability of critical staff following the earthquake were the strongest factors, while the lack of early warning systems and emergency response planning are areas for improvement. While a business continuity plan had been developed, water sector personnel did not find it effective in coping with the earthquake. In addition, developing and integrating pre-earthquake plans – i.e., disaster mitigation plan and emergency response plan – would help in fostering resilience of the water system.

The other area identified for improvement area is water quality post-disaster. Due to the good quality of groundwater, Christchurch water was not being treated in most parts of the city at the time of the earthquake. The Drinking Water Standards for New Zealand (DWSNZ) 2005 (revised 2008) has forced CCC to address the compliance of a number of wells with the secure groundwater criteria. Although the existing system may work during normal conditions, it is vulnerable following disasters such as earthquake or flooding when water contamination is a grave concern.

The results of this study show that consideration of the proposed factors and indicators can enhance the resilience of water supply to disasters. Our findings provide insights for local authorities to use in identifying existing strengths and weaknesses, and optimising investment to obtain best results for fostering water supply resilience. Other case studies are highly recommended to assess the criticality and weight of individual factors and indicators for measuring water system resilience.

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CHAPTER 7 – ECONOMIC DIMENSION

The current chapter is based on the following article:

Balaei, B., Wilkinson, S., Potangaroa, R. (2019) "Economic Factors Affecting Water Supply Resilience to Disasters"

Submitted to "*Environmental Hazards (Taylor & Francis)*"

7.1.Introduction

Due to their wide and spreading nature, water systems are susceptible to damage from natural disasters. During the 6.8 magnitude Northridge earthquake in the United States in 1994, approximately 45,000 people had no access to water services for approximately 12 days (McReynolds & Simmons, 1995). Likewise, more than one million people lost water services for up to 60 days following the Kobe earthquake in Japan in 1995 (Chung et al., 1996). Communities are faced with drastic challenges when water services and water quality are disrupted in the aftermath of disasters (Makropoulos et al., 2018; World Health Organization, 2009).

While community resilience is defined as the aggregated ability of a geographically defined area to handle an external shock and subsequently resume everyday life (Aldrich & Meyer, 2015), water supply resilience in conjunction with community is defined as the physical status of water supply system and social, organisational, and economic capacity of the community to withstand the disaster and recover to a normal level of functionality in a timely manner (Balaei et al., 2018). In studying resilience of water supply to disasters, the physical characteristics of the system is not the only dimension that can affect/be affected by the disaster. The economic state of the community, and its organisational well-being, preparedness and social capacities can affect water supply resilience significantly.

Among these factors, economic capacity plays a significant role, affecting the other three factors both directly and indirectly (Cavallo et al., 2013). Water supply resilience and the economic capacity of communities are interdependent. While the physical strengthening approach has received a lot of research attention, the role economic capacity plays in adopting appropriate mitigation measures and putting in place sustainable response and restoration measures is often neglected.

The impact of disaster on the economic state of disaster struck areas has drawn a lot of research attention. They have explored direct economic effects of disaster (Chang et al., 2002; Hochrainer, 2009; Noy, 2009) and indirect effects, such as impacts on the labour market, etc. (Belasen & Polachek, 2009; Higuchi et al., 2012; Sarmiento, 2007). Post-disaster business recovery has been another area of research interest (Briguglio, Lino Pascal, 2016; Martin & Sunley, 2015; Rose, Adam, 2004; Xiao, 2011). A number of researchers have also addressed the impact of economic capacity on communities' resilience to disasters, with different findings reported for per capita GDP following disasters. Skidmore & Toya (2002) outlined how per capita GDP increases when a disaster happens, although there are counterarguments claiming that per capita GDP decreases following disasters (Raddatz, 2005).

Despite the wide-ranging research on economic capacity in relation to disaster, there are no specific studies exploring the impact of a community's financial state on building resilience into water supply systems, as well as managing recovery following disaster. To address the existing gap, this paper proposes an innovative indicator-based resilience quantification model. A framework was utilised to identify the economic variables affecting water supply recovery time and subsequently water system resilience to disasters. The indicators were gathered through a comprehensive literature review, then verified and ranked through a series of interviews with water supply, resilience and social science specialists, and economists. The economic factors identified through this process were then investigated for the case of

Christchurch (New Zealand) following the February 2011 earthquake. The case study gives a clearer perspective on how economic factors are incorporated in water supply resilience following a certain type of disaster.

7.2.Methodology

7.2.1. Developing an Indicator-based Framework

Measuring resilience does not demand quantitative approaches per se but requires a method for translating the abstract concept of resilience into a practical tool. To be useful, this tool needs to simplify and reduce the amount of potentially collectable data, information, and measurements to a number of manageable indicators to assist with measuring resilience (Birkmann, Jorn, 2006a).

Identifying appropriate indicators to measure resilience is a key challenge in building resilience. Various indicators have been used to measure a range of variables over the past eight decades. Economic indicators emerged first in the early 1940s (Birkmann, Jorn, 2006a). Generally, these indicators are flawed as they only measure a limited number of parameters and other parameters can be neglected, especially when the system is complicated. However, indicators do provide tangible measures that planning, and investment decision makers can use to evaluate the current condition and implement action to improve it.

In order to measure resilience accurately, indicators need to be agreed in definitions, and be precise, specific and sensitive, valid and reliable, discriminative, and evidence-based (Birkmann, Jorn, 2006a; Briguglio, Lino, 2003; Hahn, 2003; Mainz, 2003). Furthermore, this paper adds a criterion called data collectability to ensure an indicator can be utilised in measuring water supply resilience to achieve an applicable tool. Data collectability considers availability, collection cost and ease of collection. In cases where there is a lack of appropriate data, an indicator with readily available data can be replaced by an indicator that may not be practical to measure in quantitative studies, even if the metrics cannot be optimised.

The Comprehensive Aggregated Resilience Estimation (CARE) model (Figure *7-1*) was utilised to identify the building blocks of water supply system resilience to the impact of disasters (Balaei et al., 2018). The CARE model defines water supply resilience based on the physical attributes of the system and the characteristics of the community. These characteristics are organisational, social, and economic factors. Figure 3-1 shows the process of measuring overall water supply resilience based on the CARE model.

As per the CARE model, potential indicators were identified through a literature review and canvassed in interviews with economists to obtain the most effective economic metrics. Next, data availability, affordability, and ease of collection were checked. Data checks help to avoid using indicators that are not cost-effective, and consequently not feasible. Afterwards, correlation between the collected indicators was taken into account. As a result, the most relevant variables were kept, and highly correlated variables removed.

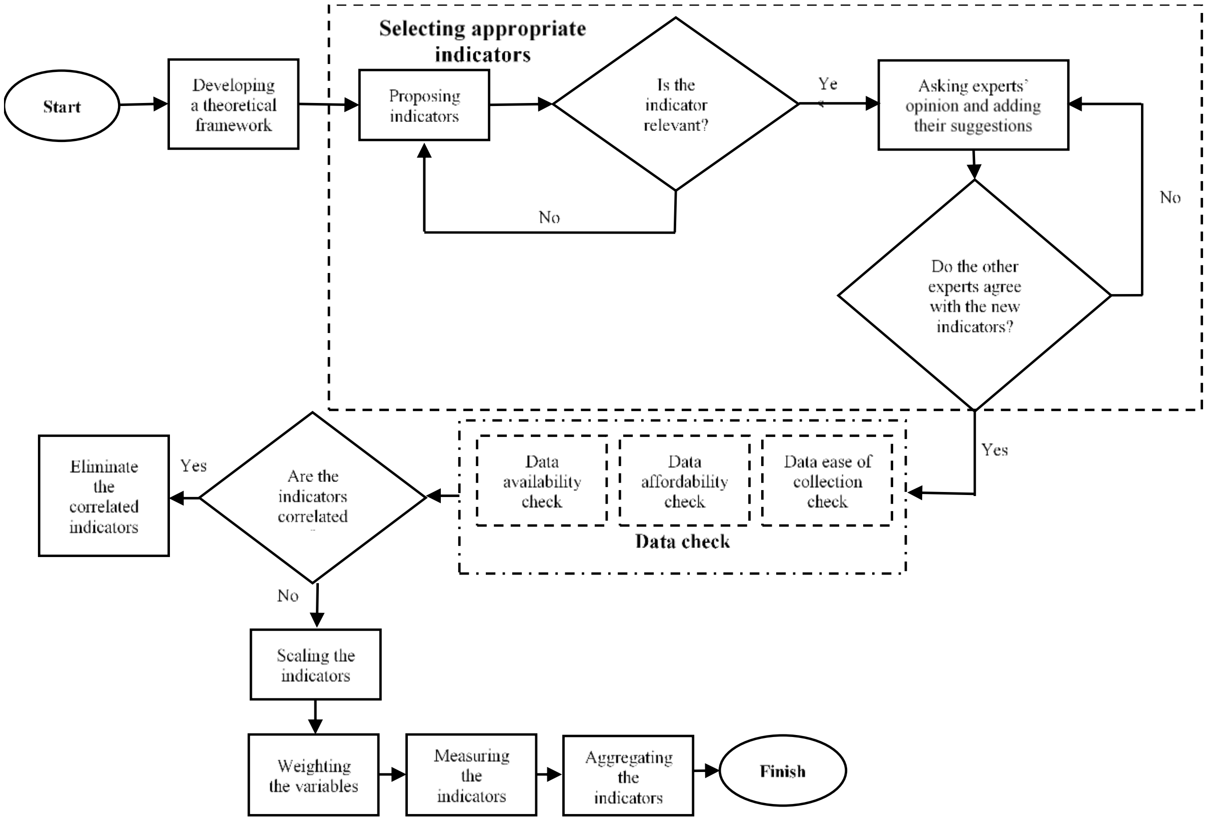

Figure 7-1: Water Supply Comprehensive Aggregated Resilience Measure (CARE) model (Balaei et al., 2018)

7.2.2. Collecting Economic Indicators Data

A series of recursive interviews was designed and conducted with 23 specialists, deemed competent by virtue of their expertise in the field, to summarise the indicators. The experts were selected in the early stages of the study from a variety of disciplines and backgrounds, namely resilience, water engineering, social science and economics. The interviewees were, variously, consultants (WSP-Opus, Jacobs, Market Economics), local authority employees (Auckland Council, Christchurch City Council, Vanuatu Water Department, and Tehran Water and Wastewater Company), academics (University of Auckland and University of Tehran), employees of international agencies (United Nation WASH Cluster) and disaster charities (ADRA New Zealand and Vanuatu), and independent experts. A semi-structured questionnaire was used to overcome the biases and heuristics that can affect the results. The experts were asked about the factors and indicators identified through literature review. They also had the option of adding new factors and/or indicators they thought could affect water supply resilience. Twelve of the experts were interviewed a second time to gauge their opinions on factors and/or indicators suggested by other experts.

7.3.Literature Review

7.3.1. Water Supply Resilience

The notion of resilience has captured the attention of a wide range of scholars across diverse disciplines. The concept of community resilience to disasters developed in the 21st century, although it was introduced earlier by Holling in relation to ecology (Holling, 1973). Klein et al. define resilience as a desirable property of natural and human systems in the face of potential stresses. They investigated the concept of resilience in relation to weather-related disasters in coastal megacities, recommending that resilience be used in a "restricted sense" to present specific system characteristics concerning (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system's self-organisation capability (Klein et al., 2003).

A significant number of researchers have developed conceptual frameworks to measure community resilience from various perspectives. According to Norris et al. (Norris et al., 2008), resilience can be understood as a set of network adaptive capacities, namely economic development, resource equity, social capital, and information and communication. Similarly, Cutter et al. (2008) proposed the DROP framework and model – Disaster Resilience of Place – to conceptualise disaster resilience at the community level. The DROP model demonstrates how resilience capacities (coping, adaptive, and absorptive) influence the degree of recovery and resilience of the community. It also includes six types of indicator: ecological, social, economic, institutional, infrastructure and community competence – to quantify a community's overall resilience.

Although most of the water supply resilience indicators focus on technical dimensions of resilience (Gay & Sinha, 2012; Jeong et al., 2017; Piratla & Ariaratnam, 2013), a few researchers have taken broader dimensions into account. One of these multidimensional studies proposed a combined water supply resilience index to measure the performance of the water distribution network based on technical, environmental, and social dimensions of resilience (Cimellaro et al., 2015). The proposed metric combines three indices of functionality and recovery, namely: the number of users who have lost water service, the quantity of water in tanks, and the water quality. The authors claim the index can be used by urban planners to estimate water supply system functionality, including the delivery of an acceptable level of service, and post-event restoration processes.

The study reported in this paper measured water supply resilience on the basis of system functionality over time. Although researchers have proposed a variety of system attributes such as robustness, redundancy, rapidity, and resourcefulness (Bruneau et al., 2003), or robustness and redundancy (Hwang, Hwee et al., 2013), we argue that robustness and recovery rapidity are the fundamental system attributes affecting system functionality following a disaster (Balaei et al., 2018). Here, "robustness" is defined as the system's ability to withstand disaster, and "recovery rapidity" is its ability to return to a new normal level, which may be different from the pre-disaster normal.

7.3.2. Impact of Disasters on Communities' Economic Capacity

The question of whether disaster is beneficial or detrimental for a community has been a continuing subject of debate among researchers. A number of researchers have argued that in the short term, particular disasters such as earthquakes, floods, or droughts can decrease per capita GDP by 2% on average, especially in low-income countries, whereas humanitarian disasters such as famine result in an average 4% loss in GDP per capita (Raddatz, 2005). On the other hand, other researchers claim that the addition of new capital can result in an increase in GDP per capita in the short term (Skidmore & Toya, 2002). Although there are some anomalies in findings for GDP per capita following disasters, the findings for short-term increases support Skidmore and Toya's claim. In most disaster-struck countries such as Japan, Chile and New Zealand, GDP per capita increased immediately after their recent earthquakes but declined after a few years. In contrast, an increasing trend for GDP per capita remained constant after the Bam earthquake in 2003 in Iran, and in Sri Lanka after the Indian Ocean Tsunami in 2004. Figure *7-2* shows per capita GDP trends in New Zealand, Japan, Chile, Iran, and Sri Lanka.

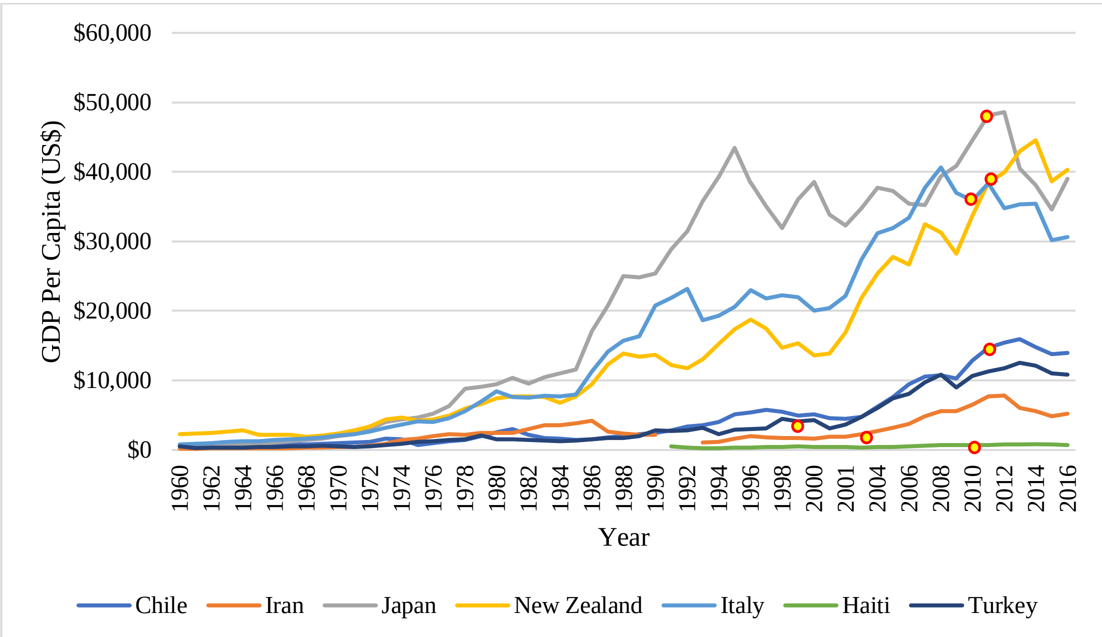

Figure 7-2: GDP per capita in disaster struck countries (The World Bank, 2018a) - circles indicate the year disasters occurred in each country

While disasters can affect a country's development track, the existing state of development affects the severity of consequences for communities and their belongings, including water supply systems (Kellenberg, Derek & Mobarak, 2011). At a certain level of development, communities can address weak organisation, reduce corruption, develop mitigation, preparedness and response plans and implement mitigation measures for water supply systems, as well as develop advanced early warning systems to help with preventative measures. These augmentations can make the water supply systems of more developed countries more resilient to disasters. However, the relationship between development and disaster impact is not linear.

Some researchers have linked the impact of disasters to effects on per capita GDP based on level of exposure to disasters. Schumacher and Strobl (2011) claim that the relationship between per capita GDP and disaster impact on the community is U-shaped in high-risk countries and an inverted U-shape in low-risk countries. Accordingly, poorer countries located in a high-risk area tend to spend a greater portion of their GDP in disaster risk reduction measures than richer countries located in low-risk areas. In contrast, the lower-risk countries invest less funding in disaster risk reduction measures as they have a small marginal benefit for risk reduction expenditures. As such, disasters affect the low-risk countries more than high-risk poor countries.

Other research has also shown an inverted-U shaped relationship between disaster impact and per capita GDP (Kellenberg, Derek K. & Mobarak, 2008). For disasters with impacts dependent on behavioural choices, such as slope failures, windstorms and floods, per capita damage increases with per capita GDP to a particular point – the peak – and then decreases as per capita GDP increases. The peak point is a per capita GDP of roughly $4500 – $5500 per annum, depending on the disaster type. This means that in communities with per capita GDP lower than $4500 – $5500, per capita damage increases with an increase in per capita GDP. In communities with per capita GDP higher than $4500 – $5500, per capita damage decreases when per capita GDP increases.

Disasters also have indirect economic impacts on communities through their effects on labour markets. The number of job openings increased significantly after the 2011 Great East Japan earthquake and tsunami, as many people left disaster struck areas. A significant portion of the new job positions were associated with the public sector (e.g. lifelines) and construction and civil engineering. However, the number of active applicants in the engineering and service sectors was far less than the number of active job openings (Higuchi et al., 2012). Statistical modelling has shown that employment rates fall by 3.4% on average in areas hit by floods, as workers run away (Sarmiento, 2007). This is despite income levels increasing in disaster struck areas (Belasen & Polachek, 2009). In another case, Canterbury's contribution to New Zealand's Small and Medium Enterprises (SME) employment figures was lowest in 2011 (the year when Christchurch Earthquake happened) and 2012, at 12.3% and 12.4% respectively. A portion of this decline in number employed (including in the water sector) was due to employees moving to other cities for a variety of reasons, including accommodation costs (IRD, 2015).

These changes in the water sector of the labour market can potentially affect water supply resilience (Chang & Rose, 2012; Lam et al., 2009). If the workers who leave the disaster struck area are trained and experienced in water supply restoration, finding appropriate replacements in a timely manner can be challenging for water companies. Advertising a new job and recruiting a trained person is often time consuming. In addition, the new employee may not be familiar with the new area, workplace, or colleagues. All of these issues can result in a longer restoration and recovery process.

7.4. The Economic Factors Affecting Water Supply Resilience

Following the CARE model, primary economic factors affecting water supply resilience were collected from the literature. The primary factors include the economic capacity of communities, the level of dependency of the business community on the water supply system, and water companies' access to funds. The economic factors and indicators investigated in this study are shown in Table 7-1.

Table 7-1. Economic Factors and Indicators Investigated in This Study

Economic Factor	Indicator	Indicator Status
Economic Capacity of the community	Unemployment rate	Low correlation with water supply resilience in past disasters.
	20th percentile gross weekly household income	Correlation with country's GDP per capita.
	Median household income	Correlation with country's GDP per capita.
	Economic inequality (Gini Coefficient)	Low correlation with water supply resilience in past disasters.
	Country's GDP per capita	Has been selected as the indicator to measure the economic capacity of communities which affects water supply resilience.
Community's business dependency on water supply systems	Community's business dependency on water supply systems	Interviewees did not agree with this indicator.
Water companies' access to funds	Quick access to finance	Has been selected as the indicator to measure water companies' access to funds which affects water supply resilience.
	Insurance	Indicator merged into "quick access to finance".
	Water company's budget per capita	Removed due to lack of data.

Five indicators were identified to measure economic capacity: unemployment rate, 20th percentile gross weekly household income, median household income, level of economic inequality, and national GDP per capita. The unemployment rate can potentially affect community resilience to climate disasters – such as draught or climate change – by increasing vulnerability at the level of the individual (Akter & Mallick, 2013) or causing urban migration (Muller, 2007) but its impact on water supply resilience is minor. Analysis of disasters also confirms a low correlation between unemployment rate and water supply resilience.

Similarly, 20th percentile gross weekly household income and median household income show strong correlation with economic capacity (Sherrieb et al., 2010), and simultaneously are significantly correlated with GDP per capita. The interviewees therefore advised keeping GDP per capita and removing 20th percentile gross weekly household income and median household income as GDP per capita data is readily available for most countries.

The interviewees did not agree with the literature with regard to "community's dependency on water supply system" as an effective factor for measuring water supply resilience to disasters. The rationale behind this is that when a disaster occurs local authorities focus on restoring drinking water as their first priority, regardless of how much industry or the agricultural sector depend on the availability of water. In other words, drinking water restoration happens perpendicular to overall community dependency on water, as water companies do not care about wider community dependency. Their first priority is to provide water for drinking, cooking and washing etc.

Three primary factors were identified to measure "Water companies' access to funds": quick access to finance, insurance, and water company's budget per capita. Water company's budget per capita was removed mainly due to a lack of data. For most of the disaster struck countries, we were not able to locate enough information on water company budgets (or water sector budgets within councils). Additionally, it is rational to assume that water companies' budget per capita follows countries' GDP per capita. Quick access to finance and insurance were merged together because different types of insurance can be perceived as a solution to access to finance quickly to restore the water network.

The following sub-sections explain how the economic capacity of communities and water companies' access to funds affect the resilience of communities and water supply systems.

7.4.1. The Role of Economic Capacity in Enhancing Disaster Resilience

Past research shows that developing countries and their low-income populations suffer the most from economic losses due to disasters (GFDRR & World Bank Group, 2014). Stronger economic capacity in communities provides the opportunity to adopt appropriate measures to mitigate disaster risk and foster the resilience of its lifelines. Noy (2009) and Horwich (2000) argue that severity of a disaster's impact is dependent on the size of the economy and the level of development. Communities with limited or less developed economies tend to invest less in disaster adaptation. When disasters happen in these countries, a bigger portion of GDP will be required to respond to the disaster.

Per capita GDP is seen as an appropriate indicator for overall safety and additional protection against disasters, as demand for safety increases with residents' income level (Wildavsky, 1988). The interviewees also agreed with the literature with regard to utilising GDP per capita as an indicator for the economic capacity of communities. Recent disasters have shown that less economically developed countries are more vulnerable to disasters than wealthier countries.

Water supply resilience can be enhanced through two categories of activity: ex-ante measures (mitigation and preparedness), and ex-post measures (response and restoration activities) (Bruneau et al., 2003; Cutter et al., 2008). With regard to fostering resilience, the emphasis in recent decades has clearly shifted to mitigation and preparedness activities prior to disaster to minimise impacts and system restoration times (Mileti, 1999; Rose, Adam, 2004).

Disaster mitigation usually involves costly investment (U. S. Department of Energy, 2013). While governments and NGOs have claimed that disaster mitigation saves between $4-7 for every $1 invested, mistakenly attributing this figure to the World Bank, there is no supporting evidence-based research (Shreve & Kelman, 2014). While retrofitted facilities or renewed pipes show better strength against disaster, it may not always be financially sensible to adopt mitigation measures (U. S. Department of Energy, 2013). A number of researchers have carried out cost-benefit analyses (CBA) to identify economic savings from mitigation measures (Hanley & Spash, 1996; Kull et al., 2008; Kunreuther & Michel-Kerjan, 2012; May, 1982). However, these studies vary in terms of hazard type and consequences, geography, and scale and do not provide appropriate information on the methods and techniques to be used in different circumstances. As such, Shreve & Kelman (2014) recommend performing CBA for each case separately to identify the yield from a specific mitigation measure for a specific hazard.

Technologies such as Early Warning Systems (EWS) can reduce damage and economic loss due to disasters. The Hyogo Framework for Action (HFA) encourages governments to develop EWS and “strengthen coping mechanisms” through establishing organisational capacities (UNISDR, 2005). Although early warning systems are considered a cost-effective instrument to minimise disaster risk within water systems, still a significant level of investment is needed for buying and installing complementary instruments such as automatic shut-off valves that connect to the EWS and activate once required.

Further, the water sector is not the only organisation that needs to apply mitigation measures to minimise the consequences of disaster on water systems. Mitigation measures may be under the control of other organisations, or a higher level of authority such as central government. An example of such mitigation measures is the flood control structures designed and constructed by the U.S. Army Engineering Corps in New Orleans that saved lives and water supply assets for over four decades, however they failed during Hurricane Katrina (Carter, 2005). In these cases, although the water organisation should ideally be consulted as a principal stakeholder, the budget to apply mitigation measures will be provided by other authorities but the water sector benefits.

Although the emphasis is clearly shifting to action for mitigation or prevention, a country's economic ability to cope with disaster plays a vital role in recovering the water system in a timely manner. Due to the chaotic conditions following disasters, restoration activities tend to cost more than pre-disaster expectations. Project pricing is riskier for contractors and this increases project costs. In addition, higher health and safety costs, issues with complicated traffic management and locating underground services, and potential clashes with other lifelines are other factors that can drain post-disaster recovery funds. Further, digging to repair water pipes can reveal breaks and faults in other services. Water companies and councils prefer to repair buried services in one run, rather than digging them up separately. This will save money and time in the long-term but increases restoration expenses in the short-term.

7.4.2. Quick Access to Finance

Crucially, budget allocation and execution procedures need to be taken into account. Although some countries have developed appropriate legislation to speed up access to funding when a disaster happens, in most countries starting response and restoration activities is subject to parliamentary approval. Effective and efficient legislation allows for an optimal risk funding strategy to ensure that budget is available when required in the aftermath of a disaster (Ghesquiere & Mahul, 2007).

Different countries have different policies for dealing with disaster. Previously, countries dealt with the economic consequences of disasters on an ad-hoc basis when a disaster happened. However, lessons learned from previous disasters has led to a change in some areas from reactive to proactive approaches to address the consequences of disasters (GFDRR & World Bank Group, 2014). In developed countries, governments generally pay a portion of post-disaster costs with public revenue from tax collection and local authorities are obliged to make financial arrangements to cover the remaining recovery costs. In contrast, developing countries usually rely on multilaterally sourced loans and relief aid from international donors as they have lower tax ratios (Ghesquiere & Mahul, 2007).

Quick access to funds is more important than the amount of funds in the first few weeks following a disaster (Figure *7-3*). Different ex-ante (proactive) and ex-post (reactive) risk financing instruments can be used to establish a risk management strategy to increase the resilience of water sectors to the impact of disasters and speed up the activities accomplished within the response and restoration phase (GFDRR & World Bank Group, 2014). It can be argued that ex-ante risk financing instruments are more reliable than ex-post instruments in terms of accessibility in the aftermath of an event.

With ex-ante risk financing, water sectors can pay the response and restoration costs from their budget contingencies and/or reserves. Using contingencies and reserves is the quickest way to access finance in the aftermath of a disaster. However, contingencies and reserves are small in terms of quantity and can be partially spent on unforeseen operational and maintenance costs. Reserves are also generally kept low because water companies are not very keen on maintaining unusable funds when the budget is limited and there are always many projects on the waiting list.

Catastrophe Deferred Drawdown Option (CAT DDO) is the other ex-ante instrument for accessing funds when a disaster happens (Clarke & Mahul, 2011). Provided by the World Bank, the CAT DDO guarantees significant liquidity following disaster by providing the recipient country with a flexible loan. All International Bank for Reconstruction and Development (IBRD) borrowers are eligible for the CAT DDO subject to the existence of or preparation for disaster risk reduction programmes prior to the disaster. Despite the low lending rate and extended terms of these loans, funding is limited to a maximum 0.25% of GDP, or the equivalent of US$500 million, whichever is smaller, to cover all response and restoration activities, including search and rescue, providing emergency shelters, lifeline restoration, etc. (World Bank, 2012).

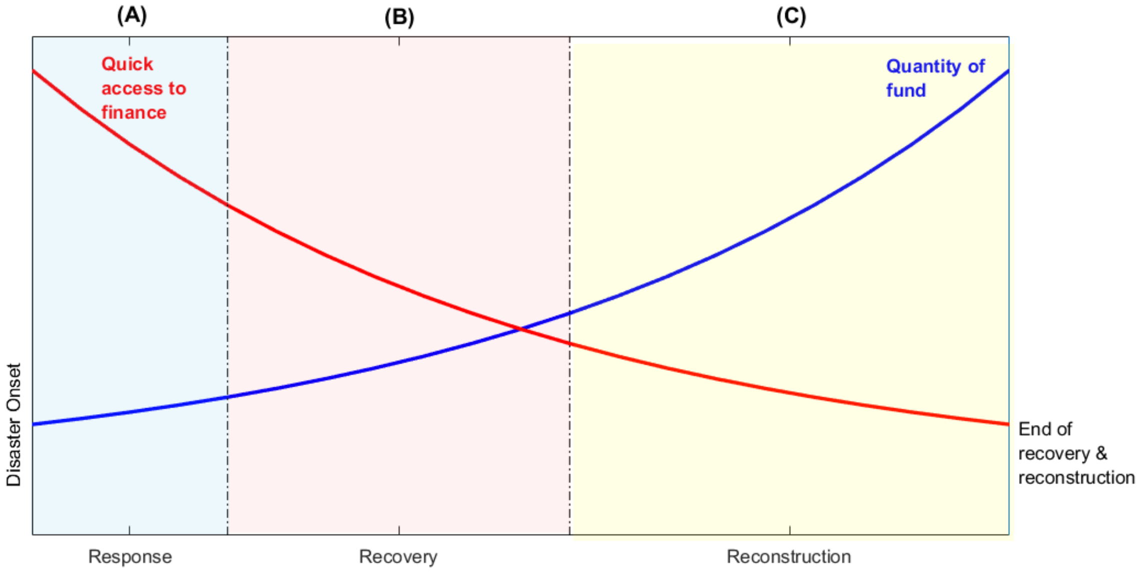

Figure 7-3: Funding accessibility and required quantity following a disaster

Governments have been encouraged to develop financial risk sharing mechanisms based on a variety of instruments such as catastrophe bonds, parametric insurance, and traditional insurance (UNISDR, 2005). Risk transfer instruments do not necessarily reduce risk; however, they do encourage organisations to identify their major risks and mitigate them, thereby paying less to insure their assets. Emerging as a response to Hurricane Andrew in 1992 in the United States and Bahamas, catastrophe (CAT) bonds provide liquid capital for commercials. CAT bonds enable reinsurer companies to protect themselves from disasters, and primary insurers can also use CAT bonds to reinsure their expenses (Goes & Skees, 2003).

As a financial risk management instrument for infrastructure organisations, insurance has become a significant part of economies, especially in developed countries (U. S. Department of Energy, 2013). The cost of mitigation plays a vital role in the strategy of organisations in choosing the most appropriate and cost-effective risk management instrument. When the mitigation or risk transfer costs are too high in comparison with loss risk due to a disaster, organisations will prefer to accept the risk and put aside funds to cover the potential losses (self-insurance). Developing countries, argue that traditional insurance may fail for a variety of reasons such as significant exposure to disaster or defective risk information. As such, it may not be an appropriate instrument to reduce financial risk due to disaster (Warner et al., 2009). The lack of evidence for traditional insurance as an instrument for reducing vulnerability challenges risk transfer instruments as an appropriate solution for financing post-disaster activities.

Further, although the quantity of funding provided through risk-sharing instruments is large, it cannot be accessed immediately after the disaster. On average, traditional risk insurance takes approximately two months to access. More recent solutions, such as parametric insurance or CAT bonds, are quicker in terms of accessibility but still less likely to be accessed immediately in the aftermath of a disaster. In large events, the lower layers of economic loss can be supported by insurers and reinsurers while CAT bonds cover the most extreme financial losses. Although CAT bonds and insurance instruments provide a large amount of finance in the aftermath of disasters, they are basically designed to protect the clients against the upper limit of economic losses (Figure *7-3*). As such, they may not be appropriate solutions for medium size disasters.

Ex-post risk financing instruments are mostly reliable in the longer term. Domestic and external credits provide an acceptable quantity of finance but are disbursed mostly from the third month following the disaster. Donor support is also generally available from the fourth month following a disaster and can be allocated to recovery and construction activities. However, donor support is not a reliable source of funds as the quantity of donor funding is not certain. The only exception in terms of quick access to finance is budget reallocation, which provides a small quantity of funding relative to the cost of post-disaster activities. Table 7-2 shows the financing post-disaster expenditure instruments.

Table 7-2: Financing post-disaster expenditure instruments and their costs and benefits (GFDRR & World Bank Group, 2014)

Instrument	Quantity of Fund Available	Disbursement (months) 0	1	2	3	4	5	6	7	8	9
Ex-ante Financing											
Budget contingencies	Small										
Reserves	Small										
Contingent debt facility (e.g. CAT DDO)	Medium										
Parametric Insurance	Large										
Alternative risk transfer (e.g. CAT bonds)	Large										
Traditional insurance (indemnity-based)	Large										
Ex-post Financing											
Donor support (recovery and reconstruction)	Uncertain										
Budget reallocation	Small										
Domestic credit (bond issue)	Medium										
External credit (e.g. emergency loans, bond issue)	Large										

7.5. Christchurch Earthquake (New Zealand)

This section takes into account the impact of the economic capacity of the Christchurch City Council (CCC) and its water sector on water supply resilience to the February 2011 earthquake. The following sub-sections report on Christchurch water supply resilience, economic capacity and CCC water sector access to finance following the earthquake.

7.5.1. Water Supply Resilience in Christchurch Earthquake

A sequence of three earthquakes hit Christchurch in New Zealand on 4 September 2010, 22 February 2011, and 13 June 2011. The February 2011 earthquake was the most devastating in the earthquake sequence, causing 181 fatalities and $11.1 billion in economic loss. This study focuses on the February earthquake, which is referred to as the Christchurch earthquake (Eidinger & Tang, 2012).

The main damage to the water supply system was broken water pipes due to lateral spreading and liquefaction. Slope failure also caused pipe damage. In the aftermath of the earthquake, more than 80% of people lost drinking water service (Ministry of Health, 2012). Two days after the earthquake, 50% of people were receiving water service although all residents were reminded to boil or add bleach to water prior to drinking (NZHerald, 2011). As expected, the Canterbury rebuild profile clearly shows that the maximum infrastructure rebuild happened immediately after the earthquake and decreased over time, while recovery of other sectors (residential and commercial) increased over the same period (New Zealand Parliament, 2011). The first priority of local authorities is to provide residents with basic hygiene services, such as water supply and wastewater, and transport to facilitate community recovery following an earthquake. Figure 7-4 shows return of drinking water service after the February 2011 earthquake in Christchurch.

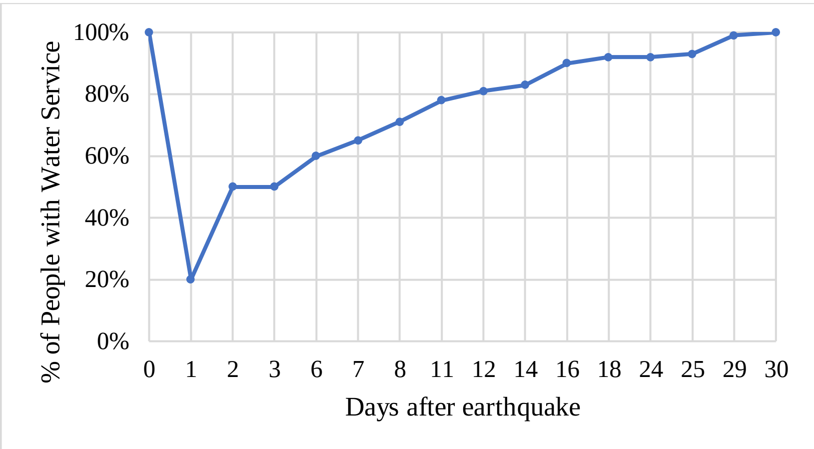

Figure 7-4: Drinking Water Service after February 2011 Earthquake in Christchurch (Ministry of Health, 2012)

7.5.2. Economic Capacity

The Canterbury region (where Christchurch located in) plays a significant role in New Zealand's economy. More than half of South Island businesses and employees are located in this region (Kachali et al., 2012). Canterbury's per capita GDP has been growing over the last 17 years, and the series of earthquakes in 2010 and 2011 did not cause a decline in per capita

GDP. A year prior to the February 2011 earthquake, per capita GDP in the Canterbury region in 2010 was recorded as NZD 42,241 (figure.nz, 2018). It had increased to NZD 44,414 by 2012 as a result of increased construction and higher payments to employees to encourage them to move to Christchurch. Figure *7-5* shows per capita GDP for the Canterbury region from 2000 to 2017.

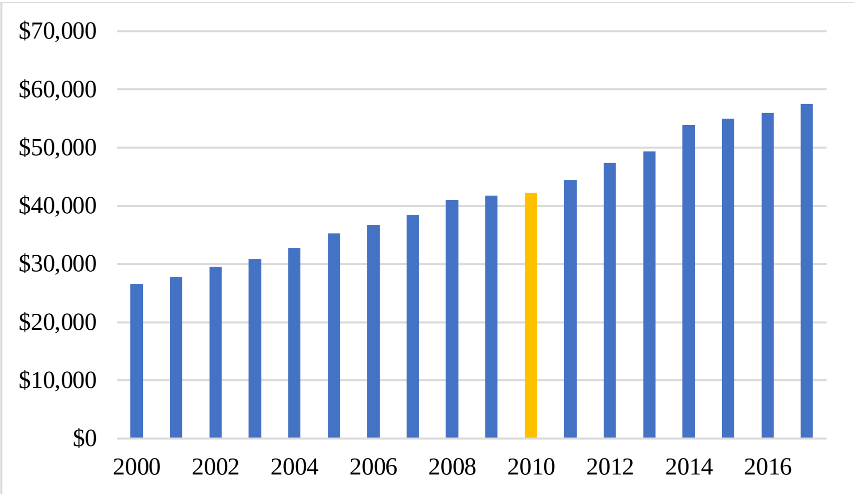

Figure 7-5: GDP per capita of the Canterbury Region (figure.nz, 2018)

Two major categories of mitigation measures had been applied to the water supply system prior to the February 2011 earthquake in Christchurch. The first was water pipe renewals. Although renewals had been outlined in the Christchurch City Council Water Supply Asset Management Plan, the September 2010 earthquake sped up the process. Where, possible, broken pipes were replaced with pipes made from flexible materials such as polyethylene. The February 2011 earthquake demonstrated the high resilience of polyethylene pipes as they generally survived the ground failure. The second category was flexibilisation of the pipe joints to the water storage tanks. The flexible joints also showed high resiliency and prevented loss of water due to joint/pipe breaks.

According to Christchurch City Council Annual Reports, prior to the series of earthquakes, service and capital expenditure on water supply was almost constant at NZD 16.5 million and NZD 11 million respectively per annum. In 2011, the service costs increased slightly to NZD 17.9 and, as expected, jumped up to over NZD 23 million in 2012 and then declined again to NZD 17.5 million in 2013. In contrast, water supply capital expenditure showed a significant increase of NZD 21 million, rocketing up to just less than NZD 33 million in 2012 (Christchurch City Council, 2018). Figure *7-6* shows Christchurch water supply expenditures from 2009 until 2014.

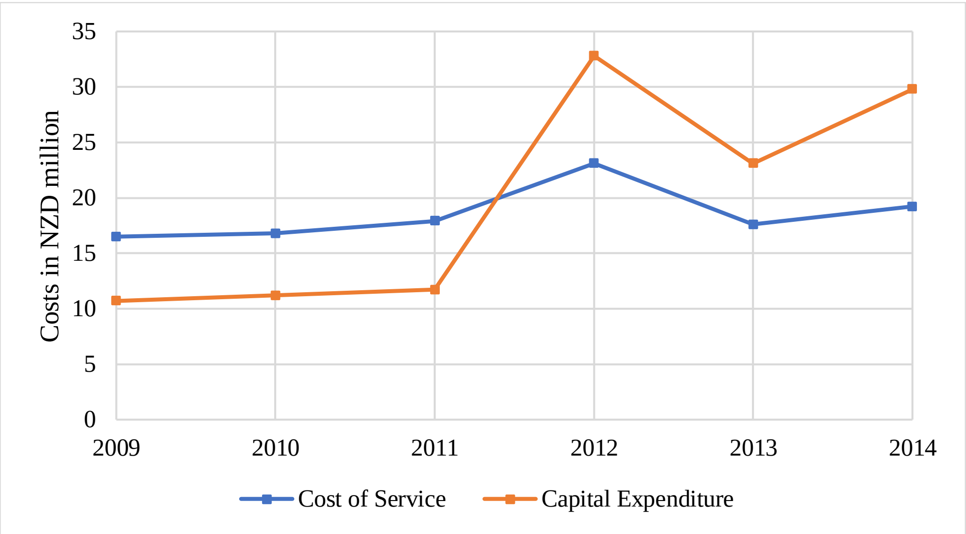

Figure 7-6: Christchurch Water Supply expenditures (Christchurch City Council, 2018)

7.5.3. Christchurch City Council Water Sector Access to Finance

Christchurch City Council has agreements with a number of companies called Council Controlled Trade Organisations (CCTO). These companies are considered arms of Council and assist in providing council services to residents. When the February 2011 earthquake happened, Council contacted City Care Ltd, one of the CCTOs that takes care of water supply in Christchurch. City Care Ltd took responsibility for restoring the water system by means of coordinating a number of sub-contractors. Thus, the existing structure saved time in searching for a contractor to restore the water service in the aftermath of the earthquake. Further, due to the agreement and trust between the Council and City Care Ltd, the Council did not have to pay prior the restoration activities.

Christchurch City Council (CCC) utilised a variety of mechanisms to provide adequate funds for repairing and restoring the water supply system. Most of the water supply restoration funding was provided through government reimbursement (the Crown) and the Local Authority Protection Programme Disaster Fund (LAPP), although other funding instruments were also utilised.

Under disaster recovery funding agreements with local authorities, established by the New Zealand Civil Defence Emergency Management (CDEM) Plan in 1993, the Crown pays a 60% portion of the recovery costs for infrastructure damaged in a disaster. Normally, local authorities implement infrastructure repairs and go through recovery processes using their reserves, and then request reimbursement from the Crown for 60% of the costs (MCDEM, 2018), above the following thresholds:

- 0.0075 percent of the net capital value of the city council, district council or unitary authority involved;
- 0.002 percent of the net capital value of unitary authorities where the assets in question are of a type ordinarily managed by regional councils; or
- 0.002 percent of net capital value in the case of regional councils.

These thresholds are set to test the need for government assistance for infrastructure recovery (MCDEM, 2015).

The drawback of the Crown funding is that councils do not have quick access to it and need to accomplish the repairs and then apply for reimbursement. This was tricky in the case of

Christchurch as the Council exhausted its reserve budget. Furthermore although the Crown was supposed to reimburse 60% of the disaster costs, it provided only 36% of the required funds following the earthquake. Crown funding was received on an ongoing basis throughout the rebuild programme. Initially funding was paid to Council as partial reimbursement for expenditure, but in the later stages it was paid directly to the contractor delivering the work. The remaining costs were met by Council through borrowing and the subsequent rates increase.

At the time the CDEM Plan made local authorities responsible for the 40% of infrastructure recovery costs not covered by central government, there was no readily available commercial insurance cover for buried infrastructure in New Zealand. As such, the New Zealand Local Government Insurance Corporation Limited (now trading as Civic Assurance) and Local Government New Zealand (LGNZ) formed a working party. The working party proposed a mutual insurance fund in the form of a charitable trust, and so the LAPP Disaster Fund was born (LAPP, 2014). LAPP is one of the only mutual funds worldwide. Twenty-one New Zealand local authorities are members and the fund has covered the recovery costs of lifelines since its inception. LAPP members make an annual contribution based on a number of factors such as the risk of exposure and the value of their assets to cover expected risk, administration costs, and reinsurance premiums.

Table 7-3 shows the Christchurch City Council's insurance arrangements for infrastructure restoration (and not mid- or long-term recovery) in the aftermath of the February 2011 earthquake.

Table 7-3: Christchurch City Council Insurance Arrangements

Assets	Roles of Entities	Insurance Financial Recovery
Above-ground	Above-ground reinsurers (insured Civil Assurance)	NZD 231 million
	Civic Assurance (insured LAPP)	

	LAPP (insured Christchurch City Council)	
Below-ground	Below-ground reinsurers (insured LAPP)	NZD 109 million
	LAPP (insured Christchurch City Council)	

The LAPP Fund pays additional unforeseen costs which are difficult to quantify and therefore cover from reserve and reinsurer funds. These additional costs are difficult to be quantify as they become apparent only after a major disaster. Following the Christchurch sequence of earthquakes (2010–2011), LAPP focused on paying out claims and rebuilding the fund to provide sufficient protection to the future disasters.

Budget contingencies were achieved by the Christchurch Council by deferring approximately NZD 50 million of capital works and using this money for response and restoration costs. The water supply component of this figure is not available from Council. After the February 2011 earthquake, Council managed its risk through the use of LAPP – which is regarded as a form of traditional insurance – and had no need of alternative options such as CAT bonds or parametric cover, both of which are very expensive and better suited to risks that can be reasonably well defined. In total, LAPP provided over NZD 340 million for infrastructure recovery (or approximately 45% of the cost of repairing the water supply system) in Christchurch and Waimakariri. Reinsurance recovered NZD 321 million (almost 95% of the amount of the claims). Of this amount, NZD 109 million was claimed for underground utilities which are basically water supply, wastewater collection, and stormwater systems (LAPP, 2011).

The pre-earthquake estimates of Probable Maximum Loss (PML) for CCC underground assets for a 1:1000 year event was NZD 41 million, of which CCC would have been responsible for 40% (NZD 16.4 million) and central government 60% (NZD 24.6 million). The February 2011 earthquake costs significantly exceeded the PML model and LAPP was forced to pay out NZD

201 million for CCC's share of its below-ground earthquake claims in April 2012, at which point LAPP's involvement with the claim ceased. There was no breakdown of claims for waste water, storm water and water supply and LAPP simply paid out to the limit of its financial abilities. Despite being more than ten times what CCC had thought might be needed, this payout was well short of what was required (LAPP, 2018).

7.6. Conclusion

This paper identifies economic capacity and quick access to finance as the most significant economic factors affecting water supply resilience to disasters in communities. In the first step, the CARE framework was utilised to obtain an overall perspective on water supply resilience to disasters. Relevant factors were identified through the literature review and confirmed by interviewing field and academic experts. Awareness of these indicators and their influence on water supply resilience in society will enable local authorities to identify existing strengths and weaknesses, and to optimise investment to obtain the best results.

Following a disaster, the amount of budget required to restore the water system increases over time. Less money is required immediately after the disaster and during the response and restoration period than in the construction phase. On the other hand, quick access to finance is significant in the early stages following the disaster. Obviously, the bigger the water sector budget based on per capita GDP, the more funding will be readily available to spend on water supply restoration following a disaster. However, availability of funding does not guarantee a quick recovery as other organisational and social factors can affect water supply recovery time significantly.

Quick access to external funding may not be possible for a variety of reasons, including government policy on funding/reimbursement. Water companies therefore need to prepare prior to the disaster by means of arranging insurance or setting up mutual funding programmes.

In the absence of immediate external funding after a disaster, water companies have to spend from their existing budget by cutting unnecessary and non-urgent expenses. While cutting Operational Expenses (OPEX) is not practical in most cases, reducing Capital Expenditure (CAPEX) by putting renewal and development projects on hold is an appropriate strategy for providing funding for the immediate response and restoration projects.

Water supply in Christchurch showed an acceptable level of resilience in the earthquake of February 2011. An appropriate level of economic capacity and quick access to finance by Christchurch City Council water sector assisted timely restoration following the earthquake. Economic capacity enabled CCC to apply mitigation countermeasures at critical spots. By employing a variety of tools and techniques such as insurance and budget reallocation, CCC was able to obtain the funds required to restore its water network. Moreover, incorporating Council Controlled Trade Organisations (CCTO) meant restoration activities were covered by readily-available finance.

Integrated infrastructure management can also facilitate funding for response and recovery. If all public lifelines are managed by one entity, budget can flow from the wealthier sections that suffered less from the disaster. This will result in prioritised response and resource consumption based on the needs of the community. For instance, the availability of safe and reliable water following a disaster is more urgent than a functional stormwater system.

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CHAPTER 8 - DISCUSSION

8.1. Discussion on Findings

In this research, water supply resilience to disasters was defined as "its ability to remain functional when a disaster happens (coping capacity) and carry out recovery activities as quickly as possible if the disaster exceeds the coping capacities". Water supply resilience is greatly dependent on the system's serviceability following a disaster. In this study, serviceability is defined as the ratio of the number of households receiving water services of an acceptable quality after the disaster to the total number of units receiving water services before the disaster.

Measuring resilience of water supply system calls for a multifaceted conceptual framework. A key challenge in measuring resilience is finding how to measure resilience as precisely as possible based on information available from previous disasters. The main contribution of this research has been in presenting a multifaceted definition of water supply resilience and a conceptual framework to measure it.

This framework is proposed for community or sub-national level because cities generally have independent water supply systems, although several cities can be fed from one water source, or a number of cities may be located in one catchment and use shared sources. Although this framework can be adapted for other urban infrastructures, and even different types of disasters, the adaptation process should be applied carefully and precisely to prevent unforeseen issues such as the infrastructure's recovery priority and its impact on society.

Although defining resilience based on different dimensions is not new, these dimensions have usually been used to show that "community" resilience, in general terms, is dependent on its technical (e.g. structures and infrastructures), social, organisational, and economic capacities.

This research argues that the relationship is reciprocal in that infrastructure (water supply systems in this case) is dependent on the technical characteristics of the system as well as the social, organisational, and economic characteristics of communities.

It is an accepted fact that community resilience depends on water supply resilience. However, in turn, water supply resilience is significantly dependent on the characteristics and capacities of a community. Instead of considering the impacts of disasters on various characteristics of the community, the Comprehensive Aggregated Resilience Estimation (CARE) model introduced in this study considers the impact of community characteristics on water supply system serviceability, from when a disaster happens until the end of recovery phase.

Measuring resilience does not demand quantitative approaches per se, but rather requires a method for translating the abstract concept of resilience into a practical tool. To be useful, this tool needs to simplify and reduce the amount of potentially collectable data, information, and measurements to a manageable number of indicators to assist with measuring resilience.

Identifying appropriate indicators for measuring resilience was another challenge in this study. Various indicators have been used to measure a range of variables over the past eight decades. Some indicators are flawed as they only measure a limited number of parameters and can neglect other parameters, especially when the system is complicated. However, indicators do provide tangible measures that planning, and investment decision makers can use to evaluate the current condition and implement action to improve it.

Despite the evident strengths of using indicators to measure resilience, there are a number of possible limitations. One issue to be aware of is the subjective selection of indicators. This is not a particular issue for a resilience index, but could become so in more empirical work, especially multivariate analysis. Subjective selection of indicators may result in using redundant indicators. A clear understanding of the objectiveness of indicators will minimise this problem.

A second concern relates to the measurement problems outlined. Although data availability, affordability, and accessibility will be checked in this approach, measurement of the indicators will be carried out by different people with different sensitivities who may unwittingly introduce measurement errors. To overcome this issue, firstly knowledgeable and skilful people should be selected to collect data. Secondly, increasing redundancy in data sources and/or the people collecting data can help to increase data collection reliability.

Another difficulty may arise when data is being gathered from the public sector, which can mean it has been exaggerated or downplayed. In these cases, using composite indicators may cause political issues by pitting one community against another. For example, in the case of government aid, lower levels of political and financial support could result for communities who score lower on the index. In this case, the fostering of resilience planning in general or variable prioritisations will not be an issue as the indices in the index are relative. Planners can still use the framework to compare the conditions for different variables to those for other variables, even though the final resilience index may not be highly accurate.

Correlation and mutual dependency of the indicators, either within one factor or across multiple factors, should be carefully considered. The indicators are expected to be correlated since they are usually rooted by the same cause; for example, crime level and perception of safety in the community are related, or quick access to finance can be influenced by the community organisational factors. Although correlation coefficients have traditionally been used in studying interconnectedness of two variables, they do not fully explore interconnected structure among the indicators. From a technical point of view, multivariate analysis methods such as Principal Component Analysis (PCA) and Discriminant Analysis (DA), can be employed to study the interdependencies and used for variable selections from the indicators. However, the usefulness and conclusiveness of these methods are practically restricted due to the limitations in data collection and reliability. Theoretical methods require large data collection and management used for model selection and validation. Empirical methods such as interviews with experts are more practical in the study of the indicators' interdependencies. However, one can still benefit from the analytical methods whilst the results should be carefully interpreted considering their limitations. In this study, we considered both empirical and analytical discussions around the indicators interdependencies. Full exploration of the interdependencies is beyond the scope of this thesis and part of the future extensions.

8.2. Applicability of CARE Framework to Different Circumstances

The Comprehensive Aggregated Resilience Estimation (CARE) framework introduced in this research is designed for application in any country, from the least to the most developed. However, some considerations should be taken into account. Water supply resilience is estimated as:

$$Resilience = a_1x_1 + a_2x_2 + \cdots + a_nx_n$$

where "x" is the indicator's value and "a" is the indicator's weight. While the indicator's value (i.e. x) variously represents the technical, organisational, social, or economic status of the case study, the indicator's weight (i.e. a) needs to be adjusted based on the significance of that factor. For example, we identified from our case studies that average level of knowledge and skills played a significant role in recovering water systems in Vanuatu. As such, the weight of the indicator "level of education" is far higher in a less developed country than a country like New Zealand, where individuals are not allowed to intervene in restoring public services such as water supply systems.

8.3. Validation and Verification

The structure of the proposed model assumes that water supply system resilience is influenced by several factors that are correlated, and interdependent on one another. The initial step in model verification was identifying all possible factors. The factors were mainly identified through technical experience and the literature review (see Chapter 2). While a considerable amount of research has investigated the impact of technical, social, economic, and organisational factors on resilience, the contribution of this thesis has been putting all the factors in one framework. Once the factors were identified, the model was verified through the first round of interviews with experts in the corresponding fields.

The traditional approach to validating a model is through repeatability of experiments, where the contributing factors can be fully controlled. However, this was not the case in this study because a society's resilience to disaster is philosophically neither repeatable nor controllable. Instead, the model was validated by the second round of expert interviews, and its practicality investigated in several case studies from Chile (Chapter 4), New Zealand (chapters 3, 4, 6, and 7), and Vanuatu (Chapter 5).

8.4. Limitations

Data availability is a major limitation on measuring water supply resilience because some quantitative data is not accessible, including water network data for all urban or rural areas. Other data are not available for all regions. For instance, we could not find data for the 20 social indicators for all the countries that have experienced disasters in the last 50 years. As such, we limited our sample population to 22 countries. However, data for all the social indicators were still not available for all 22 countries.

The other limitation of this research was data collectability. For instance, the majority of the organisational indicators were qualitative and data collection was undertaken through interviews. Although the interviewees were selected using a systematic approach, the values obtained for the indicators were dependent on the interviewees' expertise and personal knowledge. Ideally, data for these indicators should be collected from local governments, with appropriate review and approval by appropriate authorities.

In addition, some of the indicators did not have appropriate measures. In that case, we devised new measures to enable us to quantify these qualitative indicators. As an example, the majority of the organisational indicators were measured for the first time in this research.

CHAPTER 9 – CONCLUSIONS

This chapter shows how the research objectives were achieved and brings the research to a conclusion. As discussed in Chapter 1, the overarching aim of this research was to find the most significant factors affecting water supply resilience to disasters. To achieve the overarching aim, a number of objectives were developed which have been addressed in this thesis. The research objectives and final conclusions are discussed here.

9.1. Water Supply Resilience Measure

In this study, water supply resilience in conjunction with community is defined as the physical status of the water supply system and the social, organisational, and economic capacity of the community to withstand a disaster and recover to a normal level of functionality in a timely manner. In studying resilience of water supply to disasters, the physical characteristics of the system is not the only dimension to take into account. The economic state of the community, its organisational wellbeing and preparedness, and social capacities can also significantly affect water supply resilience.

Resilience is measured based on two properties: robustness and recovery rapidity. Robustness is the ability of the water system to withstand a given level of stress. In other words, robustness is the functionality of the water system in the aftermath of the disaster. Recovery rapidity is defined as the capacity of the water supply system and community to return to a normal level of functionality in a timely manner.

9.2. Research Questions Addressed

9.2.1. How can multifaceted water supply resilience be measured?

The Comprehensive Aggregated Resilience Estimation (CARE) model was developed in this study (Chapter 2) to understand the building blocks of water supply system resilience to the impact of disasters.

In summary, the CARE model defines water supply resilience based on the physical attributes of the system and the characteristics of the community the water supply serves. These are organisational, social, and economic factors that can affect water supply robustness and/or restoration rapidity when a disaster happens.

This framework consists of eight fundamental activities, as follows (Figure 9-1):

- Developing a conceptual framework,
- Selecting appropriate indicators,
- Refining the indicators based on data availability,
- Correlation analysis,
- Scaling the indicators,
- Weighting the variables,
- Measuring the indicators, and
- Aggregating the indicators.

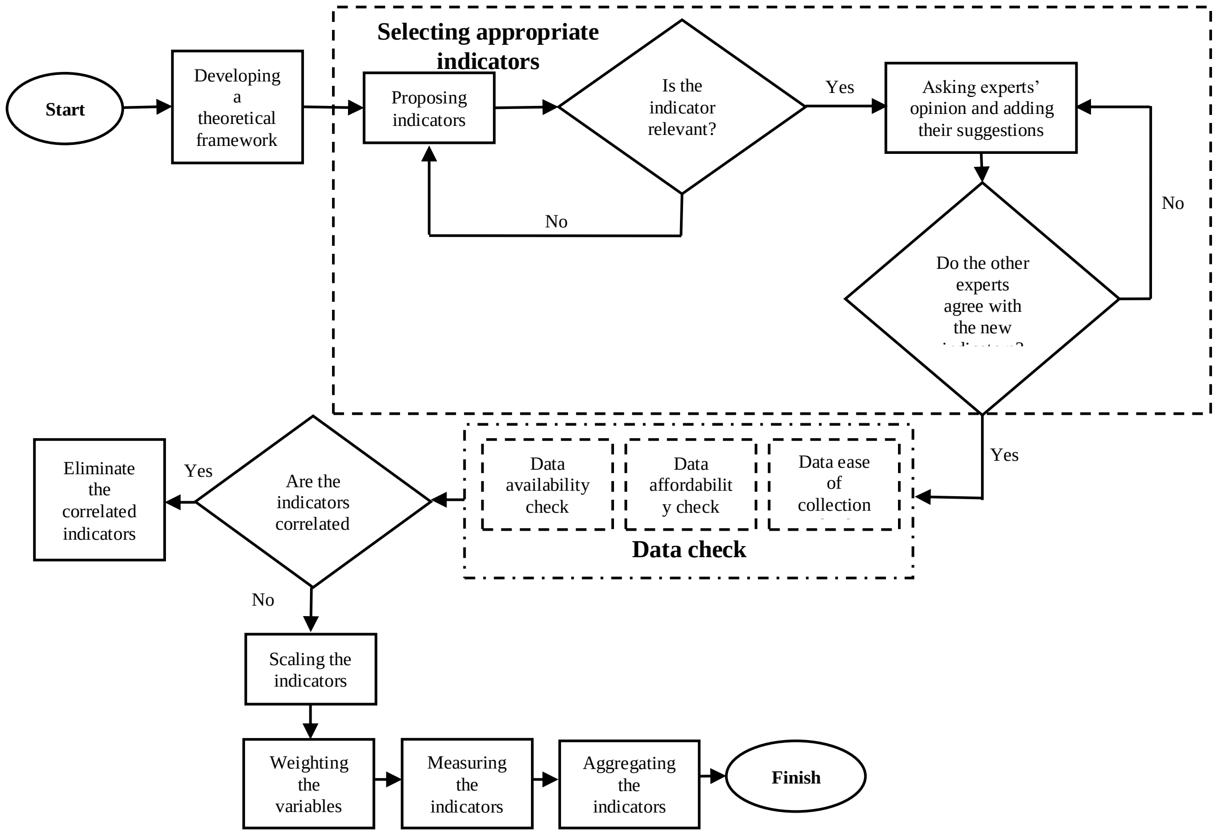

Figure 9-1: Water Supply Comprehensive Aggregated Resilience Measure (CARE) model

Data gathering for this study encompassed two parts: identifying the indicators and gathering case study information and statistics to which to apply the indicators. A set of primary technical, social, organisational, and economic indicators was collected through a literature review. A series of recursive interviews was then designed and conducted with 23 specialists, deemed competent by virtue of their expertise in the field, to summarise the indicators. The experts were selected in the early stages of the study from a variety of disciplines and backgrounds, namely resilience, water engineering, the social sciences and economics. The interviewees were consultants (WSP-Opus, Jacobs, Market Economics), local authority employees (Auckland Council, Christchurch City Council, Vanuatu Water Department, and Tehran Water and Wastewater Company), academics (University of Auckland and University of Tehran), office holders from international agencies (United Nation WASH Cluster) and charities (ADRA New Zealand and Vanuatu) involved in disaster preparedness and recovery, and independent experts. A semi-structured questionnaire was used to overcome the biases and heuristics that can affect results. The experts were asked about the factors and indicators identified through the literature review, as well as having an option to add new factors and/or indicators they thought could affect water supply resilience. Twelve of the experts were interviewed for a second time to gain their judgements on factors and/or indicators introduced by the experts in the first round of interviews.

The framework was then applied to specific cases to test its technical, social, organisational, and economic dimensions. The technical factors were tested for an Mw 7.6 earthquake scenario at Pukerua Bay in New Zealand (chapter 3). The social indicators were tested for Chile and New Zealand, which experienced earthquakes in 2010 and 2011 respectively (chapter 4). The social capacities and complexities of rural Vanuatu following TC Pam were also investigated through a site visit involving a set of interviews, a document review of Vanuatu government ministry and agency reports and plans, and a comprehensive literature review (chapter 5). Finally, data was gathered from the February 2011 Christchurch earthquake to test the organisational and economic factors and indicators (chapter 6).

9.2.2. What dimensions of communities can impact on water supply resilience?

In the CARE model, water supply system resilience comprises five dimensions, referred to as the *resilience pentagon*. Vulnerability and recovery of physical components of the water supply systems, such as pipelines, pumps, reservoirs, treatment plants etc., is a core concept in water supply system resilience and is known as the *technical dimension*.

However, the resilience of a water supply system is not solely dependent on the system's physical vulnerability, and therefore recovery is not achieved by only rebuilding the technical elements. Attributes of the community in the disaster-struck area will also affect the system's vulnerability and restoration recovery. The social dimension of the community can significantly influence water system resilience. Many recovery activities are dependent on the social capital of that community. Without taking this dimension into account, post-disaster recovery models will, at best, be hypothetical and so fail in providing an accurate expected recovery time. The social dimension is not limited to the service receivers but includes the restoration crews too.

The organisational dimension represents the capacity and performance of water agencies and other interacting organisations in relation to water supply resilience, including system robustness and recovery rapidity following a disaster. The organisational dimension of resilience is not confined to the water companies, but includes all those in the public and private sector whose performance can affect the water system's serviceability after a disaster.

The resilience of water systems can be also be affected by economic factors. Community wealth and water companies' access to finance can affect community capacity for dealing with water system damage, and restoration rapidity.

At the beginning of this research, the environmental dimension was identified as a fifth dimension of water supply resilience with significant effects. For instance, a dry, hot climate increases the need for water, both for general sanitation and/or firefighting purposes. However, the environmental dimension was removed from the scope of this study, as despite their impact on system resilience, there is zero or limited control of the environmental dimension.

9.2.3. What factors in each dimension affect water supply resilience?

Each dimension consists of a number of factors that affect water supply resilience. These factors are as follows:

a. Technical Factors

Two main technical factors were identified that affect water supply robustness and subsequently the system's resilience to disasters, namely system vulnerability and system configuration. The vulnerability of the system has a significant impact on the system's serviceability immediately after disaster (robustness). Broken elements in the water system mean it will not be able to deliver water of sufficient quantity and quality to users. Water system configuration – the way the water system is designed – can also increase/decrease the consequences of damage for the water system's serviceability.

b. Social Factors

Fostering social capabilities for dealing with disasters (for instance, by means of improving preparedness, awareness, and skills) will increase coping, adaptive, and absorptive capacities, enabling communities and their assets to return to a normal level of functionality in a timely manner.

The social factors identified in this study are individual capacities, individual involvement in the community, violence level in the community, and level of trust.

Individual capacities – physical (e.g. water self-sufficiency) or non-physical (e.g. residents' knowledge and skill level) – can affect system restoration, especially in remote areas. In communities where local authorities do not have sufficient numbers of restoration crews, locals will need to survive for a few days until the restoration crews can get there. Locals can also participate in and speed up the restoration process by fixing broken pipes and facilities themselves. In that case, their individual knowledge and skill levels can enhance the rapidity of system recovery.

The more people are involved in their community, the higher the sense of community generated. Individual involvement of residents in their community can potentially affect water supply restoration. Community members can often forget that the restoration and recovery personnel and their belongings are also affected by the disaster, and they need to mentally recover and feel safe in order to leave their families and go back to work. A lower sense of community can affect the disaster response and recovery workers' ability and willingness to return to work.

High levels of violence in a community mean insecurity for both citizens and the water authority personnel who are in the field to restore the network. In such cases, water restoration personnel will be reluctant to leave their families unattended and start work. All incentives, including money and social recognition, lose their meaning if personnel do not feel they or their families are safe.

c. Organisational Factors

This research identified six organisational factors for water supply resilience to disaster, as follows:

- Disaster Precaution

Predicting the location and magnitude of disasters prior to their occurrence can help the water sector to mitigate adverse consequences. The prediction of slow-paced hazards (such as droughts) and medium-paced disasters (such as floods) has been developed to an acceptable level of uncertainty. However, earthquakes remain one of the most challenging types of disaster in terms of prediction. While not predictive, earthquake early warning systems (EWSs) are able to determine an earthquake's source parameters and provide an estimation of the shaking intensity distribution. The output information can be distributed to a variety of users such as water systems to reduce the effect of the earthquake on the system's components, and the system as a whole.

- Roles and Responsibilities

Although water companies are the primary organisations responsible for water supply system mitigation, response, and recovery, there is crossover with other sectors. To minimise the water supply restoration time, the roles and responsibilities of all of the organisations involved in the disaster response and recovery need to be clearly identified, and the overlaps and gaps between responsibilities minimised. Confusion occurs when roles and responsibilities are not clearly defined among the organisations responsible for supplying water to residents. Both duplication and neglect can be expected, especially in the system restoration period when different organisations need to carry out their responsibilities in a timely manner.

- Pre-disaster Planning

Appropriate disaster planning can significantly improve the effectiveness and efficiency of the institutional response to disaster. Disaster planning needs to be based on systematic knowledge rather than relying solely on common sense. While poor disaster planning in water supply systems can be economically inefficient, it can nevertheless improve the water system's robustness and prepare the organisation(s) and their personnel to cope with disaster to some extent. Moreover, when reviewed, tested, and revised periodically, disaster plans can improve water sector preparedness for disaster.

- Mutual Aid Agreements

Mutual aid agreements are binding contracts between two or more authorities and are negotiated and signed in collaborative meetings. In general, it is either impossible or less cost-effective for an organisation like a water company to possess all the equipment needed to cope with a disaster. Lack of specialised personnel, spare parts or equipment can lead to chaos in the response and longer restoration times. Mutual aid agreements are crucial for increasing the water sector's capability to cope with disasters by resolving challenges arising from resource and personnel shortages that can overwhelm the organisation during disaster.

- Data Availability, Accessibility, and Information Sharing

Coordination and performance of response activities by organisations will be enhanced by good availability and accessibility of information. Further, estimating and recording details of damage in any given disaster are crucial to evaluating the scope of demands in the response phase and providing services such as housing, sanitation, etc. As with other lifelines, a lack of data reduces the effectiveness of disaster response operations by water companies. For example, decision makers in water companies need to be informed about the volumes of water required for the affected population and the duration of support, because the demand ratio for water varies over time. However, there are high levels of uncertainty immediately after disasters when accurate and reliable data is needed. Therefore, data needs to be updated and revised on a regular basis so that it is accurate at the time of the event, and in the aftermath.

- Staff, Parts, and Equipment Availability

Extra capacity in terms of human resources as well as continuous training reduce the potential for problems when operational staff become unavailable following disasters. It is crucial to have spare staff who are practiced in simulated response activities to ensure the effectiveness of operations in the event of disaster.

Damage to any part of the water system, especially critical components necessary for producing, distributing or treating water, can cause delays in the response and recovery phases after disasters. The organisation(s) needs to prepare spare parts to replace those that fail due to damage. Checking equipment availability is a routine aspect of preparedness plans. Spare equipment needs to be stored in an easy to access and safe place that is known to staff.

- Pre-disaster Maintenance

Regular pre-disaster maintenance can reveal weak points and so mitigate the adverse consequence of disasters. In case of emergency, acceptable amounts of water, water pressure (especially for firefighting) and water quality are crucial. Extending the life of equipment and structures, high performance, enhancing the reliability of the system, reducing costs and providing safe water for drinking are often the objectives of system maintenance. By means of maintenance, decision makers ensure that the system continuously performs its predesignated function. In the water supply system, these activities can include adjustment of components, tidying, greasing, repairing and replacing deteriorated equipment.

- Governance

Governance can play a crucial role in water supply restoration rapidity. This study understands governance as the traditions and institutions by which authority in a country is operationalised. By this definition, governance can affect all processes and subsequently cause projects such as system restoration to take a shorter or longer amount of time following a disaster.

d. Economic Factors

The most important economic factors affecting water supply resilience identified in this research are economic capacity and quick access to finance. The economy plays a vital role in every single activity implemented to decrease the risk of system failure, as well as in system restoration and recovery time. Water supply resilience can be enhanced through two categories of activity: ex-ante measures (mitigation and preparedness), and ex-post measures (response and restoration activities).

Stronger economic capacity in communities provides the opportunity to adopt appropriate measures to mitigate disaster risk and foster the resilience of lifelines. It is argued that the extent of a disaster's impact is dependent on the size of the economy and level of development. Communities with limited or less developed economies tend to invest less in disaster adaptation.

Technologies such as Early Warning Systems (EWS) can reduce damage and economic loss due to disasters. The Hyogo Framework for Action (HFA) encourages governments to develop EWS and "strengthen coping mechanisms" through establishing organisational capacities. Although early warning systems are considered a cost-effective instrument to minimise disaster risk within water systems, a significant level of investment is needed for buying and installing complementary instruments such as automatic shut-off valves that connect to the EWS and activate once required.

Budget allocation and execution procedures need to be taken into account. Although some countries have developed appropriate legislation to speed up access to funding when a disaster happens, in most countries starting response and restoration activities is subject to parliamentary approval. Effective and efficient legislation allows for an optimal risk funding strategy to ensure that budget is available when required in the aftermath of a disaster.

Quick access to funds is more important than the amount of funds in the first few weeks following a disaster. Different ex-ante (proactive) and ex-post (reactive) risk financing instruments can be used to establish risk management strategies to increase the resilience of the water sector to the impact of disasters and speed up the activities accomplished within the response and restoration phase. It can be argued that ex-ante risk financing instruments are more reliable than ex-post instruments in terms of accessibility in the aftermath of an event.

9.2.4. What indicators are appropriate to measure the respective factors?

Another contribution of this research has been to develop a method for selecting appropriate indicators to measure technical, social, organisational, and economic factors.

In order to measure resilience accurately, indicators need to possess the following characteristics:

- Agreed definitions: the indicators need to be unique in terms of definition to avoid ambiguity.
- Precise: the indicators need to be precisely defined in clear terms.
- Specific and sensitive: the indicators are required to describe clearly and exactly what is being measured. They also need to be sensitive enough to react when input data varies.
- Valid and reliable: the indicators need to be consistently measured over time and by data collectors.
- Discriminative: the indicators should not be correlated.
- Evidence-based: the indicators need to be collected based on research from previous disasters.

Apart from the above-mentioned criteria, a data collectability criterion was added to ensure an indicator can be utilised in measuring water supply resilience to achieve an applicable tool.

Technical Indicators

System vulnerability, redundancy, and criticality are the indicators identified in this research that can be used to measure technical factors. Obviously, vulnerability assessment techniques can be applied to the water system to evaluate its susceptibility to damage. Redundancy indices and criticality assessment techniques can be utilised to measure water supply system configuration.

Despite damage due to disaster, a water system with high-redundancy can show better serviceability than its damage state would indicate, and deliver minimum standards for quantity and quality of water to users. Topological redundancy in water distribution networks is defined as the existence of alternative paths to provide water to a particular node that can be used to address water demand when the main path is disrupted. In addition to topological redundancy, energy redundancy is a significant factor in water supply systems. A number of hydraulic characteristics of the network such as flow and head are essential to designing and managing the water system in compliance with the level of service required for water supply.

Criticality is another indicator that can affect water system robustness. Criticality assessment is usually applied element by element over the entire the network to identify how critical each element is in terms of the number of users being served. Pipes that serve greater numbers of users are more critical than pipes serving a small number of people. Therefore, the more critical pipes have greater impact on the water system’s robustness as a whole. When assessing the criticality of water system components, all assets should be measured against the same set of criteria. The severity of asset failure can be measured on a qualitative or a quantitative scale. Using interviews or questionnaires, the qualitative approach usually focuses on asset operators and technicians’ observations and opinions. In contrast, quantitative water asset criticality assessment measures the number of users who will lose water service when the asset fails. The more users losing water, the more critical the asset.

a. Social Indicators

A number of indicators have been identified that enable social factors affecting water supply resilience to be measured. Household reservoir capacity indicates the physical capacity of the community, while level of education represents and measures the level of skills and education within communities. The World Giving Index is used as an indicator for individual involvement in the community. The Giving Index itself is measured by three sub-indicators, namely helping strangers, donating money, and volunteering time.

There are two approaches to measuring violence: using formal reports of violence, and/or using perceptions of crime based on surveys of people living in the community. Recorded violence – the number of cases recorded by police – is subject to certain definitions of crime in different countries. Cultural barriers that prevent people reporting violence such as rape or domestic violence, lack of trust in police, and community structure are other reasons that can mean official reports are not fully indicative. On the other hand, the accuracy of studies into people's perceptions of violence and crime in the community is subject to sample selection and sample size. Although societal perceptions of violence and safety are highly correlated with official police statistics, they are not necessarily equivalent. However, we argue that in the context of resilience, people act based on their perception of violence rather than according to statistics and reports. For this indicator, we consider both formal reports and societal perceptions of crime.

A variety of indicators are used to measure crime levels. However, due to the nature of crime and lack of globally-agreed definitions for different crimes, extra care should be taken when working with relevant indicators. For instance, rape and domestic violence are two well-known indicators of violence levels within communities, but neither are utilised in this study. Rape was rejected because definitions of rape vary significantly. While marital rape is not recorded in most countries, it is considered a crime in countries such as Sweden. Domestic violence was not chosen either as the number of domestic violence incidents reported to police is far less than the actual number of incidents in the home, and so there are no accurate statistics.

Four sub-indicators were therefore chosen to measure reported crime levels: burglaries, robberies, assaults, and murders. Concern over being robbed, concern over being physically attacked, the problem of people using and dealing drugs, and feelings of corruption were used as sub-indicators to measure social perceptions of crime.

Four major indicators were chosen to measure trust: public trust, trust in neighbourhood, inverse trust in police, and inverse trust in army, as measured in surveys collected by the World Values Survey.

In this study, we argue that level of violence in society, as indicated by both police statistics and perceptions of violence, is reflected in public levels of trust, as well as trust in the police. Similarly, one can argue that the level of individual involvement in society is affected by levels of trust and perceptions of safety.

b. Economic Indicators

When it comes to the economic dimension, the indicators are more quantitative, and there is more data available. GDP per capita is the indicator chosen to measure economic capacity. It has been claimed that per capita GDP is an appropriate indicator for overall safety and additional protection against disasters, as demand for safety increases with residents' income level. Per capita GDP is an indicator of a country's standard of living based on gross domestic product (GDP) divided by the number of people in that country.

Quick access to finance has been defined as an indicator for how fast companies can access money following a disaster. As shown by previous disasters, quick access to funds during the restoration phase is more important than the quantity of funding. A number of financial instruments have been designed for both the international and local levels. These instruments include but are not limited to: budget contingencies, reserves and contingent debt facilities (e.g. CAT DDO), parametric insurance, alternative risk transfer (e.g. CAT bonds), and traditional insurance (indemnity-based) in the ex-ante phase; and donor support (recovery and reconstruction), budget reallocation, domestic credit (bond issue), and external credit (e.g. emergency loans, bond issues) in the ex-post phase. The literature review and experience from past disasters show that, in general, ex-ante instruments provide quick access to funds although the quantity of funds may not be necessarily large. Ex-ante instruments also appear more reliable in terms of quantity and accessibility.

c. Organisational Indicators

Table 9-1 shows all the factors, indicators, and sub-indicators developed in this study. Seventeen organisational indicators are identified in this study to measure six organisational factors. The indicators are early warning system (EWS), hazard identification, business continuity plans (BCP), disaster mitigation plans (DMP), emergency response plans (ERP), personnel training and exercises, mutual aid and assistance, availability and accessibility of databases, communication and information sharing, spare critical parts and equipment and their accessibility, availability of critical staff, regular maintenance, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption.

Five indicators are identified to measure the factor pre-disaster planning, namely hazard identification, the availability and effectiveness of a business continuity plan, disaster mitigation plan, and emergency response plan, and personnel training and regular training exercises.

There is no governance indicator specific to water sectors. Therefore, national level governance indicators are the best instruments to use. This study uses the Worldwide Governance Indicators (WGI) developed by the World Bank and covering over 200 countries from 1996.

Although WGI indicators do not directly assess governance of water sectors, they are assumed to appropriately represent different sectors including the water sector.

The WGI comprises six indicators, namely voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption. These indicators are measured based on several hundred variables obtained from over 30 different data sources. The indicators assess governance based on perceptions in the public sector, commercial business data and information provided by NGOs and other individual and business respondents across the globe. Among these indicators, voice and accountability is irrelevant to the water sector as it captures citizens’ ability to participate in selecting their government, freedom of expression, freedom of association, and a free media.

Table 9-1: Summary of Factors, Indicators, and Sub-indicators for Measuring Water Supply Resilience

Dimension	Measure/Factor	Indicator	Sub-indicators
Organisational	Disaster Precaution	Early Warning System (EWS)	N/A
	Pre-disaster Planning	Recognition (Hazards are identified)	N/A
		Business Continuity Plan (BCP)	N/A
		Disaster Mitigation Plan (DMP)	N/A
		Emergency Response Plan (ERP)	N/A
		Personnel training and exercises	N/A
		Mutual aid and assistance	N/A
	Data Availability, Accessibility, and Information Sharing	Availability and accessibility of databases	N/A
		Communication and information sharing	N/A
	Staff, parts, and equipment availability	Spare critical parts and equipment and their accessibility	N/A
		Availability of critical staff	N/A
	Pre-disaster maintenance	Regular maintenance	N/A
	Governance	Political Stability	N/A
		Government Effectiveness	N/A
		Regulatory Quality	N/A
		Rule of Law	N/A
		Control of Corruption	N/A
Social		Households' reservoir capacity	N/A

Dimension	Measure/Factor	Indicator	Sub-indicators
	Individual demands and capacities	Average knowledge and skill level of the community	Level of Education
	Individual Involvement in the community	Giving Index	Helping Stranger
			Donating Money
			Volunteering Time
	Violence level in the community	Crime Rate	Burglaries, Robberies, Assaults, Murders
		Social Perception of Crime	Perception of Crime Level, being robbed, physically attacked, dealing with drugs, corruption
		Social Perception of Safety	Feeling safe walking during day and at night
	Trust	Most people can be trusted	N/A
		Trust your neighbourhood	N/A
		Trust people you know personally	N/A
		Inverse trust in army	N/A
		Inverse trust in police	N/A
Economic	Economy Capacity	Country's GDP per capita	N/A
	Water companies' financial situation and insurance	Quick access to finance	N/A
		Insurance	N/A
Technical	System performance immediately after disaster (robustness)	Water system components' vulnerability	N/A
		Redundancy	N/A
		Criticality	

9.2.5. How to combine indicators to measure resilience?

The important technical, social, organisational, and economic factors, indicators and sub-indicators for measuring water supply resilience have been gathered in this study, and their correlation analysed. Measuring water supply resilience, however, requires other steps that are specified in the framework to be taken. In the next step, the indicators need to be standardised and weighted to accurately assess their relevance. Weighting the indicators and factors should be undertaken by means of a series of interviews (at least 30 experts).

In the following step, appropriate data from several case studies needs to be gathered to test and verify the framework and the indicator and factor weights. The barrier of lack of data can be overcome by means of involving local experts who have the required data and information.

CHAPTER 10 - FUTURE STUDY

The current chapter is based on the following article:

Balaei, B., Wilkinson, S., Potangaroa, R., McFarlane, P. (2018) "An Innovative Approach to Measuring Resilience Based on Post-Earthquake Water Demand", In Proceeding of 60th Water New Zealand Annual Conference, Hamilton, New Zealand

10.1. Introduction

In the first decade of the twenty-first century, an average of 384 disasters were reported annually, resulting in an average of 106,891 victims per year. During the same period, approximately 45.5 per cent of victims and 20 per cent of total damage caused by natural disasters resulted from geophysical incidents (Guha-Sapir et al., 2012). Further damage and losses were caused by the Tohoku tsunami and earthquake in Japan in 2011 and showed clearly how unpredictable and destructive such catastrophes can be.

Post-disaster water supply has always been of significant concern for the authorities in disaster-prone countries (Makropoulos et al., 2018). Water needs to be available without interruption in all of the four stages following an earthquake – emergency, survival, operational, and full recovery (normal) stages – addressing the target levels of service. Figure 10-1 shows the prioritised activities – emergency, survival, and operational stages – that need water after an earthquake.

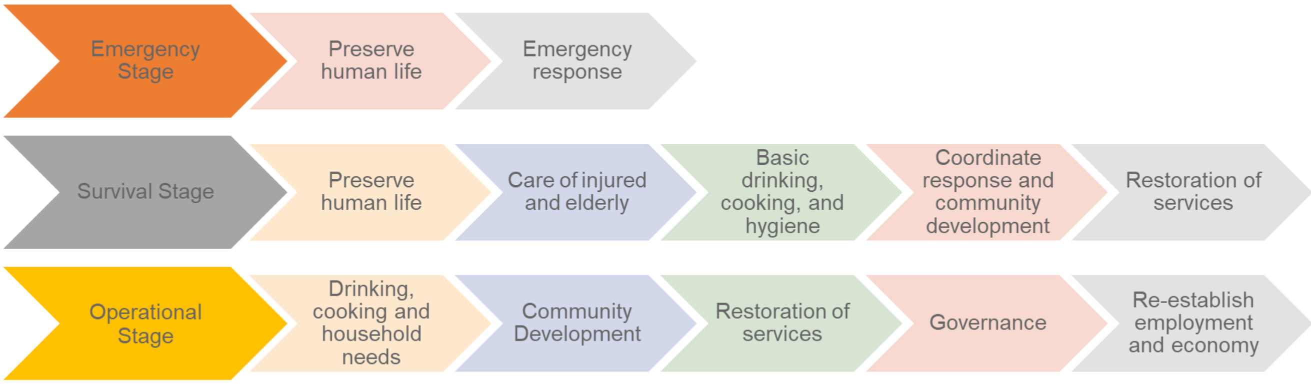

Figure 10-1: Main Activities Requiring Water Following an Earthquake (Opus International, 2017)

As noted by Opus International (2017), the first two stages (the emergency and survival stages) focus on supplying water to preserve human life, and for emergency responses, healthcare activities, and basic drinking, cooking and hygiene needs. These two stages comprise the post-disaster restoration phase in which basic and crucial needs require a response from water companies or other relevant authorities. The third phase, the operational stage, focuses on the re-opening of businesses and governance while the first two stages' water demand also need to be addressed.

Low *water consumption* following earthquakes does not represent low *water demand*. Water demand is more severe after an earthquake, but the water companies or other emergency sectors are not able to distribute sufficient quantity and quality of water to address the water demand and this is why the activities are prioritised. Damaged infrastructure, limited water resources capacity, and transport challenges are the main cause of a lack of water in an earthquake-struck area. As such, water consumption declines following earthquakes despite the increased water demand.

The resilience of a water supply system is defined as the ability of the system to withstand an earthquake and to recover to a normal level of functionality in a timely manner (Balaei et al., 2018). The concept of resilience complemented the single dimensionality of *risk* by envisaging the functionality of the system over time. *Functionality* can be defined depending on how the researcher is envisaging the system. One of the most common measurements for functionality considers how many people are receiving the service, in this case, *water* service, following an earthquake.

However, water demand is not considered in the resilience equation although the concept is basically user-centred. To bridge this gap, this study proposes an innovative approach to measure resilience based on water demand following an earthquake. In this paper, functionality is defined based on water flow in the aftermath of an earthquake. The demand-based resilience measure puts more emphasis on earthquake preparation planning to ensure the preparation measures such as resourcefulness and redundancy meet the post-earthquake water demand. The proposed measure in this paper was developed based on a review of previous research, and the method verified for the case of Christchurch following the 2011 earthquake.

10.2. Water supply vulnerability

Due to their wide-spread nature and inherent vulnerability, water supply systems can be severely affected by earthquakes. Earthquakes can cause water outage or declined levels of service due to damage to different components of water supply systems as follows (AWWA, 2001):

- Personnel shortage – earthquakes can cause personnel shortage due to their death or injury both to themselves or their families, evacuation, or other personal reasons.
- Water contamination – earthquakes can cause contamination of the raw and/or purified water supply. Excessive sediment can enter a water intake, reservoir, or any open water system due to landslides or other earthquake-induced secondary hazards.
- Air contamination – release of chlorine is a significant risk for water treatment plants where chlorine gas is in operation to purify water. Air contamination due to chlorine release can impact water system personnel severely and cause injury or death.

- Water-well damage – ground shaking can result in pipe joint break/separation and sand entering water wells. Water-well casing is also prone to bending by lateral spread. The pumps are prone to shattering from the ground shaking.

- Pipe breakage – pipe breakage presents significant challenges following an earthquake. Pipe breakage can interrupt water supply and affect water pressure within the network. The pipe breakage happens due to bending, shearing, tension (joint separation), compression (joint break), and structural collapse.

- Structure damage – dams, water intakes, water treatment plants, pump stations, storage tanks, offices, and spare parts warehouse are prone to damage due to ground shaking and/or ground failure. Structural damage can cause damage to the equipment and material and make the structures inaccessible following an earthquake.

- Power outage – electrical elements of the water supply system can fail to function in a power outage. These elements include, but are not limited to, pumps and computers.

- Communications disruption – both automatic signal equipment (telemetry) and people communication (telephones and radios) can be affected by an earthquake. Apart from physical damage, communication systems can be affected by power outages.

- Transport failure – transport failure can occur due to bridge damage, fallen debris, collapsed overpasses, etc.

Although the social, organisational, and economic factors impact on water supply systems' resilience, this paper focuses on the technical dimension of the system.

Drinking water outage, however, is not the only impact of seismic events in urban areas; other impacts can include conflagration, interruption to medical services, business continuity disruption, and other disruptions to daily life. For example, the fire following the Kanto earthquake of 1923 (which killed tens of thousands of people in Tokyo), grew because of a lack of water due to water-main breakages and to other environmental conditions like wind and high temperatures (Scawthorn et al., 2005).

10.3. Water Demand

Water supply resilience is measured based on the volume of water being accessed by users following an earthquake. The volume of water being consumed by users is equivalent to water demand. Water demand is not constant over time. The factors affecting water supply demand (IPWEA, 2015) include:

- Population growth
- Land use development patterns
- Economic development
- Government policy
- Visitors and the tourism industry
- Environmental changes (e.g. climate change)
- Increases in levels of service – additional supply areas previously not serviced
- Customer performance (increased consumption trends)

Obviously, changes in population – either growth or decline – are the most important drivers for water demand. The population can change due to birth, mortality, migration and other factors such as environmental changes, political conditions, or government policies. Growth is also affected by urban development. Several factors contribute to the composition of urban forms including land use, density of residential development, natural features, and general terrain. Figure 10-2 shows Christchurch population growth forecast by 2030.

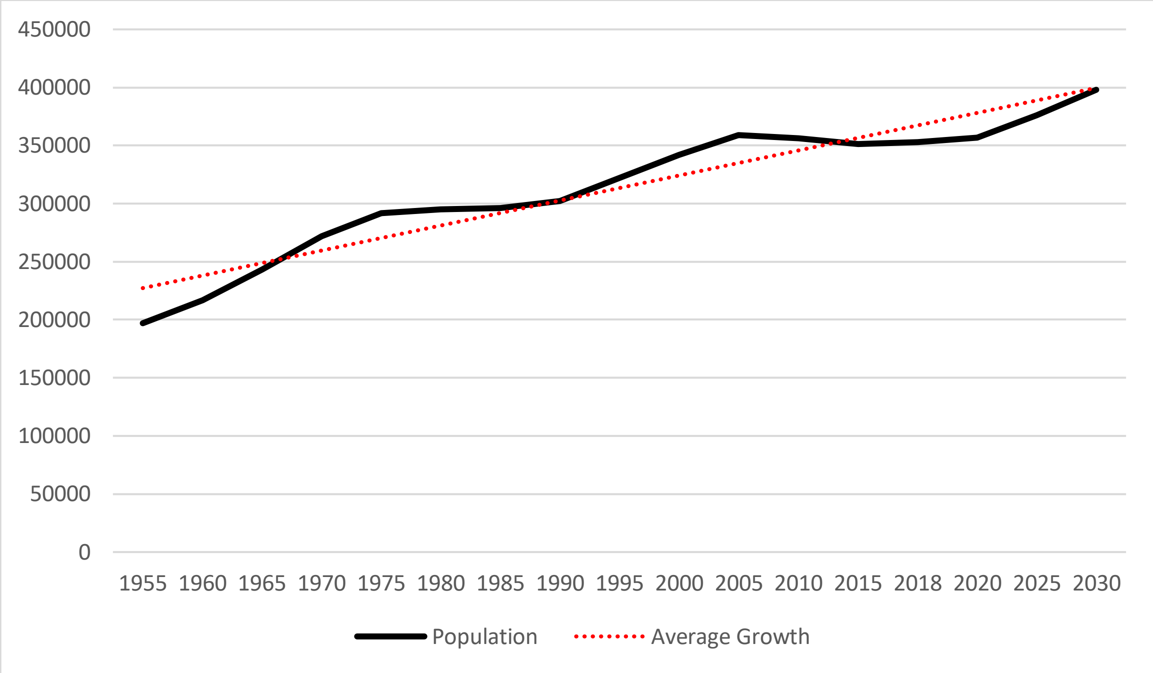

Figure 10-2: Christchurch Growth Forecast

As the water supply demand is dynamic, the resilience of water supply systems need to be defined in a dynamic way to reflect demand at any given time. Thus, the water supply capacity to address the water demand and targeted levels of service is time-dependent. Therefore, a resilient water supply system is not guaranteed to remain resilient over a particular time period.

Although water is undoubtedly required for almost all activities following an earthquake, some water-related activities are prioritised over others. These priorities need to be established to enable the authorities to plan properly for the post-earthquake water supply (AWWA, 2001).

Most healthcare and medical facilities need to be continuously functional following an earthquake. They need to be contacted by the water companies or consultants to identify their average daily water requirements. Fire Departments, police, and emergency management agencies are also prioritised to be supplied with enough water (AWWA, 2001). Table 10-1 shows the minimum water quantity and quality and the duration that water is required to be provided for the activities following an earthquake.

Table 10-1: Post-earthquake Water Supply Requirements (Opus International, 2017)

Purpose of LOS	Amount, Quality	Location, user supplied	Duration
Firefighting	SNZ PAS 4509:2008	Priority locations	▪
Emergency Response	20l/p/d SNZ PAS 4509:2008	Civil defence centres; Emergency operation centres; Ports, airports & other lifelines	2 days
Loss of life, emergency response – fire fighting	SNZ PAS 4509:2008	Relocation areas; Hospitals; Aged care centres; Prisons; Ports, airports & other lifelines; Civil defence centres; Emergency operation centres	3 days
Care of injured, elderly and others who cannot be moved	60l/p/d, potable SNZ PAS 4509:2008	Hospitals	3 days
	20l/p/d, potable SNZ PAS 4509:2008	Aged care centres Prisons	3 days
Drinking, cooking, basic hygiene	20l/p/d SNZ PAS 4509:2008	Relocation centres	3 days
	20/l/p/d	Within 500-1000m of households	3 days
	20l/p/d, potable	At household	▪
Community development, Education	20l/p/d, potable Firefighting at SNZ PAS 4509:2008	Schools	▪
Community development – meeting places	Potable water at pre-earthquake quantity, Firefighting at SNZ PAS 4509:2008	Community meeting places, e.g. cafes, sports centres	▪
Governance	Potable water at pre-earthquake quantity, firefighting at SNZ PAS 4509:2008	Central & government facilities	▪
Employment	Potable water at pre-earthquake quantity, firefighting at SNZ PAS 4509:2008	Shopping, business and industrial areas	▪
Housekeeping	70l/p/d, potable	Households	▪

10.4. Water supply resilience

The notion of resilience has captured the attention of a wide range of scholars in diverse disciplines. The concept of community resilience to disasters was proposed in the 21st century although it was introduced by Holing in ecology earlier in 1973 (Holling, 1973). Klein et al. defines resilience as a desirable property of natural and human systems in face of potential stresses and investigates the concept of resilience to weather related hazard as an example of natural hazards in coastal megacities. Through their study, Klein et al. recommend resilience to be used in a “restricted sense: to present specific system characteristics that discusses (1) the ability of the system to absorb disturbance and still function acceptably, and (2) the system’s self-organisation capability” (Klein et al., 2003).

A significant number of researchers have developed conceptual frameworks to measure community resilience from various perspectives. According to Norris et al. (2008), resilience can be understood as a set of network adaptive capacities, namely economic development, resource equity, social capital, and information and communication. Similarly, Cutter et al. (2008) proposed the DROP framework and model—Disaster Resilience of Place — to conceptualise disaster resilience at the community level. The DROP model demonstrates how resilience capacities (coping, adaptive, and absorptive) influence the degree of recovery and resilience of the community. It also includes six groups of indicators: ecological, social, economic, institutional, infrastructure and community competence, to quantify a community’s overall resilience.

This study refers to Balaei et al. (2018) to define resilience as the ability of water supply system to withstand the external shock (earthquake) and recover to a normal level in a timely manner. The magnitude of an earthquake, the vulnerability of the built environment, and user needs determine water supply capacity and dictate water requirements. Water leakage is a significant issue following an earthquake. Indian Ocean earthquake and tsunami caused 60% water leakage in Banda Aceh and had a significant adverse impact of water supply capacity. Water leakage not only decreases system capacity, it also increases water demand as the water companies have to pump excessive water into the network to address the basic needs of post-earthquake emergency activities such as firefighting, healthcare, or emergency activities.

Fire following an earthquake should not be taken lightly. Post-earthquake firefighting has always been a challenge for the authorities. After the Napier earthquake in 1931, firefighting became impossible as underground pipes had cracked and broken (Napier Council, 2018). Conflagration in San Francisco after the 1906 earthquake caused the largest life and economy loss in US history (Usami, 1996). Statistics show that 59 ignitions occurred after the earthquake and the fire department was faced with difficulties as the water supply was interrupted due to ground failure (mostly liquefaction and lateral spreading) and ground shaking. Water reservoirs were located in the intense fire zones and contained 6 per cent of the system's capacity (21 million litres). However, the fire department could not use the whole capacity as the volume of water was less than expected due to breaks and the limitations caused burning and collapsing buildings.

Firefighting, however, is not the only driver for increased water demand following an earthquake. Water provision needs to be increased to compensate for the leakage in the network. Some activities such as those in healthcare systems need to be provided with enough uninterrupted water quantities (Chang et al., 2002). When it has been decided that no live people are trapped underneath the debris, water is required to settle down the dust and toxic fumes which are released from burning materials such as asbestos. These vaporised materials are dangerous for the residents as well as to rescue workers' health. To deal with this and in regard to water leakage in the network, extra quantities of water are needed to be pumped into the network.

The Christchurch earthquake of 22 February 2011 is a good example of what happens to the water demand and capacity following earthquakes. Pre-earthquake peak day demand (in 2009) was 6,674 m3/hr. When the earthquake occurred, the peak demand increased significantly due to leakage, firefighting activities, and increasing hospital activities. Leakage caused a water flow increase of 43 per cent on average so the estimated peak flow following the earthquake reached 10,440 m3/hr (Johnson & O'Neill, 2012). There is no data on how much activities such as firefighting or hospital requirements increased water flow. In this paper, it is assumed that these activities increased by 20 per cent of flow following the earthquake (AWWA, 2001). Then, the peak flow is estimated to be 11,770 m3/hr.

Additionally, 22 wells were damaged and caused loss of capacity in the aftermath of the earthquake. Well-pump available flow rate (excluding wells out of service) was 9,495 m3/hr. As the aquifers normally serving Christchurch with drinking water are under pressure, extracting water from water wells is fairly easy and cheap. The delivery pump available flow rate reduced by 3,110 m3/hr to 7,790 m3/hr (Johnson & O'Neill, 2012). The city had predicted spare capacity to address future disturbance and external shocks in the water system. However, the earthquake depleted the extra capacity and caused loss of levels of service following the earthquake.

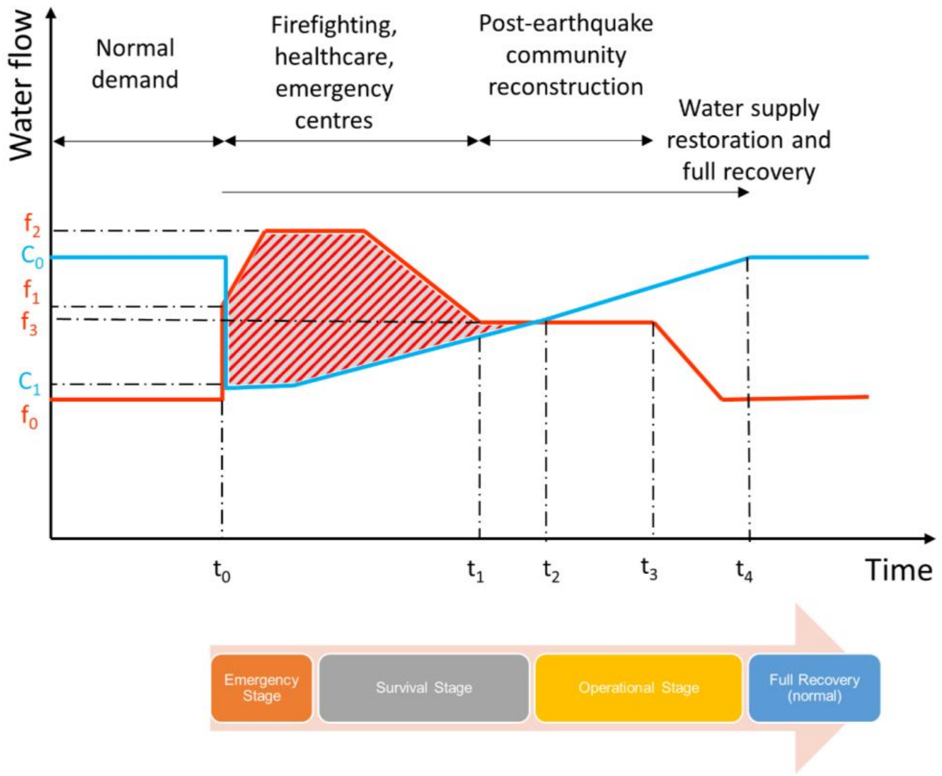

Figure 10-3: Water Supply Resilience based on Water Demand

Figure 10-3 shows a schematic view of water system resilience to seismic events. Traditionally, resilience was calculated by means of measuring the area under the blue line, which is water supply capacity over time following an earthquake, as follows:

$$Resilience = \frac{\int_{t_0}^{t_4} C_t \, dt}{(t_4 - t_0).C_0}$$

In which C_t is the water supply capacity, t_0 is the time of earthquake happening, t_4 is the time when water supply system recovery is completed, and C0 is the water supply capacity prior to the earthquake.

The post-earthquake water supply capacity (Ct) drops due to damage to pipes, reservoirs, pumps, water intakes, etc., when an earthquake happens. Lessons learnt from previous earthquakes reveal that buried lifelines' restoration is delayed as a result of other lifelines' damage (transport, communication, electricity), local traffic, and shortage of restoration crews.

The post-earthquake capacity after full recovery may be less, equal, or more than pre-earthquake water supply capacity.

However, what is not paid attention to in this definition is the water demand following an earthquake. As can be seen from the graph, the water demand (shown by red line) increases in the aftermath of the earthquake due to leakage in the system (from f0 to f1). Afterwards, some activities such as firefighting, healthcare, and emergency centres' activities increase compared to the pre-earthquake situation and water demand (and consumption) increases from f1 to f2. The post-earthquake emergency activities and water demand to address those activities fluctuate and on average, it can be said that water demand remains constant for a few days, depending on the condition of the earthquake, vulnerability of the community, etc. (at f2 level). Then, water demand starts to decline when emergency and survival stages are passed (to the level of f3).

In this stage, post-earthquake community reconstruction starts (t1) and the quantity of water demand varies depending on the dominant building type (e.g., concrete, steel, wood, etc.). By the end of the community reconstruction and recovery phase, water demand decreases to a new normal level.

The new normal level of water demand is usually greater than pre-earthquake water demand. If sufficient funding exists, authorities prefer to take the opportunity to renew the parts of the network that are past their useful life or are in poor condition and are due/overdue to be renewed. In addition, previous earthquakes show that earthquakes affect the labour market over both a short- and long-term period (Higuchi et al., 2012). In the short term, communities experience labour shortages but increasing salaries and wages encourage people to migrate to the earthquake-struck area for a higher income (Belasen & Polachek, 2009; Sarmiento, 2007). Canterbury's contribution to New Zealand's Small and Medium Enterprises (SME) employment experienced its lowest record in 2011 (the year when Christchurch earthquake happened) and 2012 with 12.3 per cent and 12.4 per cent respectively. A portion of this decline in the levels of employment (including the water sector) was because the employees moved to other cities for a variety of reasons such as accommodation costs (IRD, 2015). Increased numbers of residents, per se, results in higher water demand in the long term. However, there are a few cases that water demand's post-disaster new normal was lower than pre-earthquake water demand.

Based on the above explanation, water supply resilience in this study is estimated as follows:

$$Resilience = \min\left(\frac{\int_{t_0}^{t_2} C_t \, dt}{\int_{t_0}^{t_2} f_t \, dt}, 1\right)$$

In other words,

$$Resilience = \begin{cases} \dfrac{\int_{t_0}^{t_2} C_t \, dt}{\int_{t_0}^{t_2} f_t \, dt} & if\ capacity < demand \\ 1 & if\ capacity \geq demand \end{cases}$$

in which f_t is the water demand at time t.

When water supply capacity is equal to, or higher than, water demand, the community will not experience water shortage, then resilience is equal to one. If water supply capacity is less than water demand, it means that the users are not receiving enough quantities of water following the earthquake. In this case, water supply resilience is estimated by dividing the water supply capacity by water demand.

To measure resilience of water supply at time t, we have to consider the target levels of service to be addressed for the same time as water demand and system capacity changes over time. Referring to Christchurch earthquake in February 2011, as can be seen from Figure 10-2, Christchurch population has been increasing over time. Then, the same state of damage in the water supply system will cause more people losing water services and lower index for resilience of the water system will be obtained.

10.5. Conclusions

This study presented a novel approach in measuring water supply system seismic resilience based on water demand. In this approach, water demand is compared to water supply capacity to measure the water system's capacity in addressing the water demand following an earthquake. The authors believe that post-earthquake water demand increases in a short-term due to water leakage and emergency activities such as firefighting and hospital water requirements. In the same period and when water demand increases, water supply capacity declines. The difference between water supply capacity and water demand is considered as the actual lack of resiliency compared to the traditional definition which envisages only the capacity drop as the lack of resiliency of the system.

The proposed method is conceptual and need to be tested and verified based on real data from earthquakes. The existing data from previous earthquakes do not show accurate increase in water demand due to different activities such as firefighting or healthcare. There are also uncertainties in predicting quantity of water needed for firefighting as it highly depends on a number of factors that cannot be controlled such as wind that can spread out the fire significantly.

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APPENDIX A – SOCIAL INDICATORS

Table A-1: Value of Perception of Crime and Safety over the Globe (Numbeo, 2018)

	Crime					Safety	
Country	**Perception of crime level**	**Concern over being robbed**	**Concern over being physically attacked**	**Problem of people using and dealing drugs**	**Feeling of Corruption**	**Feeling of safety walking during day**	**Feeling of safety walking during night**
Afghanistan	70.56	66.49	59.04	64.89	72.28	46.28	32.98
Argentina	73.06	70.4	17.75	64.49	84.84	60.06	24.89
Bangladesh	73.42	69.97	40.41	68.04	89.42	49.06	24.84
Cambodia	53.73	55.88	25.37	58.82	80.15	73.53	39.55
Chile	50.52	51.46	21.97	47.57	44.05	75.21	43.15
Concepcion (Chile)	45.83	43.75	12.5	56.25	45.83	81.25	41.67
China	47.01	47.83	42.68	45.82	67.19	58.49	49.45
Egypt	52.35	53.93	31.08	55.39	78.81	72.84	49.07
Estonia	15.19	15.6	18.66	29.08	29.14	95.77	73.59
Ethiopia	44.39	50	29.33	39.22	75.49	71.63	42.31
Honduras	86.79	84.26	52.52	84.03	88.41	24.77	11.01
India	46.21	42.03	27.08	37.67	68.52	74.06	50.82
Iraq	45.61	40	39.38	33.82	62.71	63.96	52.52
Italy	47.15	43.94	25.2	50.11	62.23	77.4	51.06
Japan	10.7	10.4	12.76	12.46	15.4	90.77	87.85
Namibia	NA	NA	NA	NA	NA	NA	NĀ
New Zealand	42.68	32.62	27.17	49.69	22.56	78.94	49.39
Singapore	NA	NA	NA	NA	NA	NA	NA
Christchurch (NZ)	40.23	24.21	19.53	42.31	21.37	79.69	46.92
South Africa	83.63	77.56	62.03	72.42	85.69	38.89	11.55
Turkey	42.1	38.77	29.42	37.13	58.5	75.25	49.85
UK	46.68	39.46	29.3	55	27.64	76.71	50.08
United States	52.81	41.62	31.12	59.99	42.67	73.02	44.4
Germany	35.58	34.04	27.13	43.4	26.46	79.51	59.62
Myanmar	48.81	37.5	40.62	55.43	82.29	73.91	41.3
Haiti	73.44	70.31	31.25	59.38	89.06	42.65	15.62
Iran	50.63	48.35	20.18	58.88	71.45	73	44.43

Table A-2: Crime Rate over the Globe (Knoema, 2018)

	Per 100,000			
	Assault Rate	**Burglary Rate**	**Kidnapping Rate**	**Rubbery Rate**
Afghanistan	NA	NA	NA	NA
Argentina	415.6	NA	NA	NA
Bangladesh				
Cambodia	NA	NA	NA	NA
Chile	98.3	687.2	1.5	598.7
China	NA	NA	NA	NA
Egypt	NA	NA	NA	NA
Estonia	5.9	NA	NA	27.4
Ethiopia	NA	NA	NA	NA
Honduras	NA	NA	NA	NA
India	NA	NA	NA	NA
Iraq	83.2	0.6	3.7	NA
Italy	110.7	NA	0.5	97.6
Japan	21	73.8	0.2	2.4
Namibia	NA	NA	NA	NA
New Zealand	220.2	NA	5.2	44.9
Singapore	9.3	5.7	NA	4.2
South Africa	NA	NA	NA	NA
Turkey	NA	NA	NA	NA
UK	NA	NA	NA	NA
United States	228.9	536.3	NA	101.1
Germany	155.9	553.1	6.2	56.4
Myanmar	10.3	0.1	NA	NA
Haiti	NA	NA	NA	NA
Iran	NA	NA	NA	NA

Table A-3: Level of Education over the Globe (UNDP, 2015)

Country	Mean years of school
Afghanistan	3.2
Argentina	9.8
Bangladesh	5.1
Cambodia	4.4
Chile	9.8
China	7.5
Egypt	6.6
Estonia	12.5
Ethiopia	2.4
Honduras	5.5
India	5.4
Iraq	6.4
Italy	10.1
Japan	11.5
Namibia	6.2
New Zealand	12.5
Singapore	10.6
South Africa	9.9
Turkey	7.6
UK	13.1
United States	12.9
Germany	13.1
Myanmar	4.1
Haiti	4.9
Iran	8.2

Table A-4: Giving Index over the Globe (Charities Aid Foundation, 2015)

Country	Giving Index	Helping Stranger	Donating Money	Volunteering time
Afghanistan	28	45	24	15
Argentina	29	49	22	15
Bangladesh	29	54	19	14
Cambodia	23	22	37	10
Chile	36	51	43	15
China	18	36	13	6
Egypt	21	40	15	7
Estonia	23	36	16	18
Ethiopia	29	52	14	21
Honduras	33	46	21	32
India	29	36	28	21
Iraq	39	75	24	18
Italy	29	47	28	9
Japan	26	26	24	28
Namibia				
New Zealand	58	69	62	44
Singapore				
South Africa	40	64	23	33
Turkey	18	38	12	5
UK	55	61	74	29
United States	64	79	68	44
Germany	42	58	42	25
Myanmar	64	49	91	51
Haiti	39	45	44	29
Iran	46	62	52	24

Table A-5: Trust Value over the Globe (World Value Survey, 2018)

	Most people can be trusted		Trust your neighbourhood					Trust people you know personally				Inverse Trust in Army					Inverse Trust in Police				
Country	**Most people can be trusted**	**Need to be very careful**	**Trust completely**	**Trust somewhat**	**Trust neighbourhood**	**Do not trust very much**	**Do not trust at all**	**Trust completely**	**Trust somewhat**	**Do not trust very much**	**Do not trust at all**	**0**	**0.33**	**Army Invest Trust**	**0.66**	**1**	**0**	**0.33**	**Police Inverse Trust**	**0.66**	**1**
Afghanistan	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Argentina	19.2	77.5	22.9	47.6	70.5	23.3	5.2	29.2	50.7	14.6	4.4	6.1	22.7	28.8	43.9	23.1	4.1	20.9	25	42	32
Bangladesh	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cambodia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Chile	12.4	84.7	15.6	49.2	64.8	26.5	6.4	18.9	51	21.7	4.8	15.4	39.8	55.2	31	13	18.8	45.1	63.9	26.3	8.7
China	60.3	35.2	19	59.4	78.4	14.1	0.7	13.3	58.6	17.7	1.6	33	51	84	5.5	1.3	18	48.6	66.6	21.4	2.8
Egypt	21.5	78.5	55.9	33.5	89.4	8.4	2.1	61.3	34	4.4	0.2	0	0	NA	0	0	11.1	39.2	50.3	25.6	23.9
Estonia	39	58.3	19.5	52.6	72.1	20.3	5.6	24.4	66.7	7.9	0.4	19.3	50.5	69.8	19	7.3	19.7	57.4	77.1	17.2	4.8
Ethiopia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Honduras	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
India	16.7	77.9	34.1	52.6	86.7	10.2	2.5	30.1	47.7	16.8	3.9	51.8	30.2	82	9.4	2.7	23.2	25.9	49.1	29.8	17
Iraq	30	63.8	38.2	50.2	88.4	10.4	0.9	25.7	55.2	16.8	1.9	21.5	39.2	60.7	27.7	10.9	18.2	39.2	57.4	27.3	14.2
Italy	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Japan	35.9	56.8	3.8	52.3	56.1	29.9	5	11.7	69.3	13.4	1.4	12.5	54.6	67.1	18.7	2.5	11.2	57	68.2	22.3	3.6
Namibia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
New Zealand	55.3	42.1	NA	NA	NA	NA	NA	NA	NA	NA	NA	20.3	55.8	76.1	14.1	2.3	27.6	50.9	78.5	14	2.9
Singapore	37.3	62.5	18	60	78	19.3	2.7	30.8	59.1	9	1	24.8	52.4	77.2	20.6	2.2	24	55.4	79.4	18.3	2.3
South Africa	23.3	76.2	23.9	49.7	73.6	17.8	7.4	19.9	45.2	21.7	11.3	14.6	33.1	47.7	30.9	16.7	14	31.3	45.3	31.8	19.4
Turkey	11.6	82.9	36.9	48.5	85.4	12.2	1.6	31.9	46.9	16.7	3.7	43.5	30.4	73.9	14.7	9.1	37.8	36.6	74.4	14.4	9.8
UK	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
US	34.8	64.3	8.1	63.9	72	20.8	5.7	30.2	60.5	6.6	1.2	35.1	46.5	81.6	12.8	3.7	16.5	51.8	68.3	24.3	5.7
Germany	44.6	53.8	14.3	59.2	73.5	21.1	5.1	18.1	70.3	10.2	0.8	11.5	52.1	63.6	27.5	5.5	22.3	59.4	81.7	13.6	3.6
Myanmar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Haiti	21.3	77.2	4.4	28	32.4	35.8	29.2	8.7	34.9	29.4	24	1.7	3.9	5.6	29.3	62.5	0.5	3.8	4.3	53.8	39.6

	Most people can be trusted		Trust your neighbourhood					Trust people you know personally				Inverse Trust in Army					Inverse Trust in Police				
Country	Most people can be trusted	Need to be very careful	Trust completely	Trust somewhat	Trust neighbourhood	Do not trust very much	Do not trust at all	Trust completely	Trust somewhat	Do not trust very much	Do not trust at all	0	0.33	Army Invest Trust	0.66	1	0	0.33	Police Inverse Trust	0.66	1
Iran	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table A-6: Loadings of the indictors on first, second, and third principal components

Indicators	PC1	PC2	PC3
Giving Index	-0.185	-0.348	0.063
Helping Stranger	-0.264	-0.146	0.083
Donating Money	-0.060	-0.359	0.381
Volunteering time	-0.113	-0.349	-0.364
Perception of crime level	-0.296	0.104	0.100
Concern over being robbed	-0.292	0.108	0.149
Concern over being physically attacked	-0.269	0.173	-0.188
Problem of people using and dealing drugs	-0.294	0.067	0.082
Feeling of Corruption	-0.243	0.278	-0.005
Feeling of safety walking during day	0.275	-0.162	0.045
Feeling of safety walking during night	0.294	-0.113	-0.111
Mean years of school	0.068	-0.397	-0.226
Burglaries	-0.233	-0.161	-0.317
Assault	-0.273	-0.180	-0.078
Robberies	-0.141	-0.136	0.592
Homicide	-0.256	-0.009	-0.326
Trust neighbourhood	-0.073	0.330	-0.056
Army Inverse Trust	0.209	0.298	-0.057
Police Inverse Trust	0.242	-0.038	0.040

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